NASA-CR-195504

NASW-4435

IN-54-CR

204250

P. 53

Concepts and Embodiment Design of a Reentry Recumbent Seating System for the NASA Space Shuttle

N94-24667

Unclas

G3/54 0204250

(NASA-CR-195504) CONCEPTS AND EMBODIMENT DESIGN OF A REENTRY RECUMBENT SEATING SYSTEM FOR THE NASA SPACE SHUTTLE (Texas Univ.) 53 p

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Spring 1993
The University of Texas at Austin
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May 3, 1993

ABSTRACT

Design of a Recumbent Seating System

This report deals with the generation of a recumbent seating system which will be used by NASA to shuttle astronauts from the Russian space station Mir. We begin by examining the necessity for designing a special couch for the returning astronauts. Next, we discuss the operating conditions and constraints of the recumbent seating system and provide a detailed function structure. After working through the conceptual design process, we came up with ten alternative designs which are presented in the appendices. These designs were evaluated and weighted to systematically determine the best choice for embodiment design. A detailed discussion of all components of the selected system follows with design calculations for the seat presented in the appendices. The report concludes with an evaluation of the resulting design and recommendations for further development.

Contents

INTRODUCTION

This report discusses the analysis of a conceptual and embodiment design of a Shuttle Reentry Couch for NASA. The analysis will include all steps leading to the conceptual design and the considerations that lead, ultimately, to the final embodiment design. The design is submitted due to a proposed set of joint missions between Russia and the United States to the space station Mir, a Soviet space station developed to accommodate a crew of three astronauts for a period of ninety days. After this time, seven astronauts travel to the Mir to relieve the three station members of their duties. Extended exposure in a micro-gravity environment causes the station crewmembers' muscles to atrophy. Reentry into the Earth's atmosphere can be traumatic to the astronauts while in this weakened state. Their necks and lower spines are particularly susceptible to damage. A Shuttle Reentry Couch has been proposed to help alleviate this problem.

The space shuttle experiences frequent air disturbances upon reentry which cause vibrations that usually last around ten to twelve minutes. These rough air disturbances will create high and low frequency vibrations aboard the shuttle; however, proper design and implementation of the couch should eliminate the majority of these vibrations. Damping the high frequency vibrations will decrease the possibility of resonance in the system. Prolonged resonance in a system often leads to rapid structural and mechanical failure. Low frequency vibrations cause sudden unnatural accelerations that can result in conflicts between sensory perception modalities. These low frequency vibrations will also need to be considered since they tend to cause motion sickness and vertigo in the astronauts.

A range of forces are encountered during reentry with an average force of around 3.3 g's. The larger forces occurring during this period could be damaging to the astronauts. Forces that result from a crash could be life-threatening. The astronauts need to be protected during reentry and in possible crash situations.

The first sections of this report will present all phases of the conceptual design process for the development of the Shuttle Reentry Couch. Specification Sheets have been created to better define the considerations and parameters for this project. A Function Structure has also been developed. The alternatives for the sub-functions within the Function Structure have been analyzed independently by binary selection techniques to help yield the best way to implement each sub-function. Combinations of these choices were also rated and weighed by several methods to help produce the best solutions. Many combinations were eliminated because they were not feasible according to the specifications. The top combinations were weighed again so that the best concept selection could be selected. The top selection will be discussed in accordance with the specifications including body positioning, damping, and couch stresses.

The embodiment of this design concept is the main emphasis of this document. The embodiment section discusses the couch in more detail paying more attention to key issues including the layout and form design (dimensional constraints and force analysis) and materials selection.

CLARIFICATION OF TASK

The main objective in the design of the Shuttle Reentry Couch is to protect the returning astronauts from vibrations and crash forces. The muscle atrophy that has occurred during their stay in space has weakened the astronauts to the point that, in the unlikely event of a crash, it is highly questionable whether they would survive. Also, the unavoidable forces that are encountered during lift-off, reentry, and landing must be attenuated to help decrease the risks of injury to the crew. The design of the Shuttle Reentry Couch should be able to carry out these important functions.

Since space shuttle crashes are not an everyday occurrence, there is little information currently available on the survivability of such an event. The only knowledge available is the tolerances of the human body in space. We decided to use data from helicopter and plane crashes, where forces of the same magnitude might occur, to model such an event and aid us in analyzing the human considerations. Any design considerations that were discovered will be introduced later in the "Embodiment Design" section of this document.

SPECIFICATIONS

This section briefly discusses the specifications of the design of the Shuttle Reentry Couch. For a detailed specifications sheet listing please see Appendix A. A detailed justification of each of the specification groups is also included. Table 1 emphasizes the most important specification areas for our design.

Key Specifications
•Emergency Landing Load Factors (Design Structure)
•Emergency Landing Load Transmitted to Occupants
•Reentry Vibrations Transmitted to Occupants
•Weight of the design
•Size of the design
•Cost of the design
•Restraining of the Occupants
•Time/Ease of Set-up
•Comfort

Table 1 - Key specifications for the shuttle re-entry couch design.

FUNCTION STRUCTURE

The complete function structure for the Shuttle Reentry Couch can be seen in Appendix B. The relationships between the sub-functions will be discussed in both a later section and Appendix B. Two phases of the Function Structure are pictured in the appendix. One analyzes the "Black Box" representation, while the other has a very detailed breakdown of the sub-functions. The general "Black Box" representation can be seen in Figure 1. The next section of this document discusses sub-functions, implementation of the sub-functions, combinations, and elimination methods.

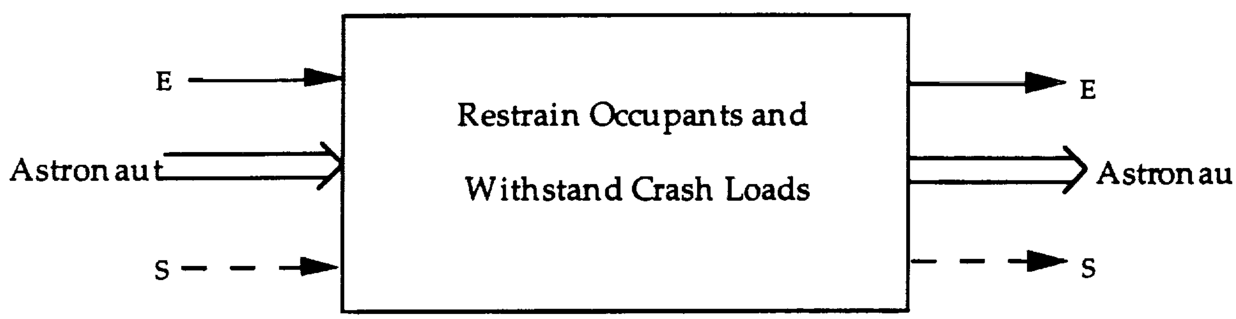


Figure 1. Black box representation of the recumbent seating system.

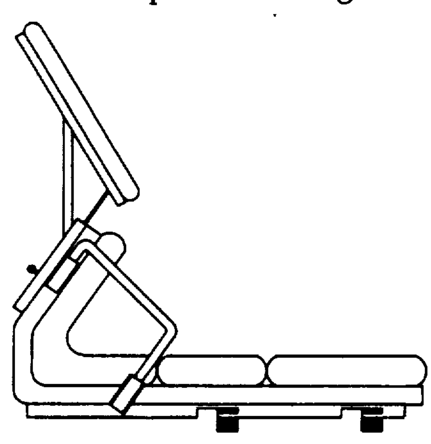
CONCEPTUAL ANALYSIS

After the Specifications and the Function Structure were developed, the next step in the conceptual design process was the elimination of concept choices. This process narrowed the large range of concepts down to the more feasible combinations. Further elimination methods yielded the best design concept.

Consult Appendix C for an informative look at the selection process. Included in the appendix are the variants for each sub-function group, binary selection charts, a weighting factor analysis of the top 10 concepts, and a listing of these concepts.

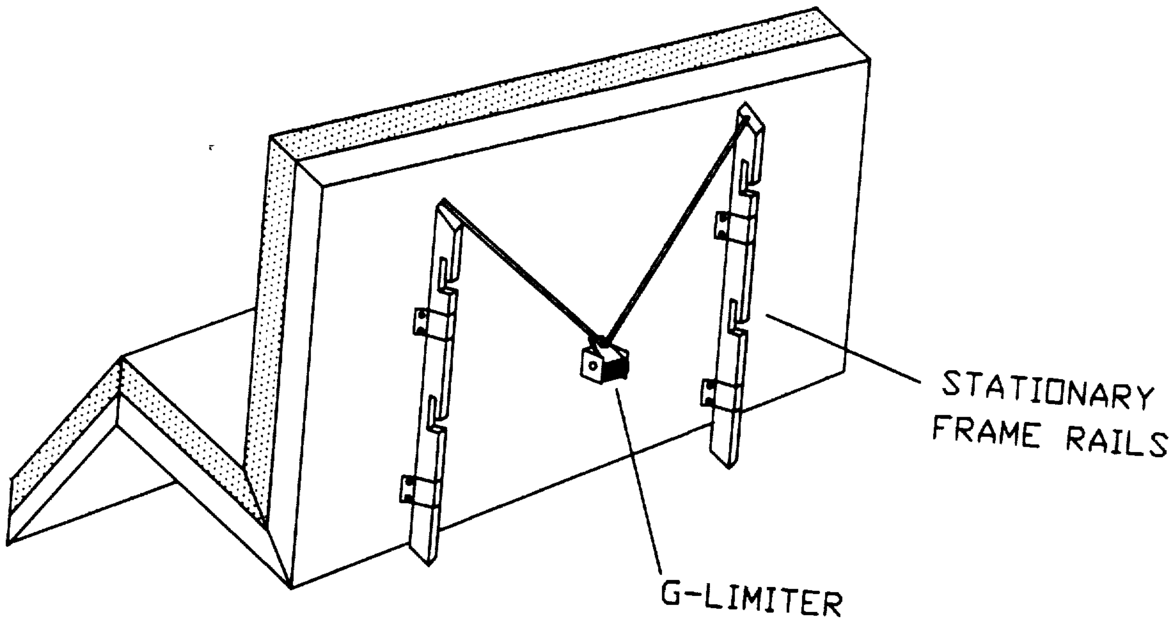
CHOICE OF CONCEPT

The top combinations were narrowed by a weighting factor analysis to further eliminate concept combinations as seen in Appendix C. Two concepts emerged as the winning combinations only differing in concept by the material used for the truss frame. One choice used a *composite material for the frame, while the other used a metal or alloy frame. Our design group concluded that completely metal frame would probably violate the specified weight restrictions. Also, from our research, the composite material would be much more effective due to its high strength and low weight. Other concepts of the top combination included a 4-point pilot restraint system, *Confor™ foam pads, and a *G-Limiter™(see Figure 2). A vibration control plate which would be attached to the middeck floor and the frame truss with latches or clamps was also considered . From further research during the embodiment design, individual vibration isolators were chosen to replace the vibration control plate for weight considerations.



