

SEATING CONSIDERATIONS FOR SPACEFLIGHT : THE HUMAN TO MACHINE INTERFACE

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ABSTRACT

Seating is one of the most critical components to be considered during design of a spacecraft. Since seats are the final interface between the occupant and the vehicle wherein all launch and landing operations are performed, significant effort must be spent to ensure proper integration of the human to the spacecraft. The importance of seating can be divided into two categories: seat layout and seat design.

The layout of the seats drives the overall cabin configuration – from displays and controls, to windows, to stowage, to egress paths. Since the layout of the seats is such a critical design parameter within the crew compartment, it is one of the first design challenges that must be completed in the critical path of the spacecraft design. In consideration of seat layout in the vehicle, it is important for the designers to account for often intangible factors such as safety, operability, contingency performance, crew rescue.

Seat layout will lead to definition of the quantity, shape, and posture of the seats. The seats of the craft must restrain and protect the occupant in all seated phases of flight, while allowing for nominal mission performance. In design of a spacecraft seat, the general posture of the occupant and the landing loads to be encountered are the greatest drivers of overall design. Variances, such as upright versus recumbent postures will dictate fit of the seat to the occupant and drive the total envelope of the seat around the occupant. Seat design revolves around applying sound principles of seated occupant protection coupled with the unique environments driven by the seat layout, landing loads, and operational and emergency scenarios.

1. SEAT LAYOUT CONSIDERATIONS

Seat layout considerations fall into two general categories – medical or operational. Medical

considerations include acceleration exposure both sustained and impulse, sensory system considerations and orthostatic intolerance concerns. Operational considerations include spacing for anthropometry variability, space suit integration and operability, and emergency egress and rescue operations.

1.1 Sustained Acceleration Limitations

During reentry, the vehicle's acceleration direction and magnitude produces a changing resultant acceleration vector of different direction and magnitude when coupled with the increasing effects of gravity. This acceleration vector profile is unique to each seat position and occupant seated therein within the vehicle. Altering the seat pitch, roll, and yaw changes the linear and rotational acceleration vector profile that the seat will undergo, and can markedly affect the seat occupant's ability to tolerate the acceleration profile and/or perform critical functions.

The cardiovascular system is profoundly affected by acceleration forces, (referred to as "G-forces") that exceed standard terrestrial gravity. It is the inability of the cardiovascular system to maintain blood flow to vital organs that limits human acceleration tolerance. Human G-tolerance is greatly influenced by the orientation of acceleration vector with respect to the body. When G-forces are directed along the long-axis of the body, from head-to-foot (referred to as "+G_z"), blood flow to the brain can be diminished, ultimately leading to decreased vision and Gravity-induced loss of consciousness (GLOC). In contrast, reversing the G-forces from foot-to-head (termed "-G_z") causes blood to pool in the brain, which also can adversely affect vision and consciousness. Orienting acceleration forces through the chest through the back (termed "+G_x") maintains the most normal distribution of blood-flow, and allow for the highest tolerance of sustained acceleration forces. It must be noted that the eye changes shape at high +G_x accelerations, leading to decreased visual acuity [4].

Sustained acceleration exposure limits employed by NASA have indicated that the post spaceflight crewmember is most profoundly affected by the sustained +Gz exposure [1]. This observation directly effects occupant seating in that it drives the vehicle to support the occupants such that their bodily Z axis lie primarily orthogonal to the entry acceleration vector. In most historical examples of spacecraft, this results in the crew being seated recumbently for landing.

1.2 Impulse Acceleration Limitations

Regardless of the vehicle landing scheme, contingency landings or emergency launch aborts are considered to be the driver for seat design and occupant protection. For seat layout evaluations it is important to position and mount the seats such that contingency acceleration energy can either be removed or sufficiently managed by the system to allow for occupant survival.

