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A Human Factors Evaluation of a Methodology for Pressurized Crew Module Acceptability for Zero-Gravity Ingress of Spacecraft

Merri J. Sanchez, PhD
Lyndon B. Johnson Space Center, Houston, Texas

March 2000

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National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas 77058

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ABSTRACT

The purpose of this research was to develop a methodology for evaluating the performance and acceptability characteristics of the pressurized crew module volume suitability for zero-gravity (g) ingress of a spacecraft. The methodology was tested by performing an evaluation of the operational acceptability of the National Aeronautics and Space Administration (NASA) crew return vehicle (CRV) for zero-g ingress of astronaut crew, volume for crew tasks, and the general crew module and seat layout.

This research is significant because no standard or methodology has ever been established for evaluating volume acceptability in human spaceflight vehicles. Volume affects the astronauts' ability to ingress and egress the vehicle, to maneuver in the vehicle, and to perform critical operational tasks inside the vehicle. Much research has been conducted in the areas of aircraft ingress, egress, and rescue in order to establish military and civil aircraft standards. However, due to the extremely limited number of human-rated spacecraft, this topic has been unaddressed.

The NASA CRV was used for this study. The prototype vehicle can return a seven-member crew from the International Space Station in the event of a medical or Station emergency. The vehicle's internal arrangement must be designed to facilitate rapid zero-g ingress, zero-g maneuverability, ease of one-g egress and rescue, and ease of operational tasks in multiple acceleration environments. A full-scale crew module mockup was built and outfitted with representative adjustable seats, crew equipment, and a volumetrically equivalent hatch.

Human factors testing of this mockup was conducted in three acceleration environments (zero g, one g, and 1.8 g's) using ground-based facilities and the KC-135 aircraft. Performance and acceptability measurements were collected. Data analysis was conducted using analysis of variance and nonparametric techniques.

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ACRONYMS

AFB	Air Force Base
AFSC	Air Force Systems Command
AGARD	Advisory Group for Aerospace Research and Development
ANOVA	analysis of variance
cm	centimeter
CO_2	carbon dioxide
CRV	crew return vehicle
CTV	crew transport vehicle
deg	degree
DH	design handbook
DOD	Department of Defense
DRM	Design Reference Mission (DRM1 **-** returning an ill or injured crew member to Earth)
ESA	European Space Agency
fps	feet per second
ft	feet
g	gravity
HRPPC	Human Research Policy and Procedures Committee
in	inch
ISS	International Space Station
JSC	Johnson Space Center
kg	kilogram
LiOH	lithium hydroxide
m	meter
MIL	military
NAS	Naval Air Station
NASA	National Aeronautics and Space Administration
NASDA	Japanese Space Agency
NATO	North Atlantic Treaty Organization
nm	nautical mile
O_2	oxygen
SAE	Society of Automotive Engineers
sec	second
STD	standard
XCRV	experimental crew return vehicle

Chapter 1
INTRODUCTION

The crew of a human spacecraft experiences an unusual set of conditions ranging from the high loads of launch, to microgravity, to atmospheric entry, and landing. The costs of components to protect the crew in these environments are high. These factors drive a critical review of every aspect of the design of the crew station accommodations, far beyond what is practical or economical for Earth-based human activities (Roebuck, 1993). The United States has used five human spaceflight vehicles, including Mercury, Gemini, the Apollo Command Module, the Apollo Lunar Excursion Module, and the Space Shuttle. To date, no established standard or methodology has been developed to evaluate the acceptability of the pressurized crew module volume of any spacecraft (A. Nicogossian [Associate Administrator, NASA Headquarters, personal communication, 1999]; R. Williams [Chief Medical Officer, NASA Headquarters, personal communication, 1999]; L. Nicholson [Director, Engineering, JSC, personal communication, 1999]; and C. Berry [Apollo Flight Surgeon, Aerospace Medical Consultants, personal communication, 1999]). Instead, the vehicles are designed and sized to minimize structure, weight, volume, and to fit designated launch vehicles. This has left the pressurized volume available to the crew to be an artifact of the volume left over after systems equipment is installed. Human factors are the first compromise in spacecraft design, and are often not addressed until late in the design cycle.

This research effort focused on the development and testing of a methodology to evaluate the acceptability of the pressurized crew module volume for zero-gravity (g) ingress of a spacecraft. This research addressed both the short-term and long-term needs of crew module design and volume acceptability. The methodology has worldwide applicability for the evaluation of the civilian and military human spacecraft being designed by all space-faring nations. In the immediate future, the research will be the basis of National Aeronautical and Space Administration (NASA) evaluations for new spacecraft.

NASA is currently prototyping the X-38 experimental crew return vehicle (XCRV) spacecraft for use as a rescue vehicle for the International Space Station (ISS). This presents a unique opportunity to develop a methodology for evaluating volume acceptability using the X-38 XCRV crew module as a test bed.

Human factors analysis and evaluations were conducted during this research activity to complement the spacecraft design and development of the crew module. The XCRV design must meet the operational requirements specified by the ISS Program. These design reference missions (DRMs) are documented in SSP 41000, System Specification for the International Space Station, paragraph 3.2.1.1.7, and in SSP 50306, International Space Station (ISS) Crew Return Vehicle (CRV) Performance Requirements. There are three DRMs that must be satisfied. These include:

1. Emergency medical return of an ill or injured crew person.
2. Return of the crew in the event that the ISS is not habitable (i.e., the ISS atmosphere has become contaminated, the ISS cannot maintain internal pressure, the ISS cannot maintain attitude, or critical ISS utilities have irrecoverably failed).
3. Return of the crew in the event that the ISS cannot be resupplied.

1.1 Background

The X-38 XCRV is currently being developed by NASA at the Johnson Space Center (JSC). After delivery in the Shuttle's payload bay (uncrewed), the CRV will be berthed to the ISS via a tunnel adapter, providing the capability to return up to seven crew members in a shirtsleeve environment to any landing site in the world. An alternate interior configuration referred to as a crew transport vehicle (CTV) is being developed by the European Space Agency (ESA) and will be launched on an Ariane 5 booster (Moskwa, 1996). The CTV will be capable of transporting three crew members to orbit and returning up to four crew members to Earth.

The current design of the XCRV is a lifting body with 700 nautical miles (nm) cross-range capability, based on a modified X-24A airframe as shown in Figure 1. After delivery to the ISS, the vehicle will remain in a semi-dormant state, with regularly scheduled systems checkouts, until required to return crew members to Earth.

The X-38 is being designed to operate without input from the onboard crew or from the ground. Provisions will be made for limited crew control of autonomous functions and selected manual backup functions. Mandatory crew functions in the spacecraft will include closing and sealing the hatch (can be accomplished from inside or outside); activating the autonomous system; unwrapping and installing lithium hydroxide (LiOH) canisters to scrub carbon dioxide (CO_2) from the crew module atmosphere; and monitoring selected systems' performance. The spacecraft currently has a systems lifetime of nine hours, which will allow a landing anywhere in the world, with at least two landing sites available at all times.

Figure 1. CRV during reentry.

When used as a rescue vehicle, the CRV will separate from the ISS, perform a deorbit burn, then eject the propulsion module from the spacecraft to ensure personnel on the ground (crew or rescue) are not exposed to toxic chemicals. After reentering the Earth's atmosphere and slowing to below Mach 1, a parachute sequence (pilot, drogue, and main parachutes) will be initiated that results in deploying a steerable 7,500-ft^2 parafoil when the vehicle is 15,000 ft over the landing site. The X-38 atmospheric flight test vehicle in parafoil flight is shown in Figure 2.

The drogue deploy loading is calculated to be 3.5 g's for 0.5 sec. The vehicle will land with approximately 10 ft per sec (fps) vertical speed and 35 fps horizontal speed. The unfiltered peak landing forces of the vehicle are estimated to be approximately 12 g's for less than 0.1 sec (Cerimele, 1999). This translates to an average peak acceleration of the human body response to impact loads of approximately 5 g's vertical and 2 g's horizontal, with the human body modeled as a spring-mass-damper system.

Figure 2. X-38 under parafoil flight.

The current crew module design has the crew members seated with supine backs, and hips and knees flexed. This seat orientation is based on the direction of the g-loading through the vehicle during various flight phases, and the postlanding orthostatic requirements for the crew members. The crew member seats will be designed to attenuate the landing loads to reduce the risk of incapacitating injury to less than 0.5% using the Brinkley Dynamic Response Index model for deconditioned, ill, or injured crew members. This model was developed by the Wright-Patterson Air Force Base (AFB) Human Effectiveness Directorate for human tolerance analysis (Brinkley, Specker, and Mosher, 1989).

Aircraft ejection seat testing at Wright-Patterson AFB has indicated that the hip angle should be 97 deg or less to prevent "submarining" out of the seat which can cause coccyx fractures (J. Brinkley, Human Effectiveness Directorate, Wright Patterson Air Force Base, personal communication, 1999). The knee angle should be based on comfort.

A restraint system will need to be developed to maintain the head-torso-lower extremity centerline axis alignment to reduce the risk of spinal injuries in the event of a side impact. Analysis of Indianapolis 500 car crashes has shown that most serious driver injuries result from side forces applied to an unrestrained head (S. L. Johnston, Flight Surgeon, JSC, personal communication, 1999).

The current seating design for the X-38 is: four seats in the back row, two in the middle row, and one in the front row (4/2/1), as illustrated by the top view in Figure 3. The hatch to enter and exit the spacecraft is located directly over the aft seats. Vehicle subsystems are packaged below the seat level with the seats removable to access the systems for maintenance. The side view of the seat layout is shown in Figure 4.

In this layout, the two seats in the middle row are tentatively designated for vehicle control, and the aft row middle or side seat will be for injured crew members, with medical monitoring equipment located next to these seats. The medical officer providing treatment will be next to the injured crew member(s). The proposed full vehicle layout is shown in Figure 5.

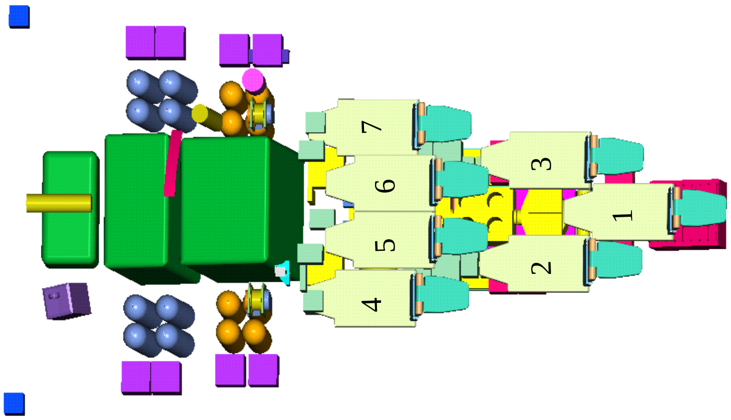

Figure 3. Top view of seating.

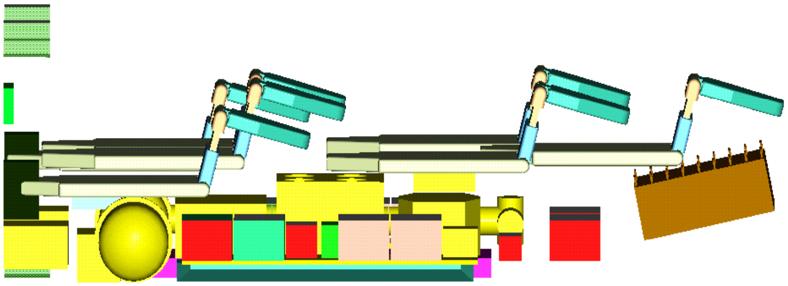

Figure 4. Side view of crew module.

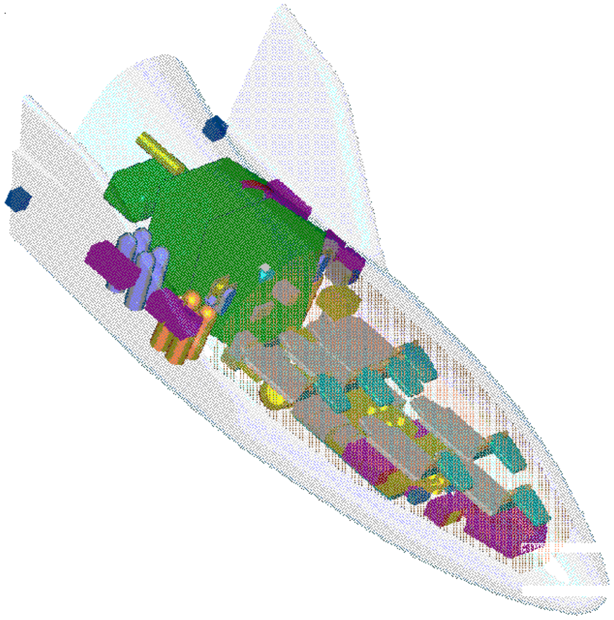

Figure 5. Full vehicle layout.

1.2 Research Objectives

The primary purpose of this research was to develop a methodology to evaluate the pressurized crew module volume suitability for zero-g ingress of spacecraft. The specific objectives of this study were to:

1. Determine the variables that should be used to develop an evaluation methodology through a Delphi study.
2. Develop an appropriate methodology to evaluate the crew module volume suitability for zero-g ingress by addressing the variables determined from the Delphi study.
3. Conduct ground and inflight evaluations to verify the methodology.

The research included collecting performance and acceptability measurements. In order to develop the methodology, the research addressed the major design issues affecting ingress, egress, and rescue. This included hatch stowage location, seat arrangement, location of equipment that needs to be installed in the crew usable volume, and operational tasks that must be performed.

As evidenced from the literature search that follows, there is a need for a methodology to determine acceptable spacecraft volumes based on ingress, egress, and layout. The X-38 is the first human-rated spacecraft to be designed, built, and flown since the Space Shuttle, which first flew in 1982, and provides a unique opportunity to develop and use a human factors evaluation methodology. The only other human-rated spacecraft in operation today is the Russian Soyuz, which was first flown in 1967, and has serious human factors limitations.

This research provides a unique contribution to the state of the art and the body of knowledge of spacecraft design by developing a standard methodology for determining acceptable and functional spacecraft volumes. The methodology can be used during the design and evaluation of all civil and military human spacecraft developed by all nations. In addition, critical information was determined on anthropometric fit and function evaluations of the seats and equipment layout, and ingress.

Chapter 2
LITERATURE REVIEW

A literature review was conducted to understand the state of the art of human factors evaluations of spacecraft, focusing on volume, ingress, egress, and rescue issues. This review was expanded to include the related areas of aircraft and escape pods from oil platforms. All these vehicles are required to allow for rapid ingress and egress, access for rescue, and to sustain life in a closed environment. Automobiles were also considered, which are required to accommodate a large anthropometric range in population. General human factors issues of the use of mockups for testing and how anthropometry affects analysis were also reviewed.

2.1 Need for Rapid Return to Earth

It has always been recognized that spaceflight is dangerous, and the hazards are unique from both environmental and high-performance vehicle perspectives. A conscious effort has been made to address these issues throughout the history of human spaceflight, but that work has mainly focused on safety, and not necessarily on general human factors and optimizing the interfaces for equipment and spacecraft operation.

Among the various world space programs, astronauts have died on the ground, during ascent, and during reentry. There have been multiple life-threatening launch aborts, aborts in orbit, and aborted reentry attempts. And within the past two years the Russian space station *Mir* suffered two of the events most feared by crew members on orbit: (1) a fire in the space station; and (2) a collision with another spacecraft resulting in a module depressurization. With almost 400 cosmonauts and astronauts flying in space to date, there have been 14 fatalities from four events, and multiple other events that could have been fatal. These are shown in Table 1 (Swenson, 1966; Hacker, 1977; Turnhill, 1978; Brooks, 1979; Oberg, 1981; Kane, 1984; Furniss, 1986; Fabian, 1988; Phillip, 1988; Compton, 1989; Severin, 1991; Burrough, 1998; Lucid, 1998; C. R. Justiz, 1999 [Research Pilot, Aircraft Operations Safety Officer, JSC, personal communication]; and Oberg, 1999).

Table 1. Fatalities, Near Fatalities, and Emergencies During Spaceflight

Date	Mission	Description
7/21/61	Mercury 4	Suborbital flight of Liberty Bell 7. Capsule door opened prematurely and flooded the capsule and astronaut's suit. Astronaut barely escaped drowning.
2/20/62	Mercury 6	False indication of landing bag deployment before reentry resulted in decision to leave retropack attached to heat shield for reentry.
5/24/62	Mercury 7	Capsule misaligned for retrofire, resulting in landing more than 200 km off target.
5/16/63	Mercury 9	Short circuit in main inverter bus bar resulted in spacecraft losing power to automatic stabilization system and control system. CO_2 levels in the cabin also elevated. Manual reentry required.
3/18-19/65	Voskhod 2	First extravehicular activity (EVA). Difficulty getting back inside, cosmonaut had to partially depressurize suit. During reentry the attitude control system failed. Reentry aborted, then conducted manually next orbit. Service module failed to separate clean during reentry. Landed 1,200 miles off target in 5 ft of snow. Cosmonaut attacked by wolves when he tried to exit spacecraft. Rescued next day.

Table 1. Fatalities, Near Fatalities, and Emergencies During Spaceflight
(continued)

Date	Mission	Description
8/21/65	Gemini 5	Missed splashdown target by over 100 miles due to errors in reentry targeting (first use of reentry targeting computer).
12/12/65	Gemini 6	Launch aborted after Titan II engines shutdown after ignition. Airborne programmer was activated before liftoff due to an electrical umbilical plug falling out.
3/16/66	Gemini 8	Short circuit in attitude control system while docked to Agena resulted in thruster being stuck on and vehicles rotating at near structural limits. Crew near blackout. Crew separated Gemini from Agena and activated reentry reaction control system to stabilize high roll rates, using 75% of the reentry fuel. Required landing early. Crew spent night in the ocean before being recovered.
6/5/66	Gemini 9	Astronaut's faceplate continually fogged over during EVA due to heavy exertion. Resulted in shortened EVA and difficulties while reentering spacecraft.
1/27/67	Apollo 1	Fire in crew module during ground test. 100% oxygen atmosphere. Hatch could not be opened. Three crew members perished.
4/24/67	Soyuz 1	Control system failed on orbit. Parachute system did not deploy after reentry due to failure of pressure sensor. Reserve chute manually deployed, but became entangled in drogue chute. Capsule destroyed on impact. Cosmonaut died.
1/18/69	Soyuz 5	Equipment module failed to separate during reentry sequence. Spacecraft tumbled during entry sustaining damage to capsule and parachutes. Module tore loose. Capsule landed 2,000 km off target in snowy steppes. Landing retro-rockets failed, resulting in hard impact. Cosmonaut had minor injuries.
7/20/69	Apollo 11	Lunar module computer overloaded during landing phase. Manual control required for lunar landing.
11/14/69	Apollo 12	Saturn V and command module struck by 2 lightening bolts immediately after liftoff due to plume of ionized exhaust gas.
4/11-17/70	Apollo 13	Mission to Moon aborted after oxygen tank ruptured. Crew used lunar module until just before reentry due to loss of most of the electrical power and oxygen. Crew returned safely.
4/23-25/71	Soyuz 10	Crew unable to enter Salyut 1 due to faulty hatch. Jammed hatch interfered with docking mechanism and prevented undocking. Able to undock after several attempts. During landing Soyuz air supply became contaminated and cosmonaut became unconscious.
6/29/71	Soyuz 11	Crew experienced small fire while docked to Salyut 1. Mission cut short. Cabin pressure failure during reentry due to pressure equalization valve coming open. First flight of three crew members in module designed for two -- no room for pressure suits. Three crew members perished.
4/5/75	Soyuz T18-1	A-2 launch vehicle second-stage separation malfunction. Ground commanded abort after crew request. Crew experienced 20 g's, landed in Siberia, tumbled down a mountainside, stopping short of a precipice, and were not rescued until following day. One cosmonaut suffered internal injuries.
8/25/76	Soyuz 21	Mission cut short due to crew member illness.
10/14/76	Soyuz 23	Landed at night, in blizzard, in ice covered lake. Rescue team unable to find capsule until next morning.
1978	Salyut 6	Fire caused space station to fill with smoke. Crew almost had to evacuate.
8/15/79	Salyut 6	During separation from Salyut, antenna on capsule snagged on station antenna. Required EVA to disconnect antenna.
6/3/80	Soyuz 36	Landing retro-rockets failed. Capsule impacted with high velocity. Seat emergency shock system actuated. Crew had minor injuries.
4/10/81	STS-1	Launch scrubbed due to timing difference between primary and backup flight software. Significant thermal protection tile damage during launch (16 lost and 148 damaged) due to over-pressurization wave created by solid rocket boosters.

Table 1. Fatalities, Near Fatalities, and Emergencies During Spaceflight

(continued)

Date	Mission	Description
9/26/83	Soyuz T-10-1	Fire started in base of launch vehicle at T-90 seconds. Crew aborted using escape rocket system seconds before explosion. Crew landed safely.
12/8/83	STS-9	2 of 4 primary flight computers failed during the mission. 2 of 3 auxiliary power units caught fire during landing.
4/23-8/8/84	Salyut 7	Hydraulic system of the station propulsion system failed. Required five EVAs to repair.
6/26/84	STS-41D	Pad abort at T-4 seconds when anomaly detected in one main engine.
7/12, 29/85	STS-51F	Pad abort at T-3 seconds due to coolant valve shutting down all 3 main engines. Abort to orbit due to one main engine shutdown during ascent.
11/21/85	Soyuz T-14 (Salyut 7)	Crew member became ill and had to be returned to Earth.
1/28/86	STS-51L	Solid rocket booster seal failure resulted in burn through that caused external tank to explode and Shuttle to be torn apart 73 seconds into flight. Seven crew members perished.
11/4/87	*Mir* 3	Kvant module failed to dock to *Mir*. Crew performed EVA to remove foreign object from docking port.
9/6-7/88	Soyuz TM-5	Infrared horizon sensor failed, causing loss of orientation, which resulted in shutdown of engines during reentry. Computer sequence got out of phase and proceeded with the reentry sequence. Crew intervention prevented premature separation of equipment module. Third attempt stopped when incorrect software loaded. Fourth attempt to reenter was successful.
7/17/90	*Mir* 6	Airlock hatch failed to seal after EVA. Crew members transferred to backup airlock. Hatch was repaired during later EVA.
3/22/93	STS-55	Pad abort at T-3 seconds due to incomplete ignition of one main engine.
8/12/93	STS-51	Pad abort at T-3 seconds due to faulty fuel flow sensor.
1/14/94	Soyuz TM-17	Soyuz bumped into *Mir* twice during fly-around when thruster control button momentarily froze.
8/18/94	STS-68	Pad abort at T-1.9 seconds when all 3 engines shut down due to high temperatures in oxidizer turbopump.
10/15/94	*Mir* 16	Oxygen generator ignited inside space station, resulting in small fire.
2/12/97	Soyuz TM-25	Landing retrorockets failed, resulting in one of the hardest landings experienced.
2/23/97	*Mir* 23	Oxygen generator ignited inside space station. Six crew members were on *Mir*, but access to one of the Soyuz capsules was through path of fire. Two-foot-long flame burned for about 14 minutes before contained. Crew had to wear respirators for several hours due to smoke and potentially toxic fumes in station. This was followed by continued problems with the oxygen, control, and thermal control systems, including a CO_2 removal system failure.
6/25/97	*Mir* 23	Unmanned Progress resupply vessel collided with Spektr module during manual docking while testing new procedures. Solar panels damaged and module penetrated causing depressurization. Module sealed off, but 30% of station power lost due to damaged solar cell. Solar cell later repaired, leak could not be found and module still unusable.
11/3/97	*Mir* 24	Kvant module outer airlock hatch failed to seal after EVA. Inner hatch was used to seal station until replacement hatch could be brought to orbit.
7/22/99	STS-93	Hydrogen leaks in coolant tubes around main engines caused early cutoff. Engine controller electrical short during ascent due to damaged wiring. Entire shuttle fleet grounded to correct significant wiring damage.

2.2 Rescue Vehicle Requirements

Construction of the ISS started in late 1998. It will grow to a permanent crew of seven in 2005. Before that time, the station will be serviced by the Shuttle and the Soyuz, and will be limited to three crew members when the Shuttle is not docked. However, a Soyuz will be attached and available for emergency return of the three-person crew. Once the station is able to support more than three crew members, additional rescue means will be required. Two Soyuz capsules will be used and the crew will be limited to six until a CRV is operational.

Several studies have been performed since the 1970s to examine the issues of escape from a space station (Fleisig and Heath, 1968; Wild and Perchonok, 1968; Bradeley and Carter, 1969; Francis, 1969; Bolger, 1970; Barnett, 1970; Wild and Schaefer, 1970; Cmiral, Dolezel, Dvorak, Pipap, and Sulc, 1971; Fleisig and Bolger, 1971; Heath, 1971; Kane, 1984; Grimard and Debas, 1988; Puls and Walbrodt, 1990; Kelly, 1991; Lloyd, Eymar, Housten, and Grimard; 1991; Daniher and Cureton, 1992; Tedeman and Wright, 1992; Grimard and Debas, 1993; and Housten 1993). These studies culminated in the design requirements for future rescue vehicles. The Design Reference Missions that the CRV must be designed to were listed in the Introduction. Other pertinent design requirements include:

- Shirtsleeve environment.
- Accommodate crew of 0 to 7 persons ranging from 95th percentile American male to 5th percentile Japanese female.
- Operate with a contaminated cabin.
- Maintain a crew compartment pressure between 3.5 psi and 16 psi.
- Provide 95% departure availability based upon single-fault-tolerant systems.
- Autonomous operation and navigation.
- Manual operation for crew intervention to permit crew consent to automated functions affecting flight-critical events.
- Capability for crew insight into vehicle state to avoid hazardous conditions.
- Manual override under emergency conditions.
- Capable of crew ingress, activation, and separation from the station within three minutes of crew arrival at the CRV hatch.
- Capable of separating from an unpowered and uncontrolled station, at any station attitude and multi-axis rotations of up to 2 deg/sec.
- Land-based return (designated sites and unplanned sites with flat open terrain).