Side View

{*These products will be discussed in greater detail in "Embodiment Design."}



Rear View

Figure 2- Concept including top sub-function combinations.

EMBODIMENT DESIGN

With the selection of our top concept, the remainder of this document will focus on the embodiment of this design. First, we must identify requirements and specifications that have crucial bearing on the design aside from those key specifications that were mentioned earlier in the "Specifications" section.

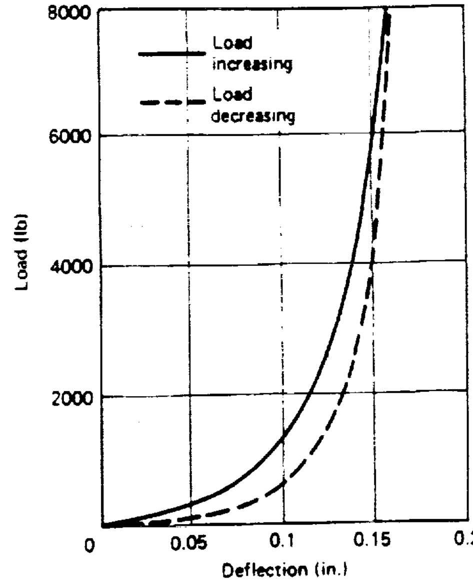
KEY ISSUES

The first concern we faced was the capability of our design to fulfill its function. As seen in the development of the conceptual design, several alternatives were considered that could perform the various sub-functions of the design.

The forward crash forces which reached up to 20g of acceleration (axially along the spine) were our main concern in the chair design. We found the G-limiter™, a device designed for helicopter crash situations, that could attenuate 20g's down to 5g's. The G-limiter™ is discussed further in the "Materials Selection" section. The next highest crash force is into the back at 10g's. Even though some of these forces will be absorbed by the vibrational insulation in the floor connections and by the Confor foam material, it should be pointed out that the human body is capable of withstanding up to 40g rearward crashes (against the back) [Sanders,1987]. According to Sanders, the other directional forces should be tolerable by humans.

We also considered the effects of the vibrational forces seen by the crew during reentry by incorporating a type of vibrational isolator at the floor connections which is composed of a stainless steel spring and mesh. While we originally wanted to use a vibration control plate, it became apparent that such a plate would push the bounds of our specified weight limit. After consulting with Dr. Mark Hamilton, we decided to implement some type of vibration and shock mounts in attachment points 1 through 8. Several types of isolators were available; however, the natural rubber cup-mounts and cylindrical mounts didn't seem capable of handling the loads seen by the RSS. We decided to use a stainless steel spring and mesh base mount which is often used in aircraft, marine, mobile, and rotary machine applications. An example of this type of mount is shown in Figure 3 accompanied by its load versus deflection curves [Wilson, 1989]. Normally, the equipment is held in the mount by gravity. In our case, the top of the mounts will have to be designed to work in a micro-gravity environment by making them screw type or pinned fixtures.

Figure 3- Vibration isolator for leg attachments.



To better withstand forces, the center of gravity of the design must be as low as possible. This will enable the design to stay more rigid in the event of a crash, and prevent tipping of the structure. The seating system should be designed in a recumbent position so forces will be better distributed over the body to improve the restraining capabilities. The recumbent seating system will also decrease the forces on the parts of the body most susceptible to injury, namely the spine and neck.

For the layout and form design, we had to consider the dimensional constraints for the position of the couch. Figure A-2 shows the layout and dimension constraints of the middeck floor, and figure 4 shows the couch position with respect to the airlock and lockers.

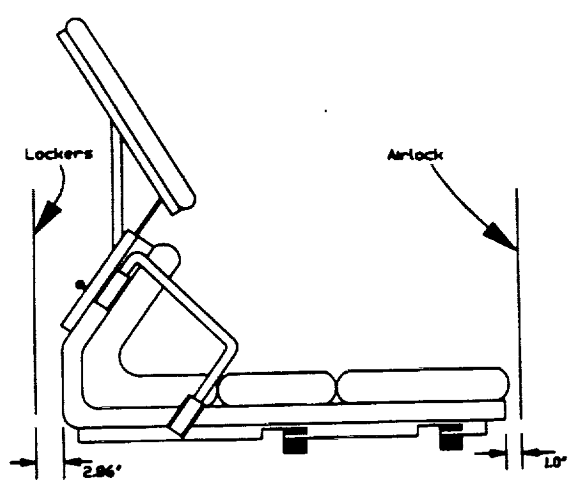


Figure 4- Couch showing relation to airlock and lockers.

We also had to consider the strengths of the critical stress areas of our couch for both stability and impact crashes. A detailed analysis of these stress areas and the materials involved can be seen in Appendix D. Calculations to determine the maximum stress possible in the composite frame show a maximum stress of 10.06 MPa at the corner. The breaking stress of the composite material is approximately 500 MPa. The composite frame should withstand all expected emergency loads.

The sliding bracket bolts experience a maximum tensile stress when a 10 g downward acceleration occurs. The minimum diameter for these bolts was found to be 0.30 inches. The half inch bolts will have sufficient tensile strength to survive the crash loads. The maximum shear stress calculations also gave acceptable results.

Another critical stress area occurs at the hard point connections to the floor. The stress occurring in the aluminum members concentrates near the 12 connection holes. Emergency landing loads produce a maximum stress around the holes of 940 psi. The maximum shear in the floor bolts is 2.4 ksi. Both the bolts and the aluminum members have satisfactory strength to survive the crash loads.

Resonance is also a consideration in our design. As specified, the natural frequency of the couch must be greater than 30Hz. In order to determine the natural frequency, a detailed, time consuming finite element analysis should be performed on the system. Based on the time constraints for completion of this stage of the design, the finite element analysis would be left as a future project.

Material corrosion is also a concern in the shuttle environment. Our basic materials consist of a composite material, the G-limiter, Confor Foam (all non-corrosive), and an aluminum alloy which is very resistant to corrosion.

Our couch design is also a very safe design. There are no moving parts, pinch points, electrical components, or sharp edges involved. In addition, most of the surfaces are padded with the Confor Foam. The Confor Foam also addresses an important issue concerning the ergonomics of the design by allowing increased blood flow at pressure points between the occupant and the couch (see "Materials Selection" section for more on the Confor foam).

Assembly of the couch must be easy and take as little time as possible. The assembly requires two astronauts to position the couch by inserting the floor trusses into the slots in the rails on the back side of the couch and pushing forward along the slots. Next, the slide rails attached to the floor trusses are moved into the vacant space in the rail slots (see Figure 5). The leg rests are then inserted into the pinned slots (see Figure 6). Total assembly time should be less than 15 minutes.

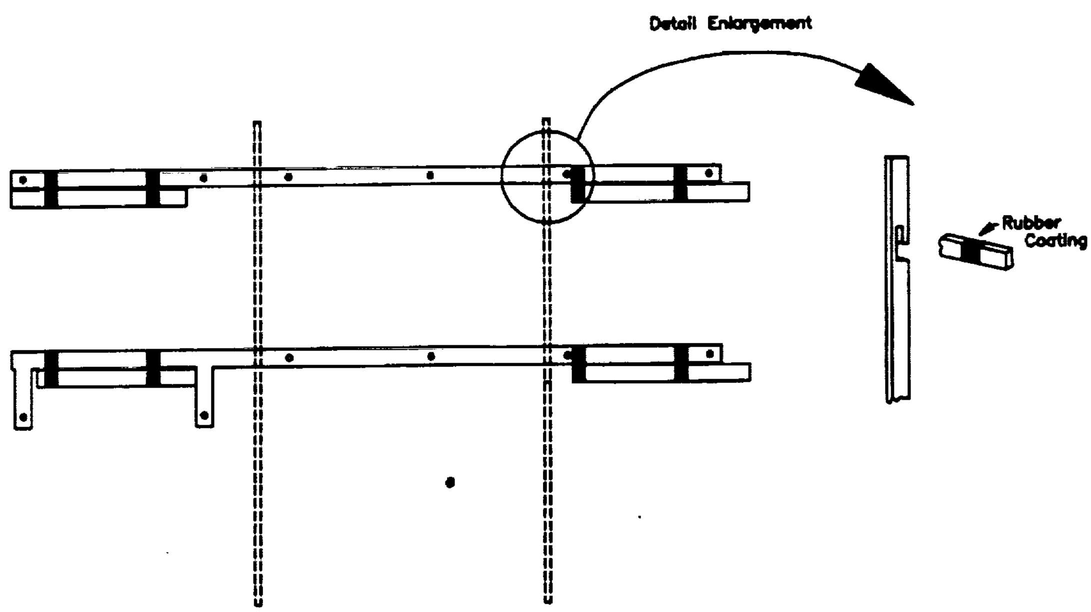


Figure 5- Floor truss and seat assembly.