To allow flexibility for landing risk analysis, NASA has most recently employed a whole body acceleration exposure limit method as characterized by the predicted dynamic response of the seated occupant to a given input acceleration of the system. This methodology was developed by personnel (Brinkley, et al) at Wright Patterson Air Force Base for ejection seat injury prediction, and later expanded in scope to allow for injury risk prediction in all bodily axes [2]. This model not only accounts for the magnitude of the acceleration exposure, but the onset rate and duration of the exposure as well.

The dynamic response of the occupant is calculated as follows:

$$DR = \omega n 2 \delta / g \quad (1)$$

Where:

ωn = undamped natural frequency and

δ = deflection of the body

Given the DR for each axis and the DR limit for that axis, an overall injury-risk criterion β can be calculated as

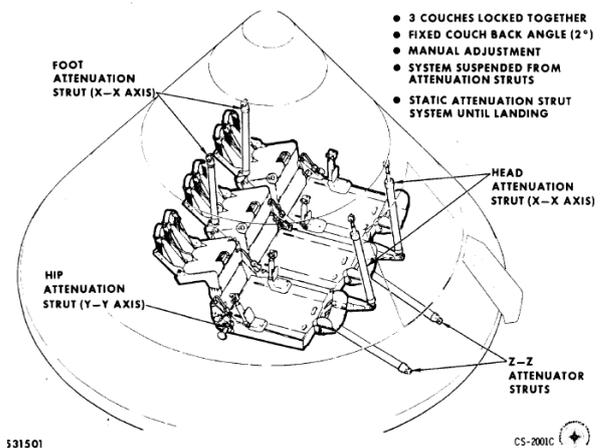
$$\beta = \sqrt{\left(\frac{DR_x(t)}{DR_x^{lim}}\right)^2 + \left(\frac{DR_y(t)}{DR_y^{lim}}\right)^2 + \left(\frac{DR_z(t)}{DR_z^{lim}}\right)^2} \quad (2)$$

There are four levels of the DR limits that correspond to increasing chance of injury as shown in Table 1-1. For each level of risk, the corresponding β calculated must be less than 1.0.

Table 1-1. Dynamic Response Limits.

	DR _{x,limit}		DR _{y,limit}		DR _{z,limit}	
	Eyeballs In	Eyeballs Out	No side restraint	With side restraint	Eyeballs Down	Eyeballs Up
Very Low Risk (≤ 0.05%)	31.0	22.4	11.8	11.8	13.1	11.0
Low Risk (≤ 0.5%)	35.0	28.0	14.0	15.0	15.2	9.0
Moderate Risk (≤ 5%)	40.0	35.0	17.0	20.0	18.0	12.0
High Risk (≤ 50%)	46.0	46.0	22.0	30.0	22.8	15.0

Through use of this model, the systems design team can account for landing or abort accelerations from the point of application to the vehicle, though all structures, and ultimately to the occupant through his or her seat. Knowing the β can aid in determination of load attenuation needs at the seat. An example of this is the shock absorbing crew couch system of NASA's Apollo spacecraft (see Figure 1.1), or the load attenuating seats found in the Russian Soyuz spacecraft.



1-1. Apollo Crew Couch Load Attenuation Layout.

1.3 Orthostatic Intolerance Considerations

Orthostatic intolerance is defined in its most common form as "the development of symptoms during upright standing relieved by recumbency", and is caused by decreases in blood pressure (hypotension) that cause a drop in blood flow to the brain [6]. Symptoms of orthostatic hypotension can include feelings of dizziness, faintness, and nausea, and can ultimately cause unconsciousness if the victim is not placed in a

supine position. Orthostatic intolerance has been observed in some astronauts returning from space with symptoms severe enough to impair crewmembers' ability to ambulate after landing. Post-spaceflight motion sickness exacerbates symptoms of orthostasis. These effects vary from individual to individual and may even vary among independent subjects based on physical state, bodily fluid levels, and duration of microgravity exposure.

Of particular interest to vehicle seating is the concept derived from the basic definition of the syndrome – alleviation of symptoms through recumbency. Recumbent seating of crewmembers is required by the NASA to maintain occupant G-loading in the Z-axis to less than 0.5 Gz, sustained [1], as also discussed in Section 1.1

This is important for post landing emergency scenarios to ensure that crew functionality is maximized to allow for effectiveness in emergency egress.