2.3 Crew Return Vehicle Medical Considerations

DRM 1 (returning an ill or injured crew member to Earth) requires that a rescue vehicle be able to complete the medical evacuation mission within 24 hours from the time the ill or injured crew member is declared to be medically stabilized and prepared for transport, and the decision is made to evacuate the crew member. Completion of the mission occurs at the time of that crew member arriving at a medical care facility. The mission time from actual separation from the ISS until landing is required to be less than three hours, and from separation to arrival at a medical care facility is required to be less than six hours. Additional requirements are that the ill or injured crew member be transported in a recumbent seat, with required medical equipment accessible to the crew medical officer, who should occupy an adjacent seat; and that the design should accommodate removal of a passive (unconscious, ill, or injured) crew member along with their required medical equipment at the landing site. Other medical requirements are documented in Johnston (1997; personal correspondence, 1998).

Recent medical evacuation risk analysis has been performed using the actual medical events experienced during the NASA and Russian space programs, including the expected probability of other medical events (S. L. Johnston, Flight Surgeon, JSC, personal communication, 1999). This analysis led to the following conclusions:

- A space station crew member has a 6% per year chance of requiring a medical evacuation.
- A space station crew member has a 1% per year chance of requiring a critical (unconscious) medical evacuation.
- The Soyuz can adequately handle 86% of all medical evacuation missions.
- The Soyuz can accommodate approximately 89% of the NASA astronaut corps anthropometrically.
- The CRV will be required approximately 14% of the time for critical (unconscious) medical evacuations.
- The CRV will be required approximately 11% of the time for four NASA ISS crew members due to anthropometrics.
- There is a probability of one medical evacuation every 5.6 years when ISS has three crew members.
- There is a probability of one medical evacuation every 2.4 years when the ISS has seven crew members.
- Assuming both the Soyuz and the CRV are available, the CRV will be required for one medical evacuation every 4.2 years (leaving the three Soyuz crew members on ISS).
- The probability of using the modified Soyuz for a medical evacuation is one every 3 years.
- The probability of the CRV doing a medical evacuation requiring all seven crew members to return is 1 every 14.2 years.

Besides accommodating ill or injured crew members requiring medical evacuation, the design of the CRV must accommodate the neuro-vestibular, musculoskeletal, and cardiovascular physiologic decrements of reentry re-adaptation that result from spaceflight (Johnston, Jones, Ross, Cerimele, and Fox, 1999). Historically, for flights of duration greater than 16 days, NASA has seen orthostatic intolerance in approximately 20% of all crew members, with 14% of the crew members determined to be unable to climb up to the overhead window that would be used for an emergency exit from the Shuttle, and 5% unable to crawl to the side hatch of the Shuttle. In addition, postflight testing of all crew members has shown average strength losses of 20% in the upper body, 40% in the back, and 40% in the lower body (S. L. Johnston, Flight Surgeon, JSC, personal communication, 1999).

Further, gender differences must also be accommodated. Wright-Patterson AFB-sponsored research has shown approximately 25% less load-bearing capability in the general population of females due to the bearing area (vertebral size) and bone density differences of gender. Russian testing of military females indicates a 15%-20% decrement (J. Brinkley, Human Effectiveness Directorate, Wright Patterson Air Force Base, personal communication, 1999).

2.4 Recent Development Efforts of Human Spacecraft

Thirteen CRV studies have been conducted since the late 1980s (Thangavelu, 1990; for information concerning additional studies, contact the Advanced Development Office at JSC). Operational concepts and requirements were studied, but only limited test hardware was ever built (Kelly, 1991; and Housten, Elsner, Redler, Svendsen, and Wenzel, 1992). A limited-scale zero-g test was performed by industry in 1991 with an 8-person capsule mockup (Daniher and Cureton, 1992).

The NASA Langley Research Center studied an enhanced lifting body spacecraft called the HL-20 for applications as a personnel launch system that could carry up to 12 people (pilot, co-pilot, and 10 passengers) to space and serve a dual role as a CRV. The vehicle was a combination of early NASA and Air Force research efforts in lifting bodies as a “spin-off” of the Northrup HL-10 aircraft tested in the 1960s, and “reverse engineering” of a Soviet lifting body that had been photographed (NASA Facts, 1992; Bush, Robinson, and Wahls, 1993; Erlich, 1993; Naftel and Talay, 1993; Stone and MacMonochie, 1993; Stone and Piland, 1993; and Urie, Floreck, McMorris, and Elvin, 1993). The passengers sat upright in five rows with a center aisle between the seats. A one-g evaluation was performed in 1991 and 1992 to look at anthropometric fit, vertical and horizontal one-g ingress and egress, and pilot viewing.

The 35 participants in the study (31 for the ingress/egress evaluations and 4 pilots for the cockpit evaluations) ranged in size from 5th percentile Japanese female to 95th percentile American male. Ground egress times were found to be acceptable, although the last two rows of seats and the cockpit areas had insufficient room for taller personnel. The maximum-height person that was able to fit in the last row was 1.68 m (5.5 ft). Also, the pilot’s view was only marginally acceptable (Willshire, Simonsen, and Willshire, 1993). NASA abandoned this design due to the requirement to develop a new heavy lift booster to launch the vehicle, the high estimated cost of the vehicle itself, and the lack of need for a crew transportation system that could carry humans only and no cargo.

The European community has wanted independent human access to space since the 1980s. They spent considerable effort developing the Hermes lifting body that was to have been launched on an Ariane 5 rocket. The vehicle was being developed such that it could carry crews of three to orbit and serve as a CRV. Much has been published on the technical design and studies of the escape system, but limited human factors analysis was completed (Baccini, Charles, Colrat, Georges, Marcoux, and Herholz 1987; Grimard and Debas, 1988; Nguyen, Rolfo, and Charles, 1988; Nguyen and Frank, 1988; and Lloyd, Eymar, Housten, and Grimard, 1991). In 1992 after the Hermes Program was canceled, ESA started a design effort on a capsule that could be used for their crew to orbit access, and that could be sold to

NASA as a CRV (Grimard and Debas, 1993). Subscale flight testing of the capsule continued until ESA decided to partner with NASA on the X-38 Project (Moskwa, 1996).

Like the Europeans, the Japanese also want independent access to space. They have an active lifting body/delta wing spacecraft research program under way to develop a spacecraft they call H-II Orbiting Plane. This vehicle is planned to initially fly without a crew starting well after 2005 to deliver logistics to the Space Station (Akimoto, Ito, Yamamoto, Bando, and Inoue, 1994; and Shirouzu, Takashi, Akimoto, Watanabe, and Shimoda, 1994).

The only other human-rated spacecraft flying today is the Soyuz. The Soyuz capsule first flew in 1967 and is still in use by Russia today. In 1992 the U.S. considered buying Soyuz capsules from the Russians and modifying them to fit the U.S. astronaut population (Housten, 1993). With a habitable volume of approximately 3 m^3 shared by three crew members, the baseline Soyuz descent module has a very narrow range of crew member heights and weights allowable, as shown in Table 2 contrasted to the NASA ranges. Approximately 46% of the current U.S. astronaut population will not fit in the standard Soyuz due to height and weight limitations (Stevenson, 1994). Several anthropometric studies have been performed on the Soyuz to understand these limitations. Required modifications involve moving the main instrument panel to accommodate the legs and knees of taller astronauts, seat changes to allow better musculoskeletal support of injured crew members, and stowage changes to allow carrying required medical equipment. Approximately 11% of the U.S. astronaut population will still not fit in a modified Soyuz. NASA astronauts may fly on the Soyuz and the initial ISS crews must be selected based on who will fit in the Soyuz.

Table 2. Crew Size and Mass Limits

	Soyuz Minimum	Soyuz Maximum	NASA Minimum	NASA Maximum
Seated Height cm (in)	80 (31.5)	96 (37.8)	n/a	n/a
Upright Height cm (in)	160 (63.0)	183 (71.7)	148.6 (58.5)	193.04 (76)
Mass kg (lb)	50 (110)	85 (187)	40 (88)	109.32 (241)

2.5 Crew Events Inside the Crew Return Vehicle

To understand the operational tasks of the crew in a CRV a simplified functional analysis was performed. The functional analysis allocates functions between humans and machines to: derive crew mission tasks; identify the information and control inputs required to perform those tasks; determine if there is adequate time to perform those tasks; ensure that displays and controls support the performance of those tasks; and specify the criteria to be used in system design (Meister and Rabideau, 1965). This analysis breaks up the tasks that must be performed into an operational period (e.g. on orbit, or return to Earth), a phase during that period (e.g. prepare to return, spaceflight, atmospheric flight, landing, etc.), a segment of the phase (e.g. alerted to problem, board the spacecraft, prepare to separate from the Station, undock and separate from the Station, etc.), the starting and ending boundaries of the segment in terms of events, and the activity required during that segment (JSC-28351; E. Walden, Integradyne, personal communication, 1998-1999). The results are characterized in Table 3. This research focused on return preparation through recovery.

The following scenario will be typical for using the CRV to evacuate the ISS. For a Station emergency (three minutes from start of ingress to separation), up to seven crew members will go to assigned seats and close the hatch (the option exists to monitor the status of the Station from inside the CRV). If time permits, they will perform a vehicle systems health check. For medical evacuation (24-hour notice), required medical equipment will be installed before ingress. A minimum of four crew members must leave the Station since Soyuz will only accommodate three crew members and all personnel must have a seat available in a reentry vehicle at all times. Within ten minutes of hatch closure, the crew must unpackage two LiOH canisters and two desiccant canisters and insert them into the air revitalization system for CO_2 and humidity removal. If the crew remains inside the vehicle for more than 4.5 hours, the LiOH canisters must be changed.

The crew then initiates the automatic separation sequence. After autonomous Station separation, the crew can select a landing site or allow the system to default to the nearest landing site (typically 1.5 to 4.5 hours to landing from site designation). From this point on, the computers will select “optimum” decisions, allowing the crew to intervene if required.

After separation, and before the deorbit burn, the crew will strap into the seats, perform any required medical services for the injured crew member(s), and monitor vehicle systems. The crew may perform designated backup operations with the vehicle as required. Emergency oxygen is available through masks for purge of a contaminated cabin or for medical purposes.

After landing, the crew will open the overhead hatch and egress. They should egress within 30 minutes of landing due to internal cooling limitations. Breathing air depletion occurs 9 hours after hatch closure. An alternate egress path will be available through the side of vehicle, accessed by igniting a linear-shaped charge to blow a hole in the side. Ground rescue forces may open either hatch from outside.

Table 3. Functional Analysis of CRV

Operations Period	Phase	Segment	Starting Boundary	Activity	Ending Boundary
On-Orbit	Attached Operations	Attached Operations	CRV configured for attached operations	CRV parameters monitored by ISS Periodic CRV subsystem checkouts & state vector updates On-orbit maintenance as required Periodic ISS crew proficiency training	Order given to prepare for CRV separation from ISS
	Return Prep (Fly-back)	Alert	Order given to prepare for CRV separation from ISS	Egress to CRV with all necessary equipment	Arrival at docking port
		Board	Arrival at docking port	Ingress CRV with all required equipment and ill or injured personnel Start power-up and activation of subsystems	CRV hatch closed
		Preparation of Separation	CRV hatch closed	CRV preparation, configuration, checkout and coordination for undocking	Execution of undocking and separation sequence
Return	Spaceflight	Undock and Separation	Initiation of undocking and separation sequence	Monitor separation maneuver	Achieve safe orbit from ISS
		Deorbit Preparation	Achieve safe orbit from ISS	Landing site availability update Select landing site Verify deorbit target Verify spacecraft attitude	Initiate deorbit burn
		Deorbit Burn	Initiate deorbit burn	Monitor deorbit burn	Termination of deorbit burn
		Deorbit Coast Prep	Termination of deorbit burn	Monitor CRV maneuvering for propulsion system jettison	Jettison of deorbit propulsion system
		Deorbit Coast	Jettison of deorbit propulsion system	Monitor vehicle attitude for entry	Entry interface (400,000 ft)
	Atmospheric Flight	Entry	Entry interface (400,000 ft)	Monitor vehicle flight path and performance	Terminal area energy management (Mach 2.5)
		Terminal Area Energy Mgmnt	Terminal area energy management (Mach 2.5)	Monitor vehicle energy management and flight path Prep for parafoil transition	Initiation of parachute deploy sequence
	Parafoil Operations	Parafoil Deploy	Initiation of parachute deploy sequence	Monitor transition to drogue chute	Parafoil deploy complete
		Parafoil Flight	Parafoil deploy complete	Check condition of parafoil Monitor parafoil flight path Monitor for extension of landing attenuation system Monitor landing site surface conditions and deviate as required Prep for landing	Landing
	Recovery	Postlanding Operations	Landing	Monitor, deactivate, and safe subsystems Open crew hatch Prep for rescue crew arrival	Search and rescue crew arrives
		Crew Egress	Search and rescue crew arrives	Safely remove crew	Crew is removed

2.6 Related Applications

The human factors involved in ingress, egress, and rescues are of concern in more areas than spacecraft design. Much work has been done to analyze the human factors of aircraft, such as safety, pilot performance, cockpit resource management, training, displays and controls, error and fatigue, and the role of human factors in aviation accidents (Mott, 1974; and Wiener and Nagel, 1988). However, in most aircraft, the environments are usually more benign than those experienced in spacecraft. Weightlessness is only experienced during aerobatics or downdrafts. Only a few military and research pilots flying above 50,000 ft generally wear pressure suits. Still, aircraft engineering does consider anthropometry during their design process. The current trend in military requirements for aircraft design is to specify the desired crew performance instead of the dimensions of the cockpit (Roebuck, 1995). The Air Force and Navy both have active research groups studying the human factors of cockpit design and egress (focusing mainly on ejection). The Human Effectiveness Directorate at Wright-Patterson AFB has done extensive research in human tolerance to loads (J. Brinkley, Human Effectiveness Directorate, Wright Patterson Air Force Base, personal communication, 1999); and the Air Crew Systems group at Naval Air Station (NAS) Patuxent River has done much research on cockpit human factors design (E. Walden [Integradyne, personal communication, 1999]; and D. Gleisman, 1999). Military and commercial aircraft must be designed to military and Federal Aviation Administration standards. Applicable standards used by NASA and the military include MIL-STD-1472, Human Engineering Design Criteria for Military Systems, Equipment and Facilities; MIL-A-25165B, Identification of Aircraft Emergency Escape System; and AFSC DH 2-2, Crew Stations and Passenger Accommodations Series 2-0. But these standards do not specifically address ingress, egress, and rescue of spaceflight crew members.

Oil platforms have their own hazards that may require all personnel to evacuate the platform. The basic needs for quick ingress and buckling into assigned seats is similar to the ingress needs for a CRV. Norway is leading the way in platform safety with Australian-designed free fall and winched lifeboats. The location and operation of these lifeboats is factored into the platform designs to ensure that rapid ingress to a lifeboat is possible to limit fatal accidents (P. Barrett, 1998; and R. Sparks, 1998).

These lifeboats come in a variety of sizes that will hold 6-50 people. The boats are completely closed, have a single entrance, and include ventilation systems; batteries; first aid equipment; inflatable rafts; food rations; emergency locator beacons; survival equipment; and radios. They are suspended on hooks that require activation by a special release. The free fall boats can fall as much as 100 ft into the ocean. The winched boats use gravity to lower the boats from a davit.

The Society of Automotive Engineers in the United States has developed a comprehensive standardization to apply in anthropometric design of passenger automobiles (Roebuck, Kroemer, and Thomson, 1975; Society of Automotive Engineers, 1990; Roe, 1993; and Roebuck, 1995). The design of automobiles involves similar anthropometric considerations that are involved in spacecraft and aircraft, but the environments to which the human is exposed are considerably different. Automobiles must also accommodate a significantly different user population (Roebuck, 1995). The closest automotive environment application is that of race cars, where significant g-forces can be experienced and the cockpits are generally made as small as possible to save weight and drag. Further, the cockpits of race cars are engineered to provide maximum protection to the driver during high-speed collisions.

2.7 Human Factors Considerations

2.7.1 Use of Mockups

The CRV mockup is a simulation tool that provides the capability for static part-task evaluation of the ingress and egress mission phases. Mockups provide the opportunity to study the design problem in three dimensions through both observations and demonstrations. Key uses of mockups include, but are not limited to (Meister and Rabideau, 1965; and Frisch, 1978):

- Evaluation of alternative equipment configurations.
- Determination of workspace difficulties from simulating operational tasks.
- Identification of accessibility problems from simulating maintenance operations.
- Planning locations for routing wiring, plumbing, etc.
- Determination of geometry or volume problems affecting ingress or egress.
- Evaluation of procedures.
- Determination of optimal placement of crew controls from clearance, reach, and visibility envelopes.

2.7.2 Anthropometry and Human Interfaces

Basic anthropometry and human engineering research, standards, and approaches are well documented and were utilized throughout this research effort (Roebuck, Kroemer, and Thomson, 1975; Salvendy, 1992; Woodson, Tillman, and Tillman, 1992; Roebuck, 1993; and Weimer, 1995). The human interface requirements of the ISS and the CRV are specified in NASA-STD-3000/T, International Space Station Flight Crew Integration Standard. The crew module and seats must be designed to accommodate year 2000 40-year-old 95th percentile American male and 5th percentile Japanese female crew members as defined by NASA-STD-3000/T, with a 3% spine stretch due to zero gravity. The three dimensions that must drive the seat design are the sitting height, the popliteal height, and the buttock to popliteal length. The applicable characteristic human dimensions for a 95th percentile American male and 5th percentile Japanese female in one-g conditions are shown in Table 4, based on a 40-year-old person in year 2000.

Table 5 compares the dimensions for a year 2000 40-year-old 95th percentile American male and 5th percentile Japanese female at the one-g (no spine stretch) and zero-g conditions (spine stretch and no buttock pressure), with a 5.08 cm (2 in.) clearance for helmets and a 2.54 cm (1 in.) clearance for dynamic movement of the body due to acceleration forces (NASA-STD-3000/T; and Peterson, 1996). Note that 1.3-2 cm (0.5-0.8 in.) is added to the zero-g sitting height due to the relief of pressure on the buttocks. The final columns with all factors (spine stretch, no buttock pressure, helmet and dynamic clearance) should be used in seat design. Since the difference in zero-g stature is due to spine stretch, this difference was added to the one-g sitting height to obtain the zero-g sitting height. The other dimensions remain unchanged in zero-g.

Table 4. Characteristic Human Dimensions (NASA-STD-3000/T)

	5th percentile Japanese Female cm (in.)	95th percentile American Male cm (in.)
Stature	148.9 (58.6)	190.1 (74.8)
Hip breadth, sitting	30.4 (12.0)	42.3 (16.6)
Sitting height	78.3 (30.8)	99.5 (39.2)
Eye height, sitting	68.1 (26.8)	86.9 (34.2)
Popliteal height	34.7 (13.6)	48.1 (19.0)
Buttock-popliteal length	37.9 (14.9)	55.5 (21.9)
Bideltoid breadth	35.6 (14.0)	53.2 (20.9)
Hip breadth	30.5 (12.0)	39.0 (15.4)
Head breadth	14.4 (5.7)	16.5 (6.5)
Thumb tip reach	65.2 (25.7)	88.2 (34.7)

Table 5. Male and Female Dimensions (NASA-STD-3000/T)

	95% American Male	5% Japanese Female	95% American Male	5% Japanese Female	95% American Male	5% Japanese Female	95% American Male	5% Japanese Female
	no spine stretch		3% spine stretch & 1.3-2 cm (0.5-0.8 in.) relief of buttock pressure		previous plus 5.08 cm (2 in.) helmet clearance		previous plus 2.54 cm (1 in.) dynamic clearance	
Stature cm (in.)	190.1 (74.8)	148.9 (58.6)	195.7 (77.04)	153.3 (60.36)	200.7 (79.04)	158.4 (62.36)	n/a	n/a
Sitting Height cm (in.)	99.5 (39.2)	78.3 (30.8)	104.6 (41.18)	81.8 (32.22)	109.6 (43.18)	86.9 (34.22)	112.2 (44.18)	89.4 (35.22)
Popliteal Height cm (in.)	48.1 (19.0)	34.7 (13.6)	48.1 (19.0)	34.7 (13.6)	48.1 (19.0)	34.7 (13.6)	48.1 (19.0)	34.7 (13.6)
Buttock-Popliteal Length cm (in.)	55.5 (21.9)	35.6 (14.9)	55.5 (21.9)	35.6 (14.9)	55.5 (21.9)	35.6 (14.9)	55.5 (21.9)	35.6 (14.9)

Chapter 3
METHODOLOGY

3.1 Overview

This study was conducted in three parts: ground evaluations, flight evaluations, and a Delphi study. The evaluations were separated into three phases. Phase 1 was a pilot study using a mockup that seated four crew members to evaluate the feasibility of the research and establish the initial procedures. Phase 2 was an evaluation with a seven-person mockup to develop the methodology, refine the procedures, and determine whether any mockup changes were required. Phase 3 was conducted to verify the final methodology using the same seven-person mockup. Data analysis was performed for Phase 3. The Delphi study was conducted between Phases 2 and 3 to determine the evaluation factors that the end users (astronauts and flight surgeons) deemed most important.

The human factors evaluations included human test participants in all phases of ground and inflight tests. The inflight tests were performed in the NASA KC-135 zero-g aircraft using the methodology developed. Further, specific design issues addressed in the evaluations included:

- Preferred hatch stowage locations.
- Suitability and function of conceptual layout (seats, stowage, displays, handholds, etc.).
- Ease of ingress for deconditioned and injured persons.
- Assessment of optimal seat locations for crew control and ill or injured crew.
- Assessment of general crew module volume.

A full-scale crew module mockup of the X-38 was built and outfitted with the proposed seat configuration, medical equipment mockups and high-fidelity training hardware, low-fidelity crew displays and controls mockups, low fidelity hatch, and volumetric mockups of spacecraft systems and stowed equipment. The evaluations were performed on a single seat layout.

Ground and flight evaluations encompassed the performance of expected crew member operations, including zero-g ingress and egress, specified medical care, hatch opening and closing, seat comfort, seat adjustments, handhold utility, reach and visibility of displays and controls, and accessing storage areas. While representative systems displays were available in Phase 2 as part of a secondary study, this research only considered the spatial and physiological aspects of display location and not the cognitive use of the displays.

Each series of evaluations began with one-g ground tests to evaluate the reach, visibility, operability, functionality, and suitability of the layout. The ground evaluation was used to evaluate the mockup and equipment layouts before flight test in order to identify any potential problems or interferences, and to dry run the inflight evaluation procedures. The participants were asked about comfort throughout the adjustment range of the seats on the ground. Pertinent comments and observations were incorporated into hardware and procedures for the flight tests on the NASA zero-g aircraft.

The flight evaluations were conducted under three acceleration environments: zero g, one g, and 1.8 g's. The flight test series for Phase 1 was conducted during four parabolic flights of 40 parabolas each, for a total of 160 parabolas. The Phase 2 evaluations were performed during three separate parabolic zero-g flights, with 46, 53, and 40 parabolas each, for a total of 139 parabolas. Phase 3 flight evaluations were conducted during two flights of 48 and 46 parabolas, for a total of 94 parabolas. The test objectives of the ground and flight evaluations are detailed in the procedures section. The three acceleration test environments allowed adequate evaluation of the crew module volume, layout, and functionality in the expected operating environment. The 1.8-g environment was used to approximate the higher-g's of spacecraft reentry, and was used to grossly simulate a deconditioned crew member's reflexes.

The NASA KC-135 aircraft was used for the flight tests. The aircraft provides an acceleration environment that most closely replicates that which will be experienced by astronauts while on orbit and during reentry. While zero g can only be maintained for a relatively short time, the evaluations can be broken into component parts and performed in steps during each parabola. A typical flight consists of 40 to 60 parabolas, each providing 20-25 seconds of zero g and about 40 seconds of 1.8 g. Figure 6 shows the typical parabola.

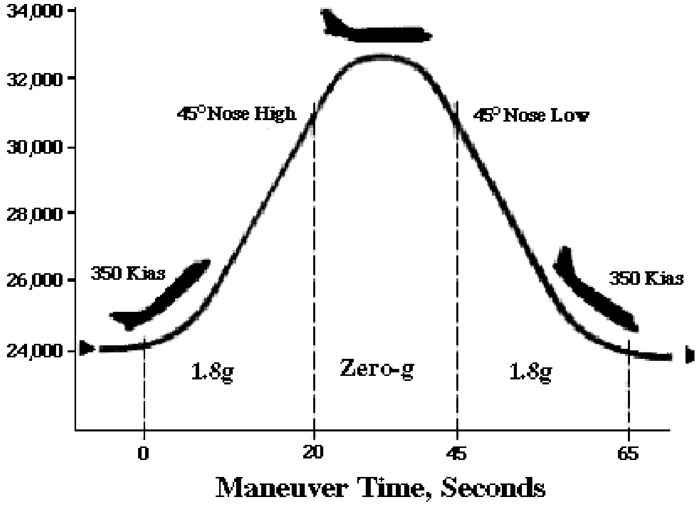

Figure 6. Typical KC-135 parabola.

The following photo documentation was used during the flight tests:

- Video camera mounted on a pedestal behind the mockup to view the hatch area
- Handheld video camera for specific internal and external views
- Handheld digital camera for specific internal and external still photographs.

Follow-on studies could include ground evaluations for egress of deconditioned, and rescue of ill or injured, crew members. In addition, further seat comfort and dynamic loading analysis could be tested in a centrifugal chamber.

3.2 Delphi Study

The RAND Corporation first developed the Delphi technique in the 1950s. It has evolved over the years from purely a predictive technique of future events in the case of uncertainty, to a method for structuring the group communication process to address any complex problem (Sweigert and Schabacker, 1974; Linstone and Turoff, 1975, Sage, 1977, and Woudenberg, 1991). With this evolution, the technique has become suited to the exploration of issues that involve a mixture of scientific evidence and social values (Webler, Levine, Rakel, and Renn, 1991). The significant components of the technique are:

- Feedback of individual contributions of information and knowledge.
- Assessment of group judgment or view.
- Opportunity for individual contributors to respond to and revise their views until a consensus is reached.

A modified Delphi study was performed to elicit and refine the opinions of the user groups of human spacecraft on the variables and factors that should be considered in an evaluation methodology. This study used the collective judgment of experts to derive a consensus position (Dalkey, 1967, Helmer, 1983, and Johnson and King, 1988).