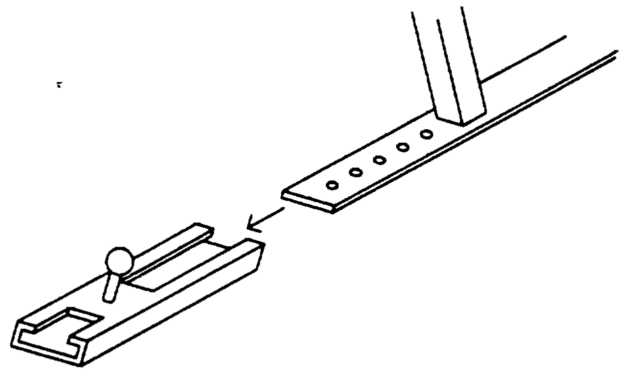


Figure 6- Leg rest assembly and adjustment.

Maintenance is also a consideration in the design. A weekly inspection of the design should take no more than 10 minutes. The modular components of the design can easily be replaced if needed during annual maintenance, and spare parts should be available onboard the shuttle in case of a component failure. The design should also be easy to care for and clean.

The total costs of the couch design are estimated to be about $45,000 , which is within the limits of the project. For a detailed breakdown of costs for this project, consult the "Cost Analysis" section of this report.

MATERIALS SELECTION

Material considerations are important in terms of strength, durability, and corrosion properties. If the design does not provide adequate strength, it is useless. Due to specifications, materials must be lightweight, yet strong enough to withstand the forces that are involved in reentry and crash situations. From research, our design group has found several material considerations for the design of the Recumbent Seating System (RSS). The following discussions will give an overview of the G-Limiter™, Confor™

foam, the lightweight composite selected for the framework of the design, and the journal bearings used on points 9-12.

The G-limiter

One of the functional requirements for the seat is a limitation of acceleration forces felt during crash situations. The largest acceleration listed in the specification list occurs parallel to the floor of the shuttle's middeck. These accelerations are also parallel to the occupants' spine while seated in the recumbent seating system. Therefore, one of our main concerns was to limit the amount of g-forces experienced by the astronauts during an emergency landing.

Analysis of helicopter accidents have shown that the structural integrity of the air frame usually remains intact, but the occupants sometimes sustain spinal injuries due to the large accelerations applied parallel to the spine. Previous energy absorbing seat systems were designed for an average weight occupant, but failed to consider the extremes of the occupant weight spectrum.

Devices have been developed that allow manual adjustment of the seat to the occupant's weight. However, these devices tend to be very complex, and if care is not taken by the occupant to individually adjust the device, injuries could still occur. The need exists for a robust design that would tackle these problems.

The G-limiter™ was designed specifically for this application. The G-limiter™ limits the acceleration experienced during crash situations regardless of the seat occupant's weight. The maximum acceleration to be experienced by the occupants is considered a design parameter. The device is designed with an extendible steel strap wrapped around a cylindrical drum (see Figure 7). When accelerations surpass the maximum design acceleration, the grip of the strap on the drum slips and the strap extends. The extension of the strap allows motion of the seat relative to the airframe. This motion reduces the acceleration experienced by the seat and its occupant. When the acceleration of the device drops below the acceleration limit, the device becomes rigid again [McCarty, 1987].

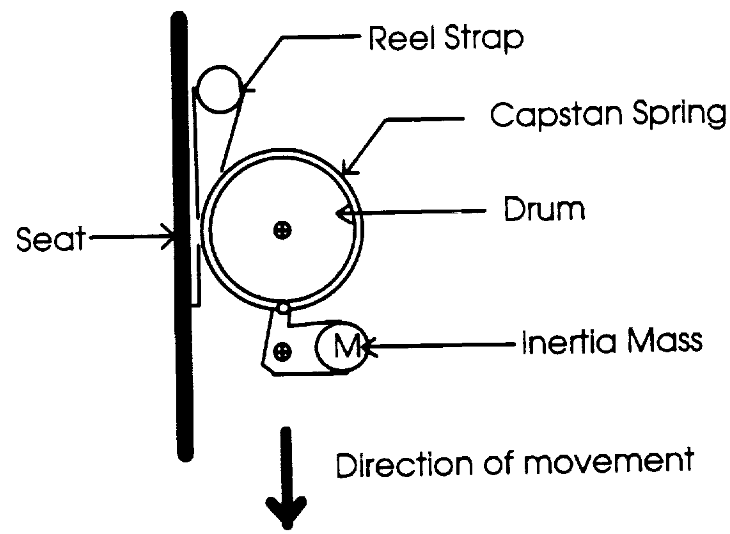


Figure 7- G-limiter.

Drop tests made by the designer of the G-limiter were used to measure the performance of the device. The test data shows that a calibration result acceleration range of 14-17.5 g's was maintained over an input range of 38-140 g's (see figure E-1). The displacement of the seat ranges between 1/4 inch and 1-1/4 inches.

Composite Frame Discussion

Weight is a major concern in the shuttle program. Composite seats have been utilized in helicopters to reduce the weight of the seat and increase the payload. The Recumbent Seating System will be launched into orbit every month over a thirty year period to retrieve astronauts from the space station. Since the cost of launching objects into space is extremely expensive, any reduction in weight will result in substantial fuel savings.

The couch design is constructed of a high strength, light-weight composite material developed by Fothergill Composites. The composite offers superior strength characteristics at a lower weight than most metals. The characteristics of the composite are compared with aluminum in Table 2. The composite is stronger than the aluminum and performs adequately for our conditions as shown in Appendix D [Design,1986].

Material	Density	Modulus of Elasticity	Ultimate Strength
Aluminum (2024-T4)	2800 Kg/m^3	27000MPa	448MPa
Composite	0.05 Kg/m^3	20000Mpa	500MPa

Table 2- Comparison of properties between aluminum and the Composite material.

The design analysis resulted in a concept using both materials. The final seat concept utilizes the composite material to form the back and foot sections of the seat, and an aluminum alloy to form the connections and floor truss apparatus.

Confor Foam

The astronauts returning from the space station will be physiologically unconditioned and will be experiencing g-forces for the first time in several weeks. The Recumbent Seating System should provide comfort and stability to the returning astronauts.

Confor™ foam is a medium density, open celled, temperature sensitive, polyurethane foam that softens on contact with a warm body and conforms to the body's shape. The result is a uniform pressure distribution that minimizes resistance and allows unconstricted blood circulation making the seat more comfortable and decreasing the stress on an unconditioned heart.

When an impact is experienced, the foam also acts as a semi-rigid substance allowing absorption of up to 97% of the impact energy. This energy absorption would remove the majority of the stress away from the body

Confor™ foam is a proven success in NASA applications for the seats aboard the space shuttles to cushion the astronauts from the shocks of launch and reentry. The foam is also fire retardant and vapor resistant which are important specifications for equipment used in a concealed environment [Specialty,1993].

Journal Bearings

Rigid base mounts could not be implemented on attachments 9 through 12 since these points could only take vertical loads of 80 lbf. We had to come up with some type of attachment that would hold the frame in the x-y plane without transmitting force in the z direction (into the floor). A reinforced Teflon coated journal bearing seemed to be the answer [Rylander, 1993]. An example of the journal bearing is shown in Figure 8. Theoretically, each bearing can take up to 2500 psi perpendicular to the Teflon surface. The inside surface can also withstand temperatures up to 500° F after which the Teflon sublimates into a gas [O'Connor, 1968]. This design is optimal since the near frictionless Teflon surface will allow the frame to deflect up and down in the bearing without passing the forces on to the floor and still constrain the frame in the x-y plane.

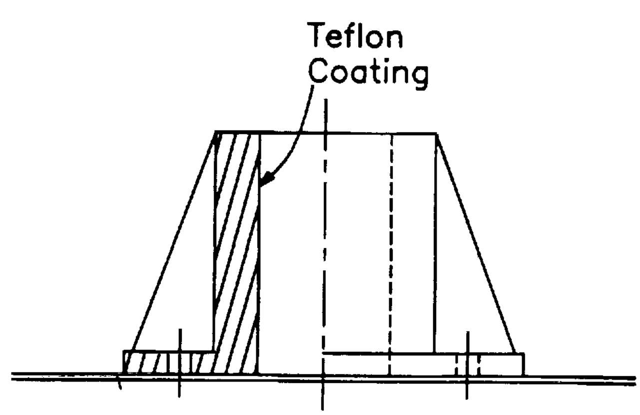


Figure 8- Teflon coated journal bearing.

COST ANALYSIS

Table 3 gives a detailed breakdown of the approximate costs involved with the couch design developed in this report.

Project Design Cost Analysis

Note: All costs are the best estimates available.
(Some products are only in the prototype stages and would require further development).

•G-Limiter:	(prototype)	$2,500.00	
composite frame:	(35.27 ft^2)	$28,216.00	Estimated at $800.00 per ft.^2
Confor foam:	(35.27 ft^2)	$515.45	Estimated at $9.66 per ft.^2 -- 2" thickness Estimated at $19.32 per ft.^2 -- 4" thickness
Aluminum frame:	(0.265 ft^3)	$26.44	Estimated at $100 per ft.^3
Journal bearings: (Attachments 9-12)		$200.00	4 bearings estimated @ $50.00 each
Spring & mesh vibration isolators: (Attachments 1-8)		$800.00	8 bearings estimated @ $100.00 each
Velcro straps:		$50.00	
Engineering & Manufacturing Processes		$15,000.00	
	TOTAL =	**$44,807.89**	

Table 3- Cost analysis of RSS parts.