1.4 Sensory System Considerations

During vehicle entry, where sustained accelerations and degraded visual conditions are frequently encountered, spatial disorientation, and motion sickness can occur as a result of the limitations of the visual, vestibular, and somatosensory systems. Piloting a spacecraft during reentry and landing after a space flight could include all of the perception and orientation errors associated with conventional aircraft flight, as well as introduce the added complication of having crewmembers that are adapted to a different gravity environment; a condition that can lead to sensory misinterpretation, hypersensitivity to head movement, reduced visual tracking, and illusions of self-motion. In addition, atmospheric entry may dictate a flight profile with a high deceleration phase coupled with simultaneous multi-axis accelerations, thereby creating other unique sensory problems. If astronauts have piloting responsibilities, this could lead to problems controlling the vehicle, thereby risking the safety of the crew and spacecraft [3].

Seat roll angle (“clocking” or rotation of seats around the vehicle x-axis) and resultant occupant body roll angle within the vehicle may have a significant effect on the vestibular system, including spatial disorientation. Crewmembers clocked towards the vehicle’s y-axis (placing them “sideways” instead of “upright” with respect to the vehicle/trajectory) would

sense these acceleration changes in the body y-axis (through the shoulders), which may be unnatural and dissimilar to conventional flying. This effect would be pronounced due to the varying reentry profile and unique effects of space flight adaptation mentioned above.

If necessary and allowable, given redundant operator workstations, “clocking” of the operators’ seats should be established in the same direction and degree to ensure common sensory cues for redundant piloting tasks. Additionally, common seat direction/position among all crewmembers is preferred to minimize effects spatial orientation among operators and non-operators alike.

In the case of severe spatial disorientation, inducing emesis, a small seat or head inclination would be beneficial to allow vomit to be pulled downward and away from the face.

Lastly, due to 0g adaptation and possible effects/damage of high-g flight to the vestibular system, spatial disorientation and motion sickness could be severe upon landing, and the ability to quickly and safely egress may be compromised. Therefore, consideration should be given for how to place or design seats to allow for aided egress of these affected crewmembers, requiring them to use only minimal head movements. To minimize performance degradations due to sensory deconditioning and motion sickness, seats should be aligned and constructed so that all crewmembers, especially those performing critical tasks during entry and landing, experience G-forces through the head in a $+G_x$ mean acceleration vector [1].

1.5 Crew Anthropometry and Fit Considerations

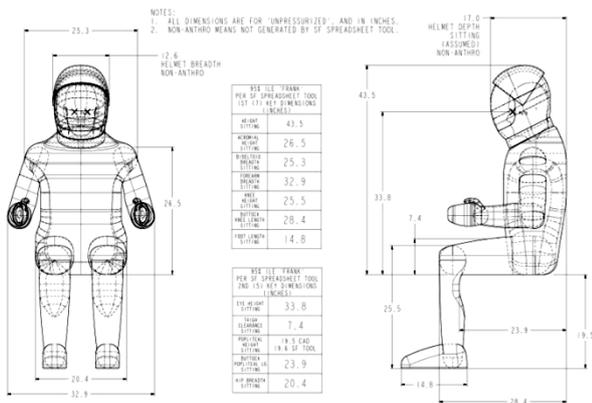
To be able to effectively operate the vehicle in nominal and emergency conditions, crewmembers must be able to view and reach displays and controls required to perform tasks under all suited flight regimes, including ascent, entry, and 0g flight. Vehicle operator spacing is especially important for adequate arm clearance to allow for vehicle piloting tasks in the case of manual operation.