The Delphi study used in this research began by working with a member of the astronaut corps to develop the basic list of factors to be considered. A questionnaire was developed that asked the participants to rate the factors in priority order. The questionnaire was distributed electronically to a group of current and former astronauts and to current flight surgeons. The group represented a 10% sample of current and former astronauts and a 40% sample of current flight surgeons. The demographics of this group are shown in Table 6.

Table 6. Delphi Participant Profiles

Demographic	Number of Participants
Total Number of Participants	21
Gender	
Male	17
Female	4
Occupation	
Pilot	5
Mission Specialist	13
Flight Surgeon	3
Spaceflight Experience	
Flown (total)	12
1 Flight	1
2 Flights	2
3 Flights	6
4 Flights	3
Unflown astronauts	6
Former astronauts	2
Current astronauts	16
Nationality (Space Agency)	
U.S. A. (NASA)	19
Japan (NASDA)	1
France (ESA)	1

Due to the availability of the respondents, only two iterations were conducted in the study. The original questionnaire required the respondents to prioritize the factors in numerical order. After the first iteration the respondents asked to modify the process. The second iteration had the respondents rate the factors using a ten-point scale with 10 as the most important. Weighting factors were then applied to the data with flown astronauts being weighted as “2” and unflown astronauts and flight surgeons weighted as “1.”

The weighted data were then averaged to derive the priority order. The Astronaut Office was provided the derived priority order for final consensus, which was obtained. Table 7 contains the final prioritized order of factors that should be considered in the methodology to evaluate human spacecraft. This information was used to refine the test procedures and focus the postflight questionnaires.

Table 7. Delphi Sequence

Priority	Factor or Variable to Consider
1	Can zero-g ingress into vehicle be accomplished within time limits, if applicable (e.g. CRV requirement)?
2	Are the body angles of seating appropriate for expected direction and level of g-forces during flight?
3	Is there adequate body clearance from structure/equipment/other crew members when seated (e.g. above head, side-to-side, etc.)?
4	Can aided zero-g ingress of ill or injured crew members be easily accomplished?
5	Will volume accommodate required number of crew members from 95th percentile American male to 5th percentile Japanese female?
6	Are required displays and controls logically and adequately located for the tasks to be performed?
7	Are the body angles of seating appropriate for expected crew member tasks to be performed?
8	Is the diameter of the hatch adequate for zero-g ingress and one-g egress of healthy, ill, and injured crew members?
9	Are displays and controls visible to all required crew members?
10	Is the reach and visibility to displays, controls, and equipment that must be accessed during g-loaded flight adequate for all crew members?
11	Can zero-g ingress of ill or injured crew members be accomplished with standard medical equipment that may be attached to the crew member?
12	Can one-g rescue be easily accomplished?
13	Are viewing angles to displays from seats adequate for all required crew members?
14	Does required flight crew equipment interfere with performing tasks in available volume (e.g. helmets, oxygen masks, etc.)?
15	Can one-g unaided egress be easily accomplished?
16	Can one-g aided egress be easily accomplished?
17	Is there adequate room to stow required equipment (medical, survival, flight crew equipment, etc.)? Note that required equipment will vary with vehicle.
18	Is the movement of the hatch into the vehicle acceptable, if applicable?
19	Is there adequate access to equipment to perform inflight maintenance?
20	Is there adequate room to perform required medical care on ill or injured crew members?
21	Do seats need to be adjustable to accommodate different crew member sizes, mission phases, or tasks?
22	Is the handhold design and placement adequate?
23	Is there a preferred seat for piloting the vehicle?
24	Is the stowage of the open hatch in the vehicle during zero-g ingress acceptable, if applicable?
25	Is there an alternate egress path?
26	Are viewing angles to windows from seats adequate for all required crew members?
27	Are all seats comfortable for all crew members?
28	Are the body angles of seating appropriate for the duration of exposure to zero-g flight (e.g. short flight or long-duration flight)?
29	Is the location of the seats with respect to the hatch adequate?
30	Is the hatch optimally located?
31	Is a particular ingress or egress order required?
32	Is there adequate room to stow extra equipment?
33	Is there a preferred seat for ill or injured crew members?

3.3 Participants

The user population for a NASA human spacecraft consists of NASA and international astronauts with anthropometry defined as falling between 40-year old, year 2000, 5th percentile Japanese female and 95th percentile North American male. The participants for the ground and flight tests were selected to match this anthropometry range.

Research by Virzi (1992) concluded that 5 participants would be able to detect 80% of the most important problems in usability tests, and 20 could detect nearly 100% of low-, medium-, and high-severity problems. The Phase 1 pilot study inflight evaluations had 22 test participants. Five of the 16 astronauts had participated in the ground evaluations. One of the 15 has the greatest sitting height in the NASA Astronaut Office (98th percentile American male), and one was 10th percentile Japanese female. The Phase 2 inflight evaluations utilized 28 participants. Phase 3 had 22 inflight participants. A subset of the inflight participants was also used in each of the ground evaluations. The tests were performed in groups to allow comparison of timing sequences. The profiles of the participants from all three phases are shown in Table 8.

Table 8. Participant Profiles

Demographic	Number of Phase 1 Participants	Number of Phase 2 Participants	Number of Phase 3 Participants
Total Number of Participants	22	28	22
Gender			
Male	17	22	20
Female	5	6	2
Occupation			
Pilot	2	4	5
Mission Specialist	13	20	13
Flight Surgeon	3	4	4
Engineer	5	--	--
Spaceflight Experience			
Flown (total)	8	9	4
1 Flight	6	3	2
2 Flights	2	4	1
3+ Flights		2	1
Unflown astronauts	7	8	14
Nationality (Space Agency)			
U.S. A. (NASA)	19	22	20
Japan (NASDA)	1	2	1
France (ESA)	2	2	1
Switzerland (ESA)	--	1	--
Spain (ESA)	--	1	--
Height			
Minimum	63 inches	65 inches	66 inches
Maximum	74 inches	76 inches	76 inches
Female	50th to >95th percentile	95th to >95th percentile	>95th percentile
Male	5th to >95th percentile	5th to >95th percentile	<5th to >95th percentile

Approximately 84% of the participants were astronauts, and the other 16% were flight surgeons. The flight surgeon participants were selected to match not only the astronaut anthropometry range, but also to match the demographics of education, health, and work experience in flight operations. The same participants were used for each seating configuration evaluation and the ground and flight tests, to allow a more consistent comparison of data. Both NASA and international astronauts were included as participants. Approximately 17% of the participants were female, compared to 20% females in the NASA astronaut corps. Seven to nine astronauts, and two to three flight surgeons participated in evaluations during each KC-135 flight, along with four to six engineers who were test conductors, safety spotters, and recorders for timing data, comments, and observations. In addition, a still photographer and videographer were used to document the flights.

KC-135 inflight evaluations are subject to the NASA/JSC Human Research Master Protocol that requires the test series to be reviewed by the Human Research Policy and Procedures Committee (HRPPC) for approval to use human test participants. The NASA/JSC Consent Form for Approved NASA Human Minimal Risk Research is used to inform test personnel of the risks that might be incurred during the tests. In addition, all test personnel on the KC-135 aircraft had to pass medical screening to receive an Air Force Class III physical, and had to complete a physiological training course.

3.4 Apparatus

The mockup used consisted of an aluminum representation of the XCRV crew module, an overhead ring representing a hatch opening, and seven articulating seats. Only the upper half of the mockup (the volume above the seat line) was used during these tests. This portion of the mockup weighs approximately

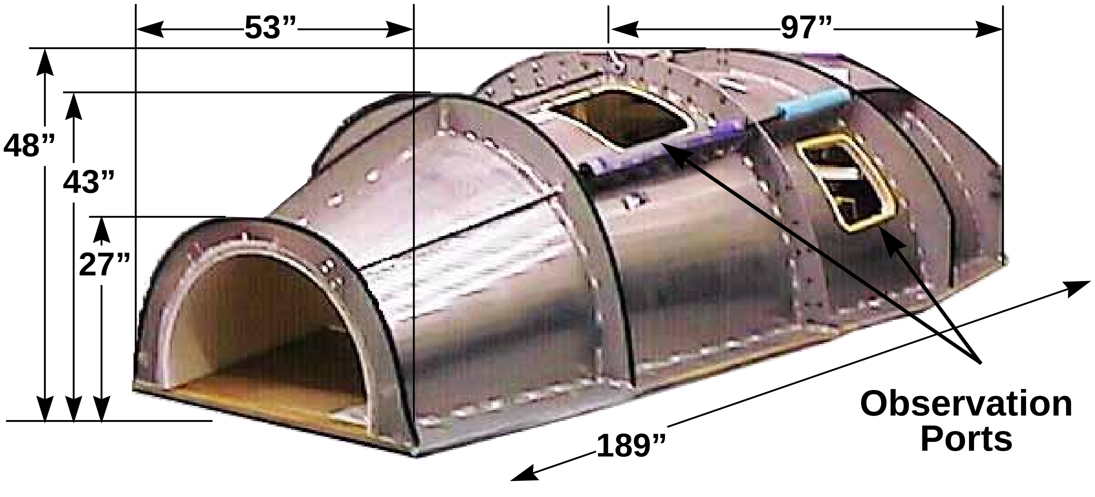

Figure 7. Crew module mockup outer shell.

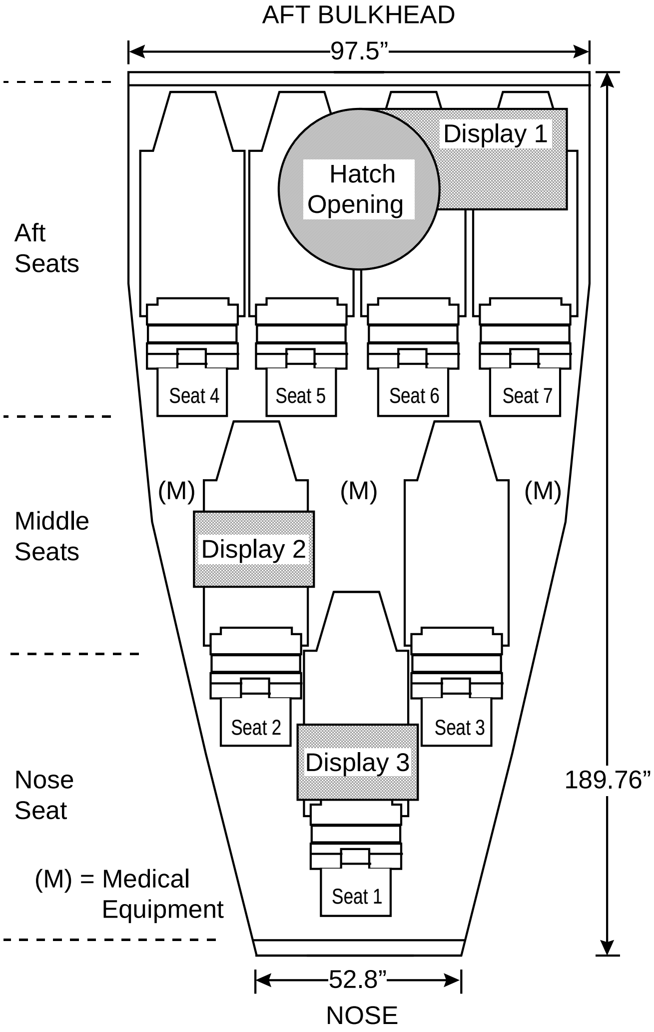

Figure 8. Mockup seat and display layouts.

363 kg (800 lb) outfitted, and is shown in Figure 7. The mockup was restrained in the KC-135 aircraft with cargo straps, and the seats were mounted to plywood with screws. The plywood was restrained under the flange of the mockup. Normal access to the interior of the mockup was through the overhead hatch, which is approximately 1.2 m (4 ft) from floor level. Steps on the aft of the mockup allowed one-g access to the hatch. Two openings approximately 0.3 m^2 (3 ft^2) were cut into each side of the mockup for viewing, and the front and back ends were open to allow access and ventilation.

The test series used a baseline seat setting of torso horizontal; thigh support 41.6 cm (16.4 in.) long (buttock to popliteal length of 50th percentile female) at an 80-deg angle to the waterline; and popliteal support at a 20-deg angle to the waterline. The seat settings were varied during the ground tests to collect comfort data.

Hatch and crew medical equipment mockups were secured with Velcro inside the mockup. Low-fidelity equipment and foam mockups were used to gather baseline data to refine the mockup layout. Follow-on tests could use a functional hatch mockup, and actual training hardware for the medical and other crew equipment. A "Rescue Randy" fully articulated first-aid mannequin was used to simulate an unconscious crew member for selected medical procedures. The seat, hatch, and medical equipment were arranged as shown in the top view of Figure 8.

3.4.1 Phase 2 Unique Hardware

Figure 9 details the seats used in Phase 2, which were padded plywood with articulating hip and knee joints, allowing the torso, thigh, and popliteal supports to be positioned at various angles. The thigh support length could also be varied. Seat restraints were provided.

The Phase 2 evaluations used foam board mockups to simulate medical equipment, and had cloth loop handholds attached at a single point. Three display configurations were also tested for a secondary study, including:

- IBM Thinkpad 760XD laptop with expansion tray mounted above the center row.
- In-Focus LitePro® 720 multimedia projector that projected a display over the aft row.
- Kaiser Electronics Virtual Interactive Enhanced Workstation head-mounted goggle display system used in the forward seat.

The displays had the capability of showing both user-selected displays and a video feed from a camera placed in the KC-135 aircraft forward cockpit window.

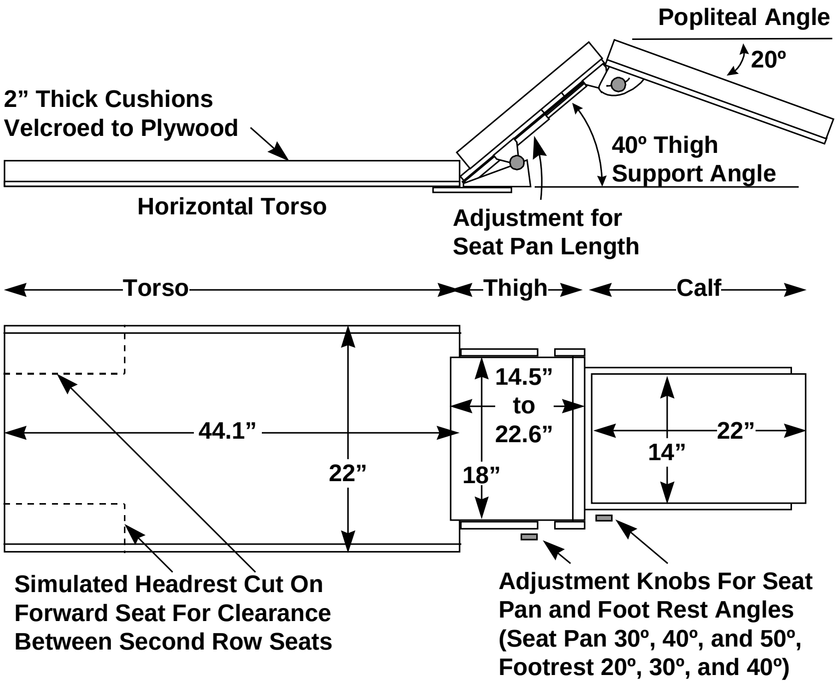

Figure 9. Articulating seat detail.

3.4.2 Phase 3 Unique Hardware

The Phase 3 evaluations included both actual medical hardware as well as foam board mockups. This allowed actual medical procedures such as intubation and resuscitation to be performed on the mannequin. The displays were foam mockups. Stowage bags were added to simulate the volume of items that need to be stowed on the CRV (e.g. rations, water, clothes, rescue radio, etc.). The hatch was modified after Phase 2 to make it volumetrically accurate and to mechanically latch into place. Two handhold designs were used including cloth handholds attached at both ends on one side of the mockup and tubular rigid handholds on the other side.

Figure 10. Interior of mockup with seats folded flat.

Most importantly, three seat designs were evaluated inside the mockup. The two outer seats in the aft row and the forward row seat remained the articulating wooden seats used in Phase 2. The inner two aft row seats were modified so that they would fold flat for ingress and then spring-lock into position when lifted. Figure 10 shows these seats installed in the mockup in the flat position. Note the stowage of items on the walls of the mockup.

Figure 11. Soyuz-style seat.

The two seats in the middle row were modeled after the Soyuz seat and have no leg supports. These seats are a padded wood back with a padded lip to prevent the buttocks from sliding down, and an aluminum foot pan that can be adjusted in the lateral and vertical directions to allow different hip and knee angles, and adjusted in rotation to allow different ankle angles. In Figure 11, a crew member is shown sitting in a Soyuz-style seat.

In addition, 12-deg and 22-deg back wedges were available for the middle row seats to evaluate the clearances resulting from inclining the torsos of the crew members who would be controlling the vehicle to a more “pilot-intuitive” position. The angles of the wedges were chosen based on the directions of g-loading in the vehicle during atmospheric flight and landing. In Figure 12, a crew member is shown in the starboard middle row seat, which has a 22-deg wedge. Note the distance between the crew member’s head and the overhead display.

Figure 12. 22-deg wedge on starboard middle row seat.

3.5 Experimental Design

The experimental design consisted of a combination of two hatch stowage locations, two handhold designs, and three seat designs tested in three acceleration environments by healthy, and simulated “ill” and “injured,” participants. Performance and acceptability measurements were also recorded. The performance measurements consist of timed exercises. The acceptability measurements were obtained from six-point bipolar scales in a postflight questionnaire. The order of the postflight acceptability measurement questions was randomized on the questionnaires. The experiment was a randomized matched block design, and was replicated on different days with the participants from each flight comprising matched groups (Cochran, 1983). The experiment was a within-subject design, in which every participant evaluated all mockup configurations.

3.5.1 Independent Variables

The independent variables for this evaluation were: (1) acceleration environment, (2) healthy versus “ill” or “injured” participants, (3) hatch stowage locations, (4) handhold design, (5) seat locations for ill or injured crew, and (6) seat design. In addition, the anthropometry of each participant is a subject variable.

3.5.2 Dependent Variables

Based on the performance and acceptability measurements evaluated in the literature (Kerlinger, 1973; and Hicks, 1982), the following were determined to be dependent variables: time to perform task and acceptability ratings. The performance measures were:

- Timed, fixed-order ingress of seven healthy crew members.
- Timed, random-order ingress of seven healthy crew members.
- Timed, fixed-order ingress of 6 healthy and 1 injured crew members.
- Timed, fixed-order ingress of 5 healthy and 2 injured crew members.
- Timed, fixed-order ingress of 3 healthy and 1 injured crew members.

The acceptability measures were collected after the flight tests. Examples of the acceptability measures are shown in Table 9. The complete postflight questionnaire is located in Appendix 2.

Table 9. Acceptability Measures

Characteristic	Rating Scale
Seating	
Q1: One-g comfort of baseline adjustable seat	very uncomfortable – very comfortable
Q5: Zero-g comfort of 90 degree collapsible seat	very uncomfortable – very comfortable
Q9: High-g comfort of Soyuz style seat	very uncomfortable – very comfortable
Q10: Seating arrangement (4/2/1)	completely unacceptable – completely acceptable
Q11: Aft row face to ceiling clearance	completely unacceptable – completely acceptable
Ingress/Egress	
Q20: Ingress order for healthy crew during station emergency	always use random order – always use fixed order
Q23: Ease of zero-g ingress of ill/injured crew	very difficult - very easy
Hatch	
Q27: Adequacy of hatch diameter for anticipated zero-g operations	completely inadequate – completely adequate
Q29: Acceptability of stowing hatch on aft wall	completely unacceptable – completely acceptable
Volume	
Q32: Adequacy of volume for 7 crew for post-separation zero-g operations	completely inadequate – completely adequate
Q33: Adequacy of volume for 7 crew for atmospheric flight and postlanding operations	completely inadequate – completely adequate
Q34: Adequacy of volume to perform rudimentary medical care	completely inadequate – completely adequate
Crew Equipment and Stowage	
Q35: Adequacy of flight crew equipment access and stowage	completely inadequate – completely adequate
Q36: Adequacy of medical equipment access and stowage	completely inadequate – completely adequate
Q38: Adequacy of design of rigid handholds	completely inadequate – completely adequate
General	
Q44: Did questionnaire adequately express views	completely inadequate – completely adequate

3.6 Procedure

3.6.1 Phase 1

The ground evaluation consisted of each crew member ingressing and egressing the vehicle twice, into a front seat and back seat, and performing a reach and visibility exercise in each seat. Each participant completed a questionnaire after the exercise. An oral debriefing was held after each test. Comments were recorded during the exercise.

The second set of evaluations were conducted on the KC-135 after modifying the existing mockup based on the lessons learned from the ground test as follows:

1) Lengthening the crew module to accommodate more head and foot room.
2) Adding an adjustable thigh support to accommodate the range of buttock to popliteal lengths between 5th percentile Japanese female and 95th percentile American male.

3) Changing the knee angle to 20 deg (was zero) to accommodate stowage of equipment below the seats.
4) Relocating the hatch to over the back row of seats.
5) Adding extra handholds.

Flight evaluations included timed zero-g ingress and egress (healthy and unconscious), hatch operations, LiOH canister operations, medical treatment, reach and visibility, handhold placement, equipment location, seat design, buttock to popliteal length evaluations, 1.8-g comfort, and suitability of three different helmet designs. Written crew comments, dynamic anthropometric measurements, and ingress and egress timing data were also collected.

3.6.2 Phases 2 and 3

One seat layout capable of accommodating multiple seat designs and seat angle configurations was evaluated in Phases 2 and 3. Evaluations were performed in three different acceleration environments using astronauts and flight surgeon test participants. All evaluations were performed using the full-scale crew module mockup with representative equipment mockups inside. The flight test had a formal test plan, procedures, and post-test questionnaire for data collection. The test plan followed the guidelines established by the JSC Flight Crew Operations Directorate. The one-g dry run test also used the flight test procedures.

A summary of the test and copies of the procedures were made available to test participants before the test. All participants in each evaluation attended a pre-test briefing, at which the test objectives were explained and a familiarization of the mockup including hatch and seat function was conducted. They also participated in a post-test debriefing where their comments were collected. Data collection included recorded times for specific events; recorded measurements of specified anthropometric data in each seat design; pertinent observations, in-test comments, and debriefing comments recorded by test conductors; post-test questionnaires completed by test participants; still photographs of tests; video of tests; and anthropometric data of astronaut test participants.

The participants conducted the evaluations by climbing into the mockup and performing one-g volumetric and operational assessments, and then performing egresses. The specific test objectives of the one-g tests included evaluations of:

- Evaluation of seat dimensions and seat comfort (torso, thigh, and popliteal lengths, hip flexion and knee flexion angles, and torso angles).
- Evaluation of hatch stowage on aft wall and overhead.
- Assessment of ease of medical care in crew module.

The participants conducted the evaluations by performing timed zero-g ingresses and hatch closure, zero-g and 1.8-g volumetric and operational evaluations inside the crew module, and zero-g timed hatch opening and egresses. An orientation parabola was used at the start of each flight to allow the evaluators to familiarize themselves with the physiological aspects of parabolic flight (steep pullup, followed by weightlessness, followed by 1.8-g pullout dive). The evaluators then conducted a practice zero-g ingress and egress to familiarize themselves with the tasks. The specific test of objectives of the zero-g flights included evaluations of:

- Timed zero-g entry through the hatch to and from each seat (aided and unaided).
- Evaluation of hatch stowage on aft wall and overhead.
- Evaluation of handhold design, placement, and number.
- Evaluation of seat layout.
- Assessment of seat designs.
- Assessment of general available volume for seven crew members.
- Assessment of optimal seat(s) for crew member responsible for interfacing with computers and/or crew displays.
- Assessment of optimal seat(s) for ill or injured crew members.
- Assessment of general access, reach, and visibility of medical equipment.
- Assessment of equipment stowage locations.
- Assessment of ease of medical care during g-loaded and zero-g flight.

The test plans and documentation required to perform the Phase 2 and Phase 3 test series were completed (Sanchez, 1998a; Sanchez, 1998b; Manley, 1998a; Manley, 1998b; Sanchez, 1999a; Sanchez, 1999b). The procedure for the Phase 3 flight test series is attached as Appendix 1, and the postflight questionnaire for Phase 3 is attached as Appendix 2.

NASA, Boeing North America, and Alenia Aerospazio jointly conducted parts of Phase 2. The NASA portion included only CRV evaluations while the Boeing portion included a reduced-volume CRV evaluation and joint CTV evaluations with Alenia as part of an industry evaluation of the XCRV design (Manley, Basile, and Sanchez, 1998). The Boeing/Alenia zero-g evaluations were in four parts using: (1) the crew module mockup in the CRV layout with reduced volume for ingress and egress tests; (2) the crew module mockup in the CTV (crew up) layout for ingress and egress tests with partial pressure suits; (3) a station adapter tunnel for timed translation tests; and (4) a station adapter tunnel and CTV mockup for translation, ingress, and volume to put on partial pressure suit tests. The reduced-volume evaluation data were included in the data analysis.

3.7 Data Analysis

The experimental data available included ingress and egress times, acceptability and comfort ratings from the post-test questionnaires, subjective comments from post-test questionnaires and debriefings, recorded observations, and still and video images. Performance and acceptability data were analyzed using Excel spreadsheet files.

No statistical analysis was performed on the Phase 1 data. The Phase 2 and Phase 3 performance data were assessed for normality using the Chi-Squared Goodness-of-Fit test. The skewness and kurtosis were also checked as a verification of normality. Analysis of variance (ANOVA) procedures were performed on all performance-dependent variables that were normally distributed. The Duncan Multiple Range test was conducted on dependent variables found to be significant at the $p<0.05$ level to determine the specific differences (Montgomery, 1991).

The Phase 3 six-point bipolar acceptability scores were assessed for normality using the Chi-Squared Goodness-of-Fit test along with skewness and kurtosis checks. ANOVA procedures were performed on the acceptability dependent variables that were found to be normally distributed. The Duncan Multiple Range test was conducted on the acceptability dependent variables that were found to be significant at the $p<0.05$ level to determine the specific differences.

Nonparametric statistics were conducted on nonnormally distributed acceptability dependent variables. A Kruskal-Wallis test was conducted on the variables, and a Wilcoxen Rank-Sum test was performed to determine specific levels of significance.