CONCLUSION AND FUTURE PERSPECTIVE

The following is a discussion of the positive and negative aspects of our final design concept. The evaluations and recommendations for the future are given below.

EVALUATION

The function of the Recumbent Seating System is to comfortably ensure the safety of returning astronauts and absorb energy from vibrations, landing, and possible crash situations. The final design concept should perform this task well, and at the same time the concept exceeds the weight constraint set by NASA. The materials selected for this concept were lightweight and strong. A complete set of dimensions for the couch design can be seen in Appendix E.

The Confor™ foam is excellent for absorbing some of the energy from low magnitude vibrations and large magnitude impacts (landings). The Confor™ foam also promotes blood circulation by evenly distributing the pressure on the body. A potential problem with this foam is that it is heat sensitive and the parachute may not adequately warm the foam. This could inhibit the performance of the Confor™ foam in the lower back area. To address this problem, the foam in the area of the parachute could be removable assuming the parachute could be used as padding.

Since it is already implemented in existing shuttles, the 4-point harness should be effective in holding the astronauts in the seat for accelerations in all directions in case of a crash. Also, the G-limiter™ is able to reduce large accelerations which makes it ideal for potential crash situations. One problem is that the mounting of the G-limiter™ permits acceleration reduction in one direction only. Future improvements could be made to permit reduction in all directions.

This concept is beneficial due to the materials and components incorporated in its design. Both materials and components are products that are readily available.

IMPROVEMENTS

The design concept meets the majority of the specifications, however there are some weaknesses and need for improvement. System storage was not considered in great detail. Given that storage position of the system must not extend beyond 6 inches, the frame must have a break somewhere along the back of the leg. An attachment design for this section can be seen in Figure 9.

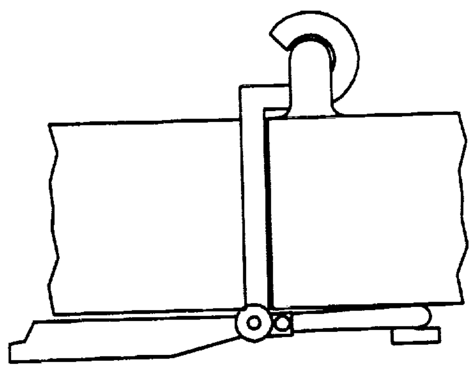


Figure 9. Frame Assembly Attachment

For the legs, some method of containment will need to be implemented. In reentry and crash situations it would not be desirable to have the astronauts' legs falling back in their faces. Also, whatever method is chosen should have a safety escape so if the astronauts' cannot reach their feet, they can pull some trigger which will automatically release their feet.

As mentioned before, NASA may want to reconsider the use of parachutes in their current configuration. It may be better to mount the parachutes in some other position like on the stomach or higher on the back. The Confor™ foam would provide much better support and protection to the critical lower back area than the parachute.

RECOMMENDATIONS

There is much analysis that still needs to be done. A finite element analysis of the total system is a must. We use a few prototype devices and some existing devices with our own changes. A FEM would prove for sure how these devices work together during operating situations. It may be that some other spring/damper system will be needed, some other alloy may have to be employed in the frame, or the frame may have to be redimensioned to prevent critical deflection.

Overall, while the design is theoretically feasible, until it is run through the full range of loads, it cannot be recommended 100%.

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Appendix A.

Appendix A.: JUSTIFICATION OF SPECIFICATIONS

Specifications have been developed by our design team for the Shuttle Reentry Couch System. Please note that the specifications are categorized by type into fifteen different categories. This section of the document will give a brief overview of each of these specification groups.

Geometry

Geometry is an important specification group for this project because space within the shuttle's airlock is limited. The constraints on the dimensions of the design are essential due to the twelve floor attachments that have been specified by NASA. The design should be modular to facilitate easy transport and assembly, while also being compatible with the shuttle's dimensions. Also, the design's storage area onboard the shuttle has the dimensions of 2' wide x 1.5' high x 3' long. The center of gravity of the design should be less than 16" from the middeck floor with the occupants and no more than 6" from the floor while stowed. While the astronauts are seated in the design, the head and thorax should be 0-6° relative to the middeck floor. With the head aft and the feet forward, the legs must be bent to insure that the low center of gravity is achieved. Another very important geometry consideration is that the design accommodates the weight and dimensions of the 95th percentile American male and 5th percentile Oriental female. The weight of the design for each cannot exceed 180 lbs.

Forces

Besides geometry, forces are definitely the most important specification group. If the integrity of the design to withstand specified forces is not insured, the safety of the astronauts involved is in question. The ultimate load factors that the seat must be able to withstand during a crash are: 20g forward (in a 20° cone area), 3.3g aft, 3.3g right and left, 10g down, and 4.4g up. Not only must the design withstand crash forces, but also the ranges of forces and vibrations involved during lift-off and landing. Values for the operational inertia loads during lift-off and landing can be seen in the Specifications Sheet. These values have been specified by NASA as constraints for the design. A range of vibration frequencies have also been specified and can be seen in the Specifications Sheet. These random vibrations occur throughout the mission; therefore, the reentry couch must be capable of withstanding fatigue under such conditions. Within the shuttle middeck seen in Figure 4, Attachments 1-8 will take all of the tension/compression loads, while Attachments 9-12 can take no more than 80 lbs. in tension or compression. All attachments have a maximum shear of 5000 lbs. each in any direction.

Energy

There should be no energy sources required to aid in the proper operation of the Shuttle Reentry Couch design.

Material

To be fully functional in space, the design must be operational within a temperature range of 65-85°F with a relative humidity of 50%. All of the component materials used in the design must meet NASA specifications for corrosiveness, flammability, and others. Also, to avoid any possible future inconvenience, a hypo-allergenic material should be used in all design components.

Signal

Since no electrical power can be required for the design, no electrical or digital signals will be available to the astronauts. However, easy-to-follow instructions will be provided to the user to help insure their safety and proper operation of the design.

Safety

This is another important specification group due to the condition of the astronauts that will be using the design. To better protect the users from unnecessary harm, the Reentry couch should have no sharp edges or loose parts. The design must conform to all NASA safety criteria and assure an ultimate safety factor of at least 1.4. Structural safety factors and fracture control of structural components shall be verified by the current standards.

Ergonomics

The main ergonomic consideration for this design is that the positioning and restraining of the occupants is comfortable.

Production

NASA specifies that only one unit is to be produced at this time.

Quality Control

The quality issue that must be considered is that the lifetime of the design be equivalent to the lifetime of the space shuttle.

Assembly

It is desired that the assembly/put away time for the design be no more than 15 minutes. Assembly and disassembly should not require tools of any kind. Also, no more than two astronauts should be needed to set-up or put away the design.

Transport

The shuttle reentry couch design should be easy to transport to the area for assembly and disassembly.

Operation

The design must be fully operational in a microgravity environment. Also, the design must restrain occupant during lift-off, reentry, and landing, as well as crash loads.

Maintenance

A weekly inspection of the design should take no more than 10 minutes. The modular components of the design are easily replaced if needed during annual maintenance. Spare parts should also be available onboard the shuttle in case of some type of component failure. The design should also be easy to care for and clean.

Cost

The first cost of the shuttle reentry couch should not exceed $100,000. Annual maintenance costs will vary as needed and should not exceed $2,000.

Schedule

The projected completion date for the shuttle reentry couch is May, 1994.

Table A1 - Specification table for volume measuring system.

D,W or C	Requirement	Rsp.
	Geometry	
C	Head and thorax to be 0-6° relative to middeck floor	
C	Head aft and feet forward; legs may be bent	
C	C.G. < 16" from middeck floor with occupant	
C	C.G. < 6" from floor in stowed configuration	
C	Weight < 180 lbs.	
C	Adjustable to accommodate weight and dimensions of 3 fully suited 95th% American males and 5th% Oriental females. - Suits w/parachutes weigh ~100lbs. each - Suits w/parachutes add 6.5" to seated height - Crew experiences 3% growth in seated height in orbit	
C	Constrained by dimensions in Figure xx.	
C	Attachment to 12 spots shown in Figure xx	
C	Storage area: 2' x 1.5' x 3' (w x h x l)	
C	Assembled/Transport size compatible with shuttle dimensions	
D	Modular to facilitate transport and assembly	
	Forces	
D	Seat shall withstand individual crash loads of (ultimate load factors): - 20g forward in a 20° cone area - 3.3g aft - 3.3g right - 3.3g left - 10g down - 4.4g up	
D	Seat must withstand operational inertia loads (takeoff and landing): x y z Lift-off ± 9.00 ± 3.20 ± 7.40 (g's) Landing ± 6.25 ± 2.50 ± 12.50 (g's)	
D	Seat must withstand fatigue from the following random vibrations (exposure duration = 7.2 sec/flight in each of x, y, and z axes): 20 - 150 Hz +6.00dB/Octave 150 - 1000 Hz 0.03 g^2/Hz 1000 - 2000 Hz -6.00 dB/Octave Composite = 6.5 g (rms)	
D	A fatigue scatter factor appropriate for the materials and method of construction is required and not less than 4.0.	
D	Seat natural frequency must be greater than 30 Hz with respect to the orbiter attachment interface.	
C	Attachments 1-8 (see Figure xx) take all tension and compression loads	
C	Attachments 9-12 take < 80 lbs. tension or compression	
C	All attachments have maximum shear of 5000 lbs. each	
D	Functional in micro-gravity environment	
D	Appropriate restraint for astronaut during use	

*D=demand, W=wish, and C=constraint

(Table A1 - Continued)