It can be assumed that the vehicle will need to accommodate ranges of sizes of crewmembers. Historically, NASA has supported ranges from the 5th

percentile Japanese female from to the 95th percentile American male (as in the Space Shuttle Program [10], and more recently with Orion, from the 1st percentile American female to the 99th percentile American male[1]. The important factor to consider in these specifications is that the ranges are applied to every segment of the body individually, not just in terms of stature. This consideration affects both seat layout and seat design. Layout is affected by defining body sizes in the plane of the seats to define spacing from person-to-person and from person-to-vehicle. Seat design considerations associated with anthropometric variations are discussed in Section 2.1.

1.5.1 Seat Spacing

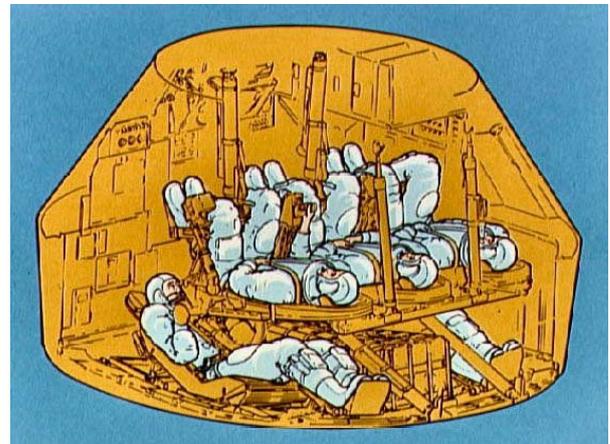
Assuming that at least some of the seated occupants lie in the same X-Y bodily plane, bideltiod (shoulder breadth and forearm-to-forearm (generally measured elbow-to-elbow) breadth drive side by side occupant spacing. Hip breadth, while important to consider in seat design, generally does not play a role in seat spacing as this dimension will fall within the previously stated dimensions. Figure 1-2 demonstrates the common dimensions that must be considered for seat layout



1-2. Common Dimensions Used For Seat Sizing and Layout (95th %ile Male Represented).

To properly space recumbently oriented seats in the body Z axis, one must consider the seated height of the occupant measured from buttocks to head (or helmet) for both occupants. While not a spacing consideration as much as an operational driver, overlapping legs or feet of occupants staggered along the Z axis must consider clearance for the lower occupants work envelope, including helmet and suit functions, as well as task performance.

In some cases it may be beneficial to arrange occupant seating in multiple levels wherein two separate XY planes of occupants are above and below each other, or even by arranging occupants in alternate facing directions. A “stacked” configuration such as was planned for, though never used for an Apollo Skylab Rescue mission, SL-R (see Figure 1-3) [8].



1-3. Skylab Rescue Seat Stacked Configuration.

In this case it will be necessary, at minimum, to space occupants based on torso depth and staggered according to buttocks to knee height (as measured orthogonally to the seatback). While the depicted image shows a contingency crew rescue layout not optimized for crew performance, in most cases ingress/egress and operational clearance will dictate this spacing for nominal seating layouts.

1.6 Launch Entry Suit Consideration

The vehicles seats are most likely to interface to the occupant directly through the crewmember’s Launch/Entry Suit (LES). That is, during seated, restrained operations the occupants of most spacecraft are wearing an LES as the interface between his/her person and the seat. This suit maintains a contingency pressurized environment around the wearer to prevent hypoxia, hypobaric injuries, and decompression sickness. In most historic applications of an LES, the suit is constructed primarily of fabric that conforms to the occupant during nominal operations and then “inflates” when pressurized to take the shape of the fabric patterning.

1.6.1 Pressurized-Suit Seat Ingress

In the event to of a cabin depressurization, a conventional soft launch entry suit will “inflate” and

become relatively stiff. The layout of the seats must provide for an unobstructed path for suited crewmembers to ingress their seats in 0g with a fully-pressurized suit. It is important to account for the different volume and mobility that pressurized suit will have versus the nominally unpressurized LES. Adequate clearance must exist to allow for translation and to prevent snags and tears of the suit.

The vehicle seat layout and cabin interaction must allow for the crewmember to access functions of his/her launch/entry suit while seated and strapped in to the seat restraints. Space around the crewmember must be maintained to allow sufficient reach to critical suit components for unhindered operation in an emergency environment. Clearance for suited operations is needed in both nominal and emergency pressurized and unpressurized vehicle operations.