These tests were conducted on all performance data from Phase 2 and Phase 3, and the acceptability data from Phase 3. The acceptability data from Phase 2 were not included since the postflight questionnaire changed between phases as a result of developing the methodology and performing the Delphi study. The performance data across both phases and across all of the test flights were analyzed to determine if differences between the phases or flights could be detected. Then, the performance data were analyzed within each test flight for the specific test tasks. The acceptability data were analyzed across all participants to detect differences. Then the acceptability data were sorted into subgroups and analyzed to see if differences between populations could be detected. The sort populations were:

- Flown astronauts.
- Unflown astronauts.
- Pilot astronauts.
- Mission specialist astronauts.
- High-aviation-experience mission specialists.
- Low-aviation-experience mission specialists.

Chapter 4
RESULTS

This chapter is divided into four sections. The first section presents the results of the Phase 1 pilot study. Sections 2 and 3 presents the results of Phases 2 and 3, respectively. Section 4 presents the differences in results between the phases. Only results that were significant at the $p<0.05$ level are described in detail.

Results are presented in the areas of statistical analysis along with a discussion of the zero-g volume acceptability for ingress and egress, seat design and configuration, hatch acceptability, handhold design and placement, medical operations acceptability, and volumetric impacts to crew operational task acceptability and equipment stowage. In addition, the constraints and limitations to the testing and how they affect the results will be identified. The results will indicate the acceptability of the methodology for evaluating the volume suitability for ingress and egress.

4.1 Phase 1: Pilot Study

A pilot study was conducted in two parts to establish the procedures for the proposed research. The first was a ground evaluation and the second was a series of zero-g flight evaluations (Sanchez, 1996a; Sanchez, 1996b; Sanchez, 1996c; and Sanchez, 1997). A four-person (one forward, three aft) crew module mockup was built from plywood and fiberglass. The X-38 was originally intended to support only four crew members, but was enlarged 20% to accommodate seven crew members. The mockup included representative seats built from foam and plywood, and representative volumes of medical equipment built from foam (E. A. Robertson, JSC, personal correspondence, 1996).

Before building the mockup seats, it was necessary to determine the differences between vertical and horizontal sitting height, and the effect of hip angle on seat back length. Four 95th-percentile stature participants (year 2000, 40-year-old North American male) were used for this determination. It was found that their horizontal sitting heights were 4.57-4.83 cm greater than their vertical sitting heights. Therefore 4.83 cm was added to the 95th percentile vertical sitting height to convert it to a horizontal sitting height. The seat hip angles were varied between 30, 40, 60, and 90 deg for each of the participants. The sitting lengths were measured at each angle, and then the measurements were averaged. The measured seat back length difference between 40-deg and 90-deg hip angles was found to be 6.35 cm. Therefore, it was assumed the seat back length at 40 deg could be 6.35 cm shorter than at 90 deg. These measurements were used to determine the corrections to vertical sitting height in order to derive horizontal sitting length, accounting for hip angles and buttock compression (Peterson, 1996).

The Phase 1 ground evaluation of the mockup included nine astronauts. Seven of the nine had flown in space. Three of the nine had been trained in the Russian Soyuz spacecraft, one of the three was too small for the Soyuz (NASA's smallest astronaut at the time, a 10th percentile 40-year-old, year 2000 Japanese female), and one was too tall for Soyuz (94th percentile 40-year-old, year 2000 American male).

As stated previously, the primary objectives of this evaluation were to determine if a standard evaluation methodology could be developed, and to determine the adequacy of the available volume for a 'lifeboat' vehicle for four crew members in a shirt-sleeve environment. The secondary objectives were to:

- Evaluate the general seat layout as pertains to zero-g ingress, one-g deconditioned crew member egress, one-g injured crew member egress aided by other crew members, and one-g injured crew member egress aided by search and rescue forces.
- Evaluate general seat comfort.
- Evaluate available free volume for desiccant and LiOH canister changeout operations, and administering medical care.
- Comment on potential hatch design and the potential locations of laptop computers for crew use.
- Obtain general information on layout, configuration, and usability.

Figure 13. Taking measurements during 1.8-g portion of 4-person mockup flight test.

The evaluation conclusions were that while the volume was adequate, the headroom for the aft occupants was inadequate. The hatch location (centered over the two rows) complicated ingress to both rows, and it was suggested to move the hatch aft over the back row. The forward seat was too cramped due to equipment stowage, and had inadequate foot room. The canister changeout operations were acceptable. The volume for medical operations was acceptable.

Figure 13 shows measurements being taken during a 1.8-g portion of the flight. Figure 14 shows an "unconscious" crew member being helped into the crew module.

Figure 14. Aided ingress of "unconscious" crew member during 4-person mockup flight test.

4.1.1 Results From Pilot Study

The pilot study provided valuable information that was incorporated into the seven-person mockup evaluations. Lessons learned include improvements to the: (1) test conduction and format, (2) test procedures, (3) postflight questionnaires, (4) hatch locations, (5) seat design, (6) helmet choice, (7) stowage, and (8) mockup construction. Specific results are detailed below (R. Husband, JSC, personal correspondence, 1996).

4.1.1.1 Zero-g Ingress and Egress

Zero-g ingress of four crew members could be accomplished in less than 20 seconds, starting at the hatch and stopping when stabilized in the seat. The optimum ingress order for a four-person vehicle was determined to be the forward seat first, the two outer aft seats second and third, and the center aft seat last. The front seat leg and foot room was found to be unacceptable. The water tanks located inside the crew module interfered with ingress to the front seats and it was determined that they should be moved or shaped confomal to the wall (the water tanks were not in the crew volume for the seven-person vehicle). The zero-g change-out of LiOH canisters was acceptable. The adjustable seat was desirable. It was also determined that more work needs to be done on seat design, especially in the thigh adjustment area.

4.1.1.2 Seat Configuration

The front seat was found to be optimal for the primary crew controls and vehicle interfaces due to the aft seats being needed for ill or injured crew members. It was also determined that an additional set of crew controls should be accessible by a crew member in the aft row. The two outside seats on the aft row were preferred for the ill or injured crew member, with the crew medical officer in the middle seat next to them. It was actually possible to fit four crew members in the aft row of seats, depending on seat design.

4.1.1.3 Hatch

The hatch location (moved aft from the initial ground test) was acceptable. The inward opening hatch appeared to be acceptable. An alternate egress path was recommended.

4.1.1.4 Handholds

The number and location of handholds was generally acceptable, but rigid ones instead of cloth loops were indicated as preferable.

4.1.1.5 Crew Volume

The available crew volume was generally acceptable as tested, along with proposed stowage locations for medical equipment. It was understood that this volume would decrease as more crew equipment is defined.

4.1.1.6 Helmets

Aircraft-type helmets were preferred to clamshell helmets due to the restricted visibility of the clamshells. The clamshell helmets were those used in the early Space Shuttle Program and have a face seal covered by a visor.

4.1.1.7 Constraints and Limitations

The final seat design, with a stroke for load attenuation, would almost certainly decrease the overall crew volume. Additional crew equipment was not represented, and its stowage would decrease the overall crew volume. Any decrease in crew volume would require additional evaluations. The zero-g and high-g test environments were evaluated during relatively short periods of time. A longer period of time for evaluating the dynamic environment (excluding the zero-g) could be obtained using a centrifuge. A longer evaluation in one g would permit further evaluation of volume to ensure it is not claustrophobic and to evaluate seat comfort. One-g egress could not be fully evaluated since the exterior of the vehicle was not represented and since the hatch was not at the actual height above ground.

4.1.2 Application of Pilot Study Results

The results from this pilot study demonstrated that valuable human factors evaluation data could be obtained from a combination of ground and flight tests. The one-g environment allowed the flight procedures to be practiced and modified as appropriate, and the general mockup to be evaluated for suitability before committing to an expensive flight test. The zero-g and 1.8-g environments obtained from the KC-135 provided a unique test environment to examine issues such as ingress, egress, maneuverability, volume acceptability, and operations in dynamic environments. The data obtained from the pilot study were directly applied to the development of the evaluation methodology, test objectives, protocol and questionnaires; and to improve the final mockup design and layout.

4.2 Phase 2

Phase 2 included data collection of timed zero-g ingress and egress of healthy and simulated injured crew members using the seven-person mockup at full and reduced volume. The same ingress and egress tests were performed on all three flights. The volume reduction was accomplished by placing 6-inch-thick pads on all the seats. Data analysis was only conducted on the performance variables.

4.2.1 Performance Variables

The testing for normality showed that all Phase 2 performance variables with three or more data points were normally distributed. These normally distributed data include zero-g ingress times for healthy crew members in both fixed and random orders, and zero-g egress times. Insufficient data points were available on ingress times of a seven-member crew with one ill crew member, and of a four-member crew with one ill crew member. Both of these tests only had two data points each. Table 10 shows the ANOVA $\underline{p}$-values for the variables.

The ANOVAs showed that there were no significant differences between the normally distributed performance variables, including the comparisons of full volume versus reduced volume. Table 11 shows the statistical data for the variables. The evaluators were able to meet the three-minute ingress requirement for all ingresses, including injured crew members in the reduced volume. The ANOVA are summarized in Appendix 3, Table 20.

Table 10. ANOVA *p*-values of Phase 2 Dependent Performance Variables

PerformanceVariable	*p*-value
Full Volume	
7 healthy crew members, fixed order ingress	0.2951
7 healthy crew members, random order ingress	0.5842
7 healthy crew members, egress	0.7714
Reduced Volume	
7 healthy crew members, fixed order ingress	0.5041
7 healthy crew members, random order ingress	0.4923
7 healthy crew members, egress	0.4294
Full Volume versus Reduced Volume	
7 healthy crew members, fixed order ingress	0.8919
7 healthy crew members, random order ingress	0.1028
7 healthy crew members, egress	0.3279
6 healthy and 1 ill crew, fixed order ingress	0.5552

Table 11. Phase 2 Dependent Performance Variables Statistical Data

Activity	Mean	Standard Error	Median	Standard Deviation	Variance	Minimum	Maximum
Full Volume							
7 healthy crew, fixed order ingress (n=4)	29.430	4.038	31.360	8.076	6.219	18.000	37.000
7 healthy crew, random order ingress (n=7)	27.576	2.531	27.000	6.698	44.857	18.000	37.000
7 healthy crew, egress (n=13)	20.555	0.933	20.560	3.362	11.306	15.000	27.200
6 healthy and 1 injured crew, fixed order ingress (n=2)	32.165	1.165	32.165	1.648	2.714	31.000	33.330
3 healthy and 1 injured crew, fixed order ingress (n=2)	20.915	0.915	20.915	1.294	1.674	20.000	21.830
Reduced Volume							
7 healthy crew, fixed order ingress (n=3)	30.243	3.691	32.200	6.394	40.879	23.100	35.430
7 healthy crew, random order ingress (n=4)	33.908	0.884	34.640	1.768	3.127	31.300	35.050
7 healthy crew, egress (n=8)	22.314	1.652	20.785	4.673	21.834	17.970	32.830
6 healthy and 1 injured crew, fixed order ingress (n=1)	33.860	0	33.860	--	--	33.860	33.860

Note: All measurements are in seconds.

4.2.2 Acceptability Variables

Data analysis was not performed on the Phase 2 acceptability data due to differences in the Phase 2 and Phase 3 postflight questionnaires. The Phase 2 acceptability data were reviewed to determine the trends and to modify the methodology and questionnaire for Phase 3. The primary objective of the Phase 2 test was to develop the new evaluation methodology and to have astronauts and flight surgeons use the methodology to evaluate the conceptual CRV seven-member crew module in a zero-g environment.

4.2.2.1 Acceptability Results From Phase 2 Full Volume Tests

The evaluations included a ground test to dry run the procedure and evaluate the suitability of the mockup, and three flight tests. The same participants were used in the ground and flight evaluations. Specific results are detailed below (R. Husband, JSC, personal correspondence, 1998). All recommendations from this phase were incorporated into Phase 3.

4.2.2.1.1 Zero-g Ingress and Egress

All participants rated zero-g ingress and egress of healthy crew members as being easy for this test. When an ill/injured crew member was simulated, it was determined that the standard ISS crew medical restraint system back board could not “turn the corner” from the hatch to the couches. This means that a patient would have to be removed from the board before ingress of the CRV. If the ill/injured crew member was to be placed in the middle row seats, additional clearance could be gained by folding the aft middle row seats flat.

Standing in the hatch during the parabola pullout (1.8-g) was used to simulate healthy deconditioned crew. This could not be simulated very well, but participants noted that it would be very difficult for a deconditioned crew member to help an injured crew member egress postlanding. A method other than a rope, such as steps or handrails, would be useful to aid 1-g egress from the vehicle. An alternate egress path out the side or front of the vehicle would help in assisting the ill/injured crew out of the vehicle. It would also allow egress if the vehicle rolled inverted.

4.2.2.1.2 Seat Configuration

Most people found the seats to be reasonably comfortable, however several of the evaluators had pressure points behind their knees and calves during the 1-g and 1.8-g periods, this was after only a few minutes in the seats. The pressure points behind the knees were likely due to a break in the foam at the seat hinge. The pressure points behind the calves were generally due to the seat being too long in the thigh dimension.

Most liked having their heads elevated. Most preferred a hip angle closer to 90 deg for comfort and for body position during the parachute sequences. A footrest would be helpful.

The optimal seat location for controlling the vehicle would be the seat in the forward row or either seat in the middle row. There was also strong consensus that a window is needed to be located in the viewing range of the crew members controlling the vehicle. More than half of the respondents also thought the forward and middle row seats would be best for the ill/injured crew member. This was primarily due to the extra room around these seats.

4.2.2.1.3 Hatch

The presence of the hatch over the aft row middle seats prevents crew displays to be matched to the eye points for these seats. The hatch also limits the stowage of medical equipment directly overhead an ill/injured crew member, and reduced available volume for cardiopulmonary resuscitation.

It would be better if the hatch structure inside the crew compartment could be minimized or eliminated. Additionally it would be better to move the hatch forward of its current location if the structural design will support the change. This would allow using the full volume of the aft seats for either controlling the vehicle or for medical procedures, as well as making the egress path more centrally located. It was subsequently determined to be a significant impact to the structural design to move the hatch with limited benefit.

4.2.2.1.4 Handholds

The handholds that were evaluated were soft, flexible loops attached at one point. There was near unanimous consensus that the handholds should be attached at two points instead of one. This would allow for better body position control in zero g. Opinions were split on whether the handholds should be soft straps or solid handrails. The handholds should contrast in color to aid in visibility. Placement was generally good, with only minor adjustments needed.

4.2.2.1.5 Medical Operations

No problems were noted with regard to reaching the medical equipment (simulated by foam core boxes), but some equipment interfered with the occupants in the outside seats of the aft row. Better stowage locations and methods were defined after the evaluation. Medical care was easiest in the forward and middle rows where there is the greatest volume around the seats.

4.2.2.1.6 Displays

The outside video feed to the displays was well liked. The evaluators noticed no discomfort or disorientation while watching the displays during the parabolas. This type of system can provide excellent situational awareness when a forward-looking window is not available.

There was near unanimous consensus that the laptop screen size was too small for the corresponding distance it was viewed from. Additionally, the laptop was too far away for some of the evaluators to reach. The display was also unreadable due to vibration during portions of the flight. The large projected display size was better in that it was easier to read and could be seen from adjacent seats. Many found the goggle design that was tested uncomfortable, and not suitable for use while lying down due to protrusions on the headband. The goggles received mixed reviews with some evaluators perceiving a sharp display and some an out of focus display. Several crew members did not like the goggles because only one person could view the display at a time, which makes it difficult to discuss the information on the display. This particular goggle design also required head movements to change displays, which are undesirable during reentry due to the potential for vestibular upset.

The evaluators considered it essential that the vehicle be designed to allow control from at least two seats. Enough displays are required to provide redundancy, and it is highly desirable that all crew members be able to see at least one display to increase situational awareness. Hand controllers should be available to manipulate the displays to avoid overhead reaches during g-loaded flight.

4.2.2.1.7 Crew Volume

Overall, the volume of the crew compartment in the configuration tested was adequate for seven crew members. The seats in the forward and middle rows had the most room. There were interferences with walls in the middle and aft row seats. Many evaluators' feet penetrated the imaginary bulkhead in front of the forward row, even those of small stature. The outside seats in the aft row have very cramped knee room, and the evaluators' knees protruded through the viewing window. The feet of taller evaluators in the aft row also interfered with the heads of evaluators in the middle row. The hatch interfered with the heads of the crew in the middle seats of the aft row.

The seat interferences were addressed by shifting the middle seats in the aft row forward to clear the hatch, angling the outer seats in the aft row to increase shoulder and knee clearance, changing the hip and knee angles to increase foot clearance, and angling the seats in the middle row to increase head clearance.

Several CRV systems boxes located on the aft bulkhead interfered with the heads of the crew in the aft row. This equipment was subsequently moved to below the seat line. Large boxes of medical equipment interfered with the shoulders of crew in the outside seats of the aft row. This equipment was subsequently broken into small packages that could be more easily stowed. The evaluators also questioned whether there was enough volume to stow all other items needed. Additional items that should be stowed were identified. This stowage was included in Phase 3 testing.

4.2.2.1.8 Helmets

Most evaluators liked using helmets for communications, oxygen, and head protection. The helmet design should be lightweight and allow a large field of view. Three helmet designs were tested, including aircraft, helicopter, and the original Shuttle clamshell helmets. Aircraft helmets were considered adequate but not optimal. Clamshell helmets were considered inadequate due to the limited field of view. Not enough data were gathered on the helicopter helmets to make a judgement.

4.2.2.1.9 Constraints and Limitations

Changes in layout and stowage may affect acceptability ratings. A full-mission-duration ground test should be performed to see what additional problems could be highlighted as a result of being in the vehicle for nine hours. All necessary crew equipment was not represented in the stowage. A detailed list of stowage items should be generated and represented in the next test.

There is still a lot of design work required to finalize the seat body angles, seat design, and seat restraints. Final seat design will have a big impact on not only crew survival, but also available volume, crew interfaces with vehicles, ingress, and egress. The hatch lacked volume and design fidelity and had to be manually repositioned rather than being mechanically assisted. The lack of actual hatch volume gave the perception of more free volume being available than actually is. The actual hatch design should be tested.

A window should be added to the vehicle design, and the location tested so that evaluators can assess window and display viewing angles for crew members in control of the vehicle. Actual medical hardware should be used in medical evaluations to obtain an accurate sense of the volume required for medical procedures.

One-g egress and rescue may be a problem. Egress tests should be performed to allow a full evaluation.

4.2.2.2 Acceptability Results From Phase 2 Reduced Volume Tests

A reduced CRV volume was obtained by placing 6-inch-thick pads on the seats. This resulted in a 20% decrease in internal volume. The purpose of this portion of the test was to determine if a large reduction in volume results in a significant impact.

4.2.2.2.1 Zero-g Ingress and Egress

Maneuvering capability inside the crew compartment was very dependent on how many crew members were inside. Maneuvering in the aft row was difficult due to the reduction in clearance between the seats and ceiling. It was also noted that the hatch mockup was significantly thinner than a flight hatch. With a six-inch hatch, the capability would be further reduced. It was possible to turn around in the area between the middle row seats.

With reduced volume, ingress order was much more important than with the baseline volume. The best ingress order is front to back. It is extremely difficult, if not impossible depending on crew size, to ingress the outside aft row seats with the inside seats already occupied. It was very difficult to get to the forward or middle rows with the aft row seats occupied.

4.2.2.2.2 Crew Volume

Overall the reduction of the crew compartment volume by 20% was unacceptable. The head and wall clearance problems were exacerbated. Stowage was inadequate. Medical care was extremely difficult. The evaluators perceived that there would be a negative psychological effect to spending nine hours in this reduced volume.

4.2.2.2.3 Constraints and Limitations

This test was worthwhile in helping to determine the minimum acceptable crew compartment volume. An actual volume hatch will significantly impact the ability to maneuver inside the vehicle. It is possible that a false sense of maneuvering capability was given using a thin hatch. Actual stowage volume was not tested in this configuration. Available volume will be greatly reduced when all stowed items are included in the mockup.

4.3 Phase 3

The intent of the Phase 3 tests was to validate the final evaluation methodology. The Phase 3 tests included data collection of timed zero-g (KC-135 flight) ingress and egress of healthy and simulated injured crew members using the full volume mockup. The same ingress and egress tests were performed on both flights. Data analysis was conducted on all performance and acceptability dependent variables.

4.3.1 Performance Variables

Table 12 shows the ANOVA $\underline{p}$-values for the performance variables. Variables that were significant at $\underline{p}<0.05$ appear in bold print. The testing for normality showed that all Phase 3 performance variables with three or more data points were normally distributed. These normally distributed data include zero-g ingress times for healthy crew members in both fixed and random orders, and zero-g egress times. Insufficient data points were available on ingress times of a seven-member crew with one or two ill crew members, and of a four-member crew with one ill crew member. These tests only had one or two data points for each group. The ANOVAs showed that there were no significant differences between the normally distributed performance variables for each group.

Table 12. ANOVA $\underline{p}$-values of Phase 3 Dependent Performance Variables

PerformanceVariable	$\underline{p}$-value
Group 1	
7 healthy crew members, fixed order ingress	0.8396
7 healthy crew members egress	0.6816
Group 2	
7 healthy crew members, fixed order ingress	0.98882
7 healthy crew members, random order ingress	0.6956
7 healthy crew members egress	0.5025
Group 1 versus Group 2	
7 healthy crew members, fixed order ingress	0.4581
7 healthy crew members, random order ingress	0.1891
7 healthy crew members egress	**0.00001**
6 healthy and 1 ill crew, fixed order ingress	0.0570
5 healthy and 2 ill crew, fixed order ingress	0.4651

An F-test and a Duncan Multiple Range test performed on the performance data to compare between the groups showed that the only significant difference between the groups was concerning the egress of seven healthy crew members ($\underline{p}=0.000014$, $F=5.2056 > F_{crit}=2.7534$). The difference in egress performance of the groups is attributed to both the difference in number of data points and practice. Egress timing data was the last priority in data collection, and most of the egress steps for the first group fell at the end of the parabola sets. Therefore, most of the egresses were performed during one-g flight. In addition, out of the three timed egresses performed by the first group, one was the practice egress and one was with a simulated injured crew member. The egress differences can therefore be dismissed and it is concluded that the data show no differences between the matched blocks for the performance variables.

Table 13 shows the statistical data for the variables. The evaluators were able to meet the three-minute ingress requirement for all ingresses, including injured crew members. The ANOVAs are summarized in Appendix 3, Table 21.

Table 13. Phase 3 Dependent Performance Variables Statistical Data (F_{crit} = 161.446)

Activity	Mean	Standard Error	Median	Standard Deviation	Variance	Minimum	Maximum
Group 1							
7 healthy crew, fixed order ingress (n=3)	28.430	4.292	26.290	7.435	55.275	22.300	36.700
7 healthy crew, random order ingress (n=2)	22.425	0.825	22.425	1.667	1.361	21.600	23.250
7 healthy crew egress (n=3)	32.710	1.355	34.010	2.348	5.511	30.000	34.120
6 healthy and 1 injured crew, fixed order ingress (n=1)	41.400	0	41.400	--	--	41.40	41.400
5 healthy and 2 injured crew, fixed order ingress (n=1)	51.660	0	51.660	--	--	51.660	51.660
3 healthy and 1 injured crew, fixed order ingress (n=1)	44.530	0	44.530	--	--	44.530	44.530
Group 2							
7 healthy crew, fixed order ingress (n=3)	24.720	1.423	24.770	2.465	6.078	22.230	27.160
7 healthy crew, random order ingress (n=3)	30.000	3.434	33.160	5.947	35.368	32.140	33.700
7 healthy crew egress (n=8)	17.223	0.984	17.545	2.782	7.739	12.750	21.710
6 healthy and 1 injured crew, fixed order ingress (n=2)	23.650	0.920	23.650	1.301	1.693	22.730	24.570
5 healthy and 2 injured crew, fixed order ingress (n=2)	48.035	1.875	48.035	2.652	7.031	46.160	49.910

Note: All measurements are in seconds.

4.3.2 Acceptability Variables

4.3.2.1 Acceptability Analysis From Phase 3

Table 14 shows the ANOVA p-values for the acceptability variables. Variables that were significant at $p<0.05$ appear in bold print. The testing for normality of the dependent acceptability variables showed that the responses to all but five of the postflight questions were distributed normally across the group of evaluators. The non-normally distributed questions were:

- Q1: Baseline adjustable wooden seat comfort for one-g.
- Q4: Baseline adjustable wooden seat comfort for zero-g.
- Q24: Ease of zero-g egress for healthy crew members.
- Q31: Adequacy of volume in current configuration for anticipated post-separation operations.
- Q37: Adequacy of crew module reach and visibility.