D,W or C	Requirement	Rsp.
	Energy	
C	Does not require power source	
	Material	
C	Working temperature range; 65º < T < 85ºF	
C	50% relative humidity	
C	Materials must meet NASA general specs (corrosiveness, flammability, etc.)	
C	Hypo-allergenic material	
	Signal	
C	Usage instructions for astronaut	
	Safety	
C	No sharp edges or loose parts	
C	Meet all NASA safety criteria	
C	Design shall assure an ultimate factor of safety ≥ 1.4.	
C	Structural safety factors shall be verified in accordance with NSTS 1700.7B	
C	Fracture control of critical structural components shall be verified in accordance with NSTS 1700.7B and NHB 8071.1.	
	Ergonomics	
D	Position and restraint comfort for occupants	
	Production	
C	One unit	
	Quality Control	
C	Lifetime equivalent to lifetime of shuttle	
	Assembly	
D	Less than 15 min. equipment assembly/ put away time	
C	No more than two astronauts required to set up/ put away	
D	Requires no tools to assemble/disassemble	
	Transport	
D	Easy to transport to area for use	
	Operation	
D	Restrains occupants during re-entry and landing	
D	Withstands crash loads	

*D=demand, W=wish, and C=constraint

(Table A1 - Continued)

D,W or C	Requirement	Rsp.
	Maintenance	
D	Weekly inspection, 10 min	
D	Annual maintenance required	
D	Modular components to facilitate replacement	
D	Standard spare parts	
D	Easy to clean	
	Cost	
C	First cost < $100,000	
C	Annual maintenance cost < $2,000	
	Schedule	
C	Complete: 05/94	

*D=demand, W=wish, and C=constraint

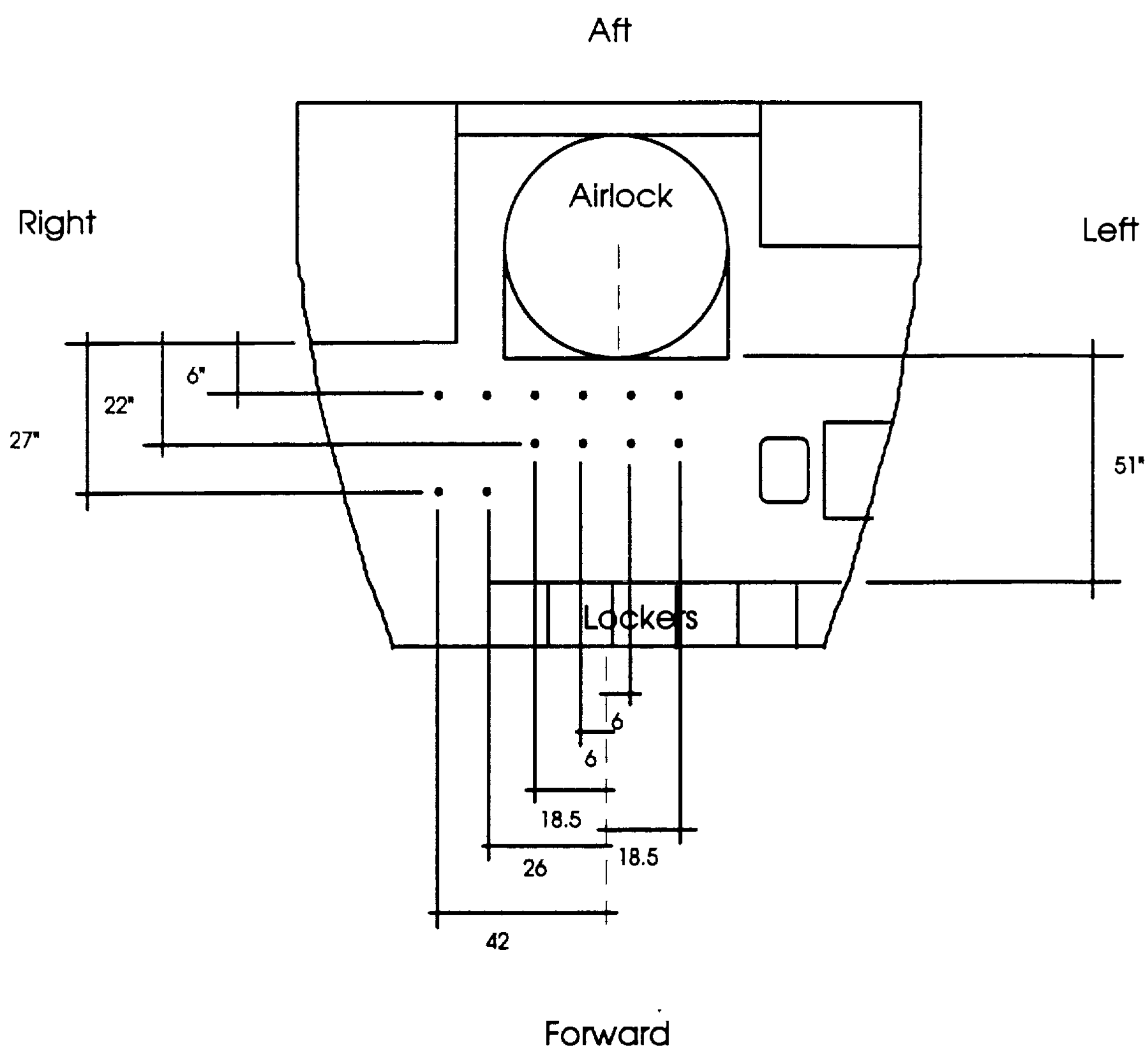


Figure A-2 - Geometric constraints of Space Shuttle middeck.

Appendix B.

Appendix B.: EXPLANATION OF FUNCTION STRUCTURE

The main function of the Recumbent Seating System is to comfortably restrain the astronaut and absorb external forces. This is illustrated in Figure B1. The functions and sub-functions of the system were developed from this "Black Box" and are shown in Figure B2.

The system will not require an external power source. However, human energy is required for the setup, assembly, and adjustment of the system. The astronaut and the shuttle seat are the material flows represented in the system.

The sub-functions required for the operation of the Recumbent Seating System include system assembly, system adjustments, buckling belts, and energy absorption. The absorption of energy includes occupant restraint, the absorption of vibrations during reentry, and the absorption of possible crash loads.

Appendix B: Function Structure

Figure B1.: "Black Box" Representation

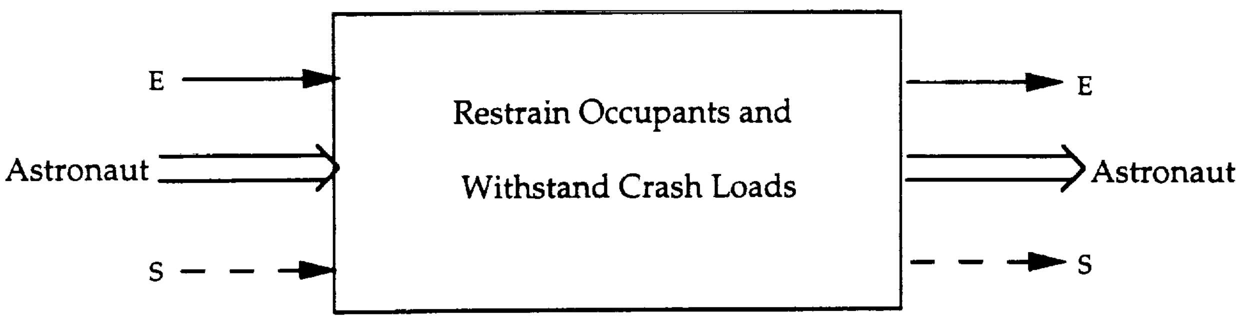
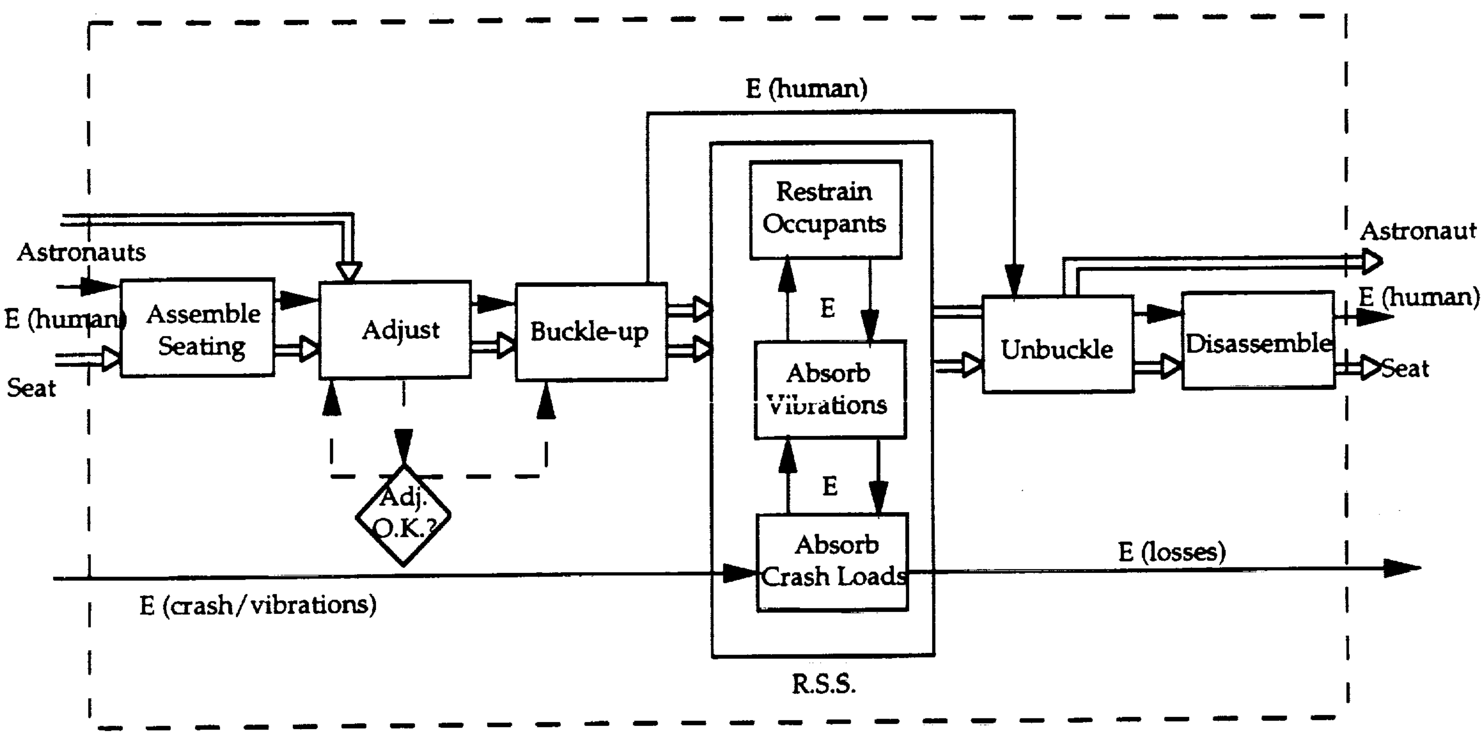