A cabin depressurization wherein the occupant is not previously seated would only occur on orbit in microgravity, the designer may take utilize the three dimensional volume of the cabin for seat ingress. Strategically-placed handholds may be required to assist crewmembers in positioning themselves properly in the seat.

Conversely, if the vehicle has sufficient consumables to maintain cabin pressure for an adequate duration to don the LES, ingress the seat, and strap in prior to suit pressurization, the engineering and operations teams may design a suitable substitute for the inflated suit ingress path needs.

1.7 Emergency Egress

During emergency scenarios in 1-G terrestrial environments, it is critical that the crew be able to egress the vehicle as quickly as possible to avoid potential hazardous event and/or conditions within the vehicle. These 1-G based emergency scenarios may be effectively divided into pre-launch emergency egress and rescue scenario and post-landing emergency egress and landing scenarios.

The first scenario includes crew self ambulation from the emergency event as well as rescue of the crew rescue by launch pad emergency personnel. Layout of the seats and seat configuration must provide a sufficient translation path for the suited crew to egress the vehicle under in the operational time necessary to clear the emergency. Additionally, the layout and seat

designs should offer operational flexibility for rescue crews to extract potentially injured or unconscious crew from the seat rapidly and without incurring further injury. This time should be defined on a vehicle and operations specifics such as emergency definition, time to safe haven, and contingency consumable air supply.

Post-landing scenarios may be resultant of contingency de-orbit landing or nominal entry with landing malfunction/mishap. Alternately, they may be the result of a launch abort scenario. Regardless, the ability for the crew to egress the vehicle to seek safe haven is potentially paramount to the crew's survival. The difficulty of defining specific requirements for vehicle egress in post-landing egress scenarios is that there is no way to predict the resultant emergency environment or vehicle state, nor is it possible to define the maximum time that the crew may be afforded for egress. Additionally, since the crew may experience the effects of orbital deconditioning (ref Sections 1.3 and 1.4), there is no way to consistently define the crew's ability to egress even in the most benign of emergency environments. Seat layout and design should consider these unpredictable possibilities to maximize crew survivability.

2. SEAT DESIGN CONSIDERATIONS

Many aspects of seat design must be considered for a space vehicle with respect to the seated occupant and mission success. Anthropometry of the crew and prospective crew dictates seat sizing and adjustability. Acceleration protection dictates the support offered by the seat and restraints. Mission concepts of operations and logistics flexibility may dictate other seat design factors such as commonality, stowability, reconfigurability and mass limitations.

2.1 Anthropometry

Seat design for accommodation of a broad range of anthropometry is critical to ensure proper support and safety of the vehicle's occupants. In order to accommodate the full range of occupants, it is important to characterize the seats as upright or recumbent. Upright seating, assuming it is forward facing on a wheeled landing vehicle, requires significantly less considerations for occupant fit than a recumbent seat, though it may require additional configurability of the restraint system to ensure proper

+X motion restraint when subject to a crash environment in a complex suit system.

While many of the same anthropometric considerations used in seat spacing are used in seat design, the following are considered the most important for recumbent seat layout in a the body coronal plane:

1. Seated Height
2. Midshoulder Height
3. Bideltoid Breadth
4. Buttocks to Popliteal Length
5. Heel to Popliteal Length
6. Hip Breadth

It is possible to support the occupant in a recumbent posture without regard for items 4 and 5, by tucking and capturing the feet at the buttocks similar to the seated posture of the Russian Soyuz seat system (Figure 2-1), however the designer must take into account the overall postural, size and spacing constraints that this may entail, such as effective elongation of seated height for layout considerations.



2-1. Russian Soyuz Seat.

Items 1, 2, 3, and 6 are necessary to ensure proper and full support of the torso and head in order to allow for proper placement of the seat restraints. It is important for the designer to also consider that Items 1 and 2 will change during spaceflight due to elongation of the spine from effects of microgravity [1].