Table 14. ANOVA p-values of Phase 3 Dependent Acceptability Variables

Acceptability Variable	**p-value**
Seating	
Q1: Baseline adjustable wooden seat comfort for 1 g	0.4162
Q2: 90-deg collapsible wooden seat comfort for 1 g	0.9976
Q3: Soyuz-style seat comfort for 1 g	0.7699
Q4: Baseline adjustable wooden seat comfort for 0 g	0.1480
Q5: 90-deg collapsible wooden seat comfort for 0 g	0.3691
Q6: Soyuz-style seat comfort for 0 g	0.0967
Q7: Baseline adjustable wooden seat comfort for high-g maneuvering	0.7838
Q8: 90-deg collapsible wooden seat comfort for high-g maneuvering	0.9977
Q9: Soyuz-style seat comfort for high-g maneuvering	0.9704
Q10: Seating arrangement (4/2/1)	0.8236
Q11: Aft row face to ceiling clearance for crew comfort	0.2925
Q12: Middle row face to ceiling clearance for crew comfort	0.2485
Q13: Forward row face to ceiling clearance for crew comfort	0.7882
Q14: Aft row knee to ceiling/wall clearance for crew comfort	0.5274
Q15: Middle row knee to ceiling/wall clearance for crew comfort	0.9268
Q16: Forward row knee to ceiling/wall clearance for crew comfort	0.8029
Q17: Aft row body to wall and body to body clearance for crew comfort	0.6695
Q18: Middle row body to wall and body to body clearance for crew comfort	0.9140
Q19: Forward row body to wall and body to body clearance for crew comfort	0.7760

Table 14. ANOVA *p*-values of Phase 3 Dependent Acceptability Variables (continued)

Acceptability Variable	***p*-value**
Ingress/Egress	
Q20: Ingress order for healthy crew members during station emergency	0.8589
Q21: Ingress order for ill/injured crew members for medical evacuation	0.7967
Q22: Ease of zero-g ingress for healthy crew members	0.2804
Q23: Ease of zero-g ingress for ill/injured crew members	0.0904
Q24: Ease of zero-g egress for healthy crew members	0.4049
Q25: Anticipated ease of one-g egress of healthy deconditioned crew members	0.7159
Hatch	
Q26: Location of hatch	0.8306
Q27: Adequacy of diameter of hatch hole for anticipated zero-g operations	0.1045
Q28: Adequacy of diameter of hatch hole for anticipated one-g operations	0.2804
Q29: Acceptability of stowing hatch on aft wall	**0.0493**
Q30: Acceptability of stowing hatch on ceiling	0.8149
Volume	
Q31: Adequacy of volume in current configuration for anticipated on-orbit station attached operations	0.8057
Q32: Adequacy of volume for 7 crew members in current configuration for anticipated post-separation 0-g operations	0.3145
Q33: Adequacy of volume for 7 crew members in current configuration for anticipated atmospheric flight and postlanding operations	0.9735
Q34: Adequacy of volume to perform rudimentary medical care	0.8840
Crew Equipment and Stowage	
Q35: Adequacy of flight crew equipment access and stowage as tested	0.8485
Q36: Adequacy of medical equipment access and stowage as tested	0.8900
Q37: Adequacy of crew module reach and visibility	0.8821
Q38: Adequacy of design of rigid handholds	0.9876
Q39: Adequacy of design of soft handholds	0.8996
Q40: Adequacy of number of handholds	0.5489
Q41: Adequacy of placement of rigid handholds	0.7372
Q42: Adequacy of placement of soft handholds	0.9007
Q43: Adequacy of standard aircraft helmet for head protection	0.3474
General	
Q44: Adequacy of questionnaire to express my views	0.6628

A Kruskal-Wallis test performed on the five non-normally distributed variables showed that there were no significant differences between the means. In addition, since n_j>/=5, the variables could be approximated by a Chi-Squared distribution. A Wilcoxen Rank Sum test was also performed, which also showed no significant differences.

In terms of the acceptability differences, only one of the 44 acceptability measures was significant at the $p<0.05$ level. This normally distributed question (Q29) concerned the acceptability of stowing the hatch on the aft wall. A Duncan Multiple Range test applied to question 29 showed no significant differences ($p=0.04931$). Table 15 shows the statistical data for the acceptability measures. The ANOVAs are summarized in Appendix 3, Table 22.

Although no significant differences were found in the responses to the acceptability questions across the entire group of evaluators, an additional set of analyses was performed to determine if there were any differences between the sub-populations. Data analysis conducted on the sub-populations compared all of the acceptability dependent variables. Table 16 shows the ANOVA p-values for the acceptability variables. The ANOVAs are summarized in Appendix 3, Table 23. Variables that were significant at $p<0.05$ appear in bold print. The sub-populations compared were:

- Flown versus unflown astronauts.
- Pilot versus mission specialist astronauts.
- High-aviation-experience versus low-aviation-experience in mission specialist astronauts.

Table 15. Phase 3 Dependent Acceptability Variables Statistical Data

Activity	Mean	Standard Error	Median	Standard Deviation	Variance	Minimum	Maximum
Seating							
Q1: Baseline adjustable wooden seat comfort for 1 g	4.575	0.132	4.750	0.591	0.349	4.000	6.000
Q2: 90-deg collapsible wooden seat comfort for 1 g	4.150	0.167	4.000	0.745	0.555	3.000	5.000
Q3: Soyuz-style seat comfort for 1 g	3.024	0.203	3.000	0.928	0.862	1.000	5.000
Q4: Baseline adjustable wooden seat comfort for 0 g	5.024	0.122	5.000	0.559	0.312	4.000	6.000
Q5: 90-deg collapsible wooden seat comfort for 0 g	4.738	0.160	5.000	0.735	0.541	3.000	6.000
Q6: Soyuz-style seat comfort for 0 g	3.833	0.266	4.000	1.218	1.483	1.000	6.000
Q7: Baseline adjustable wooden seat comfort for high-g maneuvering	4.158	0.175	4.000	0.765	0.585	3.000	5.000
Q8: 90-deg collapsible wooden seat comfort for high-g maneuvering	3.579	0.233	4.000	1.017	1.035	2.000	5.000
Q9: Soyuz-style seat comfort for high-g maneuvering	2.974	0.204	3.000	0.889	0.791	2.000	5.000
Q10: Seating arrangement (4/2/1)	5.000	0.205	5.000	0.198	0.842	3.000	6.000
Q11: Aft row face to ceiling clearance for crew comfort	4.191	0.313	5.000	1.436	2.062	2.000	6.000
Q12: Middle row face to ceiling clearance for crew comfort	4.786	0.245	5.000	1.124	1.264	2.000	6.000

Table 15. Phase 3 Dependent Acceptability Variables Statistical Data (continued)

Activity	Mean	Standard Error	Median	Standard Deviation	Variance	Minimum	Maximum
Q13: Forward row face to ceiling clearance for crew comfort	4.789	0.248	5.000	1.084	1.175	2.000	6.000
Q14: Aft row knee to ceiling/wall clearance for crew comfort	4.191	0.311	4.000	1.427	2.037	1.000	6.000
Q15: Middle row knee to ceiling/wall clearance for crew comfort	5.119	0.223	5.000	1.024	1.048	3.000	6.000
Q16: Forward row knee to ceiling/wall clearance for crew comfort	5.237	0.204	5.000	0.888	0.788	3.000	6.000
Q17: Aft row body to wall and body to body clearance for crew comfort	3.595	0.238	4.000	1.091	1.191	2.000	6.000
Q18: Middle row body to wall and body to body clearance for crew comfort	4.905	0.241	5.000	1.103	1.216	2.000	6.000
Q19: Forward row body to wall and body to body clearance for crew comfort	5.263	0.214	6.000	0.934	0.871	3.000	6.000
Ingress/Egress							
Q20: Ingress order for healthy crew members during station emergency	3.361	0.418	3.750	1.772	3.141	1.000	6.000
Q21: Ingress order for ill/injured crew members for medical evacuation	5.132	0.306	6.000	1.332	1.773	1.000	6.000
Q22: Ease of zero-g ingress for healthy crew members	5.381	0.129	5.000	0.590	0.348	4.000	6.000
Q23: Ease of zero-g ingress for ill/injured crew members	3.579	0.260	4.000	1.134	1.285	2.000	5.000
Q24: Ease of zero-g egress for healthy crew members	5.321	0.157	5.000	0.721	0.519	4.000	6.000
Q25: Anticipated ease of one-g egress of healthy deconditioned crew members	2.067	0.263	2.000	1.206	1.453	0	5.000
Hatch							
Q26: Location of hatch	5.095	0.132	5.000	0.605	0.366	4.000	6.000
Q27: Adequacy of diameter of hatch hole for anticipated zero-g operations	5.309	0.156	5.000	0.716	0.512	4.000	6.000
Q28: Adequacy of diameter of hatch hole for anticipated one-g operations	4.369	0.235	4.000	1.077	1.160	3.000	6.000
Q29: Acceptability of stowing hatch on aft wall	4.825	0.196	5.000	0.878	0.770	3.000	6.000
Q30: Acceptability of stowing hatch on ceiling	3.132	0.241	3.000	1.052	1.107	1.000	5.000
Volume							
Q31: Adequacy of volume in current configuration for anticipated on-orbit station attached operations	4.667	0.174	5.000	0.796	0.633	3.000	6.000

Table 15. Phase 3 Dependent Acceptability Variables Statistical Data (continued)

Activity	Mean	Standard Error	Median	Standard Deviation	Variance	Minimum	Maximum
Q32: Adequacy of volume for 7 crew members in current configuration for anticipated post-separation 0-g operations	4.191	0.222	5.000	1.018	1.037	2.000	5.000
Q33: Adequacy of volume for 7 crew members in current configuration for anticipated atmospheric flight and postlanding operations	4.350	0.212	5.000	0.947	0.897	2.000	5.000
Q34: Adequacy of volume to perform rudimentary medical care	3.556	0.246	4.000	1.042	1.085	2.000	5.000
Crew Equipment and Stowage							
Q35: Adequacy of flight crew equipment access and stowage as tested	4.052	0.175	4.000	0.762	0.584	3.000	5.000
Q36: Adequacy of medical equipment access and stowage as tested	4.028	0.263	4.000	1.118	1.249	1.000	6.000
Q37: Adequacy of crew module reach and visibility	4.548	0.189	5.000	0.865	0.748	2.000	6.000
Q38: Adequacy of design of rigid handholds	5.095	0.217	5.000	0.995	0.991	2.000	6.000
Q39: Adequacy of design of soft handholds	4.071	0.268	4.000	1.228	1.507	2.000	6.000
Q40: Adequacy of number of handholds	4.809	0.225	5.000	1.031	1.062	2.000	6.000
Q41: Adequacy of placement of rigid handholds	4.905	0.231	5.000	1.056	1.116	2.000	6.000
Q42: Adequacy of placement of soft handholds	4.191	0.274	4.000	1.256	1.587	2.000	6.000
Q43: Adequacy of standard aircraft helmet for head protection	4.768	0.300	5.000	1.375	1.891	2.000	6.000
General							
Q44: Adequacy of questionnaire to express my views	5.118	0.163	5.000	0.674	1.454	3.500	6.000

Note: All measurements are in seconds.

Table 16. ANOVA *p*-values Comparing Phase 3 Subpopulation Dependent Acceptability Variables

Acceptability Variable	**Flown vs Unflown** ***p*-values**	**Pilot vs Mission Specialist** ***p*-values**	**High vs Low Aviation Experience** ***p*-values**
Seating			
Q1: Baseline adjustable wooden seat comfort for 1 g	0.2306	0.1460	0.8487
Q2: 90-deg collapsible wooden seat comfort for 1 g	0.7115	0.8591	0.4810
Q3: Soyuz-style seat comfort for 1 g	0.7420	0.1020	0.5902
Q4: Baseline adjustable wooden seat comfort for 0 g	0.1757	0.5916	**0.0212**
Q5: 90-deg collapsible wooden seat comfort for 0 g	0.8725	0.1606	0.0929
Q6: Soyuz-style seat comfort for 0 g	0.5462	**0.0064**	0.1730
Q7: Baseline adjustable wooden seat comfort for high-g maneuvering	0.1841	0.8687	0.8611
Q8: 90-deg collapsible wooden seat comfort for high-g maneuvering	1.0000	0.8151	0.9103
Q9: Soyuz-style seat comfort for high-g maneuvering	0.9416	0.6327	0.7927
Q10: Seating arrangement (4/2/1)	0.5582	0.2449	0.2411
Q11: Aft row face to ceiling clearance for crew comfort	**0.0231**	0.3235	0.8339
Q12: Middle row face to ceiling clearance for crew comfort	0.0541	0.2602	0.2356
Q13: Forward row face to ceiling clearance for crew comfort	0.3976	0.6454	0.1313
Q14: Aft row knee to ceiling/wall clearance for crew comfort	0.4151	0.0796	0.2463
Q15: Middle row knee to ceiling/wall clearance for crew comfort	0.4069	**0.0044**	0.5328
Q16: Forward row knee to ceiling/wall clearance for crew comfort	0.1960	0.7333	0.2283
Q17: Aft row body to wall and body to body clearance for crew comfort	0.3302	0.3347	0.5650
Q18: Middle row body to wall and body to body clearance for crew comfort	0.4346	0.6190	0.7321
Q19: Forward row body to wall and body to body clearance for crew comfort	0.3899	0.9367	0.2821
Ingress/Egress			
Q20: Ingress order for healthy crew members during station emergency	0.4362	0.7851	0.8583
Q21: Ingress order for ill/injured crew members for medical evacuation	0.6325	0.2870	0.6922
Q22: Ease of zero-g ingress for healthy crew members	0.6192	0.6570	**0.0239**
Q23: Ease of zero-g ingress for ill/injured crew members	0.0627	**0.0131**	0.5527
Q24: Ease of zero-g egress for healthy crew members	**0.0345**	0.5195	0.3147
Q25: Anticipated ease of one-g egress of healthy deconditioned crew members	0.9578	0.0675	0.7573
Hatch			
Q26: Location of hatch	0.3520	0.6877	0.2085
Q27: Adequacy of diameter of hatch hole for anticipated zero-g operations	**0.0376**	.03725	0.0841
Q28: Adequacy of diameter of hatch hole for anticipated one-g operations	0.0542	0.1527	0.6953
Q29: Acceptability of stowing hatch on aft wall	0.4652	0.2511	**0.0003**
Q30: Acceptability of stowing hatch on ceiling	0.8328	0.1802	0.8704

Table 16. ANOVA p-values Comparing Phase 3 Subpopulation Dependent Acceptability Variables (continued)

AcceptabilityVariable	Flown vs Unflown p-values	Pilot vs Mission Specialist p-values	High vs Low Aviation Experience p-values
Volume			
Q31: Adequacy of volume in current configuration for anticipated on-orbit station attached operations	0.2735	0.4202	0.5090
Q32: Adequacy of volume for 7 crew members in current configuration for anticipated post-separation 0-g operations	**0.0499**	0.2472	0.6126
Q33: Adequacy of volume for 7 crew members in current configuration for anticipated atmospheric flight and postlanding operations	0.6458	0.7333	0.3215
Q34: Adequacy of volume to perform rudimentary medical care	0.8537	0.9258	0.3383
Crew Equipment and Stowage			
Q35: Adequacy of flight crew equipment access and stowage as tested	0.2918	0.4873	0.5922
Q36: Adequacy of medical equipment access and stowage as tested	0.8415	0.4182	0.3936
Q37: Adequacy of crew module reach and visibility	0.5685	0.8305	0.3746
Q38: Adequacy of design of rigid handholds	0.6722	0.8888	0.2351
Q39: Adequacy of design of soft handholds	0.6453	0.6615	0.8223
Q40: Adequacy of number of handholds	0.0968	0.1257	0.5615
Q41: Adequacy of placement of rigid handholds	0.1324	0.3774	0.5228
Q42: Adequacy of placement of soft handholds	0.3790	0.6631	0.3409
Q43: Adequacy of standard aircraft helmet for head protection	0.1309	0.7084	**0.0429**
General			
Q44: Adequacy of questionnaire to express my views	0.2857	0.5274	1.0000

In terms of the acceptability differences across the populations, 4 of the 44 acceptability questions were significant at the $p<0.05$ level comparing astronauts who have spaceflight experience with those who have not flown yet. Three questions were significant when comparing pilot astronauts to mission specialist astronauts. And four were significant when comparing mission specialists with a high level of aviation experience (defined here as greater than 500 hours) with those without that level of experience.

4.3.2.1.1 Flown Versus Unflown Astronauts

Question 11 concerned the aft row face to ceiling clearance for crew comfort. A Duncan Multiple Range test applied to question 11 showed the difference to be significant ($p=0.02313$). The flown astronauts had an average rating of 2.75 while the unflown astronauts had an average rating of 4.571. These reflect an unacceptable rating from the experienced astronauts and an acceptable rating from the inexperienced ones.

Question 24 concerned the ease of zero-g egress for healthy crew members. A Duncan Multiple Range test applied to question 24 showed the difference to be significant ($p=0.03454$). The flown astronauts had an average rating of 4.75 while the unflown astronauts had an average rating of 5.554. The experienced astronauts considered the task to be easy, and the inexperienced astronauts very easy.

Question 27 concerned the adequacy of the diameter of the hatch hole for anticipated zero-g operations. A Duncan Multiple Range test applied to question 27 showed the difference to be significant (p=0.03764). The flown astronauts had an average rating of 4.75 while the unflown astronauts had an average rating of 5.536. The experienced astronauts considered the task to be adequate, and the inexperienced astronauts completely adequate.

Question 32 concerned the adequacy of the volume for seven crew members in the current configuration for anticipated post-separation zero-g operations. A Duncan Multiple Range test applied to question 32 showed no significant difference (p=0.04998). The flown astronauts had an average rating of 3.375 while the unflown astronauts had an average rating of 4.536. The experienced astronauts considered the task to be marginally adequate, and the inexperienced astronauts adequate.

The data reflects the role of spaceflight experience in understanding how a human really operates in zero g. In the data points where differences were noted, and in all but 6 other of the 44 questions, experienced crew members were more cautious in their answers and gave the tasks lower ratings than inexperienced astronauts.

4.3.2.1.2 Pilot Versus Mission Specialist Astronauts

Question 6 concerned the Soyuz-seat comfort in zero g. A Duncan Multiple Range test applied to question 6 showed the difference to be significant (p=0.00636). The pilot astronauts had an average rating of 2.6 while the mission specialist astronauts had an average rating of 4.346. These reflect an uncomfortable rating from the pilots and a comfortable rating from the mission specialists.

Question 15 concerned the middle row knee to ceiling and wall clearance for crew comfort. A Duncan Multiple Range test applied to question 15 showed no significant difference (p=0.0044). The pilot astronauts had an average rating of 5 while the mission specialist astronauts had an average rating of 5.038. These reflect an acceptable rating from both groups with the mission specialists slightly more favorable.

Question 23 concerned the ease of zero-g ingress for ill or injured crew members. A Duncan Multiple Range test applied to question 23 showed the difference to be significant (p=0.01321). The pilot astronauts had an average rating of 2.6 while the mission specialist astronauts had an average rating of 4. These reflect a difficult rating from the pilots and a marginally easy rating from the mission specialists.

The data reflect the differing experience base and expected task requirements for pilot and mission specialist astronauts. In these data points where differences were noted, and in all but 15 of the 44 questions, pilot astronauts were more cautious in their answers and gave the tasks lower ratings than mission specialist astronauts.

4.3.2.1.3 High-Aviation-Experience Versus Low-Aviation-Experience Mission Specialists

Question 4 concerned the baseline adjustable wooden seat comfort in zero-g. A Duncan Multiple Range test applied to question 4 showed the difference to be significant (p=0.02121). The high-aviation-experience mission specialist astronauts had an average rating of 5.278 while the low-aviation-experience mission specialist astronauts had an average rating of 4.5. These reflect a very comfortable rating from the high-aviation-experience and a comfortable rating from the low-aviation-experience mission specialists.

Question 22 concerned the ease of zero-g ingress for healthy crew members. A Duncan Multiple Range test applied to question 22 showed a significant difference (p=0.02387). The high-aviation-experience mission specialist astronauts had an average rating of 5.313 while the low-aviation-experience mission specialist astronauts had an average rating of 5. These reflect a very easy rating from the high-aviation-experience and an easy rating from the low-aviation-experience mission specialists.

Question 29 concerned the acceptability of stowing the hatch on the aft wall. A Duncan Multiple Range test applied to question 29 showed the difference to be significant (p=0.00025). The high-aviation-experience mission specialist astronauts had an average rating of 5.167 while the low-aviation-experience mission specialist astronauts had an average rating of 3.5. These reflect a completely acceptable rating from the high-aviation-experience and a marginally acceptable rating from the low-aviation-experience mission specialists.

Question 43 concerned the adequacy of using standard aircraft helmets for head protection. A Duncan Multiple Range test applied to question 43 showed a significant difference (p=0.04298). The high-aviation-experience mission specialist astronauts had an average rating of 5.389 while the low-aviation-experience mission specialist astronauts had an average rating of 3.75. These reflect a completely adequate rating from the high-aviation-experience and a marginally adequate rating from the low-aviation-experience mission specialists.

The data reflects the differing experience bases for mission specialist astronauts with a high experience level in aviation in comparison to those with little aviation experience. Those with the higher levels of experience are familiar with and comfortable in a cockpit environment and typically are willing to make due with less than optimal conditions for a “lifeboat.” This was evident in the comments on the postflight questionnaire, in the debriefings, and in their ratings on the questions. In those data points where differences were noted, and in all but 4 other of the 44 questions, high-aviation-experience mission specialist astronauts were more positive and accepting in their answers and gave the tasks higher ratings than low-aviation-experience mission specialists.

4.3.2.2 Acceptability Results From Phase 3

The evaluations conducted in this phase included two ground tests to dry-run the procedure and evaluate the suitability of the mockup, and two flight tests to gather data. The first ground test focused on medical operations and the second on ingress and crew operations. The same participants were used in the ground and flight tests. An overview of the parabolas is shown in Table 17. Specific results are detailed subsequently. All ratings discussed are averages and are based on the six-point bipolar scale from one to six, where one is the most negative response and six is the most positive response. The statistical data for the questions were previously shown in Table 15.

Table 17. Phase 3 Parabola Overview

Parabola Set/Task	Number Parabolas Planned	Flight 1 Parabolas Conducted	Flight 2 Parabolas Conducted
Parabola Set #1			
Orientation	1	1	1
Practice Ingress	2	2	1
Practice Egress	2	2	1
Pause	1	--	--
Ingress (7 healthy, fixed order), Close Hatch	2	2	1
Strap In, Volume Assessments	4	2	2
Open hatch, Egress	1-g egress	2	1
Ingress (7 healthy, fixed order, increment seat), Close Hatch		2	1
Volume Assessments			2
Open Hatch, Egress		1-g egress	1
Free Parabola			1
Total	12	12	12
Parabola Set #2			
Ingress (7 healthy, random order, increment seat), Close Hatch	2	1	1
Strap In, Volume Assessments	5	3	1
Open hatch, Egress	2	3	1
Ingress (7 healthy, random order, increment seat), Close Hatch		1	1
Strap In, Volume Assessments		1	1
Open Hatch, Egress		1	1
Ingress (7 healthy, random order, increment seat), Close Hatch			1
Strap In, Volume Assessments			1
Open Hatch, Egress			1
Total	9	9	9
Parabola Set #3			
Ingress (6 healthy, 1 ill, fixed order, increment seat), Close Hatch	3	2	1
Strap In, Volume and Medical Assessments	1	1	1
Open Hatch, Egress	2	2	1
Ingress (5 healthy, 2 ill, fixed order, increment seat), Close Hatch	3	2	2

Table 17. Phase 3 Parabola Overview (continued)

Parabola Set/Task	Number Parabolas Planned	Flight 1 Parabolas Conducted	Flight 2 Parabolas Conducted
Parabola Set #3, cont.			
Strap In, Volume and Medical Assessments	1	2	1
Open hatch, Egress	2	1 plus 1-g	1
Ingress (5 healthy, 2 ill, fixed order, increment seat), Close Hatch			2
Strap In, Volume and Medical Assessments			1
Open Hatch, Egress			1
Free Parabola			1
Total	12	10	12
Parabola Set #4			
Ingress (3 healthy, 1 “dummy”, fixed order), Close Hatch, Strap In	3	3	1-g ingress
Medical Evaluations	10	4	13
Open Hatch, Egress	1	egress from bottom access hole	1-g egress
Ingress		1	
Medical Evaluations		3	
Egress		1	
Ingress (3 healthy, 1 injured)		2	
Medical Evaluations		2	
Egress		1	
Total	14	17	13
Flight Total	48	48	46

4.3.2.2.1 Zero-g Ingress and Egress

Participants rated zero-g ingress and egress of healthy crew members as being very easy for the configuration tested (rated 5.4 and 5.3, respectively). Evaluators exhibited a natural tendency to ingress the crew module feet first and to egress head first. It was noticeably more difficult to ingress and egress when the two middle seats in the aft row were in the up position rather than being folded flat. Ease of ingress of an ill or injured crew member was rated as marginal (3.6). It was noted that this task will be exacerbated if the crew member is unconscious. It is difficult to control the mass and inertia of an injured person without a backboard, and the standard station backboard will not fit through the hatch and turn the corner into the seats. It is possible to injure a crew member worse during an aided ingress.

Ingress order was not considered to be particularly important for healthy crew members during a station emergency (3.4). It is easiest to fill the vehicle from the forward row first. There is adequate room to maneuver and rearrange if time for hatch closure or vehicle separation from the station is critical. A fixed ingress order should be used for a medical evacuation (5.1). The middle row should be filled first so that the vehicle can be activated, and so that there is help from inside the vehicle to guide the injured person to his/her seat. Medevac is not a time-critical ingress and emphasis should be on the safe transport of the crew. Figure 15 shows astronauts during a zero-g ingress as well as two data collectors.

Figure 15. Zero-g ingress into mockup.

It is anticipated to be very difficult for healthy deconditioned crew members to egress the vehicle postlanding (rated 2.1). The hatch of this vehicle will be 6 to 9 feet above the ground after landing. A method needs to be developed to aid the crew in getting down out of the vehicle. An alternate emergency hatch in the side of the vehicle would help the crew egress and help rescuers have better access to the inside of the vehicle. While not posed as a question, evaluators commented during the debriefings that rescue of injured crew members will also be difficult. Seats that fold flush will help.

4.3.2.2.2 Seat Configuration

The evaluators were almost evenly split on seat angle preferences of the wooden adjustable seats based on one-g comfort during the ground tests. Equal numbers of crew members like hip angles of 40 deg, 60 deg, and 90 deg to the waterline. While 55% preferred their lower legs to be 90+ deg to the waterline, 45% preferred an angle of 40 deg.

The evaluators found all three seat designs to be reasonably comfortable in all test acceleration environments. However, there was a marked preference for the baseline adjustable wooden seat. The least liked seat was the Soyuz-style seat. Table 18 shows the mean and standard deviation for the seat comparisons. The statistical data were previously shown in Table 15, and the ANOVAs are included in Appendix 3, Table 22. The relevant questions are 1 through 9.

Table 18. Seat Comfort Comparisons

Seat	Zero-g Mean (Std Dev)	One-g Mean (Std Dev)	1.8-g Mean (Std Dev)
Baseline adjustable wooden seat	5.024 (0.559)	4.575 (0.591)	4.158 (0.765)
90-deg collapsible wooden seat	4.738 (0.735)	4.150 (0.745)	3.579 (1.017)
Soyuz-style seat	3.833 (1.218)	3.024 (0.928)	2.974 (0.889)

The actual Soyuz- seat, while protecting its occupants, is uncomfortable. The knees are drawn up near the cosmonauts' chests and restrained to keep them from opening or moving away from the chest toward the instrument panel. Side movement is constrained by the wall and the other crew members' knees. Evaluators in this test did not like having unsupported knees in this style of seat. A restraint would have to prevent movement in all directions, including the knees falling to one side to prevent injury.