Figure B2.: Functions & Sub-functions



Appendix C.

Appendix C.: EXPLANATION OF CONCEPTUAL ANALYSIS

After the Specifications Sheet and the Function Structure were developed, the next step in the Conceptual Design process was the elimination of concept choices. This process helps to narrow the large range of concepts down to the more feasible combinations. Further elimination methods will yield the best design concept.

The first step was the analysis of each of the sub-functions within the Function Structure. Our design team broke each of the sub-functions down to possible ways of implementation. The choices for each of the sub-function groups can be seen in the "Variants" section within this appendix. After all choices were obtained, a binary matrix was used to evaluate the choices within each sub-function category, and the top two choices for each sub-function were combined into all possible combinations. To better evaluate these combinations, the points from each sub-function were summed in accordance with the combination.

The top ten point totals were then selected as the "Top 10 Combinations." A weighting factor analysis was done on the top 10 combinations to help in the elimination of incompatible combinations. Each sub-function group was weighted by our design group by its overall importance to the design itself. These weights were assigned in accordance with the specifications. "Emergency Landing Load Transmitted to Occupants" was given the highest weighting of a 0.30 out of 1. Our design team felt that this was definitely the most important specification because it dealt with the safety of the astronauts. "Weight" was given a weight factor of 0.12 due to the constraints of the shuttle floor. Next, "Emergency Landing Load Factors," "Reentry Vibrations Transmitted to Occupants," "Costs," "Time/Ease of Set-up," and "Comfort" were all given equal weights of 0.10 out of 1. These are all important issues that were really indistinguishable in terms of importance to the design of the Shuttle Reentry Couch. Lastly, the "Size" and "Restraining" specifications were given a rating of 0.05 out of 1 because they could be implemented successfully in several ways that would not be dependent on the design itself. For example, "Restraining" can be done by a 5-point belt or a 4-point belt and be equally successful independent of the other design considerations.

After weighting factors were assigned, the "Top 10 Combinations" were ranked in accordance with each of the Key Specifications. The rating scale was from 1 to 4, where: 1=poor, 2=will do, 3=good, and 4=excellent. Please refer to the "Weighting Factor Analysis" section of this appendix for each of these ratings per specification.

Concepts that involved *Confor Foam and a *G-Limiter were all given high rankings for structural load, occupant load transmission, and reentry vibration transmission specifications. For weight considerations, the concepts that used a lightweight *Composite frame received the highest marks.

All concepts received similar rankings for the size specification. As explained earlier, the size of the design can be carried out successfully by several means; therefore, it is difficult to ascertain which concept would rank higher than the next.

The same concepts were evaluated considering the costs. It appears from preliminary estimates that most concepts would not exceed the specified cost limit; therefore, it is again difficult to distinguish one concept as being better than another.

All combinations that used a 4-point pilot belt received higher rankings as opposed to the 5-point pilot belt. Comfort was the main consideration in this decision. We felt that a 4-point belt would be much more comfortable to the astronauts than the 5-point belt's intrusive strap between the legs. From our research, we found that the 4-point belt is currently being used onboard the space shuttle already, and our design team felt this would be sufficient.

The highest rankings were awarded to concepts using latches or clamps for floor attachments and a *Composite framework. The quick, easy-to-use latches or clamps would be a plus, while the Composite frame would be lightweight and easy to assemble. These ideas would facilitate a design that was easy to set-up, as well as a quick set-up.

Design combinations involving the Confor foam were given fair marks for specifications regarding comfort. The highest rankings went to combinations involving some type of spring/damper system in the truss framework connected to the middeck floor.

After all of the rankings were completed, these rankings for each of the concepts were multiplied by the weighting factors corresponding to a respective specification. The products were totaled for each combination and can be seen in the "Totals" column of "Weighting Factor Analysis" in this appendix.

*These products will be explained in great detail in the "Embodiment" section of this document.

Figure C1: Variants Used in Binary Charts

Seat Attachments:
1. Permanent tracks
2. Quick release pins
3. Hand screws
4. Clamps or latches

Impact Vibration Resistance
1. Spring or damper in truss
2. Truss shears to absorb energy
3. **G-Limiter
4. Track w/friction springs

Restraint System
1. Lap & Shoulder belt
2. 4-point pilot belt
3. 5-point pilot belt
4. Lap with shoulder bar
5. Air bags

Absorption of Reentry Vibrations
1. Seat cushions
2. Spring or damper system
3. Vibration control plate
4. **G-Limiter
5. None

Cushion Material
1. Foam material
2. Parachute alone
3. *Confor foam
4. Air
5. Liquid or Gel

Frame Material
1. Metal
2. Plastic
3. Composite
4. None

*Confor foam™—EAR Specialty Composites
**G-Limiter -- Pacific Scientific, Kin-Tech Division

Figure C2: Binary Charts for Specified Sub-functions

Seat Attachments

		1	2	3	4
	1	x	0	0	?
	2	1	x	1	1
	3	1	0	x	1
	4	?	0	0	x
total:		2	0	1	2

Impact Vibration Resistance

		1	2	3	4
	1	x	1	1	0
	2	0	x	1	0
	3	0	0	x	0
	4	1	1	1	x
total:		1	2	3	0

Restraint System

		1	2	3	4	5
	1	x	1	1	0	0
	2	0	x	0	0	0
	3	0	1	x	0	0
	4	1	1	1	x	0
	5	1	1	1	1	x
total:		2	3	4	1	0

Absorption of Re-entry Vibrations

		1	2	3	4	5
	1	x	1	1	0	0
	2	0	x	1	0	0
	3	0	0	x	0	0
	4	1	1	1	x	0
	5	1	1	1	1	x
total:		2	3	4	1	0

Cushion Material

		1	2	3	4	5
	1	x	0	1	0	0
	2	1	x	1	1	1
	3	0	0	x	0	0
	4	1	0	1	x	1
	5	1	0	1	0	x
total:		3	0	4	1	2

Frame Material

		1	2	3	4
	1	x	0	1	0
	2	1	x	1	0
	3	0	0	x	0
	4	1	1	1	x
total:		2	1	3	0

Table C3 : Weighting Factor Analysis on Top 10 Concepts

Specification	Weighting Factor	Concepts									
		1	2	3	4	5	6	7	8	9	10
Emergency Landing Structural Load Factors		2	3	2	3	2	3	2	3	2	3
rating	0.10	0.20	0.30	0.20	0.30	0.20	0.30	0.20	0.30	0.20	0.30
Emergency Landing Vibrations Transmitted to Occupants		4	4	4	4	3	3	4	4	4	4
rating	0.30	1.20	1.20	1.20	1.20	0.90	0.90	1.20	1.20	1.20	1.20
Reentry Vibrations Transmitted to Occupants		4	4	4	4	3	3	3	3	4	4
rating	0.10	0.40	0.40	0.40	0.40	0.30	0.30	0.30	0.30	0.40	0.40
Weight		3	4	3	4	3	4	3	4	2	3
rating	0.12	0.36	0.48	0.36	0.48	0.36	0.48	0.36	0.48	0.24	0.36
Size		2	3	2	3	2	3	2	3	2	3
rating	0.05	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15
Cost		2	2	2	2	3	3	2	2	3	3
rating	0.08	0.16	0.16	0.16	0.16	0.24	0.24	0.16	0.16	0.24	0.24
Restraining		3	3	2	2	3	3	3	3	3	3
rating	0.05	0.15	0.15	0.10	0.10	0.15	0.15	0.15	0.15	0.15	0.15
Ease of Setup		3	4	3	4	3	4	2	3	3	4
rating	0.10	0.30	0.40	0.30	0.40	0.30	0.40	0.20	0.30	0.30	0.40
Comfort		3	3	2	2	2	2	4	4	3	3
rating	0.10	0.30	0.30	0.20	0.20	0.20	0.20	0.40	0.40	0.30	0.30
Totals:	1.00	3.17	3.54	3.02	3.39	2.75	3.12	3.07	3.44	3.13	3.50

