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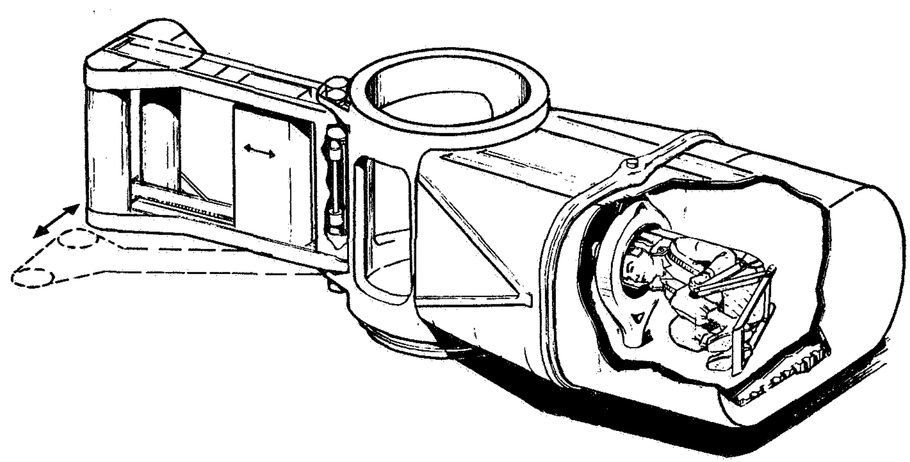

Final Report

THE ORBITAL RESEARCH CENTRIFUGE: CONTINUED DESIGN AND FEASIBILITY STUDY

GENERAL DYNAMICS
Convair Division

8 July 1969

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Final Report

THE ORBITAL RESEARCH CENTRIFUGE: CONTINUED DESIGN AND FEASIBILITY STUDY

Prepared under Contract NAS 1-8751

by

CONVAIR DIVISION OF GENERAL DYNAMICS

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER

ACKNOWLEDGMENTS

This report has been prepared under the cognizance of Mr. H. George Hausch, NASA LRC Technical Monitor for Contract NAS 1-8751. Work was performed under the direction of Mr. J. E. Stumm, Convair Study Project Manager. Major contributors to the work include Mr. R. W. Saunders in the areas of experiment equipment and mechanisms design and Mr. R. C. Mc Namara who was responsible for structural concept development.

Security classification approved per requirements of Paragraph 10, DOD 5520.22-M.

J. E. Stumm
Project Manager
Centrifuge Study

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SYMBOLS

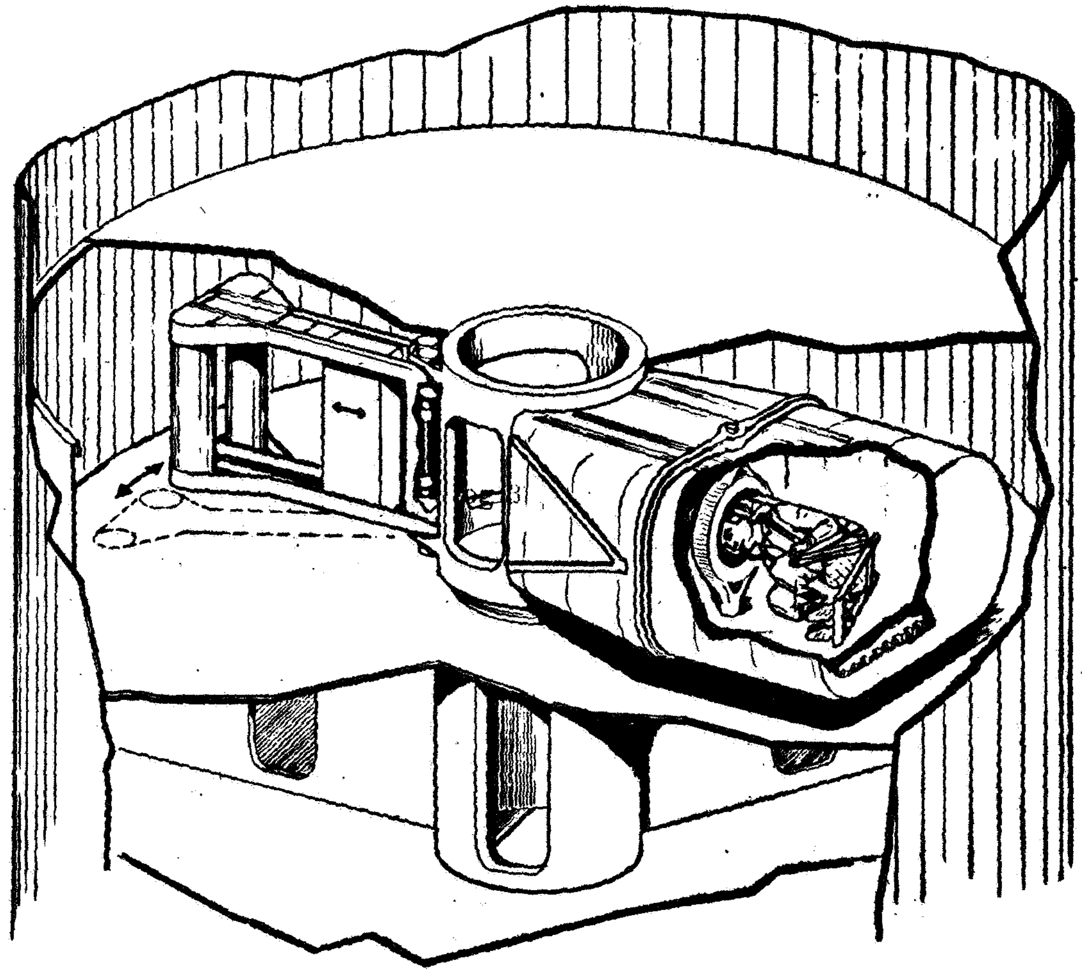
Symbols			Units
A	-	Area	ft^2
A	-	Amplitude	
C	-	Fixity coefficient	
C_d	-	Drag coefficient	
CP	-	Circular pitch	
CG	-	Center of gravity	
DP	-	Diametral pitch	
E	-	Modulus of elasticity	lbs/in^2
F	-	Force	lbs
F_c	-	Euler column stress	lbs/in^2
H_A	-	Momentum of the atmosphere	ft-lbs-sec
H_Z	-	Hertz	cps
I	-	Moment of inertia	in^4
I_o	-	Mass moment of inertia	$lbs\text{-}ft^2$
K	-	Buckling coefficient or Spring rate	 ft-lbs/rad
L	-	Length	ft
M	-	Bending moment	in-lbs
M_o	-	Momentum	ft-lbs-sec
N	-	Rotational speed	RPM
N_R	-	Reynolds number	
P	-	Axial load	lbs
PD	-	Pitch diameter	in
S	-	Allowable tensile stress	lbs/in^2

SYMBOLS (CONTINUED)

Symbols			Units
T	-	Torque,	lbs-in
X	-	Spin axis direction	
Y	-	Lateral direction	
$\bar{Y}$	-	Distance to neutral axis	in
Z	-	Spin plane direction	
f_n	-	Natural frequency	cps
g	-	Load, gravities	32.2 ft/sec^2
q	-	Dynamic pressure	lbs/ft^2
r	-	Radius	ft
t	-	Material thickness	in
v	-	Velocity	ft/sec
w	-	Material density	lbs/in^3
α	-	Angular acceleration	rads/sec^2
μ	-	Poisson's ratio	
ω	-	Angular velocity	rad/sec
λ	-	Continuity factor	
ρ	-	Radius of gyration or mass density	in lbs/ft^3
σ_c	-	Applied compression stress	lbs/in^2
σ_{cc}	-	Allowable crippling stress	lbs/in^2
σ_t	-	Applied tensile stress	lbs/in^2
η	-	Efficient factor	
δ	-	Static deflection	in

ABBREVIATIONS

CMG	-	Control moment gyro
cps	-	Cycles per second
DC	-	Direct current
ECLS	-	Environment control and life support
HP	-	Horse power
KW	-	Kilowatt
MOM	-	Missions operations module
MORL	-	Manned orbital research laboratory
NOM	-	Nominal
RM	-	Restricted mobility
RPM	-	Revolutions per minute
R_S	-	Replications
SRC	-	Space research centrifuge
S_S	-	Subjects
UM	-	Unrestricted mobility



Orbital Research Centrifuge facility concept.

SUMMARY

The Orbital Research Centrifuge

The centrifuge has had a long history as a versatile and familiar article of laboratory test equipment, its unique advantage being that it can alter the inertial force acting on a body (increasing it from the normal one-g background) by superimposing an easily controlled and sustainable linear acceleration on the body. Also, the angular velocity and acceleration environments which it can provide are in themselves, useful stimuli. In its usual laboratory application as a test devise, the centrifuge serves as a means of altering these conditions so that the reaction of a test article (or human subject) to the induced environment can be observed and measured. In this way, certain properties, functional capability and performance can be assessed. Comparable applications of laboratory equipment for this purpose are typical in many areas of scientific inquiry, for example, in the use of tensile testers in determining material properties or bombardment devices in particle physics.

Considering that one of the goals of the space program is the exploitation of the orbital environment for scientific and experimental purposes, it is reasonable to assume that the centrifuge will have equal if not greater utility as an experiment support device in space than it has in ground based laboratories. This is based on the primary observation that, in orbit, the inertial background is again a static reference (zero-g) or possibly an artifically induced condition resulting from spacecraft rotation. Use of the centrifuge in space can increase our base of information as to the effects of both of these situations on physiological as well as physical phenomena. In this study, as in several previous studies (NAS 1-7309 and 8548), these assumptions have been validated by identification of specific experiments, priority selection and preliminary design of experiment procedures, detail definition of the centrifuge and its systems and feasibility studies of the orbital centrifuge concept.

Study Objectives

In the preceding study, NAS 1-7309,an orbital centrifuge design was evolved which was based on a fixed series of experiments which were concerned mainly with measuring human cardiovascular and vestibular responses during centrifugation and the effects of extended zero-g exposure on these systems. This study has as its objective the improvement of the previous centrifuge design in the areas of greater flexibility for physical installation and of increased experimental capability. The installability of the device is improved by the addition of a passageway of up to 42 inches in diameter through the center of the machine to allow transfer of personnel through this area during centrifuge operation. Centrifuge height is also minimized

in order to reduce the spacecraft volume occupied by the machine. The experimental capability of the centrifuge is increased by the addition of a number of experiments which utilize the inertial support potential of the device. These include tests of walking and mobility, personal hygiene (shower and waste collection) and the performance of bench tasks such as maintenance and repair.

Experiment Program

The centrifuge configuration evolved in this study was designed to support a specific list of orbital experiments which are considered of highest priority in expanding our base of knowledge with regard to 1) The physiological effects of long exposure to zero-g; 2) Physiological considerations for operations in a rotating environment in space (Rotating space-base design criteria); 3) Operational support capability of the short radius internal centrifuge in space and 4) Purely scientific investigation of human physiology. A list of these experiments is as follows:

1) Determination of Grayout Thresholds.
2) Evaluation of the therapeutic potential of centrifugation.
3) Determination of angular acceleration thresholds.
4) Tilt-table experiments (cardiovascular response).
5) Measurement of the effects of coupled angular velocities.
6) Determination of g-sensitivity in the pitch and roll axis (referenced to the human subject).
7) Simulation of re-entry g-profiles.
8) Mass measurement by centrifugation.
9) Evaluation of centrifugation for inertial support in walking and mobility.
10) Evaluation of centrifugation for inertial support in personal hygiene functions such as showering and waste collection.
11) Evaluation of centrifugation for inertial support in performing bench tasks such as inspection, repairs, instrumentation or component assembly, etc.

These experiments were used to establish the physical characteristics of the centrifuge, the range of rotational velocity, acceleration, control requirements, positioning capability and other features. It is by no means a complete list of experimental capability. In configuring the centrifuge, consideration has been given to other areas of application so that additional investigations may be introduced without major modifications of the machine. These may include:

1) Study of habituation to the short radius rotational environment.

2) Performance of experiments with g-sensitive physical phenomena such as flame propagation, particle migration and convection.

3) Emergency use as a hospital bed area for patient rest or minor surgery.

4) Qualification of components for use in rotating space stations.

5) Bath separation, settling or filtration of fluid/solid mixtures in support of other experiments.

6) Providing one-g control environment for biophysics experiment specimens.

7) Calibration of instrumentation.

8) Study of transition between zero-g/artificial-g areas of rotating stations.

9) Provision of a variable g-environment and instrumentation to increase the scope of additional physiological studies (pulmonary physiology is a candidate area).

Centrifuge Description

General Arrangement. - The principal features of the centrifuge are the experiment chamber, the hub, and the counterbalance assembly.

The experiment chamber is a room-like enclosure which houses all experiment activity. It is designed as a continuous shell and contains a walking floor and attachment fixtures for the orientation and support of experiment equipment.

The hub assembly serves as the interface connection between the experiment chamber, the counterbalance equipment and the spacecraft. The hub consists essentially of two ring structures connected by three equally spaced posts or columns, one of which is in line with the counterbalance assembly attachment and the other two aligned with the hub/chamber wall intersection. Openings between the posts provide access from within the hub into the experiment chamber and the centrifuge installation chamber. Interface with the spacecraft is accomplished by providing a bearing (roller support system) and motor drive at one end of the hub. It is assumed that the center passageway will incorporate a stationary cylindrical sleeve, with appropriate access openings and doors, to permit traffic through the hub during centrifuge operation without exposure to rotating equipment. The hub also serves as a mounting structure for the main drive inverter, controls and additional batteries.