The flush folding seat improved maneuverability inside the mockup. An alternate seat design was suggested that would include an upper leg support and footrest, but no lower leg support.

Crew members preferred the 12-deg wedge for the middle row seats over the 22-deg wedge or being flat. The 22-deg wedge was too high and positioned some crew evaluators' heads too close to the overhead displays. It was noted that additional testing should be performed to determine if there is a performance difference in controlling the vehicle between having the torso supine or inclined. It is recognized that there is a psychological benefit from raising the torso to a more "pilot-intuitive" position. Figure 16 shows evaluators in the mockup with the two different wedges. The 22-deg wedge is in the left seat and the 12-deg wedge is in the right seat. The head of the crew member in the front row can be seen, as well as the feet of the crew members in the aft row.

Figure 16. Middle row seats inside mockup.

The 4/2/1 seating arrangement was considered to be highly acceptable with a rating of 5. The two middle aft row seats had been shifted 6 inches forward for this test to improve the clearance for stowing the hatch on the aft wall. It was noted that they should be moved several additional inches to obtain complete clearance between the crew members' heads and the stowed hatch. The forward row was also shifted back for this test, which eliminated the foot to bulkhead interferences seen in Phase 2 testing. And the two outer seats in the aft row were angled with the feet slightly more inboard for clearance room from the middle row heads.

Clearances were judged to be generally acceptable, but there were still some problems with clearances between crew members' bodies and vehicle structure. The aft row is the most confining with face, knee, and side clearance ratings of 4.2, 4.2, and 3.6, respectively. The middle row is clearly acceptable with ratings of 4.8, 5.1, and 4.9 for the face, knee, and ceiling clearances. The forward row is the roomiest with face, knee, and ceiling clearances of 4.8, 5.2, and 5.3, respectively. Consideration should be given to assigning crew seats based on body size, whenever onboard tasks do not dictate a different seat. If lateral body supports are incorporated into the seat design, these acceptability ratings will change.

The optimal seats for ill or injured crew members were determined to be the middle seats in the aft row. These seats provide adequate room for medical care and access from all directions. There is adequate stowage for required medical equipment within easy reach. Being under the hatch also allows the injured crew member to be best positioned for postlanding aided egress or rescue. The medical officer will have to close the hatch.

The optimal seats for controlling the vehicle are the two middle row seats. There is sufficient room for displays and controls for both crew members, including hand controllers. The seats are also positioned close enough to each other to allow the crew members to cross reference each other's display and to share the workload.

A window had been outlined on the ceiling between the two seats and slightly behind the displays. It was felt that this was a good location because it allowed the crew members controlling the vehicle to see the displays and out the window with minimal head movements. A window shade will be necessary to keep the sun out of crew members' eyes during atmospheric flight.

4.3.2.2.3 Hatch

The hatch location over the aft seats was clearly acceptable with a rating of 5.1. The hatch should be designed to be operated by one person with minimal effort since deconditioned crew members can lose over 20% of their strength. Figure 17 shows evaluators preparing to move the hatch from the aft wall stowage to the closed position.

Figure 17. Preparing to close hatch in mockup.

The hatch diameter for zero-g activities was completely adequate with a rating of 5.3. The only negative was the inability to use the standard station backboard, but the backboard can be modified to fit. The diameter was also adequate for one-g operations with a rating of 4.4. The main detriment was the room for a paramedic and an injured crew member to fit through simultaneously. The hatch diameter meets the NASA standard.

Crew members preferred stowing the hatch on the aft wall (4.8) rather than stowing it on the ceiling (3.1). Ceiling stowage interfered with displays located above the middle row, and negatively impacted ingress, egress, and maneuverability. The location of the emergency hatch marked on the inside of the mocked was considered to be okay.

4.3.2.2.4 Handholds

Both types of handholds were acceptable, but the evaluators clearly preferred the rigid tubular handholds (5.1) to the nylon fabric handholds (4.1). It was suggested to modify the shape of the rigid handholds to a dog-bone shape, which has been found to offer superior torsion control for EVAs. The size could also be reduced. The soft handholds eliminated the head bump hazard of the rigid ones, but gave less body control. The number and placement of handholds was adequate (4.8 and 4.9, respectively). Two continuous handholds of either type down each side of the vehicle could also be substituted for multiple smaller ones.

4.3.2.2.5 Medical Operations

The volume is marginally adequate to perform medical care, with a rating of 3.6. This rating was based on performing complex activities such as intubations and defibrillations. It is more likely that a crew medical officer will only have to perform monitoring tasks during a medical evacuation.


Figure 18. Providing air and medical care to Rescue Randy.

The aft bulkhead provides a good brace to do a traditional intubation from behind the patient's head. It was also discovered that face-to-face intubations are possible in zero g using the ceiling as a brace for the medical officer. Face-to-face intubations are extremely difficult to perform in one g. Figure 18 shows a crew medical officer performing medical care and maintaining an airway for Rescue Randy.

4.3.2.2.6 Displays

The location of the displays was adequate. Two displays are desired for redundancy. Some crew members experienced difficulty touching the displays when flat or at a 12 deg torso wedge angle. Hand controls should be available so that crew members don't have to reach overhead to the displays during g-loaded flight.

4.3.2.2.7 Crew Volume

Crew volume in the tested configuration was considered to be adequate for on-orbit station attached operations, post-separation zero-g operations, and atmospheric flight and postlanding operations with ratings of 4.7, 4.2, and 4.4, respectively. Access to stowed flight crew equipment and medical equipment was also adequate (4.1 and 4, respectively). Evaluators did feel that the equipment stowed on the walls and bulkheads should be minimized to prevent potential crew injury. Some stowed items were found to interfere with crew members, but alternate stowage locations were found. Stowage needs to be continually evaluated as designs are refined and new items are identified.

4.3.2.2.8 Helmets

Standard aircraft helmets were clearly adequate with a rating of 4.7. Custom helmets that are lower profile and lighter weight would be better. The concept of head restraints was good. Headrests are not necessary.

4.3.2.2.9 Constraints and Limitations

Seat design is still immature. More tests need to be conducted after the seats are designed. The Soyuz-style seat was not rigid enough for adequate evaluation and had no knee restraints. Negative opinions of the seat may change if these deficiencies are corrected for follow-on testing. Displays were only foam mockups so final assessments of back angles could not be performed. Eye points need to be defined and fixed, and then the displays and seats can be designed in concert to meet the eye point. Consideration should be given to anthropometrics when defining the eye points. Vehicles typically use adjustable seats and fixed displays to accommodate a population range. This may be more difficult to do with supine seats.

4.4 Differences Between Phases

Phases 2 and 3 were essentially the same tests with small modifications to the seat layout and stowage. The same performance data were collected during each phase. Slightly different acceptability data were collected from the two phases as a result of the Delphi study. Data analysis was conducted to compare the performance between the two phases to determine if the mockup and seat changes had a significant impact on the data. Table 19 shows the ANOVA p-values for the performance variables from comparing Phase 2 to Phase 3. Variables that were significant at $p<0.05$ appear in bold print.

A Duncan Multiple Range test of the performance data for the zero-g ingress of 3 healthy and 1 ill crew member showed a significant difference ($p=0.04257$). There was only one data point for this egress type from Phase 3. The difference in the data could be explained after reviewing the videotapes for the test. One evaluator became entangled in some unrelated support equipment near the mockup at the start of the ingress parabola, and did not attempt an ingress until the following parabola. On the basis of these results, we conclude that no significant differences to the performance data can be attributed to the mockup changes between the phases.

Table 19. ANOVA *p*-Values Comparing Phase 2 and Phase 3 Dependent Performance Variables

PerformanceVariable	***p*-value**
7 healthy crew members, fixed-order ingress	0.5160
7 healthy crew members, random-order ingress	0.8749
7 healthy crew members, egress	0.7083
6 healthy and 1 ill crew, fixed-order ingress	0.7585
3 healthy and 1 ill crew, fixed-order ingress	**0.0427**

Chapter 5
DISCUSSION

The protocol for evaluating the pressurized crew module volume suitability for zero-g ingress of a spacecraft was developed and tested during this research. The protocol consists of a Delphi Study to identify user concerns unique to a particular spacecraft, ground and zero-g performance and acceptability evaluations of the ingress tasks, and a postflight questionnaire to obtain the acceptability data. This research focused on validating the protocol with the Phase 3 testing.

The results of this research affirm the applicability and validity of the protocol. It was clearly demonstrated through an actual evaluation of a spacecraft mockup that the protocol provides critical human factors information to the designers on volume suitability for zero-g ingress through assessments of performance and acceptability variables. The performance evaluation is important when a time-critical operation, such as emergency evacuation, must be performed. The acceptability evaluation is important to ensure that the crew module form, fit, and function consider the human factors of the required tasks, environmental affects (such as zero-g or high-g), and population demographics (such as anthropometry and strength). The resulting information can be directly applied to either: 1) validate the acceptability of the design as is; or 2) indicate areas that are marginally acceptable or unacceptable which will require further design work. The protocol can be repeated during the development process as the spacecraft design evolves and is refined. When applied early in the development process, critical human factors design shortcomings can be resolved with minimal impacts to cost and schedules.

The results of Phase 2 and Phase 3 show consistent performance data using the protocol. The performance data did not appear to differ significantly across the phases. The mockup had modifications in stowage and seat design between the two phases. But differences in the mockup seat design, stowage, and the other minor changes could not be detected in any performance variables. These results imply that while actual seat design and stowage affect crew operations and crew comfort when interfacing with the vehicle during flight operations and one-g egress, they are not significant factors for zero-g ingress. The geometry of the free volume from the hatch to the seats, the availability of an obstacle free translation path to each seat, and appropriately located handholds along the path to allow control of body position is of more importance in an ingress protocol. This is reinforced by the reduced volume tests performed in Phase 2.

Significant Phase 3 acceptability differences were detected in only 1 out of 44 questions across the responses of the entire population of evaluators. We detected 9 significant differences when comparing the sub-populations of the evaluators. It is apparent that while there may be minor differences of opinions among the individual evaluators or between the sub-populations, the combination of the group data results in a consensus. A representative group opinion can be obtained that will reflect astronaut corps consensus when attention is given to the demographics of the evaluation groups when assessing zero-g volume.

Pilot and mission specialist astronauts should both be represented in the evaluation groups. The two groups typically have different responsibilities and a thorough evaluation needs to examine the vehicle from both points of view. In addition, due to the unique experience that relates to spaceflight and the operational environment, flown astronauts are preferred as evaluators over unflown ones, and mission specialists with a high-aviation-experience base are preferred over those with a low-aviation-experience base. Additional aviation experience is gained though training in the astronaut corps.

5.1 Performance Variable Discussion

Performance variables did not appear to differ significantly across the phases or blocks of evaluators. A difference was noted in the Phase 3 zero-g egress time, but the number of data points taken and the practice of the evaluators can explain it. This type of evaluation is a valid method to determine the zero-g ingress performance parameters. The protocol could be applied to any time critical task that must be performed in the spacecraft.

5.2 Acceptability Variable Discussion

Only one variable was found to be significant from the acceptability scales. That variable concerned the acceptability of stowing the hatch on the ceiling. While this variable was significant at the $p<0.05$ level ($p=0.049$), a Duncan Multiple Range test showed no significant differences.

This suggests that in general, the questions were written such that they were easily understood. The six-point bipolar scale was specifically chosen to force respondents to favor one side or the other of the middle, or average. A discussion follows on how each section of procedures and questions are applicable to the protocol methodology. While some of the discussion points appear to focus on this specific evaluation, they are applicable to the design of any human spacecraft.

5.2.1 Ingress/Egress

The zero-g ingress tests were extremely valuable. They not only allowed the collection of performance data, but also provided insight to how astronauts will actually utilize the vehicle design. Observations of body orientations, body impacts with structure, and body control allow better identification of the optimal locations of crew aids such as handholds, lights, ventilation, etc. Test conductors can observe what parts of the mockup and fittings help or hinder ingress. In this particular test, several areas were identified that should be reinforced to help support crew loads from astronauts using the surface in an unanticipated manner.

The zero-g egress tests were valuable from an observational point of view, but are not of primary concern for this protocol. Astronauts will be going in and out of the vehicle for maintenance tasks on orbit. But the egress timing data, while interesting, appears to add little value to the methodology, and will be eliminated from future procedures.

Essential observational data were gathered by observing the zero-g aided ingress of injured crew members. This type evaluation provides the basis for developing operational procedures and support equipment to efficiently and safely transfer incapacitated crew members without causing further injury.

Ground tests revealed a serious shortcoming of this particular vehicle's design. One-g egress of healthy deconditioned crew members will be very difficult. Follow-on tests should be conducted to further evaluate the one-g egress scenarios. These tests should include egress, egress aids, and rescue. The zero-g volume methodology developed in this study could be extended in the future to include one-g human factors aspects in other areas, such as egress and rescue.

5.2.2 Seating

It was determined from the performance data that seat design is not necessarily a strong factor influencing zero-g ingress. Seat layout affects the translation path to each seat. But it was not used as a variable during this research. In the interest of completeness, the data gathered on seat design are discussed.

One-g comfort of the seats was assessed during relatively short ground tests. Each evaluator spent approximately five minutes in each seat design. This length of time is not adequate to identify any but the most severe pressure points. As seat design of a vehicle progresses, evaluators should spend a greater amount of time to get a complete seat comfort perception.

Zero-g seat comfort is directly tied to the seat restraint system and how easy it is for a crew member to maintain a stable body position. It is assumed that crew members will free-float in a vehicle cabin until time for reentry. They will use handholds and other fittings in the vehicle to maintain body position to perform operational tasks.

High-g seat comfort can be tested in parabolic flight, but the acceleration is limited to 1.8 g's. Additional testing of prototype seat designs should be conducted in a centrifuge that can replicate the actual mission acceleration profile.

The combination of ground and parabolic flight-testing is an excellent method to evaluate seating layouts and body-to-surface clearances. The three acceleration environments allow you to identify all of the interference problems.

5.2.3 Hatch

Hatch evaluations are paramount in evaluating zero-g ingress. During Phase 2 it was thought that the hatch should be moved to allow easier ingress and egress. This would have been a very expensive design structural change. The test phasing supported an iterative approach to hatch evaluations. This resulted in the user population determining that the hatch location was adequate. The zero-g and 1.8-g comparisons in hatch stowage locations contrasted the ingress, stowage volume, and human motion impacts. Hatch movements during 1.8 g's grossly simulated a deconditioned crew member opening the hatch postlanding. A more through evaluation of hatch design should be performed with a mechanically accurate hatch.

5.2.4 Volume

Zero-g volume can only be accurately assessed in zero-g. It is very difficult to identify all the ways a crew member will interact with a zero-g environment in one g. Performing evaluations during parabolic flight allows insight into how crew members stabilize their bodies during the short duration periods of zero g. Researchers can observe how a stowed item is reached, where an item can be "tucked" away if it's inconvenient to restow it, what translation paths are used and what obstacles interfere with the paths, and what volume is really utilized for the zero-g operational tasks.

Parabolic flight is expensive and physiologically uncomfortable to both the evaluators and the data collectors. Thorough preparation of test procedures and one-g verifications of the procedures need to be performed to ensure that effective use of the parabolic flight is realized.

5.2.5 Crew Equipment and Stowage

The general rule of thumb in spacecraft utilization is that there is never enough stowage. Ground and zero-g evaluations allow assessment of the adequacy and access of stowed items. Different items are required at different times during the mission, and stowage access can be planned and demonstrated accordingly.

The design and placement of crew aids like handholds can only be adequately assessed in a zero-g environment. This is because the mass and inertia of the astronaut's body has to be controlled through the grip on the handhold. Different tasks require different levels of body stability and different equipment to be used. Each task can be performed and each piece of equipment demonstrated and assessed in zero g using this methodology.

Several helmet designs were assessed. The zero-g and 1.8-g environments revealed the shortcomings of all of the tested helmets regarding size, weight, field of view, etc. Additional helmet testing should be performed in these acceleration environments.

5.2.6 General

The evaluators felt that the acceptability questions very adequately allowed them to express their views, as evidenced by the 5.1 rating. This demonstrates the applicability of the format and topics of the questions.

It was also determined that the blocks were well matched, with no significant performance difference between the test groups and phases. In addition, while there are significant differences in the acceptability data between the various sub-populations in the astronaut corps, such as flown, unflown, pilot, mission specialist, or level of aviation experience, it was determined that there are no significant differences when the entire group of evaluators is considered. As in all human factors evaluations, care must be given to ensuring the evaluators are representative of the demographics of the entire user population.

In addition, it was determined that the XCRV crew module as currently proposed meets the DRM requirements for zero-g ingress and operations. Acceptability criteria were:

- Meeting the DRMs of the ISS Program as listed in SSP 50306 (ingress and hatch closure in less than three minutes).
- Meeting the NASA human factors and ergonomics standards as specified in NASA-STD-3000/T.
- Acceptable zero-g unaided ingress evaluations and volumetric assessments by the end users—members of the NASA Astronaut Office.
- Acceptable zero-g aided ingress and inflight medical monitoring evaluations by the NASA Flight Medicine community.

Chapter 6
CONCLUSIONS AND FURTHER STUDY

6.1 Conclusions

This research was begun with the objective to develop a methodology for evaluation of crew volume acceptability for zero-g ingress of spacecraft. The resulting methodology, the “Sanchez Protocol,” consists of:

- A Delphi study that determined the evaluation factors most important to the end users.
- Procedures for the conduct of ground and inflight (zero-g and 1.8-g) evaluations of the crew volume.
- Postflight questionnaire using six-point bipolar scales to ascertain acceptability variable data.
- Data analysis techniques to assess performance and acceptability data.

The results of this research validate the protocol. The blocks were well matched, with no significant performance difference between the test groups and phases. In addition, while there are significant differences in the acceptability data between the various sub-populations in the astronaut corps, such as flown, unflown, pilot, mission specialist, or level of aviation experience, it was determined that there are no significant differences when the entire group of evaluators is considered. As in all human factors evaluations, care must be given to ensuring the evaluators are representative of the demographics of the entire user population.

While this protocol was specifically designed to evaluate the zero-g ingress task, it is applicable to the human factors evaluation of any zero-g task performed in a spacecraft. The basic protocol is far reaching, and the only modifications required to expand it would be to refocus the Delphi questions and to modify the procedural steps and postflight questions to focus on the new task.

The development of the protocol expands the state of the art of human factors evaluations in zero g. No standard evaluation methodology has been previously used. The Sanchez Protocol is proposed as the new standard for any future human factors evaluations of zero-g tasks in spacecraft that are performed by the government, industry, or foreign space agencies.

6.2 Further Study

This protocol specifically focuses on zero-g ingress. During evaluation of the protocol, several other areas and questions were identified that require further research. The methodology could be expanded to other human factors related areas of spacecraft assessment including one-g egress and rescue, displays, maintenance tasks, and other operational tasks.

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APPENDIX 1

7-Person KC-135 Flight Test Procedure

TEST PROCEDURE CHECKLIST

X-38 Project Seven-Person Crew Module Mockup KC-135 Evaluation

General Comments and Guidelines

- The Test Conductor will be responsible for the safe conduct of all evaluations. Any participant may call a halt to any portion of the evaluations if there is a safety concern. The Test Conductor will direct the start and stop of each evaluation step, and will determine the number of participants to ingress and egress each parabola.
- Comments and observations will be recorded on a separate sheet. All steps are to be accomplished during zero-g maneuvers unless otherwise noted.
- A Test Monitor will be located at each of the following mockup stations: aft end, forward end, right side view ports, and left side view ports. These Test Monitors are responsible for writing down all comments, helping to take measurements, recording data, and assisting the Test Conductor.
- A Timer will be located near the hatch and at one of the side view ports of the mockup to obtain timing. The Timer near the hatch should obtain times for all participants to ingress, and for hatch opening and closure. The timer at the view port will time each participant from entry to arriving at assigned seat and stabilizing (fastening restraint). During timed runs, they will call out timing hacks. The nearest Test Monitor will record the times obtained by the timer. For those evaluations requiring more than one parabola, the timer will stop the timing when the “everyone down” call is given, and restart with participant movement the next parabola.
- The videographer and photographer will position themselves to obtain the best documentary footage available. All participants are being recorded in both video and audio.
- All ingresses and egresses should be accomplished in an expeditious, but orderly manner to prevent injury.
- Mockup seats (other than the Soyuz style) will be configured as follows for all anthropometric measurements during the evaluation unless otherwise noted:
  - Torso - horizontal to mockup waterline (and aircraft floor)
  - Bideltoid (shoulder) width - 22” (95th percentile American male plus dynamic clearance)
  - Seat back length - 42.8” (95th percentile Japanese female plus spine stretch, helmet, and dynamic clearance)
  - Buttock to popliteal length - 16.4” (50th percentile Japanese female)
  - Popliteal length - 16.3”
  - Foot rest width - 12-14” (seat location dependent)
  - Hip angle - 40 deg and 90 deg from waterline
  - Knee angle - 20 deg and to deg from waterline
- Mockup seats are numbered: 1 (starboard aft), 2 (starboard center aft), 3 (port center aft), 4 (port aft), 5 (starboard center), 6 (port center), and 7 (forward).
- A measuring tape is used instead of a standard anthropometer. Based on the use of the data, the accuracy of calipers and anthropometers are not required. In those areas where the right side cannot be measured, the left side will be substituted, with the substitution noted. Dimensions used in this evaluation are:
  - Sitting Height (Torso). The participant places the buttocks firmly in the seat pan. The measurement is taken from the top of the midline of the head (or helmet) down the back to the seating surface (defined as the joint line of the seat).
  - Popliteal Length. The participant places the buttocks firmly in the seat pan and holds the legs against the supports, with the ankles relaxed. The measurement is taken from the bottom the right shoe heel to the underside of the right knee.
  - Buttocks-to-Popliteal Length. The participant places the buttocks firmly in the seat pan, holding the legs against the supports, ankles relaxed. The measurement is taken from the most posterior aspect of the right buttock (defined as the joint line of the seat) to the most anterior prospect of the right knee.

Parabola Overview

Parabola Set/Task	**Number of Parabolas**
Parabola Set #1	
Orientation	1
Practice Ingress	2
Practice Egress	2
Pause	1
Timed Ingress (healthy, fixed order)	2
Close Hatch, Strap In, Volume Assessments	4
Open Hatch, Egress	0 - egress in 1 g
Total	12
Parabola Set #2	
Timed Ingress (healthy, random order)	2
Close Hatch, Strap In, Volume Assessments	5
Open Hatch, Egress	2
Total	9
Parabola Set #3	
Timed Ingress (7 crew, 1 injured, fixed order)	3
Close Hatch, Strap In,	1
Open Hatch, Egress	2
Timed Ingress (7 crew, 2 injured, fixed order)	3
Close Hatch, Strap In,	1
Open Hatch, Egress	2
Total	12
Parabola Set #4	
Timed Ingress (4-7 crew, 1 injured, fixed order)	2
Close Hatch, Strap In,	1
Medical Evaluations	10
Open Hatch, Egress	1
Total	14
Parabola Set #5	
Timed Ingress (healthy, random order)	2
Close Hatch, Strap In, volume assessments	3
Open Hatch, egress	2
Timed Ingress (healthy, fixed order)	2
Close Hatch, Strap In, Volume Assessments	3
Open Hatch, Egress	1
Total	12
Total Number of Parabolas	60

Preflight

1. Record name of participant, assigned seat, and helmet type (if not aircraft) before mockup familiarization. The participant number will be the initial seat assignments. Participants will wear their number to aid test monitors in identification. Note any helmet changes if they occur during the flight. During subsequent parabolas, participants will rotate one seat number higher than in previous parabola. Seats in standard configuration.

Name	Participant Number	Helmet Type
	1	
	2	
	3	
	4	
	5	
	6	
	7	
	8	
	9	
	10	

2. During the mockup familiarization on the ground, participants will enter the mockup and go to their assigned seat. Baseline measurements will be conducted in the baseline adjustable seat. Participants will firmly place their buttocks against the seat pan, while the Test Conductor and Test Monitors use the installed and portable measuring tapes to obtain the measurements listed below. The torso measurements will be made with helmets on and off. Record all measurements in the table below:

Name	Seat	Torso to Top of Helmet	Torso to Top of Head	Buttock to Popliteal Length	Popliteal Length

3. During mockup familiarization, each participant will fasten and unfasten the seat restraint, and will close and open the hatch, maneuvering it into both the aft and overhead stowage locations.

4. During mockup familiarization, the Test Conductor and Test Monitors will adjust hip angles, knee angles, torso angles, and thigh lengths on seats to see which combination each participant finds most comfortable. Also note if any are very uncomfortable.

Name	**Hip Angle**	**Knee Angle**	**Buttock to Popliteal Length**	**Torso Angle**	**Comments**

Parabola Set #1

Timed Ingress/Egress 7 Healthy, Fixed Order

1. Test participants put on helmets before first zero-g parabola.
2. Participants proceed to mockup before first zero-g parabola. The first parabola will be used as a zero-g orientation and no ingresses will be performed.
3. The next 4 parabolas will be used for practice ingress and egress in a random order.
    a. Record comments and observations on ease of ingress and egress.

    b. Record the time required to ingress **starting with the first participant entering the top of the hatch, and ending with the hatch closed**; if able, record individual ingress times also:

    Total time for all to ingress: ___________________

    c. Record the time required to egress **starting with first participant movements and ending with clearance of top hatch**; if able, record individual egress times also:

    Total time for all to egress: ___________________

4. At start of the next zero-g parabola participants will start ingressing the mockup through the overhead hatch. Seat assignments will be incremented by one. Ingress will be performed **in order from seats 7-6-5-4-1-3-2**. The participants will close the hatch and fasten their seat belts.
    a. Record comments and observations on ease of ingress and location of hatch.

    b. Record the time required to ingress **starting with the first participant entering the top of the hatch, and ending with the hatch closed**; if able, record individual ingress times also:

    Total time for all to ingress: ___________________

Name	Seat	Time to Ingress
	7	
	6	
	5	
	4	
	1	
	3	
	2	

Hatch, Volume, Handhold , and Stowage Evaluations

5. During parabola, participant in seat 2 will reposition hatch from the hatch hole to the aft wall and back to the hatch hole. Record comments and observations.