Table C4: Top 10 Combinations

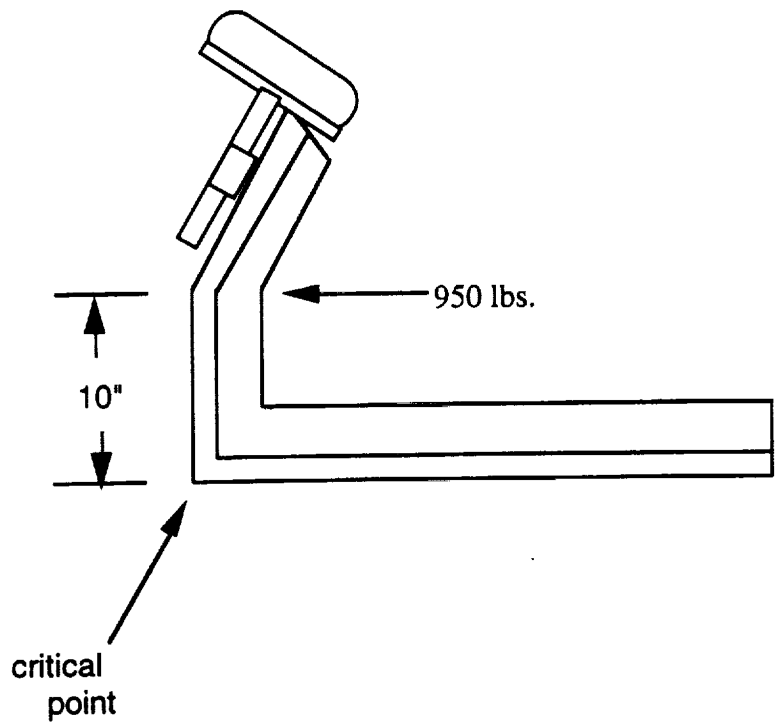
Combination Number	Components
1	Permanent tracks fixed to vibration control plate, 4-point pilot belt, Confor™ foam pads, G-Limiter™, Vibration control plate attached to middeck floor, Composite truss.
2*	Clamps or latches to fix truss to vibration control plate, 4-point pilot belt, Confor™ foam pads, G-Limiter™, Vibration control plate attached to middeck floor, Composite truss.
3	Permanent tracks fixed to vibration control plate, 5-point pilot belt, Confor™ foam pads, G-Limiter™, Vibration control plate attached to middeck floor, Composite truss.
4	Clamps or latches to fix truss to vibration control plate, 5-point pilot belt, Confor™ foam pads, G-Limiter™, Vibration control plate attached to middeck floor, Composite truss.
5	Permanent tracks fixed to vibration control plate, 4-point pilot belt, alternate foam pads, G-Limiter™, Vibration control plate attached to middeck floor, Composite truss.
6	Clamps or latches to fix truss to vibration control plate, 4-point pilot belt, alternate foam pads, G-Limiter™, Vibration control plate attached to middeck floor, Composite truss.
7	Permanent tracks fixed to vibration control plate, 4-point pilot belt, Confor™ foam pads, G-Limiter™, Spring and damper system mounted in the truss, Composite truss.
8	Clamps or latches to fix truss to vibration control plate, 4-point pilot belt, Confor™ foam pads, G-Limiter™, Spring and damper system mounted in the truss, Composite truss.
9	Permanent tracks fixed to vibration control plate, 4-point pilot belt, Confor™ foam pads, G-Limiter™, Vibration control plate attached to middeck floor, Metal truss.
10*	Clamps or latches to fix truss to vibration control plate, 4-point pilot belt, Confor™ foam pads, G-Limiter™, Vibration control plate attached to middeck floor, Metal truss.

* Top combinations from weighting factor analysis.

Appendix D.

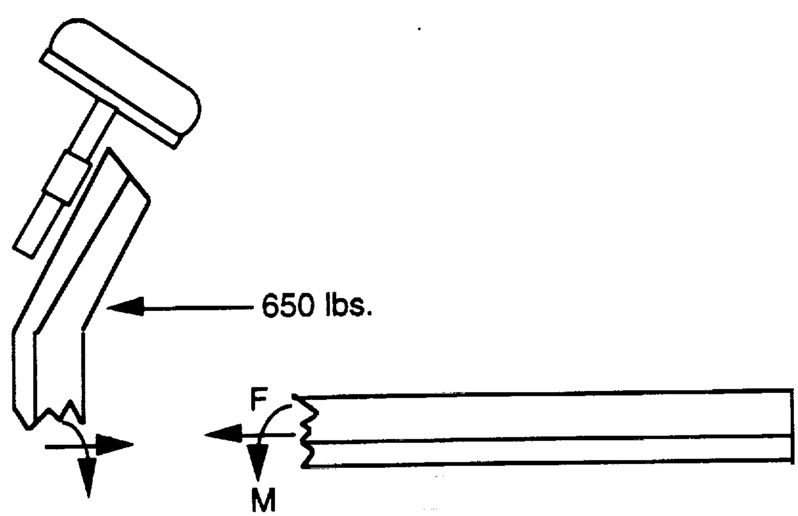
Appendix D.: Specified Calculations

Case 1: Seat Structure Critical Point Analysis



Assumptions:

- worst case couch weight: 180 lbs.
- Total astronaut weight: 950 lbs.
- G-Limiter attenuates accelerations above 5 g's to 5 g's



(continued)...

$$M = (F_{astronaut})(10") + (80lbs)(24") =$$
$$(5g)(950lbs)(10") + (5g)(80lbs)(24") = 57100lb - in$$

$$F = (5g)(950lbs + 80lbs) = 5150lbs$$

: stress at critical point

•Assuming: Back of chair cross-section is 2"x 60.5"

$$\sigma = \frac{MY}{I} + \frac{F}{A}$$
$$I = \frac{bh^3}{12} = \frac{(60.5")(2^3)}{12} = 40.3in^4$$

•Take y=1" for maximum stress at edge of composite.

$$\sigma = \frac{(57100lb - in)(1")}{(40.3in^4)} + \frac{(5150lbs)}{(121)} = 1459.4psi = 10.06MPa$$
$$\sigma_{breakofcomposite} = 500MPa$$

•Suggest rounded corners to reduce stress concentrations w/ breaking stress of 500 MPa. Critical point is well within the safety range.

Case 2: Attachment Bolts for Slider Brackets and G-Limiter

All bolts take a maximum of 10g load in tensile direction.
Tensile stress on bolts:

F = (seat) + (astronauts)
= 180 lbs. + 950 lbs. = 1130 lbs.

•Each point feels 1/8 of the force, so: $\sigma = \frac{F}{8A} = \frac{(1130lbs)(10)}{8\pi r^2}$

Using 2014-0-TF Wrought Aluminum Alloy:

Safety Factor=SF=2 ••$\sigma_u = 62ksi$ and ••$\sigma_y = 42ksi$

••[From Fundamentals of Machine Component Design, p. 634, App. C-10]

(continued)...

$r_{min} = 0.146 in.$ •(3.4 times smaller than 1/2" bolts)

Aluminum Alloy - 2014

tensile stress: (5 g's) $21ksi = \frac{P}{BA} = same$

- •Need 8, 1/2" bolts to connect brackets to the back of the seat.
- •Minimum diameter of 1/4" bolts to withstand 10g loading.

Volume Calculations for Aluminum Base

Pieces of Aluminum:

# pieces	Dimensions (inches)	Volume (in.^{3})
2	62 x 1.5 x 0.5	93.0
2	7 x 1.5 x 0.5	10.5
4	45 x 1.5 x 0.5	135.0
	Total Volume =	238.5

The 62" pieces connect seat to points 1-8, 11 & 12.
The 7" pieces are welded to the 62" pieces to connect points 9 & 10 to system.
Two of the 45" pieces are permanently connected to the composite seat structure.
The other to are connected to the base structure described above.

Weight of Aluminum components:

$m = \rho_{Al} V_{total}$

$m = (2800 kg/m^3)(3.89e\text{-}3 m^3) = 10.9$ kg

$W_{Al} = 106.9$ Newtons = 24 pounds

(continued)...

Stress Analysis of Floor Connection Bolts

There are 12 floor connection bolts. Eight of the bolts will carry tensile stress loads. All 12 bolts will carry shear loads (see specifications). The floor connection bolts will carry the entire weight of the seat plus the occupants under crash conditions.

For 1/2" bolts:

$$A_{cross\ section} = 0.196\ in^2$$

(continued)...Stress Loads in Floor Bolts

Shear:

The maximum acceleration causing shear in the floor bolts will be 5 g's (see G-limiter discussion). Assuming all bolts carry the same load, the maximum shear will be:

$$\tau_{max} = \frac{(1130 lbf)(5g's)}{12(0.196 in^2)} = 2.4 ksi$$

where the worst case weight of the seat and astronauts is:

$$W_{seat,astronauts} = 1130\ lbf$$

The S_y of the 2014 aluminum alloy is 14.0 ksi. The maximum shear stress is at an acceptable level.

Tension:

The maximum acceleration causing tension or compression in the floor bolts will be 10 g's. Again, assuming 8 bolts carry the load evenly:

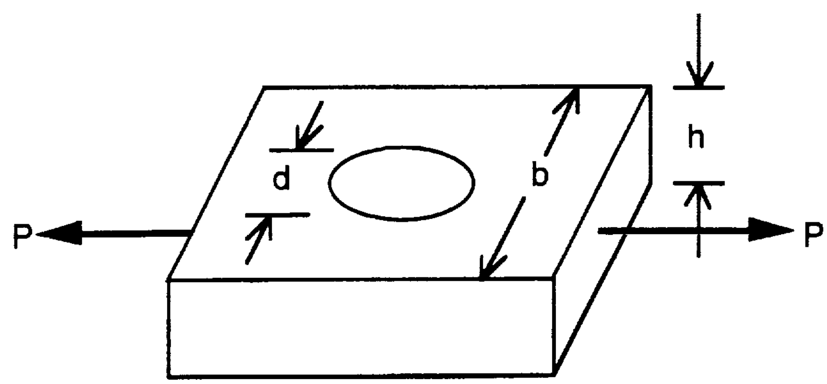
$$\sigma_{max} = \frac{(1130 lbf)(10g's)}{8(0.196 in^2)} = 7.2 ksi$$

This value also gives a maximum tensile stress within the yield stress of the aluminum alloy.