Installation. - The design of the centrifuge is based on the application to a space vehicle having a 240 inch cylindrical outer shell and a 42 inch clear passageway through the center of the vehicle. Centrifuge chamber height should be approximately 65 inches to allow sufficient clearance for the rotating assembly. The bulkhead utilized for attachment of the roller support system must be sufficiently rigid to provide a high natural frequency for the total assembly. In addition, a control station for centrifuge operation must be provided in the near vicinity with easy access between the control station and the experiment chamber. Connections for battery charging and water system servicing must also be made available.

Centrifuge Characteristics. - The maximum radial dimension of the centrifuge is 112.0 inches (to the bottom of the walking floor). The outside width of the experiment chamber is 54.0 inches which with allowances for structure, provides a chamber floor width of 4.0 feet. The length of the walking floor is approximately 7.5 ft.

The maximum weight and moment of inertia of the rotating assembly during operation are 1207 lbs and 1475 ft-lb-sec respectively, and the maximum momentum generated during experimentation (Re-entry) is 7225 ft-lb-sec. Maximum experimental capability required of the machine is 6.5 g and corresponds to a maximum angular velocity of 4.9 rad/sec. Total facility equipment weight, including control station, counter momentum CMG's and other stationary support systems is approximately 1720 lbs at the time of launch.

Major Subsystems. - The major centrifuge subsystems characteristics are described briefly as follows:

1) Structure: Aluminum alloy sheet metal and machined fitting built-up assemblies are recommended for general centrifuge structure with the exception of the experiment chamber. The experiment chamber is designed as an integrally stiffened shell fabricated as a lay-up of graphite - epoxy composite.

2) Primary Drive: Primary rotation is provided by a voltage/frequency controlled 3.5 HP AC motor mounted on the rotating assembly at the hub drive ring. It contains an integral gear reduction and is balanced against an inverter installed on the opposite side of the hub.

3) Power: Power for all centrifuge functions is supplied by rechargeable batteries which are integrated with the counterweight.

4) Communications: All communication with the centrifuge rotating assembly is accomplished by RF link.

5) Imbalance Sensing: Imbalance sensing is accomplished through a network of three force sensor pairs, mounted between the drive ring and the centrifuge hub structure. The sensor pairs are spaced at intervals of 120° and are aligned with the hub structural posts.

6) Counterbalance: Counterbalance of the centrifuge is accomplished by automatic positioning of the counterweight (approximately 200 lbs) in response to imbalance forces and torques computed from the sensor network signals. The counterweight is positioned by rotation of the counterweight swing frame through a range of ± 30° from center, linear translation of the counterweight carriage within the swing frame of 44 inches maximum and axial translation of the counterweight within the carriage of ± 14 inches from center. This motion envelope allows full static and dynamic balancing of the machine. Dual motor/gear drive units for swing and radial counterweight motion are located at the top and bottom pivot collars on the swing frame. The axial drive unit is an integral part of the counterweight.

7) Countermomentum: Dual-single degree of freedom Control Moment Gyros are required to absorb the spin-up momentum of the centrifuge. Based on a maximum momentum requirement of 7225 ft-lb-sec. and an initial momentum vector angle of 30°, each gyro must be sized for 2100 ft-lb-sec. Using current vendor data for single degree of freedom CMG's of this capacity, a weight estimate of 250 lbs per unit is considered conservative at this time.

8) Water: A water system for the hygiene experiments is integrated into the centrifuge. Water storage and collection tanks with a capacity of 10 gallons are located at the outboard end of the counterweight swing frame. The system provides water on demand by pressure expulsion of fluid from the supply tanks.

9) Experiment Equipment: Experiment equipment is provided in discrete packages which are tailored to the specific research being performed. The major packages are the couch, the hygiene package, the workbench package and the instrument package.

Conclusions

From the results of this study, it is concluded that the incorporation of a passageway of up to 42 inches in diameter through the hub of the centrifuge is a fully feasible and desirable feature. It is further recommended that such a configuration be maintained even if not required by spacecraft traffic pattern or arrangement. This is based on the following observations:

1) The stiffness requirement of the imbalance sensors is reduced by locating them at a larger radius than that of the center passage suggested.

2) Eliminating the center passageway would not reduce the recommended bearing track diameter significantly because of the natural frequency requirements of the total assembly.

3) The center passageway provides excellent access to the experiment and centrifuge chambers at a minimum weight penalty.

The feasibility of using the centrifuge for the evaluation of walking, balancing and coordinating in various g-environments; for evaluation of the benefit of inertial support to performance of personal care functions; and as a workshop and laboratory has also been established with confidence. These and other experimental applications can best be implemented with the "room" or experiment chamber concept and the use of individualized experiment equipment packages. Such a configuration is readily adaptable to any of the current module or space station concepts including the MORL or dry S-IVB workshop. The basic centrifuge design can also be adapted to a larger radius configuration. In addition, the configuration has excellent characteristics for adaptation to new or changing experiment requirements.

Recommendations

In view of the close correspondence of the detail requirements of centrifuge design with the demands of the experiments, the establishment of a firm and well defined experiment program is recommended as the next step in the orderly development of the centrifuge facility. A progressive plan for attainment of this objective is outlined as follows:

1) Establish a project organization to serve as the coordinating link between NASA and the scientific users. This organization should establish experiment development priorities based on the importance of the experiment data in supporting the evolution of NASA space

programs, the impact of the experiment requirements on the design of the centrifuge and the scientific value of the resulting work.

2) Designate principle scientific investigators in the areas of highest priority and proceed with firm experiment design.

3) Maintain and coordinate the flow of information between current NASA programs (space base, experiment module, logistics vehicle, etc.), continued centrifuge design studies and the experiment development program.

4) Proceed with selective design and bread-board of critical centrifuge subsystems (Counterbalance System) and support experiment development with design and mockup work.

As this program matures and NASA overall objectives become firm, definition of a ground based engineering development prototype of the centrifuge may be phased into the work. Design, fabrication and test of such equipment leads directly to orbital hardware design and may be paced by overall NASA schedules.

INTRODUCTION

Program Objectives

The requirements of this study developed from a review of design and analysis performed under contract NAS 1-7309 which examined the feasibility of placing a research centrifuge in orbit to allow performance of a series of experiments in human physiology. From evaluation of this work it was recognized that the design of such a device is highly sensitive to 1), the demands of the experiment and 2), the requirements of the spacecraft or orbital complex into which the centrifuge is introduced. Initially, work was concentrated on rearrangement of the centrifuge to increase its compatibility with existing spacecraft concepts, particularly the MORL and the Dry Launched S-IVB Workshop. Later, additional experimental capability and flexibility were introduced.

In the previous centrifuge design, the machine was suspended from a single central bearing which attached to the hub structure at one side. Positioning mechanisms were employed which included the capability of placing the test subjects head at the axis of rotation. Such an arrangement was not fully compatible with the popular concept of using the central core of the spacecraft as a passageway for personnel transfer and for installation of plumbing, power and communications lines. As a result, the installation of the centrifuge was generally restricted to "end locations" in the spacecraft concepts where it must compete for space with docking facilities, telescopes and other instrumentation which utilize such locations to their advantage. In order to increase the options for installation of the centrifuge in the various spacecraft concepts, this study undertakes a redesign of the device to allow a passageway of up to 42 inches diameter to be incorporated in the hub. In addition, the alternatives of placing the test subjects head at the center of spin during some experiment sequences, or supplying alternate methods of inducing this condition is examined.

The original series of experiments which were used as a driving requirement for the previous centrifuge design (see reference 3) were concerned mainly with human cardiovascular and vestibular physiological measurements. An additional objective of this study involved broadening the experiment base so that advantage could be taken of the equipment as a general laboratory tool, with sufficient adaptability for the inclusion of new experiments or modification of existing protocols. The major modifications include the addition of a floor or walking area for mobility studies, a hygiene facility and water supply, and a workbench for the evaluation of inertial support in the performance of repair, inspection, test and other bench tasks. The inclusion of these capabilities produces a facility which may be further adapted to studies of habituation to rotation and experiments involving physical phenomena which are g dependent.

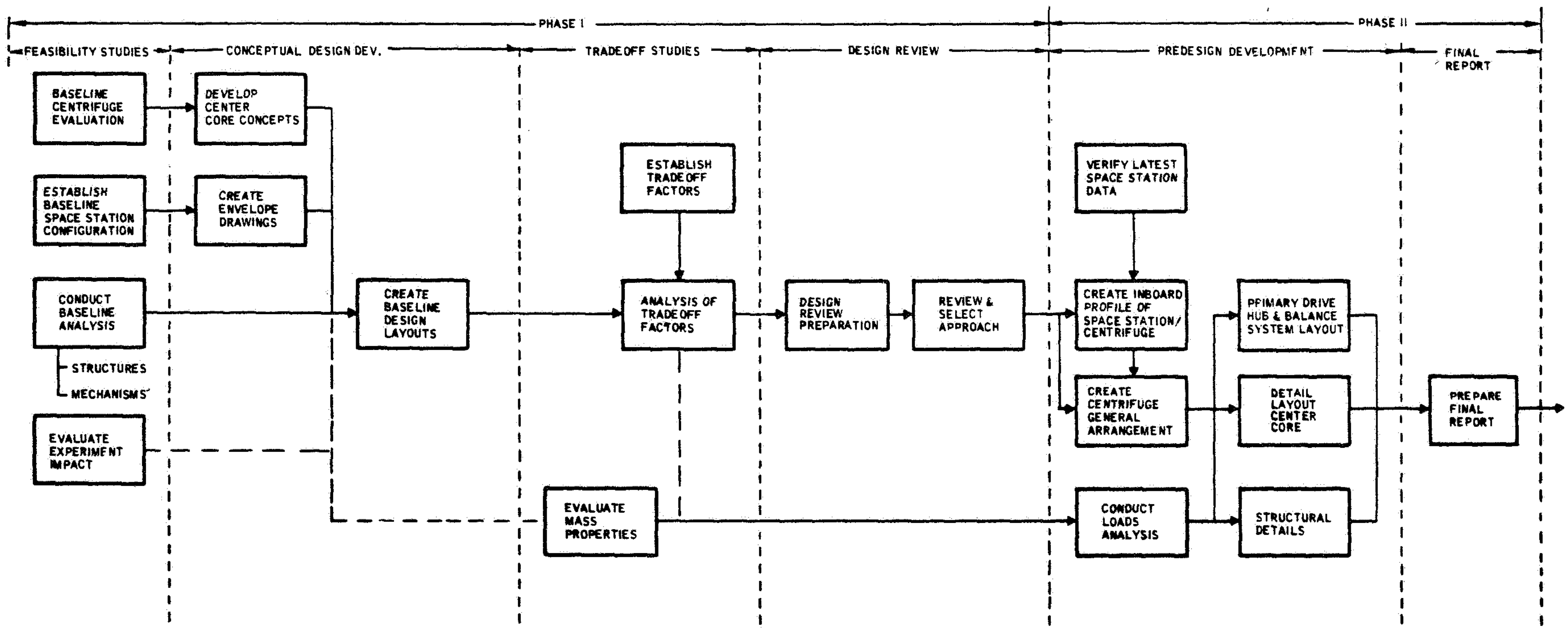


Figure 1. Study Task Flow Diagram

Study Approach

The study was accomplished in two sequential phases as is shown by the task flow diagram in Figure 1. Phase I included such preliminary tasks as a general review of the impact of the center passageway on centrifuge feasibility, conceptual design layout and trade-off studies. (Ref. App.-B) These tasks were directed toward defining a new centrifuge baseline configuration which was selected during the mid-term design review. The baseline was selected to minimize weight and inertia, and to offer the least compromise to experimental capability and operational safety. Vehicle interface and space requirements (particularly centrifuge height) were kept to a minimum. Centrifuge structures and mechanisms were selected on the basis of safety, reliability, performance maintainability and weight. In the case of the structural approach, high stiffness was the main additional consideration. In the second phase of the study, the selected baseline centrifuge concept was given a detailed predesign definition. Emphasis in this predesign work was placed on systems which changed dramatically from previous concepts or were new to the configuration. New systems include the "package" concept for experiment support equipment such as the hygiene experiment, and the water system. Considerable detail has been provided in defining realistic structural systems and in working out the structural/mechanical systems integration necessary for test subject positioning and counterweight manipulation. In addition, the implementation of the imbalance sensing and control system have been specified in greater detail.

In the following sections, the evolution and final description of the baseline centrifuge is developed to a level of detail which provides confidence in the feasibility of the machine and realism to the weight, inertia, power and interface requirements specified.