For upright seated considerations wherein frontal accelerations are the primary off-nominal event, items 2 and 6 are critically important to ensure that the restraint harness is properly placed for occupant protection.

2.2 Acceleration Protection

Proper fit is especially important in conventional capsule type vehicles that land under parachutes because the loads experienced by the occupant are generally much higher than on runway wheeled landing type spacecraft such as NASA's retired Space Shuttle Orbiter.

The beauty of the relative simplicity and effectiveness of the acceleration induced injury risk model discussed in Section 1.2 must be balanced with a warning of its limitations. While it is relatively easy to apply for the seat and vehicle designers, this model is inherently limited in that it only remains valid when the underlying assumptions and test conditions upon which it was built remain intact. In this case, it is important to consider the following caveats [2]:

1. Seatbelt restraint must be minimally effective as a 5-point harness to control torso motion
2. There should be no gaps or compressive material between the body and the supporting structure that would allow for dynamic overshoot
3. The helmet, while specified to have protection minimally equivalent to ANSI Z-90, must not apply excessive mass to the head.

Item 1 is relatively simple to incorporate through use of a 5, 6, or 7 point harness. Equivalent restraint has additionally been demonstrated in NASA/US Air Force testing using a 4-point harness given proper posturing and seat support to prevent occupant "submarining" below the lap belts [9].

Item 2 is especially important for consideration of suit architecture. While most launch/entry suits are soft fabric suits, in some cases it is desirable to have metal bearings at joints to maximize pressurized flexibility. This is common at the wrists, and in some cases in the neck connection to the helmet. In space suits that exhibit more pressurized mobility, such as NASA's Extravehicular Mobility Unit (EMU) or the Russian Orlan suit, bearings may be placed in the upper arms, shoulders, thighs and waist. System level decisions regarding seated occupant safety must be made for inclusion of these advanced mobility features as they tend to create void space within the suit that prevents proper seat belted restraint. The bearings or other mobility features have also demonstrated in NASA studies to increase the probability of blunt force trauma

to the seated occupant [7]. This is not explicitly predicted or accounted for in the dynamic response models and must be evaluated on a case by case basis.

Finally, caveat 3 mentioned above is specifically important to space helmet applications since they are often two to three times as heavy as the helmets used to create this model. This may increase the potential for cervical or thoracic spine injuries in an acceleration event due to increased head mass and resultant force. To control the effect of increased mass, it may be necessary for the designer to control the motion of the helmet through bolsters or supporting structure to reduce the ultimate force applied to the occupant's head and neck.

2.1 Launch Entry Suit Restraint

Suit considerations for seat design effect overall seat and restraint sizing by altering body anthropometrics and mass. Due to consideration 2 in Section 2.2, is critically important that the seat be designed to accommodate the anthropometry of the unpressurized suit to allow for proper restraint to the seat with no human-to-suit voids that would allow for motion within the suit. As such, the dimensions stated in Section 2.1 are to nominally constructed from a suited, but unpressurized occupant range.

For emergency return scenarios with a depressurized vehicle, the seat must be able to accommodate and hold the pressurized suit to allow for a pressurized suit entry, but landing and nominal fit should occur in the natural "soft" state of the LES.

2.2 Logistics

For long duration missions, accessibility to critical spacecraft systems and stowage drives seat layout and design. This is not only for readily operable tasks, but also for reconfiguration of the vehicle if necessary for operations or long term habitation considerations.

In many instances, seating may need to be altered in position or configuration to allow for access to stowage bays nominally located behind the seat plane. Seats themselves may also be reconfigured and removed for stowage on orbit to increase habitable volume, as were the Mission Specialist seats on NASA's Space Shuttle Orbiter.

For missions wherein multiple crewmembers may sit in the same seat at different mission phases, it is

important to allow for in-flight reconfigurability or adjustability to accommodate their differences. If supplemental components are used to supplement seat fit, the designer considerations must be made for the transport and storage of those components when not in use.

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