6. During parabola, participant in seat 2 will reposition hatch from the hatch hole to the ceiling. Record comments and observations.

7. During, parabola, participant in seat 3 will reposition hatch from the ceiling to the hatch hole. Record comments and observations.

8. During parabola, participant in seat 3 will reposition hatch from the hatch hole to the aft wall and back to the hatch hole. Record comments and observations.

9. During parabolas and high-g maneuvering, all participants will evaluate handhold design number and location. Record comments and observations.

10. During parabolas, participants will assess acceptability of available volume in crew module for zero g. Anticipated zero-g operations will include monthly systems checkout, removing seats to access LRUs, transporting and monitoring ill/injured crew members from station to Earth, emergency evacuation of healthy crew members from damaged station, and some TBD crew interfaces with vehicle during return to Earth (TBD system monitoring and management, etc.) Consideration should be given to the fact that there will be additional equipment not shown during this flight that will need to be stowed. Record comments and observations.

11. During high-g maneuvers, participants will assess acceptability of available volume in crew module for reentry and atmospheric flight. Anticipated g-loaded operations will include monitoring ill/injured crew members during flight, and some TBD crew interfaces with vehicle during return to Earth (TBD system monitoring and management, backup parachute controls, parafoil guidance, etc.) Consideration should be given to the fact that there will be additional equipment not shown during this flight that will need to be stowed. Record comments and observations.

12. All participants will evaluate other potential stowage locations and available volume that lend themselves for stowage, based on the existing mockup moldlines. This stowage would be for equipment not mocked up during zero-g, i.e. radios, communications equipment, crew displays, crew controls, survival equipment, LiOH canisters, or waste product bags. Record comments and observations.

13. At the Test Conductor's direction, participants will open the hatch, placing it in their preferred stowage location, and begin egressing the mockup through the overhead hatch. Egress will be performed **in reverse order from ingress: 2-3-1-4-5-6-7**.
    a. Record comments and observations on ease of egress and location of hatch.
    b. Record the time required to egress **starting with first participant movements and ending with clearance of top hatch**; if able, record individual egress times also:

       Total time for all to egress: __________________

Name	Seat	Time to Egress
	2	
	3	
	1	
	4	
	5	
	6	
	7	

Parabola Set 2

Timed Ingress/Egress 7 Healthy, Random Order

1. At start of the next zero-g parabola participants will start ingressing the mockup through the overhead hatch. Seat assignments will be incremented by one. Ingress will be performed **in random order**. The participants will close the hatch and fasten their seat belts.
    a. Record comments and observations on ease of ingress and location of hatch.

    b. Record the time required to ingress **starting with the first participant entering the top of the hatch, and ending with the hatch closed**; if able, record individual ingress times also:

    Total time for all to ingress: __________________

Name	Seat	Time to Ingress

Hatch, Volume, Handhold , and Stowage Evaluations

2. During parabola, participant in seat 2 will reposition hatch from the hatch hole to the aft wall and back to the hatch hole. Record comments and observations.

3. During parabola, participant in seat 2 will reposition hatch from the hatch hole to the ceiling. Record comments and observations.

4. During, parabola, participant in seat 3 will reposition hatch from the ceiling to the hatch hole. Record comments and observations.

5. During parabola, participant in seat 3 will reposition hatch from the hatch hole to the aft wall and back to the hatch hole. Record comments and observations.

6. During parabolas and high-g maneuvering, all participants will evaluate handhold design number and location. Record comments and observations.

7. During parabolas, participants will assess acceptability of available volume in crew module for zero g. Anticipated zero-g operations will include monthly systems checkout, removing seats to access LRUs, transporting and monitoring ill/injured crew members from station to Earth, emergency evacuation of healthy crew members from damaged station, and some TBD crew interfaces with vehicle during return to Earth (TBD system monitoring and management, etc.) Consideration should be given to the fact that there will be additional equipment not shown during this flight that will need to be stowed. Record comments and observations.

8. During high-g maneuvers, participants will assess acceptability of available volume in crew module for reentry and atmospheric flight. Anticipated g-loaded operations will include monitoring ill/injured crew members during flight, and some TBD crew interfaces with vehicle during return to Earth (TBD system monitoring and management, backup parachute controls, parafoil guidance, etc.) Consideration should be given to the fact that there will be additional equipment not shown during this flight that will need to be stowed. Record comments and observations.

9. All participants will evaluate other potential stowage locations and available volume that lend themselves for stowage, based on the existing mockup moldlines. This stowage would be for equipment not mocked up during zero-g, i.e. radios, communications equipment, crew displays, crew controls, survival equipment, LiOH canisters, or waste product bags. Record comments and observations.

10. At the Test Conductor’s direction, participants will open the hatch, placing it in their preferred stowage location, and begin egressing the mockup through the overhead hatch. Egress will be performed **in random order**.
    a. Record comments and observations on ease of egress and location of hatch.

    b. Record the time required to egress **starting with first participant movements and ending with clearance of top hatch**; if able, record individual egress times also:

    Total time for all to egress: _________________

Name	Seat	Time to Egress
	2	
	3	
	1	
	4	
	5	
	6	
	7	

Parabola Set 3

Timed Ingress/Egress 7 Crew, 1 Injured, Fixed Order

1. At start of the next zero-g parabola participants will start ingressing the mockup through the overhead hatch. Seat assignments will be incremented by one. The participant in seat 2 is **"unconscious"** but medically stable. Participants in seats 5, 6, and 7 will ingress first. Two other participants will maneuver the "unconscious" participant into the preferred medical seat and fasten the seat restraint. The participants will close the hatch.
   a. Record comments and observations on ease of ingress and location of hatch.

   b. Record the time required to ingress **starting with the first participant entering the top of the hatch, and ending with the hatch closed**; if able, record individual ingress times also:

   Total time for all to ingress: _________________

Name	Seat	Time to Ingress

2. At the Test Conductor's direction, participants will open the hatch, placing it in their preferred stowage location, and begin egressing the mockup through the overhead hatch. Egress will be performed **in random order**.
   a. Record comments and observations on ease of egress and location of hatch.

   b. Record the time required to egress **starting with first participant movements and ending with clearance of top hatch**; if able, record individual egress times also:

   Total time for all to egress: _________________

Name	Seat	Time to Egress
	2	
	3	
	1	
	4	
	5	
	6	
	7	

Timed Ingress/Egress 7 Crew, 2 Injured, Fixed Order

3. At start of the next zero-g parabola participants will start ingressing the mockup through the overhead hatch. Seat assignments will be incremented by one. The participants in seats 2 and 3 are **"unconscious"** but medically stable. Participants in seats 6 and 7 will ingress first. Two other participants will maneuver the "unconscious" participant into the preferred medical seat and fasten the seat restraint. The participants will close the hatch.

    a. Record comments and observations on ease of ingress and location of hatch.

    b. Record the time required to ingress **starting with the first participant entering the top of the hatch, and ending with the hatch closed**; if able, record individual ingress times also:

    Total time for all to ingress: _________________

Name	Seat	Time to Ingress

4. At the Test Conductor's direction, participants will open the hatch, placing it in their preferred stowage location, and begin egressing the mockup through the overhead hatch. Egress will be performed **in random order**.

    a. Record comments and observations on ease of egress and location of hatch.

    b. Record the time required to egress **starting with first participant movements and ending with clearance of top hatch**; if able, record individual egress times also:

    Total time for all to egress: _________________

Name	Seat	Time to Egress
	2	
	3	
	1	
	4	
	5	
	6	
	7	

Parabola Set 4

Timed Ingress/Egress 4-7 Crew, 1 Injured, Fixed Order

1. At start of the next zero-g parabola participants will start ingressing the mockup through the overhead hatch. Seat assignments will be incremented by one. The participant in seat 2 is **“unconscious.”** A mannequin can be used for the unconscious person. Three participants prepare the unconscious one for transport, then the participant in seat 5 will ingress first. Two other participants will maneuver the unconscious participant into the preferred medical seat and fasten the seat restraint. The participants will close the hatch.
    a. Record comments and observations on ease of ingress and location of hatch.

    b. Record the time required to ingress **starting with the first participant entering the top of the hatch, and ending with hatch closed**; if able, record individual ingress times also:

    Total time for all to ingress: ___________________

Name	Seat	Time to Ingress

Medical Equipment Evaluations

2. All participants will evaluate available volume for typical medical procedures (as briefed by medical personnel) during zero g. Record comments and observations.

3. All participants will evaluate stowage locations for foam mockups of selected medical equipment during zero-g and high-g maneuvers. For example, how is the general reach to the equipment (and visibility if training hardware is installed instead of foam mockups)? Record comments and observations.

4. At the Test Conductor’s direction, participants will open the hatch, placing it in their preferred stowage location, and begin egressing the mockup through the overhead hatch. Egress will be performed **in random order**.
    a. Record comments and observations on ease of egress and location of hatch.

b. Record the time required to egress **starting with first participant movements and ending with clearance of top hatch**; if able, record individual egress times also:

Total time for all to egress: _________________

Name	Seat	Time to Egress

Parabola Set 5

Timed Ingress/Egress 7 Healthy, Random Order

1. At start of the next zero-g parabola participants will start ingressing the mockup through the overhead hatch. Seat assignments will be incremented by one. Ingress will be performed **in random order**. The participants will close the hatch and fasten their seat belts.
    a. Record comments and observations on ease of ingress and location of hatch.

    b. Record the time required to ingress **starting with the first participant entering the top of the hatch, and ending with the hatch closed**; if able, record individual ingress times also:

    Total time for all to ingress: __________________

Name	Seat	Time to Ingress

Hatch, Volume, Handhold, and Stowage Evaluations

2. During parabola, participant in seat 2 will reposition hatch from the hatch hole to the aft wall and back to the hatch hole. Record comments and observations.

3. During parabola, participant in seat 2 will reposition hatch from the hatch hole to the ceiling. Record comments and observations.

4. During, parabola, participant in seat 3 will reposition hatch from the ceiling to the hatch hole. Record comments and observations.

5. During parabola, participant in seat 3 will reposition hatch from the hatch hole to the aft wall and back to the hatch hole. Record comments and observations.

6. During parabolas and high-g maneuvering, all participants will evaluate handhold design number and location. Record comments and observations.

7. During parabolas, participants will assess acceptability of available volume in crew module for zero g. Anticipated zero-g operations will include monthly systems checkout, removing seats to access LRUs, transporting and monitoring ill/injured crew members from station to Earth, emergency evacuation of healthy crew members from damaged station, and some TBD crew interfaces with vehicle during return to Earth (TBD system monitoring and management, etc.) Consideration should be given to the fact that there will be additional equipment not shown during this flight that will need to be stowed. Record comments and observations.

8. During high-g maneuvers, participants will assess acceptability of available volume in crew module for reentry and atmospheric flight. Anticipated g-loaded operations will include monitoring ill/injured crew members during flight, and some TBD crew interfaces with vehicle during return to Earth (TBD system monitoring and management, backup parachute controls, parafoil guidance, etc.) Consideration should be given to the fact that there will be additional equipment not shown during this flight that will need to be stowed. Record comments and observations.

9. All participants will evaluate other potential stowage locations and available volume that lend themselves for stowage, based on the existing mockup moldlines. This stowage would be for equipment not mocked up during zero-g, i.e. radios, communications equipment, crew displays, crew controls, survival equipment, LiOH canisters, or waste product bags. Record comments and observations.

10. At the Test Conductor’s direction, participants will open the hatch, placing it in their preferred stowage location, and begin egressing the mockup through the overhead hatch. Egress will be performed **in random order**.
    a. Record comments and observations on ease of egress and location of hatch.

    b. Record the time required to egress **starting with first participant movements and ending with clearance of top hatch**; if able, record individual egress times also:

       Total time for all to egress: _________________

Name	Seat	Time to Egress
	2	
	3	
	1	
	4	
	5	
	6	
	7	

Timed Ingress/Egress 7 Healthy, Fixed Order

11. At start of the next zero-g parabola participants will start ingressing the mockup through the overhead hatch. Seat assignments will be incremented by one. Ingress will be performed **in order 7-6-5-4-1-3-2**. The participants will close the hatch and fasten their seat belts.
    a. Record comments and observations on ease of ingress and location of hatch.

    b. Record the time required to ingress **starting with the first participant entering the top of the hatch, and ending with hatch closed**; if able, record individual ingress times also:

    Total time for all to ingress: _________________

Name	Seat	Time to Ingress
	7	
	6	
	5	
	4	
	1	
	3	
	2	

Hatch, Volume, Handhold , and Stowage Evaluations

12. During parabola, participant in seat 2 will reposition hatch from the hatch hole to the aft wall and back to the hatch hole. Record comments and observations.

13. During parabola, participant in seat 2 will reposition hatch from the hatch hole to the ceiling. Record comments and observations.

14. During, parabola, participant in seat 3 will reposition hatch from the ceiling to the hatch hole. Record comments and observations.

15. During parabola, participant in seat 3 will reposition hatch from the hatch hole to the aft wall and back to the hatch hole. Record comments and observations.

16. During parabolas and high-g maneuvering, all participants will evaluate handhold design number and location. Record comments and observations.

17. During parabolas, participants will assess acceptability of available volume in crew module for zero-g. Anticipated zero-g operations will include monthly systems checkout, removing seats to access LRUs, transporting and monitoring ill/injured crew members from station to Earth, emergency evacuation of healthy crew members from damaged station, and some TBD crew interfaces with vehicle during return to Earth (TBD system monitoring and management, etc.) Consideration should be given to the fact that there will be additional equipment not shown during this flight that will need to be stowed. Record comments and observations.

18. During high-g maneuvers, participants will assess acceptability of available volume in crew module for reentry and atmospheric flight. Anticipated g-loaded operations will include monitoring ill/injured crew members during flight, and some TBD crew interfaces with vehicle during return to Earth (TBD system monitoring and management, backup parachute controls, parafoil guidance, etc.) Consideration should be given to the fact that there will be additional equipment not shown during this flight that will need to be stowed. Record comments and observations.

19. All participants will evaluate other potential stowage locations and available volume that lend themselves for stowage, based on the existing mockup moldlines. This stowage would be for equipment not mocked up during zero-g, i.e. radios, communications equipment, crew displays, crew controls, survival equipment, LiOH canisters, waste product bags, etc. Record comments and observations.

20. At the Test Conductor’s direction, participants will open the hatch, placing it in their preferred stowage location, and begin egressing the mockup through the overhead hatch. Egress will be performed **in fixed order 2-3-1-4-5-6-7**.

    a. Record comments and observations on ease of egress and location of hatch.

    b. Record the time required to egress **starting with first participant movements and ending with clearance of top hatch**; if able, record individual egress times also:

    Total time for all to egress: _________________

Name	Seat	Time to Egress
	2	
	3	
	1	
	4	
	5	
	6	
	7	

APPENDIX 2

7-Person KC-135 Flight Test Postflight Questionnaire

APPENDIX 2: POSTFLIGHT QUESTIONNAIRE

X-38 Project Seven Person Crew Module Mockup
KC-135 Evaluation

Subject Number:		
Name:		Test Date:
Number of spaceflights:		Duration of longest:
Aviation experience: _____ hours military, _____hours civilian		
___ Male or ___ Female	Height:	Weight:
General body description:		

Directions:

The following questions will be used to determine your views on the acceptability of the X-38 crew module. A six-point bipolar scale is used for all ratings. A rating of 1 is extremely negative (e.g. totally unacceptable, no redeeming qualities in the design). A rating of 6 is extremely good (e.g. the design can't be improved, don't change anything). Please circle the rating number that mostly closely describes your view of the question. If you feel that ratings alone are inadequate to express your views, you may comment in the space below the questions.

Seating

1. Rate the seats on comfort for *one g* with respect to: torso angle, hip angle, knee angle, and seat dimensions (especially thigh length).

Baseline adjustable wooden seat:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Uncomfortable Very Comfortable

90-deg collapsible wooden seat:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Uncomfortable Very Comfortable

Soyuz-style seat:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Uncomfortable Very Comfortable

2. Rate the seat on comfort for *zero g* with respect to: torso angle, hip angle, knee angle, and seat dimensions (especially thigh length).

Baseline adjustable wooden seat:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Uncomfortable Very Comfortable

90-deg collapsible wooden seat:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Uncomfortable Very Comfortable

Soyuz-style seat:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Uncomfortable Very Comfortable

3. Rate the seat on comfort for *high g* maneuvering with respect: torso angle, hip angle, knee angle, and seat dimensions (especially thigh length).

Baseline adjustable wooden seat:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Very
Uncomfortable Comfortable

90-deg collapsible wooden seat:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Very
Uncomfortable Comfortable

Soyuz-style seat:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Very
Uncomfortable Comfortable

4. Rate seating arrangement (4 aft, 2 center, 1 forward). Assume some type of overhead display will be used.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

5. Rate the face to ceiling clearance for crew comfort for

aft row:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

middle row:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

forward row:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

6. Rate knee to ceiling/wall clearance for crew comfort for:

aft row:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

middle row:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

front row:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

7. Rate body to side wall and body to body clearance for crew comfort for

aft row:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

middle row:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

forward row:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Unacceptable
Completely Acceptable

8. Which seat(s) are the best location for ill/injured crew members (circle and comment):

1 2 3 4
5 6
7

9. Which seat(s) are the best location for crew member(s) interfacing with vehicle systems through a computer (circle and comment).

1 2 3 4
5 6
7

10. Which seat(s) did you ingress (circle and comment)?

1 2 3 4
5 6
7

Ingress/Egress

1. Rate ingress order for healthy crew members during station emergency:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Always Use Random Order
Always Use Fixed Order

2. Rate ingress order for ill/injured crew members for medical evacuation::

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Always Use Random Order
Always Use Fixed Order

3. Rate ease of zero-g ingress of healthy crew members.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Very
Difficult Easy

4. Rate ease of zero-g ingress of ill/injured crew members.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Very
Difficult Easy

5. Rate ease of zero-g egress of healthy crew members.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Very
Difficult Easy

6. Rate anticipated ease of one-g egress of healthy deconditioned crew members.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Very Very
Difficult Easy

Hatch

1. Rate the location of the hatch.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

2. Rate adequacy of diameter of hatch hole for anticipated zero-g operations (ingress of healthy and ill/injured crew members, passing crew equipment through).

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

3. Rate adequacy of diameter of hatch hole for anticipated one-g operations (unaided and aided egress of healthy and ill/injured deconditioned crew members).

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

4. Rate acceptability of stowing hatch on aft wall.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

5. Rate acceptability of stowing hatch on ceiling.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Unacceptable Acceptable

Volume

1. Rate adequacy of volume in current configuration) for anticipated on-orbit station attached operations (monthly systems checkout, removing seats for IFM and LRU replacement, etc.).

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

2. Rate adequacy of volume for seven crew members in current configuration for anticipated post-separation zero-g operations (systems activation and monitoring/interaction through displays and controls, changing LiOH canisters, monitoring ill/injured crew members, and getting situated for reentry).

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

3. Rate adequacy of volume for seven crew members in current configuration for anticipated atmospheric flight and postlanding operation (systems monitoring/interaction through displays and controls, parafoil guidance as manual backup, monitoring ill/injured crew members, and getting situated for landing and egress)

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

4. Rate adequacy of volume to perform rudimentary medical care (as described by flight surgeons in pretest briefing).

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

Crew Equipment and Stowage

1. Rate adequacy of flight crew equipment access and stowage as tested.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

2. Rate adequacy of medical equipment access and stowage as tested:

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

3. Rate adequacy of crew module reach and visibility.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

4. Rate adequacy of the design of handholds.

Rigid handholds

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

Soft handholds

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

5. Rate adequacy of the number of handholds.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

6. Rate adequacy of the placement of handholds.

Rigid handholds

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

Soft handholds

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

7. Rate adequacy of standard aircraft helmet for head protection.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

General

1. In general this questionnaire adequately expressed my views.

+----------+----------+----------+----------+----------+
1 2 3 4 5 6
Completely Completely
Inadequate Adequate

2. Other issues I would suggest addressing include:

3. Other comments I'd like to share are:

APPENDIX 3

ANOVA Summary Tables

APPENDIX 3 – ANOVA SUMMARY TABLES

Table 20. Single Factor ANOVA Summary of Phase 2 Dependent Performance Variables

Full Volume: 7 Healthy Crew Members, Fixed Order, Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	97.2196	1	97.2196	1.9752	0.2951	18.5128
Within Groups	98.4392	2	49.2196			
Total	195.6588	3				

Full Volume: 7 Healthy Crew Members, Fixed Order, Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	17.2176	1	17.2176	0.3417	0.5842	6.6079
Within Groups	251.9247	5	50.3849			
Total	269.1424	6				

Full Volume: 7 Healthy Crew Members, Egress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.0850	1	1.0850	0.0887	0.7714	4.8443
Within Groups	134.5845	11	12.2349			
Total	135.6695	12				

Reduced Volume: 7 Healthy Crew Members, Fixed Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	40.3523	1	40.3523	0.9746	0.5041	161.4462
Within Groups	41.405	1	41.405			
Total	81.757267	2				

Reduced Volume: 7 Healthy Crew Members, Random Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.4180	1	2.4180	0.6944	0.4923	18.5128
Within Groups	6.9643	2	3.4821			
Total	9.3823	3				

Reduced Volume: 7 Healthy Crew Members, Egress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	16.3306	1	16.3306	0.7178	0.4294	5.9874
Within Groups	136.5074	6	22.7512			
Total	152.838	7				

Full vs Reduced Volume: 7 Healthy Crew Members, Fixed Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.1340	1	1.1340	0.0204	0.8919	6.6079
Within Groups	277.4161	5	55.4832			
Total	278.5501	6				

Full vs Reduced Volume: 7 Healthy Crew Members, Random Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	102.0511	1	102.0511	3.2976	0.1028	5.1174
Within Groups	278.5246	9	30.9472			
Total	380.5758	10				

Full vs Reduced Volume: 7 Healthy Crew Members, Egress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	15.312	1	15.312	1.0084	0.3279	4.3808
Within Groups	288.5075	19	15.1846			
Total	303.8195	20				

Full vs Reduced Volume: 6 Healthy and 1 Ill Crew Members, Fixed Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.9154	1	1.9154	0.7056	0.5552	161.4462
Within Groups	2.7145	1	2.7145			
Total	4.6298	2				

Table 21. Single Factor ANOVA Summary of Phase 3 Dependent Performance Variables

Group 1: 7 Healthy Crew Members, Fixed Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6.8694	1	6.8694	0.0663	0.8396	161.4462
Within Groups	103.68	1	103.68			
Total	110.5494	2				

Group 1: 7 Healthy Crew Members Egress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.535	1	2.535	0.2987	0.6816	161.4462
Within Groups	8.4872	1	8.4872			
Total	11.0222	2				

Group 2: 7 Healthy Crew Members, Fixed Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0038	1	0.0038	0.0003	0.9888	161.4462
Within Groups	12.1525	1	12.1525			
Total	12.1562	2				

Group 2: 7 Healthy Crew Members, Random Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	14.9784	1	14.9784	0.2686	0.6956	161.4462
Within Groups	55.7568	1	55.7568			
Total	70.7352	2				

Group 2: 7 Healthy Crew Members Egress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.2341	1	4.2341	0.5087	0.5025	5.9874
Within Groups	49.9411	6	8.3235			
Total	54.1752	7				

Group 1 vs Group 2: 7 Healthy Crew Members, Fixed Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	20.6462	1	20.6462	0.6730	0.4581	7.7087
Within Groups	122.7056	4	30.6764			
Total	143.3518	5				

Group 1 vs Group 2: 7 Healthy Crew Members, Random Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	68.8568	1	68.8568	2.8652	0.1891	10.128
Within Groups	72.0965	3	24.0322			
Total	140.9532	4				

Group 1 vs Group 2: 7 Healthy Crew Members, Egress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	523.3367	1	523.3367	72.2427	**0.00001**	5.1176
Within Groups	65.1974	9	7.2442			
Total	588.5341	10				

Group 1 vs Group 2: 6 Healthy and 1 Ill Crew Members, Fixed Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	210.0417	1	210.0417	124.0794	**0.057**	161.4462
Within Groups	1.6928	1	1.6928			
Total	211.7345	2				

Group 1 vs Group 2: 5 Healthy and 2 Ill Crew Members, Fixed Order Ingress

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	8.7604	1	8.7604	1.2459	0.4651	161.4462
Within Groups	7.0313	1	7.0313			
Total	15.7917	2				

Table 22. Single Factor ANOVA Summary of Phase 3 Dependent Acceptability Variables

Question 1: Baseline adjustable wooden seat comfort for one g

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.2396	7	0.3199	1.0412	0.4162	2.2164
Within Groups	14.1354	46	0.3073			
Total	16.375	53				

Question 2: 90 degree collapsible wooden seat comfort for one g

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.4263	7	0.0609	0.1077	0.9976	2.2263
Within Groups	24.8814	44	0.5655			
Total	25.3077	51				

Question 3: Soyuz-style seat comfort for one g

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.7646	7	0.5378	0.5785	0.7698	2.2074
Within Groups	44.6238	48	0.9297			
Total	48.3884	55				

Question 4: Baseline adjustable wooden seat comfort for 0-g

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.2202	7	0.4600	1.6364	0.1480	2.2074
Within Groups	13.4941	48	0.2811			
Total	16.7143	55				

Question 5: 90 degree collapsible wooden seat comfort for 0-g

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.7151	7	0.5307	1.1154	0.3691	2.2074
Within Groups	22.8385	48	0.4758			
Total	26.5536	55				

Question 6: Soyuz-style seat comfort for 0-g

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	16.8825	7	2.4118	1.8637	0.0967	2.2074
Within Groups	62.1175	48	1.2941			
Total	79	55				

Question 7: Baseline adjustable wooden seat comfort for high-g maneuvering

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.1784	7	0.3112	0.5595	0.7838	2.2555
Within Groups	21.6939	39	0.5563			
Total	23.8723	46				

Question 8: 90 degree collapsible wooden seat comfort for high-g maneuvering

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.8142	7	0.1163	0.1053	0.9977	2.2429
Within Groups	45.3082	41	1.1051			
Total	46.1225	48				