Expanded Capability Centrifuge Facility

With the introduction of the additional experiment requirements for mobility, inertial support workbench and personal hygiene, several attempts were made to modify previous designs by adding walking platforms, integrating hygiene facilities into the experiment couch and otherwise adapting these approaches to the new experiments. It soon became evident that salvage of these designs was impractical and that a completely fresh evaluation should be made of the centrifuge facility. Accordingly, a new design was postulated which would accommodate the full range of experimental capability. The characteristics of this new design were depicted as shown by

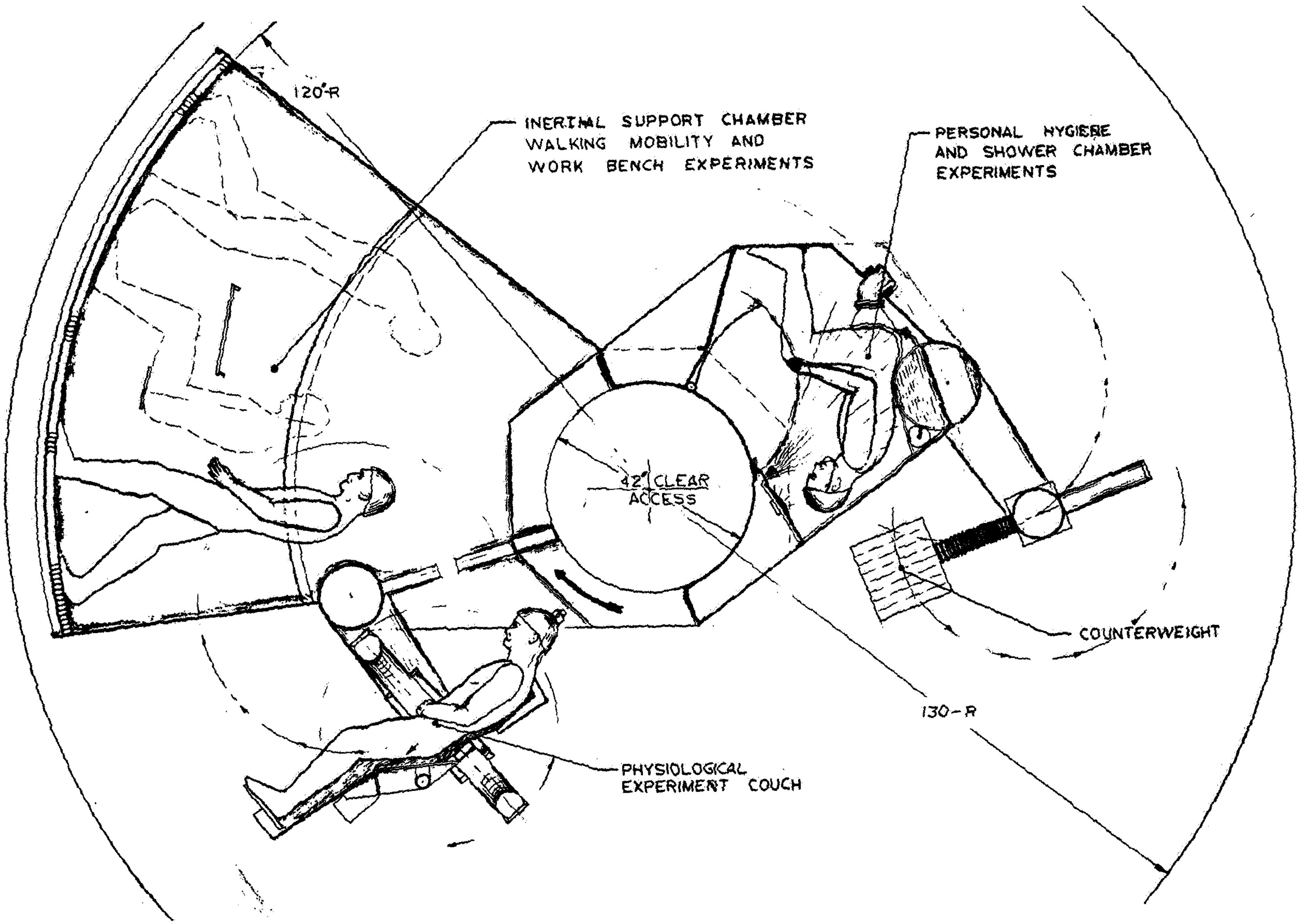


Figure 2 - Centrifuge Facility Concept With Expanded Capability for Inertial Support and Hygiene Experiments

figure 2, which served as a point of departure from earlier design concepts. Several attempts were then made to implement this approach which culminated in detail study of two competing designs which are designated Concepts 1A and 2A.

Concept 1A. - The approach taken here utilized a cone shaped shell to enclose all experiment activity as illustrated by figure 3. This shell, or room, was balanced across the hub and center passageway by a swinging frame which contained the counterweight. Counterweight motion within the swinging frame was assumed in both the radial and axial directions. The concept of removable packages of experimental equipment was specified for all experiments except the shower and waste collection experiments. This equipment was contained in a shallow circular well beneath the walking floor. Access to the experiment room was achieved through an opening into the hub area and doors were provided in the sides of the room to allow passage into the centrifuge chamber. An eight-pair force sensing network with bearings at both interfacing bulkheads was evaluated for the suspension system. A weight breakdown of the major elements of this concept is contained in table 1.

Concept 2A. - The arrangement examined in Concept 2A is illustrated by figure 4. Again, a room like enclosure is utilized as the main area of experimentation. In this case, however, the shower and hygiene facilities are located in a special enclosure on the opposite side of the hub from the main room. Counterbalance is also effected by a combined swing, radial and axial motion of the counterweight. For the 2A version, however, the counterweight swing pivot axis is shifted further outboard from the centrifuge spin axis and is driven through a sectioned spur gear. The hub structural approach is quite different from the 1A concept, and consists of rings at both ends of the hub separated by four posts which transmit loads between the rings. Openings to the experiment chamber, centrifuge chamber and hygiene experiment chamber are provided through the hub wall. A weight breakdown for the rotating mass of this concept is contained in table 2.

Selection of Baseline Configuration

From the detail analysis of Concepts 1A and 2A, characteristics of an optimum design concept were deduced. These characteristics are discussed in the following section and were incorporated into the baseline design of the centrifuge.

Experiment Equipment. - The package concept for experiment support equipment and instrumentation appears to be the most flexible approach to follow. Less compromise is offered to individual experiments and greater growth capability is provided if the experiment support equipment is tailored to specific rather than general requirements. The package concept also provides some experiment development scheduling advantages in as much as all experiment packages need not be available at the initial launch of the basic centrifuge facility. Such equipment could be orbited by subsequent resupply flights. From the analysis of Concepts 1A and 2A