(continued)...

Stress Analysis of Holes in Aluminum Truss

The following analysis assumes that all holes carry the same load.
P_{total} = 5 g's(1130 lbs) = 5650 lbs
P_{each} = 5650 lbs/12 bolts = 470 lbs



The above diagram corresponds to the stress calculation for holes in a member under tensile stress.

$$\sigma = \frac{P}{A} = \frac{P}{(b-d)h} = \frac{470\text{lbf}}{(1.5-0.5\text{in.})(0.5\text{in.})} = 940\text{psi}$$

The stress that occurs at each hole during an emergency landing does not exceed the critical stress given a safety factor of 2.

Volumes and Weights of Design Components

Calculation of weight of design without frame and floor attachments.

Volume (foam pads) = (3")(60.5")(45"+7"+1")+(22")(1.5")(60.5")
Volume (composite) = (2")(60.5")(63")+(1")(60.5")(22")=8954in^3
Volume of Aluminum alloy parts=(3.14)(1")^2(28")(2)

corner=44 in^3
leg move bar=(22 in^3)(3)=66 in^3
positioning bar=(8.5 in^3)(3)=25.5 in^3
leg bar brace=(12 in^3)(3)=36 in^3

$=(1.5'')(0.5'')(45'')(2)=33.75\,in^3$

Total volume of Al=205.25 in^3=0.00336 m^3
Total volume of foam=13431 in^3=0.22009 m^3
T.tal volume of Composite=8954 in^3=0.14673 m^3

$$\rho_{foam} = 102.4\frac{kg}{m^3} = 102.4\frac{kg}{m^3} \qquad \rho_{comp} = 520\frac{g}{m^3} = 0.520\frac{kg}{m^3}$$

$$\rho_{Al} = 2.8\frac{g}{m^3} = 2800\frac{kg}{m^3}$$

Maximum weight=180 lbf = 4.4482 N/lbf = 800.676 N

Mass of foam = (0.22009)(102.4) = 22.537 kg
Mass of Composite = (0.14673)(0.520) = 0.0763 kg
Mass of Al-alloy = (0.00336)(2800) = 9.408 kg

Total Weight - (G-Limiter) - (Velcro) -(4-point belts) = 314.129 N

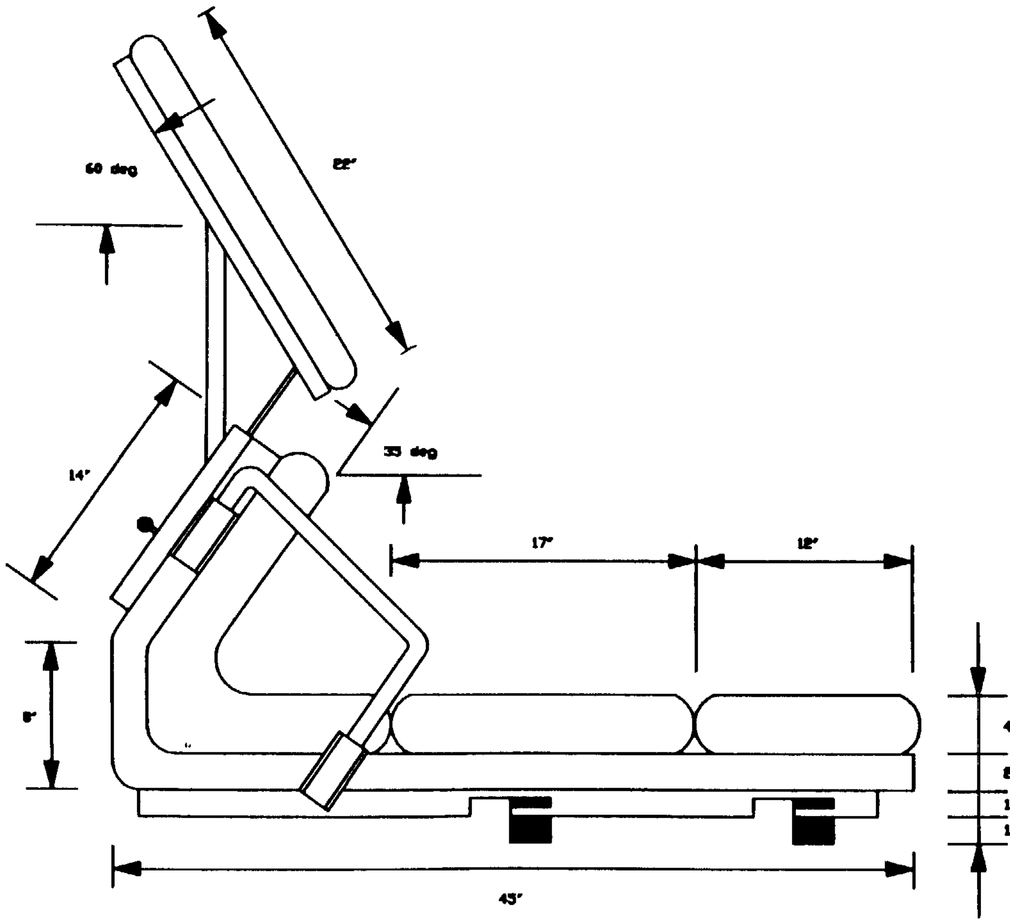
• Assume: weight of G-Limiter = 2 lbf
(3) 4-point pilot belts & Velcro straps = 3 lbf
total = 5 lbf = 22.24 N

$$W_{seat} = 314.129N \qquad W_{attach} = 22.241N \qquad W_{Al} = 106.9N$$

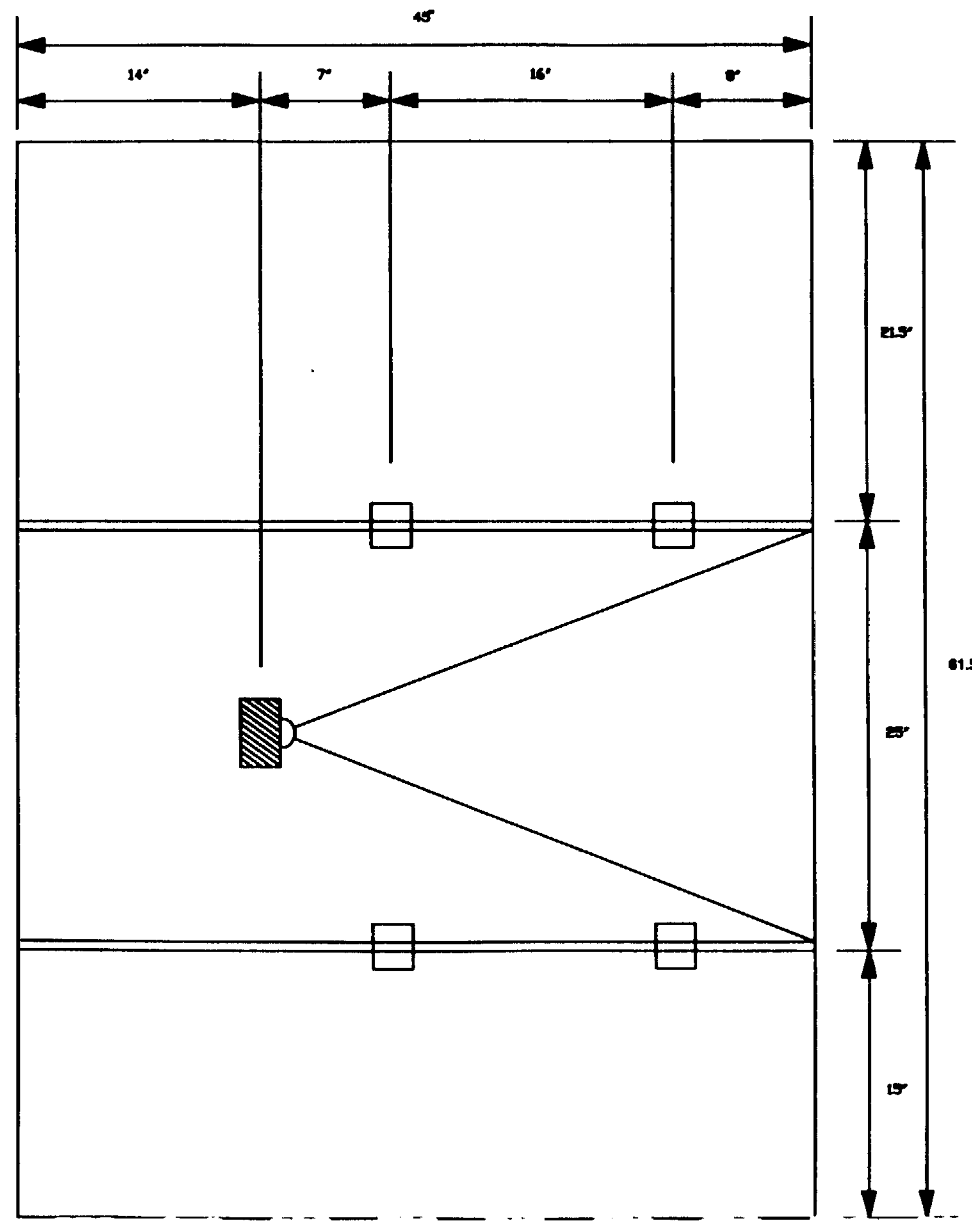
Total weight = 443.27 N

Appendix E.

RSS SIDE VIEW



RSS REAR VIEW



E1

Floor Trusses