Question 9: Soyuz-style seat comfort for high-g maneuvering

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.0476	7	0.2925	0.2466	0.9704	2.2490
Within Groups	47.4472	40	1.1862			
Total	49.4948	47				

Question 10: Seating arrangement (4/2/1)

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.9904	7	0.4272	0.5080	0.8236	2.2212
Within Groups	37.8397	45	0.8409			
Total	40.8302	52				

Question 11: Aft row face to ceiling clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	16.9949	7	2.4278	1.2552	0.2924	2.2074
Within Groups	92.8444	48	1.9343			
Total	109.8393	55				

Question 12: Middle row face to ceiling clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.2498	7	1.6071	1.3505	0.2485	2.2118
Within Groups	55.932	47	1.1900			
Total	67.1818	54				

Question 13: Forward row face to ceiling clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.6638	7	0.6663	0.5541	0.7882	2.2429
Within Groups	49.2954	41	1.2023			
Total	53.9592	48				

Question 14: Aft row knee to ceiling/wall clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	10.9982	7	1.5712	0.8821	0.5274	2.1992
Within Groups	89.0578	50	1.7812			
Total	100.056	57				

Question 15: Middle row knee to ceiling/wall clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.8392	7	0.4056	0.3489	0.9268	2.2074
Within Groups	55.7992	48	1.1625			
Total	58.6384	55				

Question 16: Forward row knee to ceiling/wall clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.8994	7	0.4142	0.5352	0.8029	2.2315
Within Groups	33.2771	43	0.7739			
Total	36.1765	50				

Question 17: Aft row body to wall and body to body clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6.4571	7	0.9224	0.7028	0.6695	2.2074
Within Groups	63.0028	48	1.3126			
Total	69.4598	55				

Question 18: Middle row body to wall and body to body clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.9327	7	0.5618	0.3722	0.9140	2.2074
Within Groups	72.4557	48	1.5095			
Total	76.3884	55				

Question 19: Forward row body to wall and body to body clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.051	7	0.4359	0.5699	0.7759	2.2429
Within Groups	31.3572	41	0.7648			
Total	34.4082	48				

Question 20: Ingress order for healthy crew members during station emergency

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	10.8381	7	1.5483	0.4581	0.8589	2.2371
Within Groups	141.9419	42	3.3796			
Total	152.78	49				

Question 21: Ingress order for ill/injured crew members for medical evacuation

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6.4983	7	0.9283	0.5432	0.7967	2.2371
Within Groups	71.7817	42	1.7091			
Total	78.28	49				

Question 22: Ease of zero-g ingress for healthy crew members

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.6934	7	0.3848	1.2798	0.2804	2.2074
Within Groups	14.4316	48	0.3007			
Total	17.125	55				

Question 23: Ease of zero-g ingress for ill/injured crew members

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	13.2216	7	1.8888	1.9197	0.0904	2.2371
Within Groups	41.3234	42	0.9839			
Total	54.545	49				

Question 24: Ease of zero-g egress for healthy crew members

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.2882	7	0.4697	1.0576	0.4049	2.2074
Within Groups	21.319	48	0.4441			
Total	24.6071	55				

Question 25: Anticipated ease of one-g egress of healthy deconditioned crew members

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6.204	7	0.8863	0.6458	0.7159	2.2074
Within Groups	65.8760	48	1.3724			
Total	72.08	55				

Question 26: Location of hatch

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.2883	7	0.1840	0.4989	0.8306	2.2074
Within Groups	17.7072	48	0.3689			
Total	18.9955	55				

Question 27: Adequacy of diameter of hatch hole for anticipated zero-g operations

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.4298	7	0.7757	1.8227	0.1045	2.2074
Within Groups	20.4273	48	0.4256			
Total	25.8571	55				

Question 28: Adequacy of diameter of hatch hole for anticipated one-g operations

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	9.002	7	1.286	1.2799	0.2803	2.2074
Within Groups	48.2302	48	1.0048			
Total	57.2321	55				

Question 29: Acceptability of stowing hatch on aft wall

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	10.0525	7	1.4361	2.2237	**0.0493**	2.2164
Within Groups	29.7067	46	0.6458			
Total	39.7593	53				

Question 30: Acceptability of stowing hatch on ceiling

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.1563	7	0.4509	0.5193	0.8148	2.2371
Within Groups	36.4688	42	0.8683			
Total	39.625	49				

Question 31: Adequacy of volume in current configuration for anticipated on-orbit station attached operations

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.6332	7	0.3762	0.5323	0.8057	2.2074
Within Groups	33.9204	48	0.7067			
Total	36.5536	55				

Question 32: Adequacy of volume for 7 crew members in current configuration for anticipated post-separation zero-g operations

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	8.0044	7	1.1435	1.2123	0.3145	2.2074
Within Groups	45.2768	48	0.9433			
Total	53.2813	55				

Question 33: Adequacy of volume for 7 crew members in current configuration for anticipated atmospheric flight and postlanding operations

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.5457	7	0.2208	0.2382	0.9735	2.2118
Within Groups	43.5634	47	0.9269			
Total	45.1091	54				

Question 34: Adequacy of volume to perform rudimentary medical care

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.5592	7	0.5085	0.4200	0.8840	2.2490
Within Groups	48.4199	40	1.2105			
Total	51.9792	47				

Question 35: Adequacy of flight crew equipment access and stowage as tested

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.2684	7	0.3241	0.4734	0.8484	2.2315
Within Groups	29.4375	43	0.6846			
Total	31.7059	50				

Question 36: Adequacy of medical equipment access and stowage as tested

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.2169	7	0.4596	0.4107	0.8900	2.2490
Within Groups	44.7623	40	1.1191			
Total	47.9792	47				

Question 37: Adequacy of crew module reach and visibility

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.9200	7	0.2743	0.4246	0.8821	2.2074
Within Groups	31.0085	48	0.6460			
Total	32.9286	55				

Question 38: Adequacy of design of rigid handholds

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.1583	7	0.1655	0.1830	0.9876	2.2074
Within Groups	43.3953	48	0.9041			
Total	44.5536	55				

Question 39: Adequacy of design of soft handholds

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.4296	7	0.6328	0.3967	0.8996	2.2074
Within Groups	76.5704	48	1.5952			
Total	81	55				

Question 40: Adequacy of number of handholds

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7.2478	7	1.0354	0.8542	0.5489	2.2074
Within Groups	58.1808	48	1.2121			
Total	65.4286	55				

Question 41: Adequacy of placement of rigid handholds

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.4962	7	0.7852	0.6194	0.7372	2.2074
Within Groups	60.8430	48	1.2676			
Total	66.3393	55				

Question 42: Adequacy of placement of soft handholds

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.7317	7	0.6759	0.3948	0.9007	2.2118
Within Groups	80.4683	47	1.7121			
Total	85.2	54				

Question 43: Adequacy of standard aircraft helmet for head protection

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	13.6898	7	1.9557	1.1525	0.3474	2.2074
Within Groups	81.4486	48	1.6968			
Total	95.1384	55				

Question 44: Adequacy of questionnaire to express my views

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.3499	7	0.3357	0.7112	0.6628	2.2429
Within Groups	19.3542	41	0.4721			
Total	21.7042	48				

Table 23. Single Factor ANOVA Summary of Phase 3 Subpopulation Dependent Acceptability Variables

Question 1: Baseline adjustable wooden seat comfort for one g

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.5602	1	0.5602	1.5617	0.2306	4.5431	0.7414	1	0.7414	2.3516	0.146	4.5431	0.0104	1	0.0104	0.0383	0.8487	4.9646
Within Groups	5.3809	15	0.3587				4.7292	15	0.3153				2.7188	10	0.2719			
Total	5.9412	16					5.4706	16					2.7292	11				

Question 2: 90 degree collapsible wooden seat comfort for one g

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.0916	1	0.0916	0.1421	0.7115	4.5431	0.0208	1	0.0208	0.0327	0.8591	4.6001	0.25	1	0.25	0.5357	0.4810	4.9646
Within Groups	9.6731	15	0.6449				8.9167	14	0.6369				4.6667	10	0.4667			
Total	9.7647	16					8.9375	15					4.9167	11				

Question 3: Soyuz-style seat comfort for one g

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.1200	1	0.1200	0.1122	0.742	4.494	2.7284	1	2.7284	3.0091	0.1020	4.494	0.3077	1	0.3077	0.3077	0.5902	4.8443
Within Groups	17.116	16	1.0698				14.508	16	0.9067				11	11	1			
Total	17.236	17					17.236	17					11.308	12				

Question 4: Baseline adjustable wooden seat comfort for zero g

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.5714	1	0.5714	2.0078	0.1757	4.494	0.0942	1	0.0942	0.2997	0.5916	4.494	1.6752	1	1.675214	7.2107	**0.0212**	4.844338
Within Groups	4.5536	16	0.2846				5.0308	16	0.3144				2.5556	11	0.232323			
Total	5.125	17					5.125	17					4.2308	12				

Question 5: 90 degree collapsible wooden seat comfort for zero g

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.0159	1	0.0159	0.0266	0.8725	4.494	1.1387	1	1.1387	2.161	0.161	4.494	1.2308	1	1.2308	3.3846	0.0929	4.8443
Within Groups	9.5536	16	0.5971				8.4308	16	0.5269				4	11	0.3636			
Total	9.5694	17					9.5694	17					5.2308	12				

Question 6: Soyuz-style seat comfort for zero g

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.6706	1	0.6706	0.3801	0.5462	4.494	11.010	1	11.010	9.846	**0.0064**	4.494	2.0534	1	2.0534	2.1231	0.1730	4.8443
Within Groups	28.232	16	1.7645				17.892	16	1.1183				10.639	11	0.9672			
Total	28.903	17					28.903	17					12.692	12				

Question 7: Baseline adjustable wooden seat comfort for high-g maneuvering

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	1.1045	1	1.1045	1.9682	0.1841	4.6672	0.0182	1	0.0182	0.0283	0.8687	4.6001	0.0167	1	0.0167	0.0327	0.8611	5.3176
Within Groups	7.2955	13	0.5612				8.9818	14	0.6416				4.0833	8	0.5104			
Total	8.4	14					9	15					4.1	9				

Question 8: 90 degree collapsible wooden seat comfort for high-g maneuvering

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0	1	0	0	1	4.6001	0.0727	1	0.0727	0.0568	0.8151	4.6001	0.013	1	0.013	0.0134	0.9103	5.1174
Within Groups	18	14	1.2857				17.927	14	1.2805				8.7143	9	0.9683			
Total	18	15					18	15					8.7273	10				

Question 9: Soyuz-style seat comfort for high-g maneuvering

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.0052	1	0.0052	0.0056	0.9416	4.6001	0.3879	1	0.3879	0.2396	0.6327	4.6672	0.0812	1	0.0812	0.0733	0.7927	5.117357
Within Groups	13.104	14	0.9360				21.045	13	1.6189				9.9643	9	1.1071			
Total	13.109	15					21.433	14					10.045	10				

Question 10: Seating arrangement (4/2/1)

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.3269	1	0.3269	0.3587	0.5582	4.5431	1.3333	1	1.3333	1.4737	0.2448	4.6001	0.9423	1	0.9423	1.5356	0.2411	4.8443
Within Groups	13.673	15	0.9115				12.667	14	0.9048				6.75	11	0.6136			
Total	14	16					14	15					7.692308	12				

Question 11: Aft row face to ceiling clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	10.321	1	10.321	6.3083	**0.0231**	4.494	2.2231	1	2.2231	1.0377	0.3235	4.494	0.1047	1	0.1047	0.0461	0.8339	4.8443
Within Groups	26.179	16	1.6362				34.277	16	2.1423				24.972	11	2.2702			
Total	36.5	17					36.5	17					25.077	12				

Question 12: Middle row face to ceiling clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	4.5873	1	4.5873	4.322	0.0541	4.494	1.6925	1	1.6925	1.3624	0.2602	4.494	2.3438	1	2.34375	1.5924	0.2356	4.9646
Within Groups	16.982	16	1.0614				19.877	16	1.2423				14.719	10	1.4718			
Total	21.569	17					21.569	17					17.063	11				

Question 13: Forward row face to ceiling clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.8478	1	0.8478	0.7613	0.3976	4.6001	0.2557	1	0.2557	0.2212	0.6454	4.6001	3.3247	1	3.3247	2.756	0.1313	5.1174
Within Groups	15.59	14	1.1136				16.182	14	1.1558				10.857	9	1.2063			
Total	16.438	15					16.438	15					14.182	10				

Question 14: Aft row knee to ceiling/wall clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	1.5089	1	1.5089	0.6999	0.4151	4.494	6.4692	1	6.4692	3.5051	0.0796	4.494	1.5515	1	1.5515	1.4742	0.2463	4.6672
Within Groups	34.491	16	2.1557				29.531	16	1.8457				13.682	13	1.0524			
Total	36	17					36	17					15.233	14				

Question 15: Middle row knee to ceiling/wall clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.8343	1	0.8343	0.7254	0.4069	4.494	0.0053	1	0.0053	0.0044	0.9477	4.494	0.4808	1	0.4808	0.4148	0.5328	4.8443
Within Groups	18.402	16	1.1501				19.231	16	1.2019				12.75	11	1.1591			
Total	19.236	17					19.236	17					13.231	12				

Question 16: Forward row knee to ceiling/wall clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	1.3946	1	1.3946	1.8438	0.196	4.6001	0.1026	1	0.1026	0.1208	0.7333	4.6001	1.1303	1	1.1303	1.6277	0.2283	4.8443
Within Groups	10.59	14	0.7564				11.882	14	0.8487				7.6389	11	0.6944			
Total	11.984	15					11.984	15					8.7692	12				

Question 17: Aft row body to wall and body to body clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	1.3581	1	1.3581	1.0086	0.3302	4.494	1.3335	1	1.3335	0.9892	0.3347	4.494	0.5009	1	0.500947	0.356816	0.565004	5.117357
Within Groups	21.545	16	1.3465				21.569	16	1.3481				12.635	9	1.403935			
Total	22.903	17					22.903	17					13.136	10				

Question 18: Middle row body to wall and body to body clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.8343	1	0.8343	0.6425	0.4345	4.494	0.3419	1	0.3419	0.2572	0.619	4.494	0.2137	1	0.2137	0.1233	0.7321	4.8443
Within Groups	20.777	16	1.2985				21.269	16	1.3293				19.056	11	1.7323			
Total	21.611	17					21.611						19.269	12				

Question 19: Forward row body to wall and body to body clearance for crew comfort

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.5192	1	0.5192	0.7875	0.3898	4.6001	0.0045	1	0.0045	0.0065	0.9367	4.6001	0.8312	1	0.8312	1.3091	0.2821	5.1174
Within Groups	9.2308	14	0.6593				9.7455	14	0.6961				5.7143	9	0.6349			
Total	9.75	15					9.75	15					6.5455	10				

Question 20: Ingress order for healthy crew members during station emergency

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	2.2042	1	2.2042	0.6454	0.4362	4.6672	0.2761	1	0.2761	0.0775	0.7851	4.6672	0.1368	1	0.1368	0.0334	0.8583	4.8443
Within Groups	44.396	13	3.4151				46.324	13	3.5634				45.056	11	4.096			
Total	46.6	14					46.6	14					45.192	12				

Question 21: Ingress order for ill/injured crew members during medical evacuation

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.4908	1	0.4908	0.2390	0.6325	4.6001	2.3526	1	2.3526	1.2252	0.287	4.6001	0.2131	1	0.2131	0.1672	0.6922	5.1174
Within Groups	28.744	14	2.0531				26.882	14	1.9201				11.469	9	1.2743			
Total	29.234	15					29.234	15					11.682	10				

Question 22: Ease of zero-g ingress for healthy crew members

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.0992	1	0.0992	0.2569	0.6192	4.494	0.0833	1	0.0833	0.2059	0.657	4.6001	1.2273	1	1.2273	7.3636	**0.0239**	5.1174
Within Groups	6.1786	16	0.3862				5.6667	14	0.4048				1.5	9	0.1667			
Total	6.2778	17					5.75	15					2.7273	10				

Question 23: Ease of zero-g ingress for ill/injured crew members

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	4.1683	1	4.1683	4.0896	0.0627	4.6001	6.7375	1	6.7375	8.062	**0.0131**	4.6001	0.3889	1	0.3889	0.3889	0.5527	5.5915
Within Groups	14.269	14	1.0192				11.7	14	0.8357				7	7	1			
Total	18.438	15					18.438	15					7.3889	8				

Question 24: Ease of zero-g egress for healthy crew members

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	2.0089	1	2.0089	5.3373	0.0345	4.494	0.2120	1	0.2120	0.4338	0.5195	4.494	0.4794	1	0.4794	1.1340	0.3147	5.1174
Within Groups	6.0223	16	0.3764				7.8192	16	0.4887				3.8047	9	0.4227			
								17										
Total	8.0313	17					8.0313						4.2841	10				

Question 25: Anticipated ease of one-g egress for healthy deconditioned crew members

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.0025	1	0.0025	0.0017	0.9678	4.494	4.6803	1	4.6803	3.846	0.0675	4.494	0.1508	1	0.1508	0.1004	0.7573	4.8443
Within Groups	24.149	16	1.5093				19.471	16	1.2169				16.52	11	1.5018			
Total	24.151	17					24.151	17					16.671	12				

Question 26: Location of hatch

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.2867	1	0.2867	0.9191	0.352	4.494	0.0547	1	0.0547	0.1676	0.6877	4.494	0.6175	1	0.6175	1.785	0.2085	4.8443
Within Groups	4.9911	16	0.3119				5.2231	16	0.3264				3.8056	11	0.346			
Total	5.2778	17					5.2778	17					4.4231	12				

Question 27: Adequacy of diameter of hatch hole for anticipated zero-g operations

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	1.9206	1	1.9206	5.137	**0.0376**	4.494	0.3951	1	0.395085	0.842	0.3725	4.494	1.5577	1	1.5577	3.6073	0.0841	4.8443
Within Groups	5.9821	16	0.3739				7.5077	16	0.4692				4.75	11	0.4318			
Total	7.9028	17					7.9028	17					6.3077	12				

Question 28: Adequacy of diameter of hatch hole for anticipated one-g operations

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	3.9375	1	3.9375	4.3169	0.0542	4.494	2.2889	1	2.2889	2.2548	0.1527	4.494	0.1368	1	0.1368	0.1617	0.6953	4.8443
Within Groups	14.594	16	0.9121				16.242	16	1.0151				9.3056	11	0.846			
Total	18.531	17					18.531	17					9.4423	12				

Question 29: Acceptability of stowing hatch on aft wall

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.4525	1	0.4525	0.5620	0.4650	4.5431	1.0871	1	1.0871	1.4251	0.2511	4.5431	7.6923	1	7.6923	28.205	**0.0002**	4.8443
Within Groups	12.077	15	0.8051				11.442	16	0.7628				3	11	0.2727			
Total	12.529	16					12.529	17					10.692	12				

Question 30: Acceptability of stowing hatch on ceiling

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.0469	1	0.0469	0.0463	0.8328	4.6001	1.8802	1	1.8802	0.1802	0.1802	4.6001	0.0104	1	0.0104	0.0280	0.8704	4.9646
Within Groups	14.188	14	1.0134				13.229	14	0.9449				3.7188	10	0.3719			
Total	14.234	15					15.109	15					3.7293	11				

Question 31: Adequacy of volume in current configuration for anticipated on-orbit station attached operations

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.8929	1	0.8929	1.2862	0.2735	4.494	0.4923	1	0.4923	0.6845	0.4202	4.494	0.4188	1	0.4188	0.4659	0.5090	4.8443
Within Groups	11.107	16	0.6942				11.508	16	0.7192				9.8889	11	0.899			
Total	12	17					12	17					10.308	12				

Question 32: Adequacy of volume for 7 crew members in current configuration for anticipated post-separation 0-g operations

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	Df	MS	F	P-value	F crit
Between Groups	4.1915	1	4.1915	4.495	**0.0499**	4.494	1.5803	1	1.5803	1.4423	0.2472	4.494	0.2585	1	0.2585	0.2716	0.6126	4.8443
Within Groups	14.92	16	0.9325				17.531	16	1.0957				10.472	11	0.9520			
Total	19.111	17					19.111	17					10.731	12				

Question 33: Adequacy of volume for 7 crew members in current configuration for anticipated atmospheric flight and postlanding operations

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.2232	1	0.2232	0.2194	0.6458	4.494	0.1231	1	0.1231	0.1202	0.7333	4.494	0.8547	1	0.8547	1.0779	0.3215	4.8443
Within Groups	16.277	16	1.0173				16.377	16	1.0236				8.7222	11	0.7929			
Total	16.5	17					16.5	17					9.5769	12				

Question 34: Adequacy of volume to perform rudimentary medical care

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.0401	1	0.0401	0.0353	0.8537	4.6001	0.0102	1	0.0102	0.009	0.9258	4.6001	1.2987	1	1.2987	1.0227	0.3383	5.1174
Within Groups	15.897	14	1.1355				15.927	14	1.1377				11.426	9	1.2698			
Total	15.938	15					15.938	15					12.727	10				

Question 35: Adequacy of flight crew equipment access and stowage as tested

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.75	1	0.75	1.2	0.2918	4.6001	0.3333	1	0.3333	0.5091	0.4873	4.6001	0.25	1	0.25	0.3061	0.5922	4.9646
Within Groups	8.75	14	0.625				9.1667	15	0.6548				8.1667	10	0.8167			
Total	9.5	15					9.5	15					8.4167	11				

Question 36: Adequacy of medical equipment access and stowage as tested

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.0545	1	0.0545	0.0416	0.8415	4.6672	0.8727	1	0.8727	0.6992	0.4182	4.6672	0.5919	1	0.5919	0.8028	0.3936	5.1174
Within Groups	17.045	13	1.3112				16.227	13	1.2483				6.6354	9	0.7373			
Total	17.1	14					17.1	14					7.2273	10				

Question 37: Adequacy of crew module reach and visibility

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.254	1	0.2548	0.3391	0.5684	4.494	0.0361	1	0.0361	0.0474	0.8305	4.494	0.3611	1	0.3611	0.8563	0.3746	4.8443
Within Groups	11.982	16	0.7480				12.2	16	0.7625				4.6389	11	0.4217			
Total	12.236	17					12.236	17					5	12				

Question 38: Adequacy of design of rigid handholds

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.1944	1	0.1944	0.1857	0.6722	4.494	0.0214	1	0.0214	0.0202	0.8887	4.494	0.6175	1	0.6175	1.5777	0.2351	4.8443
Within Groups	16.75	16	1.0469				16.923	16	1.0577				4.3056	11	0.3914			
Total	16.944	17					16944	17					4.9231	12				

Question 39: Adequacy of design of soft handholds

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.3968	1	0.3968	0.2202	0.6453	4.494	0.3592	1	0.3592	0.199	0.6615	4.494	0.0769	1	0.0769	0.0529	0.8223	4.8443
Within Groups	28.839	16	1.8025				28.877	16	1.8048				16	11	1.4545			
Total	29.236	17					29.236	17					16.077	12				

Question 40: Adequacy of number of handholds

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	3.1111	1	3.1111	3.1111	0.0968	4.494	2.6803	1	2.6803	2.6101	0.1257	4.494	0.4808	1	0.4808	0.3585	0.5614	4.8443
Within Groups	16	16	1				16.431	16	1.0269				14.75	11	1.3409			
Total	19.111	17					19.111	17					15.231	12				

Question 41: Adequacy of placement of rigid handholds

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	2.5804	1	2.5804	2.5144	0.1324	4.494	0.9308	1	0.9308	0.8242	0.3774	4.494	0.5817	1	0.5817	0.4357	0.5228	4.8443
Within Groups	16.412	16	1.0262				18.069	16	1.1293				14.688	11	1.3352			
Total	19	17					19	17					15.269	12				

Question 42: Adequacy of placement of soft handholds

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	1.5089	1	1.5089	0.8187	0.379	4.494	0.3769	1	0.3769	0.1969	0.6631	4.494	1.5	1	1.5	1	0.3409	4.9646
Within Groups	29.491	16	1.8432				30.623	14	1.9139				15	10	1.5			
Total	31	17					31	15					16.5	11				

Question 43: Adequacy of standard aircraft helmet for head protection

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	4.4534	1	4.4534	2.5343	0.131	4.494	0.2925	1	0.2925	0.145	0.7084	4.494	7.4380	1	7.4380	5.2317	**0.043**	4.8443
Within Groups	28.116	16	1.7573				32.277	16	2.0173				15.639	11	1.4217			
Total	32.569	17					32.569	17					23.077	12				

Question 44: Adequacy of questionnaire to express my views

Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.5208	1	0.5208	1.2324	0.2856	4.6001	0.1875	1	0.1875	0.42	0.5274	4.6001	0	1	0	0	1	4.9646
Within Groups	5.9167	14	0.4226				6.25	14	0.4464				5.5	10	0.55			
Total	6.4375	15					6.4375						5.5	11				

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13. ABSTRACT *(Maximum 200 words)*

This project aimed to develop a methodology for evaluating performance and acceptability characteristics of the pressurized crew module volume suitability for zero-gravity (g) ingress of a spacecraft and to evaluate the operational acceptability of the NASA crew return vehicle (CRV) for zero-g ingress of astronaut crew, volume for crew tasks, and general crew module and seat layout.

No standard or methodology has been established for evaluating volume acceptability in human spaceflight vehicles. Volume affects astronauts' ability to ingress and egress the vehicle, and to maneuver in and perform critical operational tasks inside the vehicle. Much research has been conducted on aircraft ingress, egress, and rescue in order to establish military and civil aircraft standards. However, due to the extremely limited number of human-rated spacecraft, this topic has been unaddressed.

The NASA CRV was used for this study. The prototype vehicle can return a 7-member crew from the International Space Station in an emergency. The vehicle's internal arrangement must be designed to facilitate rapid zero-g ingress, zero-g maneuverability, ease of one-g egress and rescue, and ease of operational tasks in multiple acceleration environments. A full-scale crew module mockup was built and outfitted with representative adjustable seats, crew equipment, and a volumetrically equivalent hatch.

Human factors testing was conducted in three acceleration environments using ground-based facilities and the KC-135 aircraft. Performance and acceptability measurements were collected. Data analysis was conducted using analysis of variance and nonparametric techniques.

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