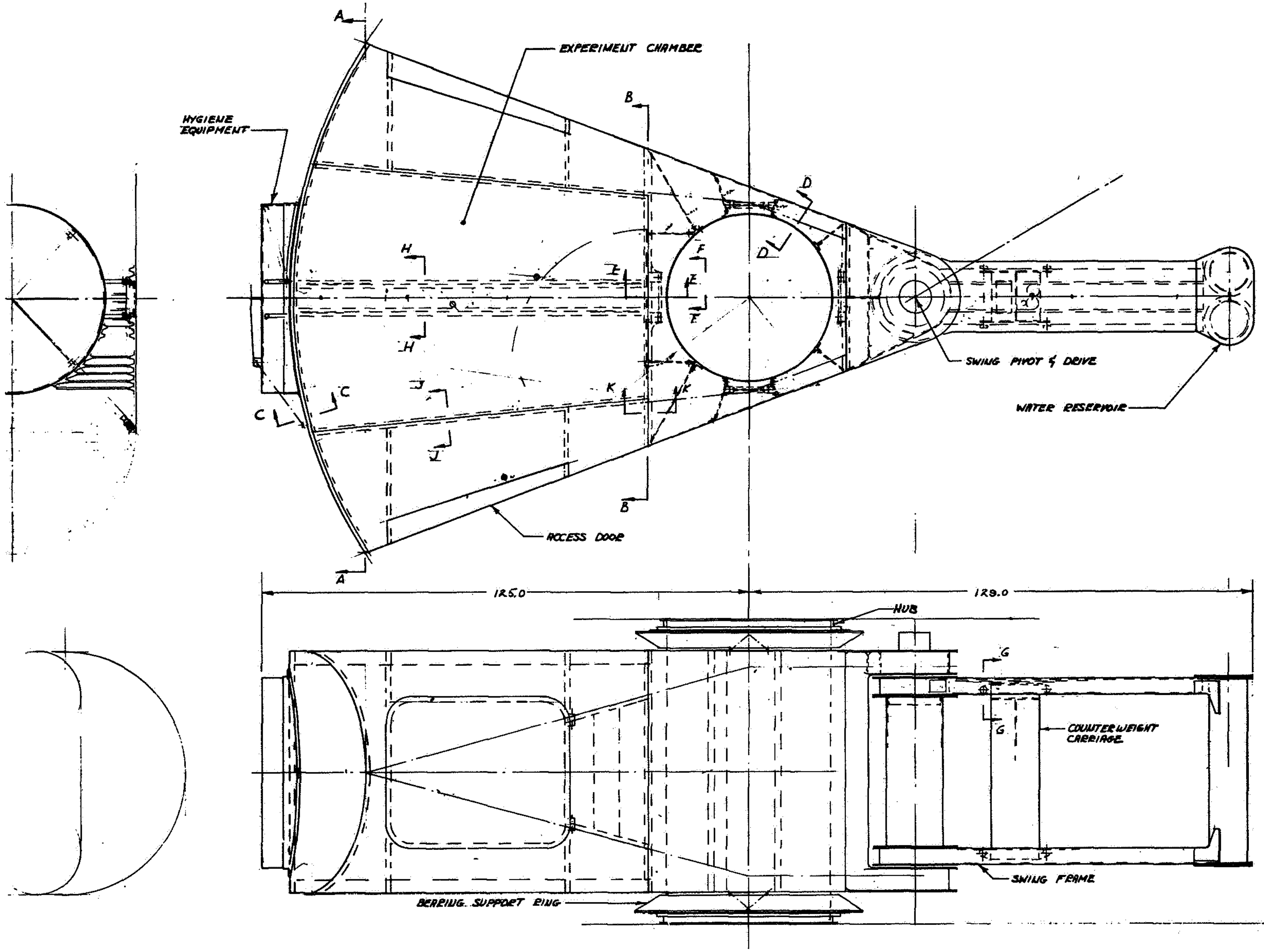


Figure 3a. -Centrifuge Structural Arrangement - Concept No. 1A

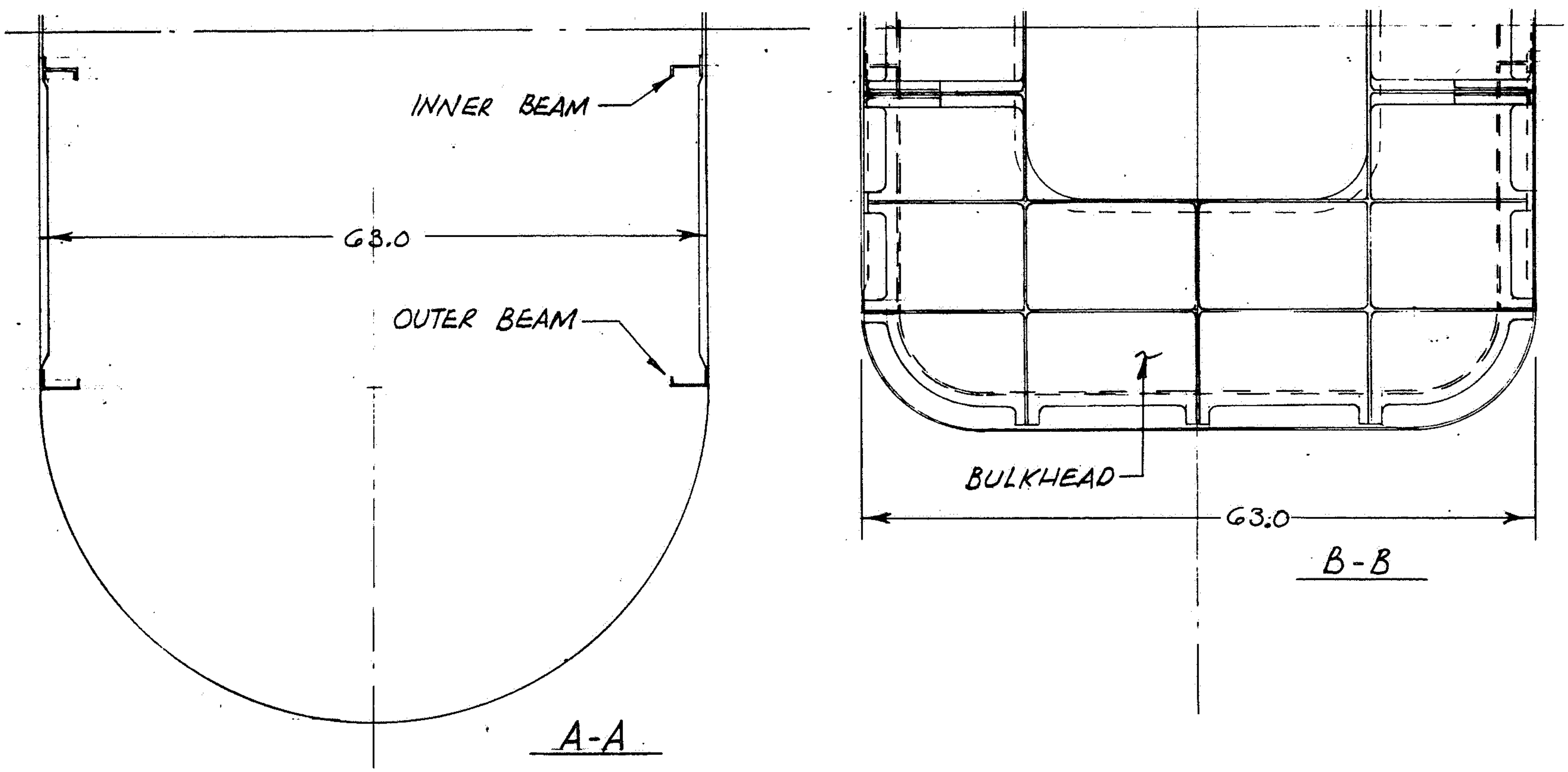


Figure 3b. - Centrifuge Structural Arrangement - Concept No. 1A

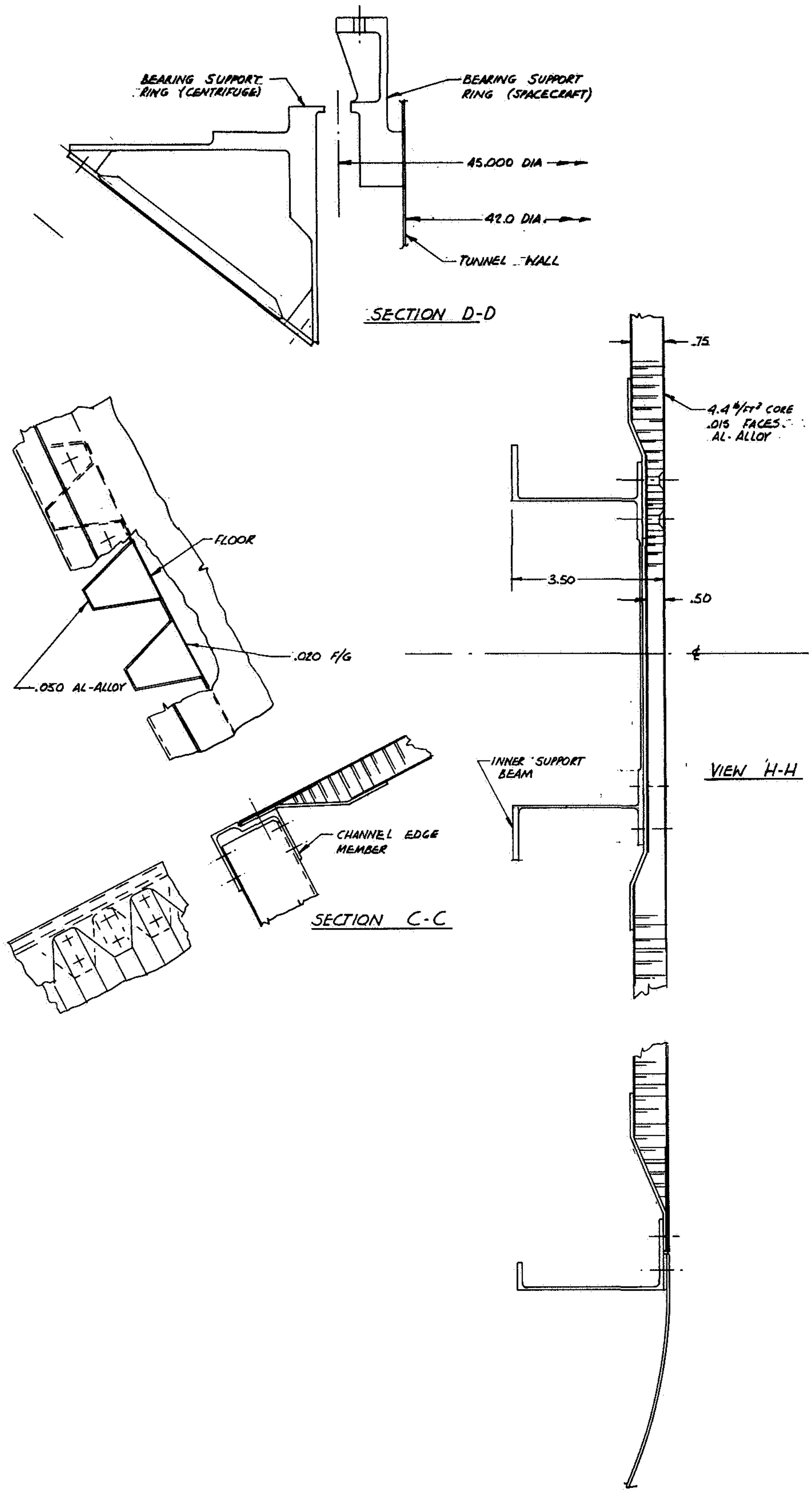


Figure 3c. - Centrifuge Structural Arrangement - Concept No. 1A

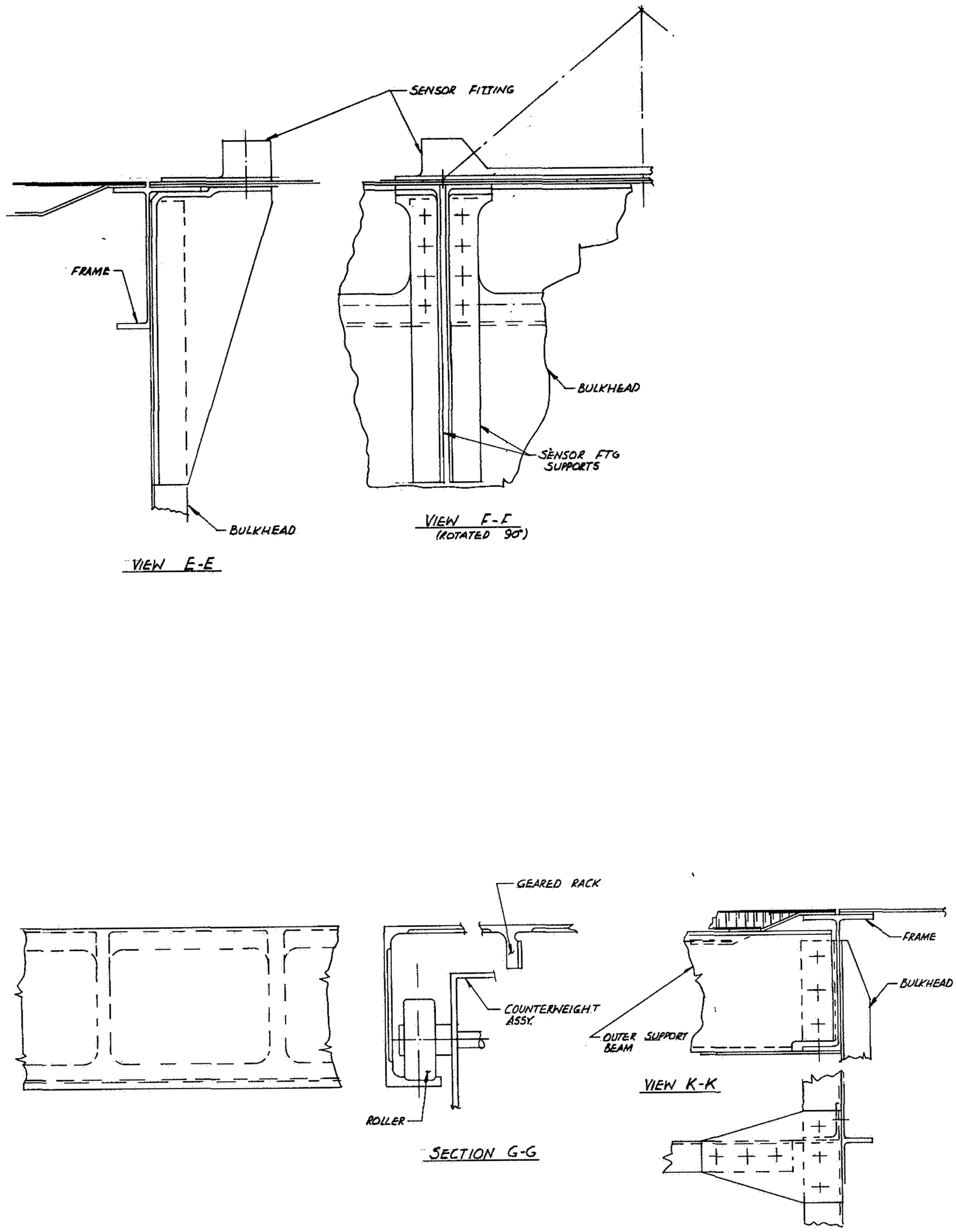


Figure 3d. Centrifuge Structural Arrangement - Concept No. 1A

Table 1. Weight Summary, Concept 1A Rotating Mass

Item		Weight (Lbs)
Floor (Includes Hygiene Compartment)		113.6
Room		165.6
Hub Structure		285.1
Counterweight Support Fitting		30.0
Counterweight Arm		68.4
Counterweight Structure		20.4
Counterweight		320.0
Water		150.0
Main Drive Motor		20.0
Couch		60.0
Couch Frame		55.0
Man		200.0
Force Sensors		20.0
Power Conditioning and Communication		120.0
Roll Ring		80.0
	Total	1707.1

Maximum Moment of Inertia, 3020 ft-lb-sec^2

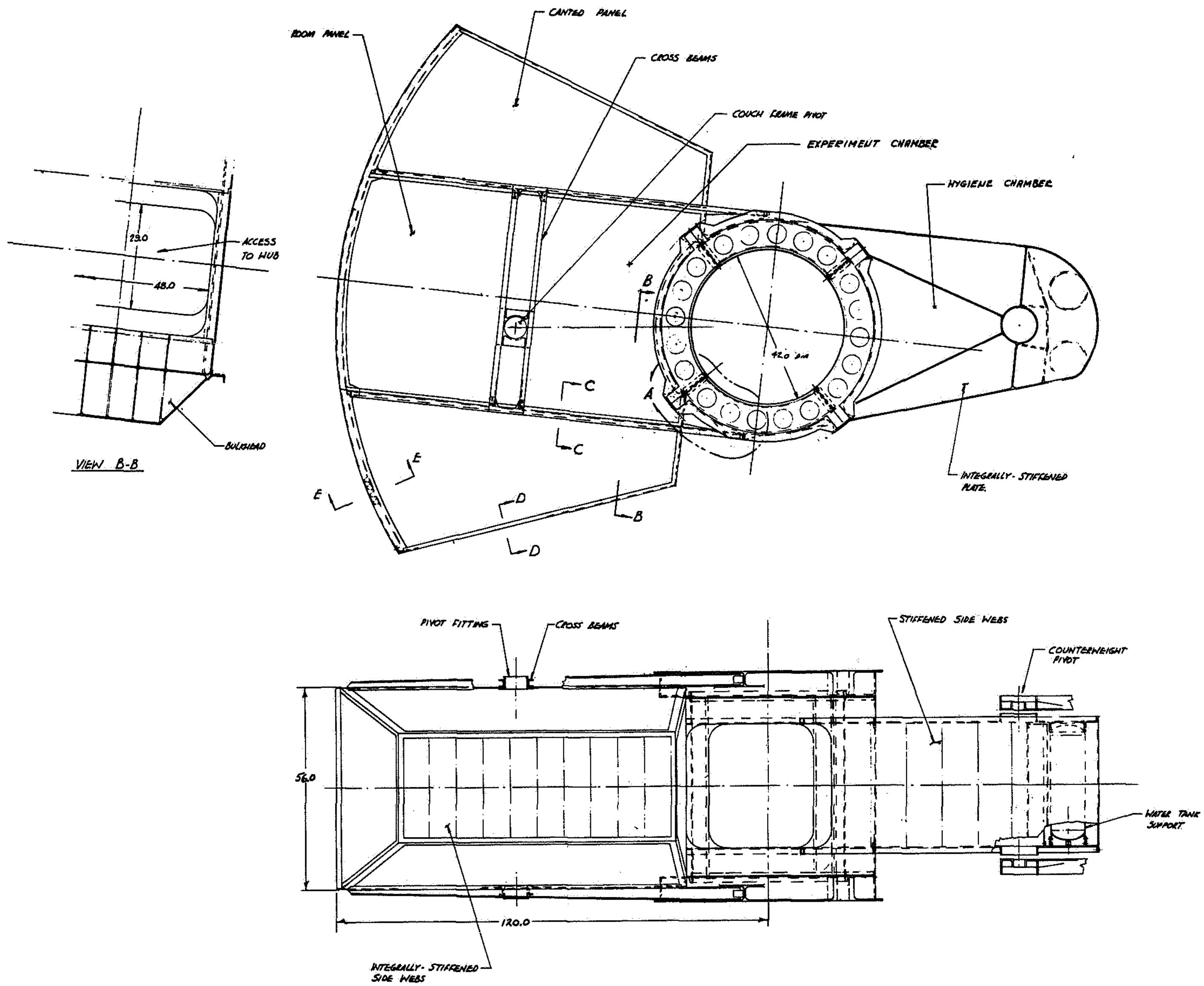


Figure 4a. -Centrifuge Structural Arrangement - Concept No. 2A

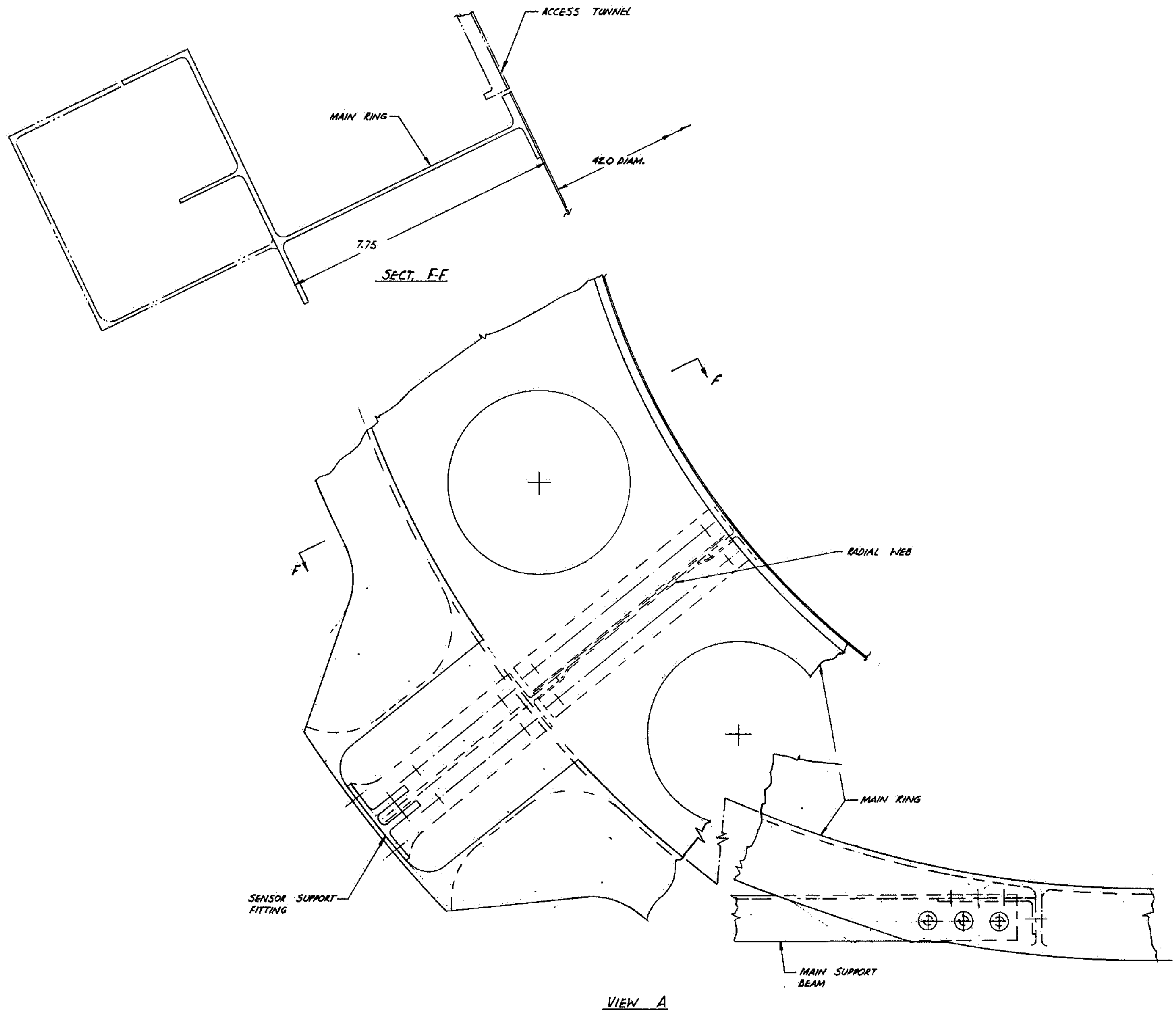


Figure 4b. Centrifuge Structural Arrangement - Concept No. 2A

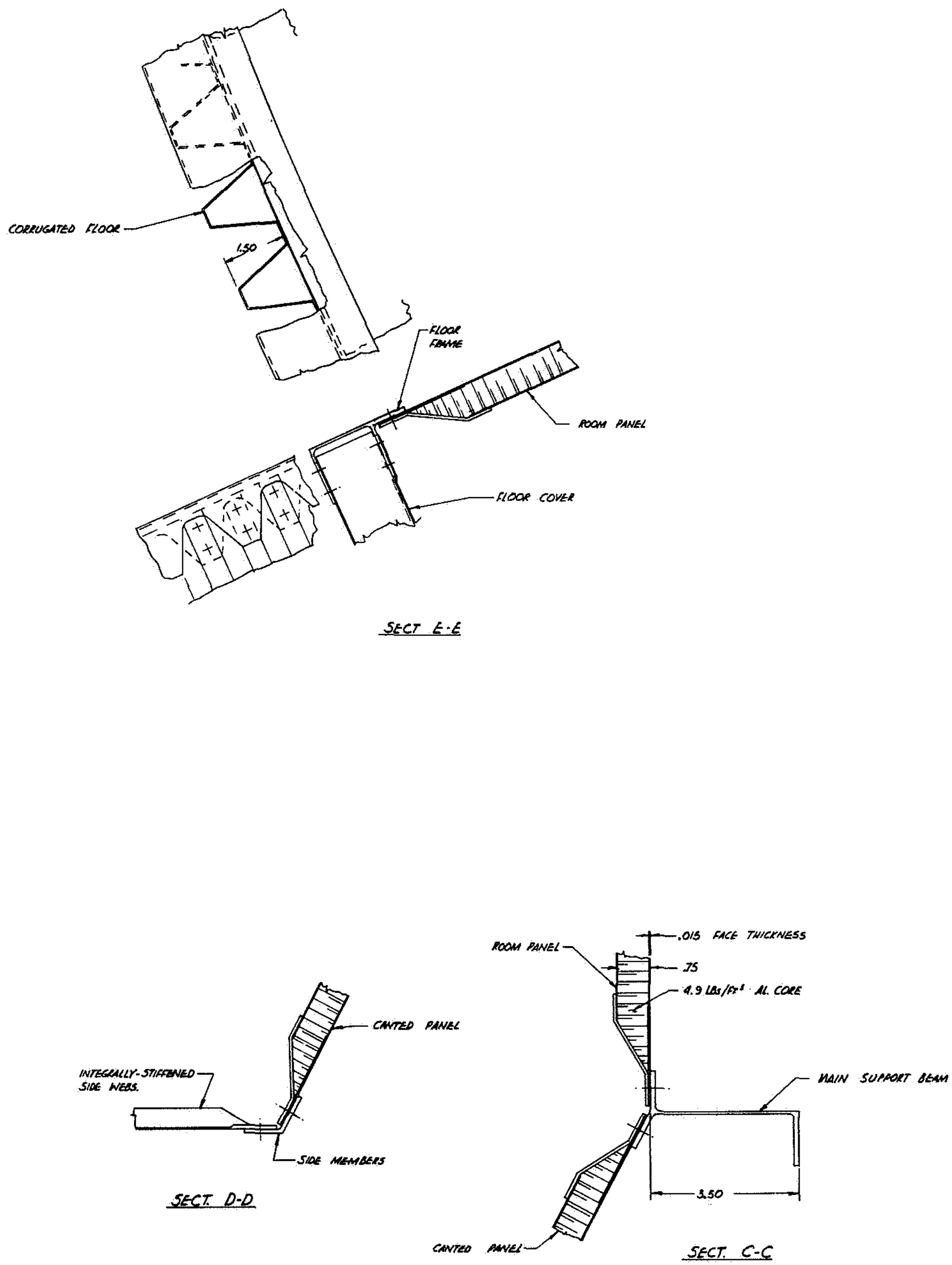


Figure 4c. - Centrifuge Structural Arrangement - Concept No. 2A

Table 2. Weight Summary, Concept 2A Rotating Mass

ITEM	WEIGHT (LBS)
Floor	77.8
Room	256.7
Hub Structure	217.7
Counterweight Support (Hygiene Comp.)	120.7
Counterweight Arm	40.0
Counterweight Structure	20.4
Counterweight	250.0
Water	150.0
Main Drive Motor	20.0
Couch	60.0
Couch Frame	55.0
Man	200.0
Force Sensors	20.0
Power Conditioning and Communication	120.0
Total	1612.1

Maximum Moment of Inertia, 2530 ft-lb-sec^2

it appears most desirable to extend the package concept to the shower and hygiene experiment equipment. In the 1A concept, locating this equipment permanently below the walking floor increased the inertia of the machine appreciably and limited the maximum radial distance of the floor by several inches. Placing this equipment in a special enclosure on the opposite side of the hub from the experiment chamber resulted in a large weight penalty and complicated the balance of the machine from the standpoint of both mass distribution and counterweight authority. The most desirable solution requires the development of a portable shower and hygiene package which is used within the experiment chamber.

With the experiment chamber concept, the chamber structure assumes the structural support and positioning functions of the roll ring in previous designs. This allows consideration to be given to other methods of providing test subject Z axis rotation for the angular accelerating experiment. Design studies performed in conjunction with concept 2A examined this approach and found that direct rotation of the couch was both a practical and lighter method of providing the required motion. Elimination of the roll ring also reduces counterweight requirements and decreases the overall moment of inertia.

Experiment Chamber. - The experiment chamber concept provides an optimum facility for performance of the mobility experiments and is found to be of considerable advantage in the other areas of investigation. In addition to providing structural support and positioning references for the couch and other experiment packages, this enclosure has a positive value in eliminating air motion around the test subject and visual clues to rotation. The safety aspects of this enclosure are also highly desirable. Structural trade-offs examined indicate that the shell approach of concept 1A is preferable from the standpoint of weight and rigidity. The chamber has a very large influence on the moment of inertia of the machine, so that considerable expense can be justified in reducing the mass of the structure to a minimum.

Centrifuge/Spacecraft Interface. - Study of the interface between the centrifuge and the spacecraft confirms that, as previously recommended, the machine should be attached only at one bulkhead through a single bearing assembly. All loads between the bearing assembly and the rotating assembly must be passed through a sensing network. Minimum weight and sensing system complexity will be achieved with six sensors located symetrically in three pairs in a plane perpendicular to the spin axis. The main requirement for both the spacecraft interface and the sensor support structure is high stiffness. This must be sufficient to keep the natural frequency of the rotating assembly well above the natural frequency of the spacecraft and centrifuge operating frequencies.

Hub Structure. - Analysis of the two hub structural arrangements represented by Concepts 1A and 2A shows a clear weight advantage for the 2A approach. Allowing access through the hub to both the experiment chamber and the centrifuge chamber eliminates any need for access doors through the experiment chamber wall and permits this assembly to be constructed as a continuous shell. This further reduces its weight and inertia. In addition, the hub end-ring provides a relatively stiff platform on which to mount the imbalance sensors.

Counterbalance. - With the elimination of the roll ring and the reduction in experiment equipment mass afforded by the package concept, the test subject becomes the major source of c. g. change in the system. It may be expected, then, that counterweight mass will roughly correspond to test subject mass, and that the motion of the counterweight will tend to follow the subjects c. g. motion. Positioning of the counterweight by radial and axial translation combined with pivoting about a radially displaced axis parallel to the spin axis proves to be an ideal and easily mechanized method of providing such a counterweight motion envelope. For adequate authority, however, the displacement of the pivot or "swing" axis from the spin axis should be kept to a minimum. While counterweight lateral authority is decreased at minimum counterweight radial positions, the conical shape of the experiment chamber also decreases the lateral range over which the test subjects, c.g. can be shifted at short radius. This results in adequate correspondence in the motion envelopes of both subject and counterweight.

CENTRIFUGE GENERAL DESCRIPTION

(Selected Design)

The recommended centrifuge configuration evolved from the preliminary concept studies is illustrated by figure 5. The apparatus described provides the capability to perform the full range of experimental research required and has adequate flexibility to accept future modifications or growth in the experiment program.

Emphasis has been placed on minimizing the mass, inertial properties and space requirements of the machine and on providing a design which is compatible with a wide range of possible module or space station installations utilizing the center passageway arrangement. Mechanization has been effected in a manner which is simple, reliable and within the current state-of-the art.

General Arrangement

The principal features of the centrifuge are the experiment chamber, the hub, and the counterbalance assembly.

The experiment chamber is a room-like enclosure which houses all experiment activity. It is designed as a continuous shell and contains a walking floor and attachment fixtures for the orientation and support of experiment equipment.

The hub assembly serves as the interface connection between the experiment chamber, the counterbalance equipment and the spacecraft. The hub consists essentially of two ring structures connected by three equally spaced posts or columns, one of which is in line with the counterbalance assembly attachment and the other two aligned with the hub/chamber wall intersection. Openings between the posts provide access from within the hub into the experiment chamber and the centrifuge installation chamber. Interface with the spacecraft is accomplished by providing a bearing (roller support system) and motor drive at one end of the hub. It is assumed that the center passageway will incorporate a stationary cylindrical sleeve, with appropriate access openings and doors, to permit traffic through the hub during centrifuge operation without exposure to rotating equipment. The hub also serves as a mounting structure for the main drive inverter, controls and additional batteries.

Installation

The design illustrated by figure 5 is based on the application to a space vehicle having a 240 inch cylindrical outer shell and a 42 inch clear passageway through the center of the vehicle. Centrifuge chamber height should be approximately 65 inches to allow sufficient clearance for the rotating assembly. The bulkhead utilized for attachment of the roller support system must be sufficiently rigid to provide a high natural

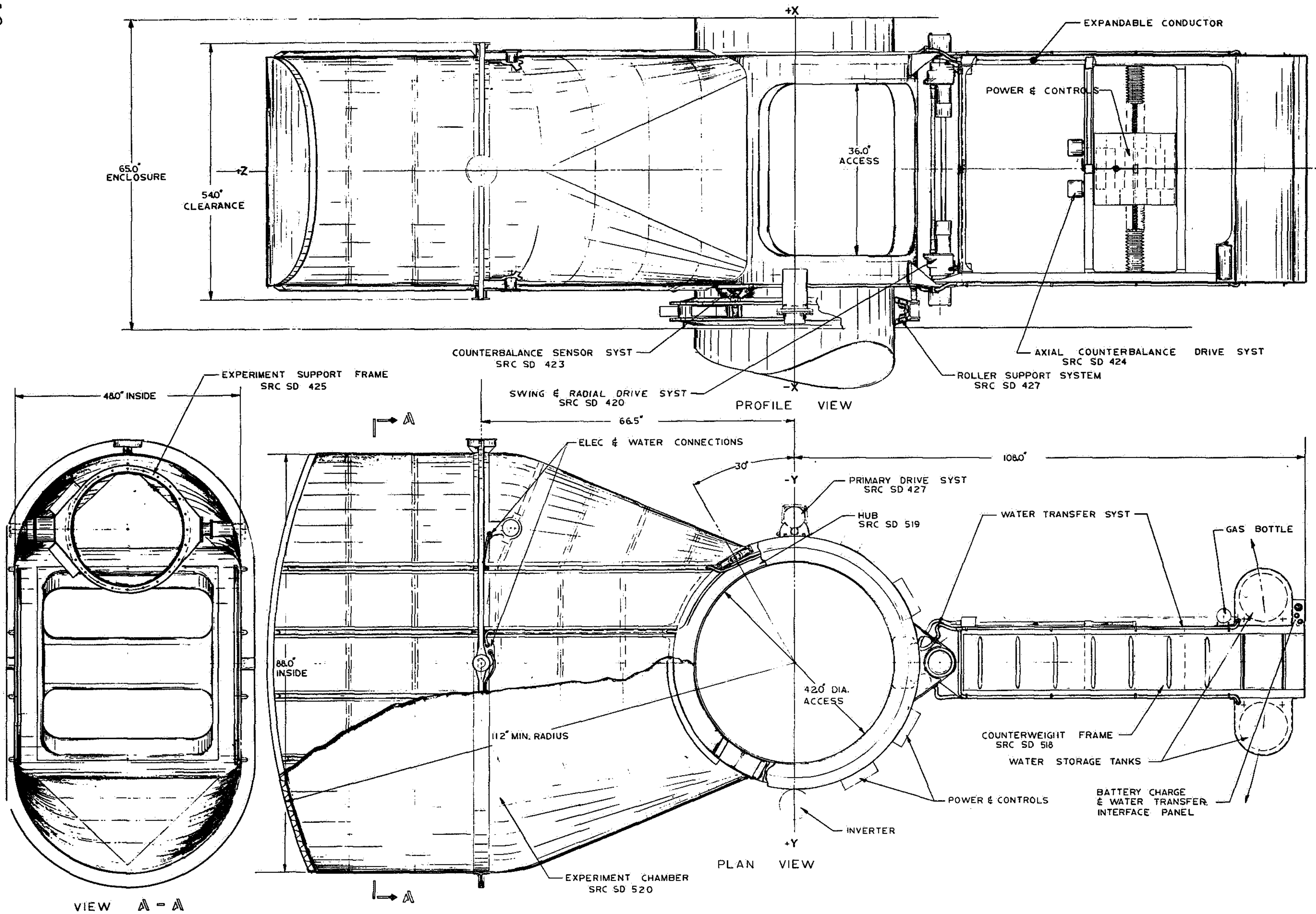


Figure 5. Space Research Centrifuge General Arrangement (SRC-SD-122)

frequency for the total assembly (in the order of 8 cps). In addition, a control station for centrifuge operation must be provided in the near vicinity with easy access between the control station and the experiment chamber, and connections for battery charging and water system servicing made available.

Centrifuge Characteristics

The maximum radial dimension of the centrifuge is 112.0 inches (to the bottom of the walking floor). The outside width of the experiment chamber is 54.0 inches which, with allowances for structure, provides a chamber floor width of 4.0 feet. The length of the walking floor is approximately 7.5 ft.

The maximum weight and moment of inertia of the rotating assembly during operation are 1207 lbs and 1475 ft-lb-sec^2 respectively, and the maximum momentum generated during experimentation (Re-entry) is 7225 ft-lb-sec. Maximum experimental capability required of the machine is 6.5 g and corresponds to a maximum angular velocity of 4.9 rad/sec. Total facility equipment weight, including control station, counter momentum CMG's and other stationary support systems is approximately 1720 lbs at the time of launch.

Major Subsystems

The major centrifuge subsystems characteristics are described briefly as follows:

1) Structure: Aluminum alloy sheet metal and machined fitting built-up assemblies are recommended for general centrifuge structure with the exception of the experiment chamber. The experiment chamber is designed as an integrally stiffened shell fabricated as a lay-up of graphite - epoxy composite.

2) Primary Drive: Primary rotation is provided by a voltage/frequency controlled 3.5 HP AC motor mounted on the rotating assembly at the hub drive ring. It contains an integral gear reduction and is balanced against an inverter installed on the opposite side of the hub.

3) Power: Power for all centrifuge functions is supplied by rechargable batteries which are integrated with the counterweight.

4) Communications: All communication with the centrifuge rotating assembly is accomplished by RF link.

5) Imbalance Sensing: Imbalance sensing is accomplished through a network of three force sensor pairs, mounted between the drive ring and the centrifuge hub structure. The sensor pairs are spaced at intervals of 120° and are aligned with the hub structural posts.

6) Counterbalance: Counterbalance of the centrifuge is accomplished by automatic positioning of the counterweight (approximately 200 lbs) in response to imbalance forces and torques computed from the sensor network signals. The counterweight is positioned by rotation of the counterweight swing frame through a range of ± 30° from center, linear translation of the counterweight carriage within the swing frame of 44 inches maximum and axial translation of the counterweight within the carriage of ± 14 inches from center. This motion envelope allows full static and dynamic balancing of the machine. Dual motor/gear drive units for swing and radial counterweight motion are located at the top and bottom pivot collars on the swing frame. The axial drive unit is an integral part of the counterweight.

7) Countermomentum: As previously recommended, dual-single degree of freedom Control Moment Gyros are required to absorb the spin-up momentum of the centrifuge. Based on a maximum momentum requirement of 7225 ft-lb-sec. and an initial momentum vector angle of 30°, each gyro must be sized for 2100 ft-lb-sec. Using current vendor data for single degree of freedom CMG's of this capacity, a weight estimate of 250 lbs per unit is considered conservative at this time.

8) Water: A water system for the hygiene experiments is integrated into the centrifuge. Water storage and collection tanks with a capacity of 10 gallons are located at the outboard end of the counterweight swing frame. The system provides water on demand by pressure expulsion of fluid from the supply tanks.

9) Experiment Equipment: Experiment equipment is provided in discrete packages which are tailored to the specific research being performed. The major packages are the couch, the hygiene package, the workbench package and the instrument package

EXPERIMENT PROGRAM

Increased Scope

The experiment program defined in Vol. III of NASA report CR-66651 (Ref. Contract NAS 1-7309) was analyzed and redefined to reflect incorporation of the three additional experiment capabilities requested by NASA.

1. Walking Mobility and Balance
2. Work Bench Task Performance
3. Hygiene and Personal Care Capability

Redefinition of the experiment protocols was driven primarily by two significant centrifuge configuration changes resulting from the incorporation of these experiments.

Experiment Room - Inclusion of a Walking Mobility and Balance Experiment established a requirement for an experiment chamber which would enable the test subject to move about freely, within a confined area, and without being endangered by intrusive apparatus not associated with the experiment.

Water Storage - Incorporation of a shower system, as a part of the hygiene experiment, established a requirement for handling fluids on the rotating portion of the centrifuge. While this additional capability creates a potential balancing problem, in some of the experiment configurations, it provides a considerable increase in experiment flexibility on the centrifuge.

Ground Rules

Consideration of these new configuration requirements resulted in the adoptions of some basic ground rules for the development of the centrifuge and the associated experiments.

Centrifuge Adaptability - The centrifuge should be configured to provide a wide range of experiment flexibility. It should be designed as a basic inertial support experiment tool rather than being designed around specific experiments.

Experiment Packaging - Experiments requiring inertial support should be designed around the capabilities of the basic centrifuge. Each experiment should be self contained as a separate package which could be interfaced with the centrifuge on a flexible schedule basis.

Experiment Chamber - The experiment chamber structure should have incorporated in its design a system of attachments and fittings to enable maximum utilization of the structure for experiment support.

Baseline Experiment Equipment - Two basic elements of experiment equipment, the subject couch and the experiment support frame, are considered as part of the basic centrifuge. These elements are not only utilized to support a major part of the experiment program, but are also required to facilitate the static balance requirements in some of the experiment configurations.

Revised Experiment Protocols

Within the framework of these ground rules an evaluation of the, previously defined, and the new experiment requirements was made and the following protocols established.

Walking Mobility and Balance as a Function of Rotationally Induced Inertial Support

Specific Objective - The objective of this experiment is to establish the capability of man to effectively locomote and maintain postural equilibrium at various levels of centrifugation.

General Description - Subjects will be tested in a two-part standing/mobility test, with the complete test being performed at each of four centrifuge load factors (0.1, 0.2, 0.3, and 0.4 g). Test design will permit quantitative rating of test performance as a function of the g level. Testing will involve both tangential and axial excursion components, with radial components limited to marginal limb movements parallel with the subject's long-body axis.

The experiment chamber (see Figure 6) will consist of 26 square feet of cushioned surface (comparable to Ensolite) marked off in a grid of 6 by 6 inch squares,

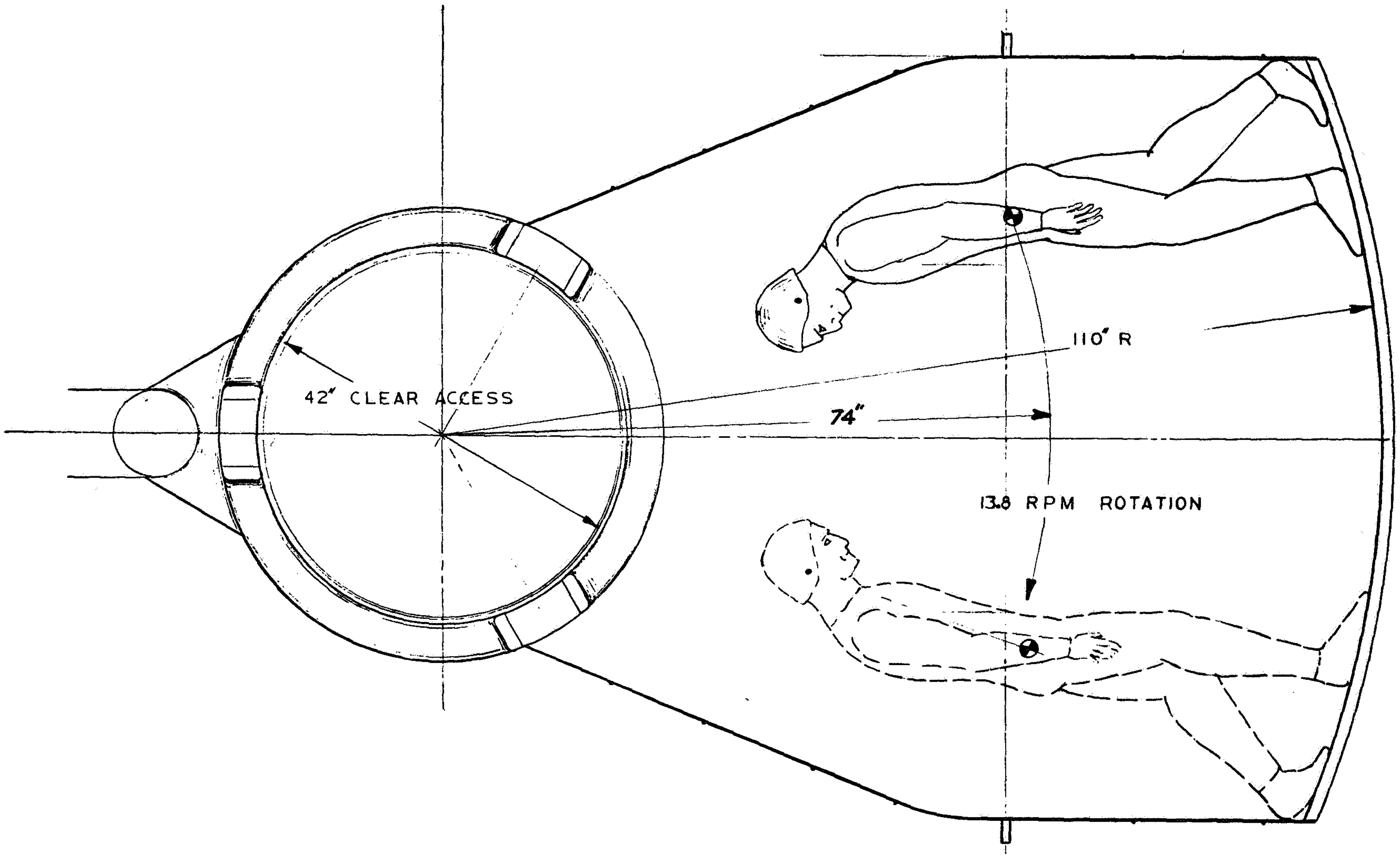


Figure 6. Mobility Experiments (.4 g at c.g.)

each of whose coordinates is boldly designated alphanumerically to facilitate performance rating. The deck is curved circumferentially to render it of equal radius at all points. The subject is unrestrained but wears a protective headgear. The subject's clothing shall be marked with fluorescent lines or spots, for purpose of wide-angle motion picture evaluation of walking.

The first part of the standing/mobility test involves restricted mobility (RM); the second part unrestricted mobility (UM). The first offers the advantages of greater experiment control, easier scoring quantification, and a substantial normative and experimental data bank from previous ground-based testing. The UM relates more directly to operational mobility requirements.

The RM testing includes standing with eyes closed and walking with eyes closed both performed with feet tandemly heel to toe, arms folded against the chest, and body erect. Scoring rates standing time, and number of in-balance steps and their direction along oblique lines AA' and BB' (Figure 7). UM testing requires normal walking and emergency running rates around path CC', including intra-trial reversals in mobility direction. UM scoring is based on timing of mobility direction, timing of mobility cycle, numbering of required steps, subject anecdotal ratings, and gait parameters to be subsequently extracted from cinematographic records.

Full testing sequences (RM+ UM) will be repeated at all g levels during one testing session. Balancing of cumulative artifacts will be effected by scheduling a complete testing session eight times (each utilizing a different primary g-level permutation) during a mission for each subject, requiring a mission time-commitment of 8 times 1 1/3 hours, or 11 hours/subject.

Operation Constraints - During all test sequences, changes in extra-personal stimuli, such as lighting and noise level, should be minimized.

Mode of Operation - The centrifuge facility will be configured such that the couch is stored outside of the inertial support experiment chamber. The centrifuge will then be spun-up and rotated in automatic mode.

Crew Support - Approximately 10 hours of ground based training and practice will be required to ensure an asymptotic level of proficiency for each subject.

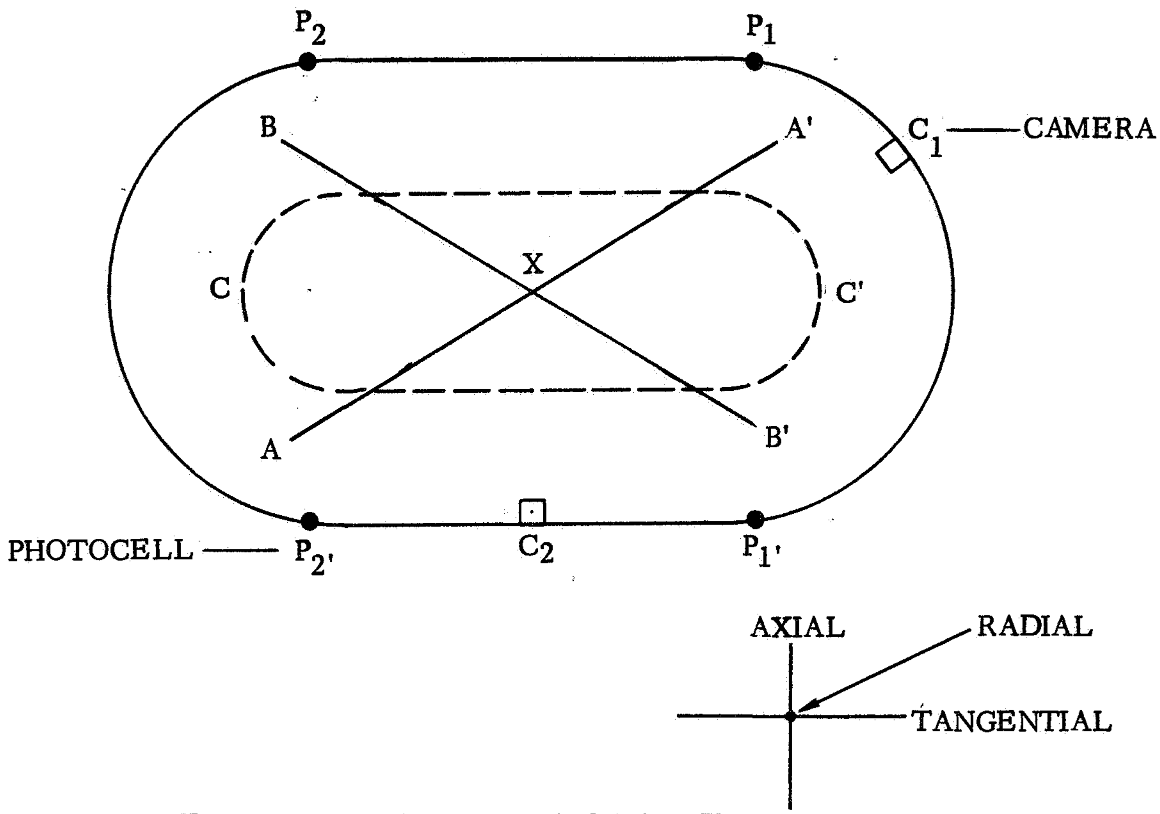


Figure 7. Radial View of Mobility Test Area

Bench Task Performance as a Function of
Rotationally Induced Inertial Support

Specific Objective - The objective of this experiment is to establish the capability of man to perform work tasks such as repair, maintenance, operations, record keeping, etc. at various levels of artificial gravity (Ref. Figure 8).

General Description - The subjects will be tested on a battery of perceptual-motor tasks that encompass all of the fundamental hand-eye abilities required to adequately perform all bench tasks, with a majority of the perceptual-motor tasks approaching an orthogonal relationship to a fundamental perceptual-motor ability. The battery of tests is integrated into two consoles (subject's and examiner's) for both logistic and testing efficiency. The range of artificial g will be provided by the onboard centrifuge.

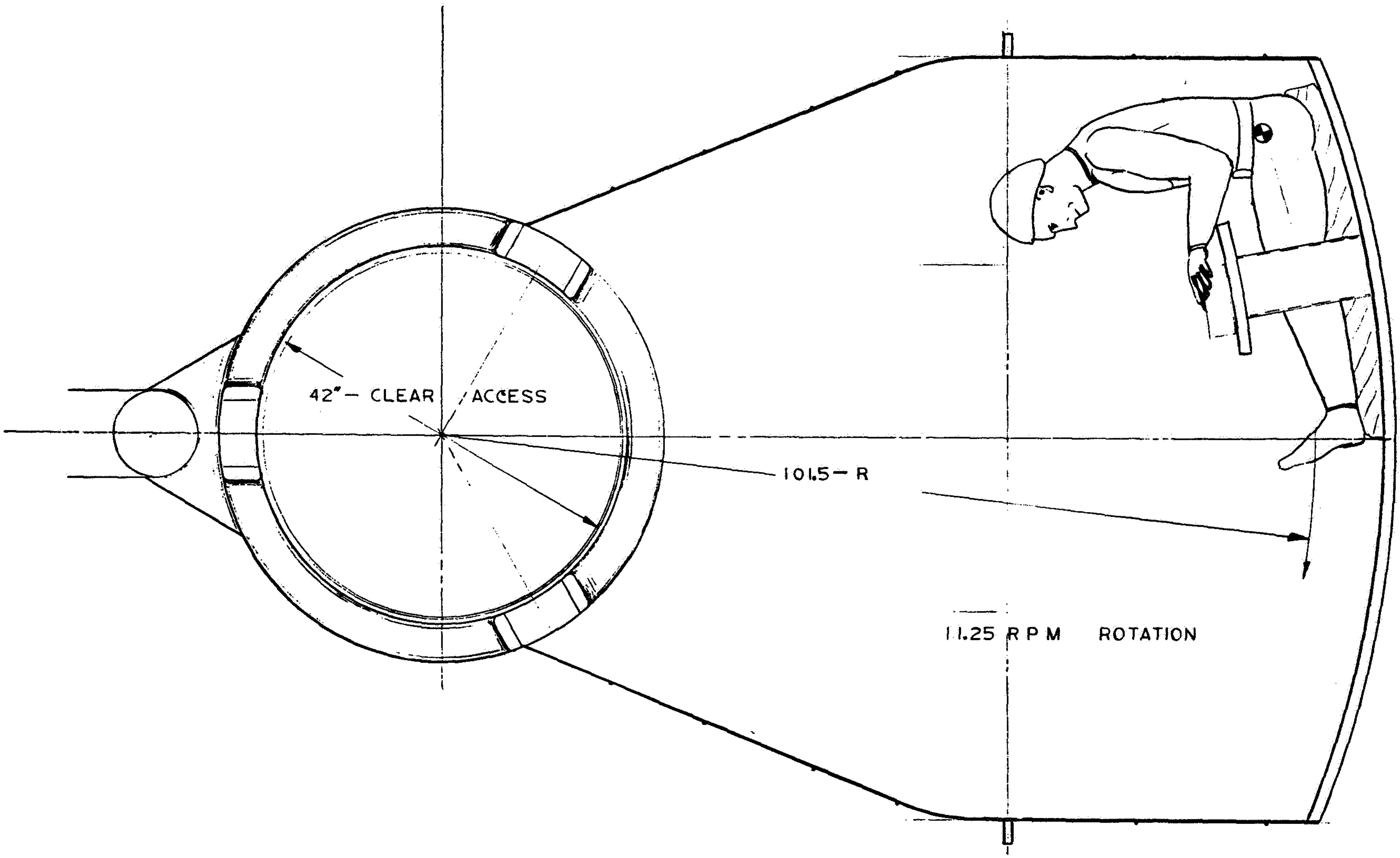


Figure 8. Workbench Experiment (.4 g at c.g.)

The console battery includes 18 perceptual-motor tests which score on 21 perceptual-motor performance parameters. Subject will be tested facing tangentially but not axially as it has already been determined that the former is significantly more desirable as it precludes vestibular coriolis stimuli due to pitching head movements. Subject will repeat battery of tests at each of four floor g-levels (0.1, 0.2, 0.3, and 0.4) at one continuous testing period. Scores will be related to normative data levels established in ground laboratory baseline testing subsequent to training to an asymptotic proficiency. Four degrees of primary ordering freedom (g sequence ascending and descending, tangential facing with and against rotation) recommend four complete testing sessions for each subject. Each session will require approximately three hours.

Operation Constraints - Perturbations in force field, noise level, and illumination in all extra-personal stimuli should be minimized. Where such variations are unavoidable, effort should be made to make them quantitatively consistent during testing at all of the g levels.

Mode of Operation - Each test is programmed and conducted automatically from the examiner's console. Paper and pencil data transcription from the console readouts is suggested.

Crew Support - Approximately 40 hours of ground laboratory training and practice will be required to raise each subject to an asymptotic level of proficiency in performing the test.

Time Line Analysis - Bench Task Performance vs. g

Minimum Sampling Requirements - 4 Subjects (Ss) x 4 Replications (Rs)/S = N = 16.

Testing Matrix -

Task Order	Dynamics			
	UA	UW	DA	DW
1 thru 18	Subjects 1 & 2			
18 thru 1	Subjects 3 & 4			

A = Subject orientation against spin
W = Subject orientation with spin
U = g-progression upscale (0.1 thru 0.4g)
D = g-progression downscale (0.4 thru 0.1g)

Testing Sequence - Subject 1 = UA, UW, DA, and DW
Subject 2 = DA, DW, UA, and UW
Subject 3 = UW, DA, DW, and UA
Subject 4 = DW, UA, UW, and DA

Mission Testing Schedule

Mission Days (in orbit)	2	3	4	5	6	7	8	9	Rs	Hr/R	Total Hr
Subject 1	x		x		x		x		4	3	12
Subject 2	x		x		x		x		4	3	12
Subject 3		x		x		x		x	4	3	12
Subject 4		x		x		x		x	4	3	12
Total Hours	6	6	6	6	6	6	6	6			48

Set-up and Tear-down Time - Approximately 15 minutes each = 30 minutes per replication per subject. This can probably be halved if each day's 2 replications are run without an intervening tear-down.

Other Scheduling Constraints - Each subject's replications should take place as consistently as is feasible at the same point in his work-rest-sleep cycle. It is also recommended that the starting time be selected such that the subject will be at least 1 hour post-prandial and unfatigued.

Personal Care Capability as a Function of Rotationally Induced Inertial Support

Specific Objective - The objective of this experiment is to establish the capability of man to perform special personal care functions, e.g., defecation and bathing, at various levels of artificial gravity, and in various positions with respect to the gravity vector. (See Figure 9)

General Description - Each time a crewman performs, in the course of his normal daily routine, one of the personal care tasks constituting a dependent variable in this study, he will do so at a predetermined g level as scheduled by the ordering of the four g-levels (0.1, 0.2, 0.3, and 0.4) at 66.5 inch radius constituting the range of exposures. Various body angles will also be predetermined to evaluate the effectiveness fecal separation and trajectory. The crew member will rate each performance

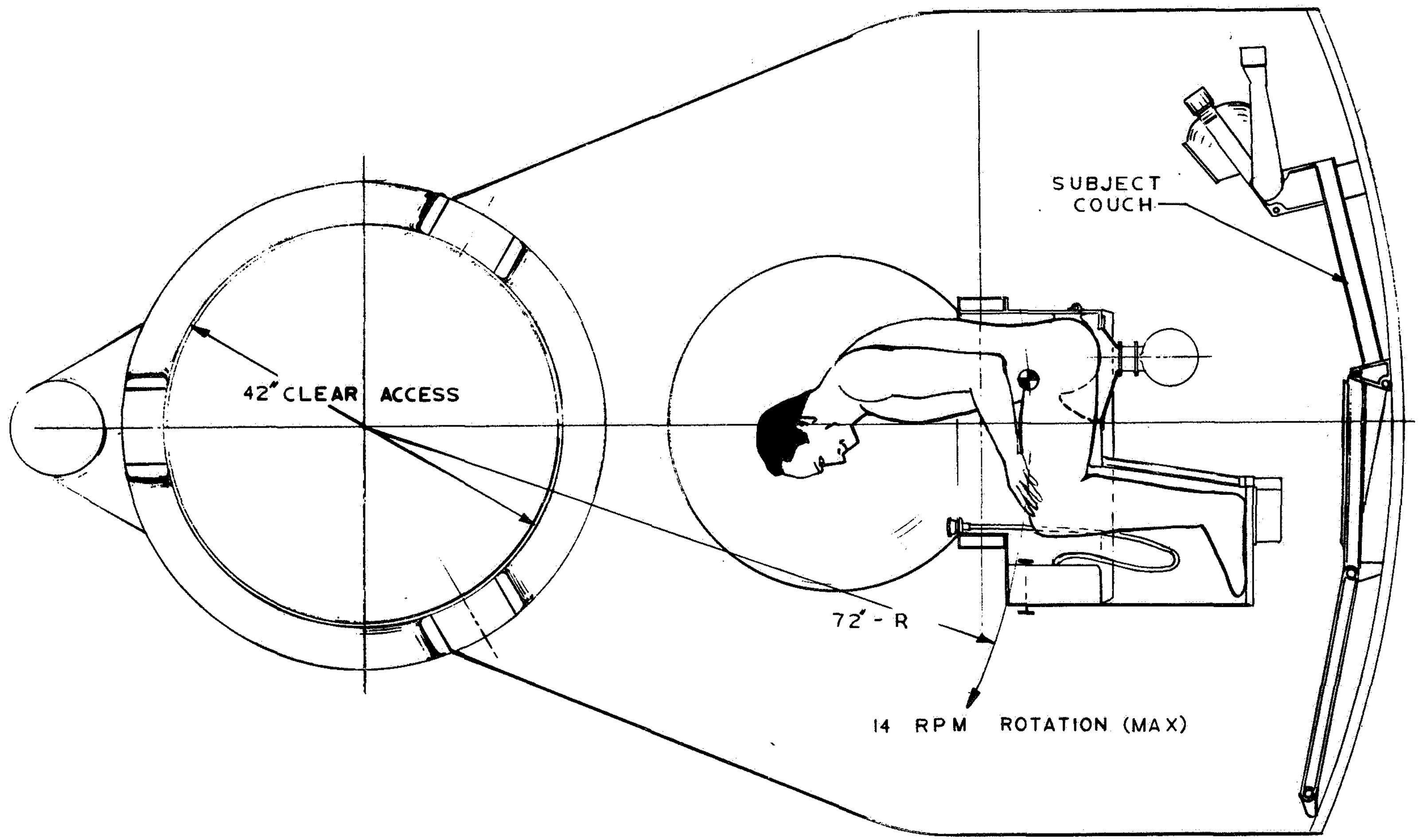


Figure 9. Hygiene Experiment (.4 g at c.g.)

immediately following its completion by ranking a list of appropriate parameters on a semi-quantitative habitability scale. At mission's (or study's) end, therefore, each crewman will have performed and rated each function nearly an equal number of times at each of the four g levels, permitting designers something approaching a statistical evaluation of each task and its implementing facilities as a function of g level.

Although more quantitative rating indices could be used, e.g., topical microbiologic assays of personnel and facilities, they tend not only to be techniquely prone to unreliability, but, more importantly, are easily invalidated by the usual non-uniformity of such personal care procedures. Therefore, a rating on habitability rather than hygienic contingencies is preferable.

Below are two representative examples of parametric rating lists, intended for the functions of defecation and bathing. Rating of each factor will be done by listing a 0 (intolerable), 1 (marginal), 2 (tolerable), or 3 (comparable to 1g) after it, with space alloted for clarifying remarks and recommendat ons, and the listing and rating of parameters not included on the original list.

<u>Defecation</u>:

(1) Facility Availability (Demand)
(2) Facility Accessibility
(3) Facility Sizing
(4) Interface Comfort
(5) Postural Equilibrium
(6) Defecation
(7) Urination
(8) Feces Detachment
(9) Feces Transfer
(10) Urine Transfer
(11) Perianal Cleaning
(12) Odor Control
(13) Tissue Disposal
(14) Illumination
(15) Dizziness
(16) Stomach Awareness
(17) Nausea

<u>Bathing</u>:

(1) Facility Availability
(2) Facility Accessibility
(3) Facility Sizing
(4) Postural Equilibrium
(5) Undressing
(6) Water Transfer
(7) Water Pressure
(8) Water Temperature
(9) Water Quantity
(10) Drying
(11) Odor Control
(12) Post-Shower Air Temperature
(13) Post-Shower Humidity
(14) Mirror Fogging
(15) Illumination
(16) Dressing
(17) Dizziness
(18) Stomach Awareness
(19) Nausea

Whereas some of the above listed parameters, e.g., facility sizing, may seem patently independent of g level, variations in subjective rating of such factors may provide significant clues to crew acceptance.

Operation Constraints - In order to minimize astronaut discomfort while performing personal care functions, spacecraft stabilization must be maintained such that the cross product of angular velocities remains below $100^{o}/sec^{2}$.

Mode of Operation - After the astronaut has entered the personal hygiene area, the centrifuge will enter into automatic mode of rotation.

Crew Support - The crew should spend at least a week using the personal care facilities in the ground-based simulator to familiarize themselves with the techniques and facilities and to provide a baseline for rating the same in flight. Special training will be required for operation of the facility by the experiment monitor.

Reentry Acceleration Profile Simulation

Specific Objectives - Exposure of the astronaut to zero-g over prolonged missions is expected to result in increasing habituation to that environment and a corresponding decrease in g-tolerance. The objective of this experiment is to measure the rate and level of this habituation and its influence on the ability of the astronaut to fly a ballistic entry maneuver and perform necessary control tasks. In addition, observation is to be made of the degree to which reentry g exposure may decrease reentry tolerance. (See Figure 10)

General Description - The reentry acceleration profile simulation will be performed a minimum of six times. A representative performance schedule based on a 45 day zero-g exposure period would utilize the 7th, 14th, 21st, 29th, 35th, and 40th days. A corresponding distribution ratio for crew rotation periods up to 90 days is acceptable to the experiment. The minimum subject sample is one crew member; however, participation of up to four astronauts is desirable for statistical validity and to allow observation of changes in g-tolerance as a function of exposure to the reentry acceleration profile.

Each test is estimated to require a preparation time of 45 minutes, a test time of 11 minutes, and a period of 27 minutes for removal and storage of instrument and other functions. During the test period, an acceleration profile as illustrated by

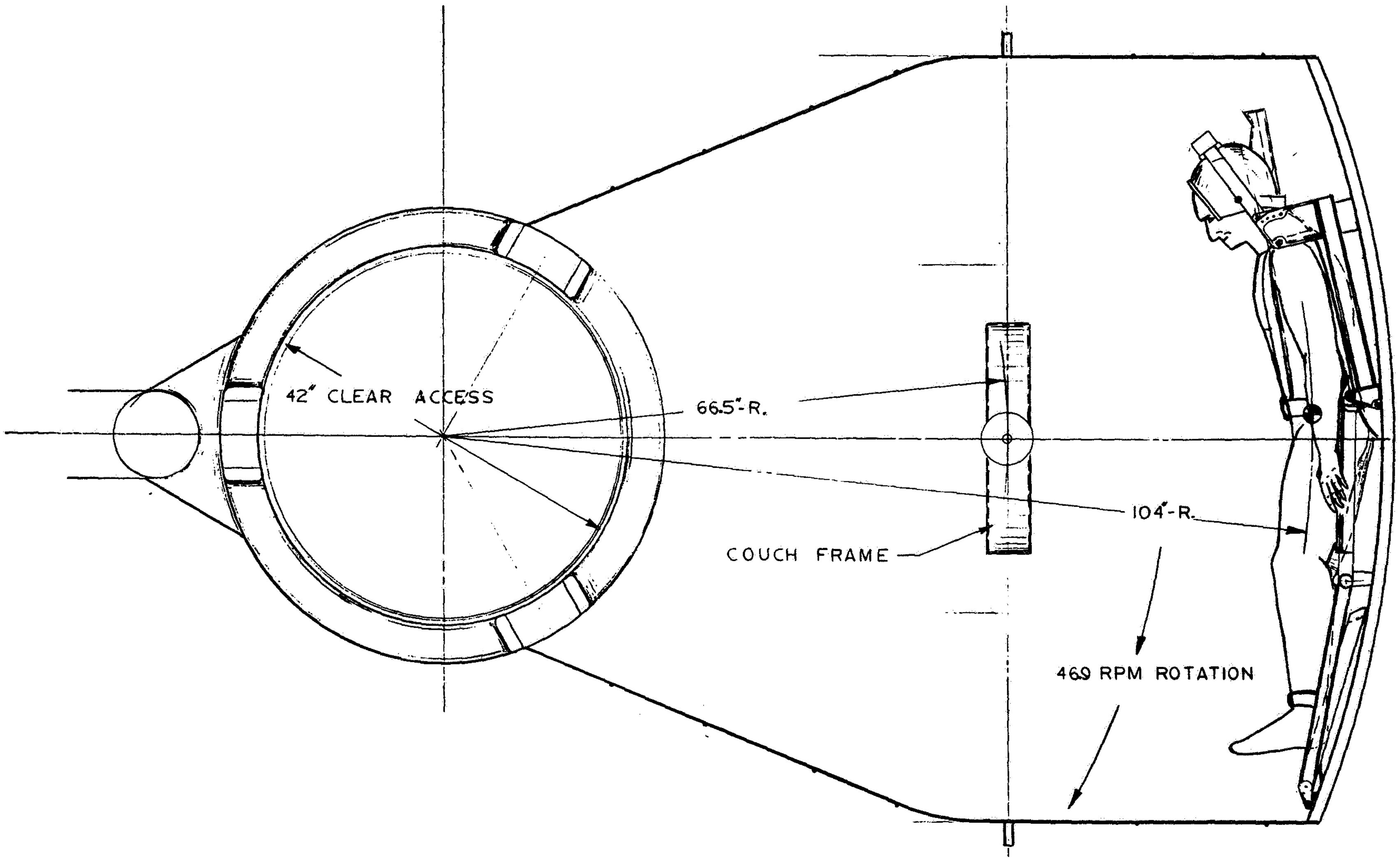


Figure 10. Re-entry Experiment (6.5 g at c.g.)

Figure 11 will be imposed on the test subject by automatic programming of centrifuge rate. The test subject will perform a simple perceptual motor test while under acceleration.

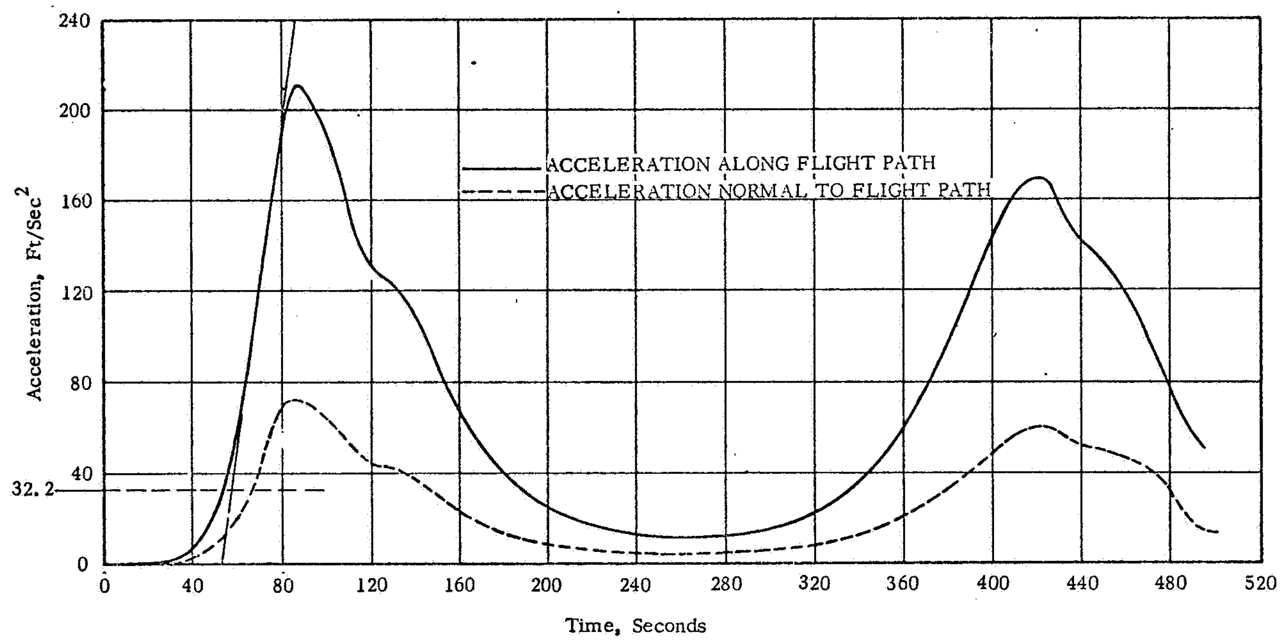


Figure 11. Acceleration Load Profile for Re-entry Experiment

Operational Constraints - Due to divergent physiological effects, test subjects involved in this experiment should be different from those utilized in the centrifuge therepeutic effects experiment. To eliminate the possibility of artifactual disorientation and performance loss, stabilization of the spacecraft must be maintained such that the cross product of angular velocities remains below $100^{o}/sec^{2}$.

Mode of Operation - The centrifuge facility will be configured so that experiment couch is positioned at maximum radius (110 in. approx.) and orientated at 78 degrees with respect to the radius vector. The centrifuge will operate in automatic mode during the entry profile.

Crew Support - Special training will be required for operation of the facility by the experiment monitor. Crew skills will be required for the application of instrumentation for electrocardiogram and blood pressure records of the test subject and for medical monitoring during the test. The test subject must be trained to baseline proficiency in the perceptual motor test.

Cardiovascular and Vestibular Effects

Specific Objective - The experimental objectives are to establish the effects on man of weightlessness, reduced gravity and rotation in the absence of earth's gravity and during space flights. This experimental area may be broken down in two categories: (a) investigation of orthostatic and acceleration tolerance effects, and (b) threshold of response and sensitivity and interaction of otolith and semicircular canals.

General Description - A representative performance schedule based on a 45-day zero-g exposure period has been developed for each experiment. A corresponding distribution ratio for crew station in periods longer than 45 days is acceptable to the experiments. The experiments may be performed as a group in one crew rotation period if the crew work schedule should permit, or they may be performed individually throughout the life of the mission.

a. Study of Grayout Thresholds by Use of Peripheral Vision Lights - This experiment will involve two astronauts on days 7, 14, 21, 28, 35, and 42 of an assumed 45-day crew rotation period. Time required for the experiment will be 79 minutes per day per subject. During the test period, the subject will be positioned in the couch and restrained to the experiment chamber wall with his feet on the chamber floor (Ref. Figure 12). He will then be subjected to a specific rate of acceleration onset for a time duration sufficient to record the times at which the peripheral vision lights are lost to the subject's vision.

b. Tolerance to Tilt Simulation - This experiment will involve three astronauts on days 5, 12, 19, 26, 33, and 40 of the assumed 45-day crew rotation period. Time required will be 77 minutes per day per test subject. During this test, the subject is restrained.

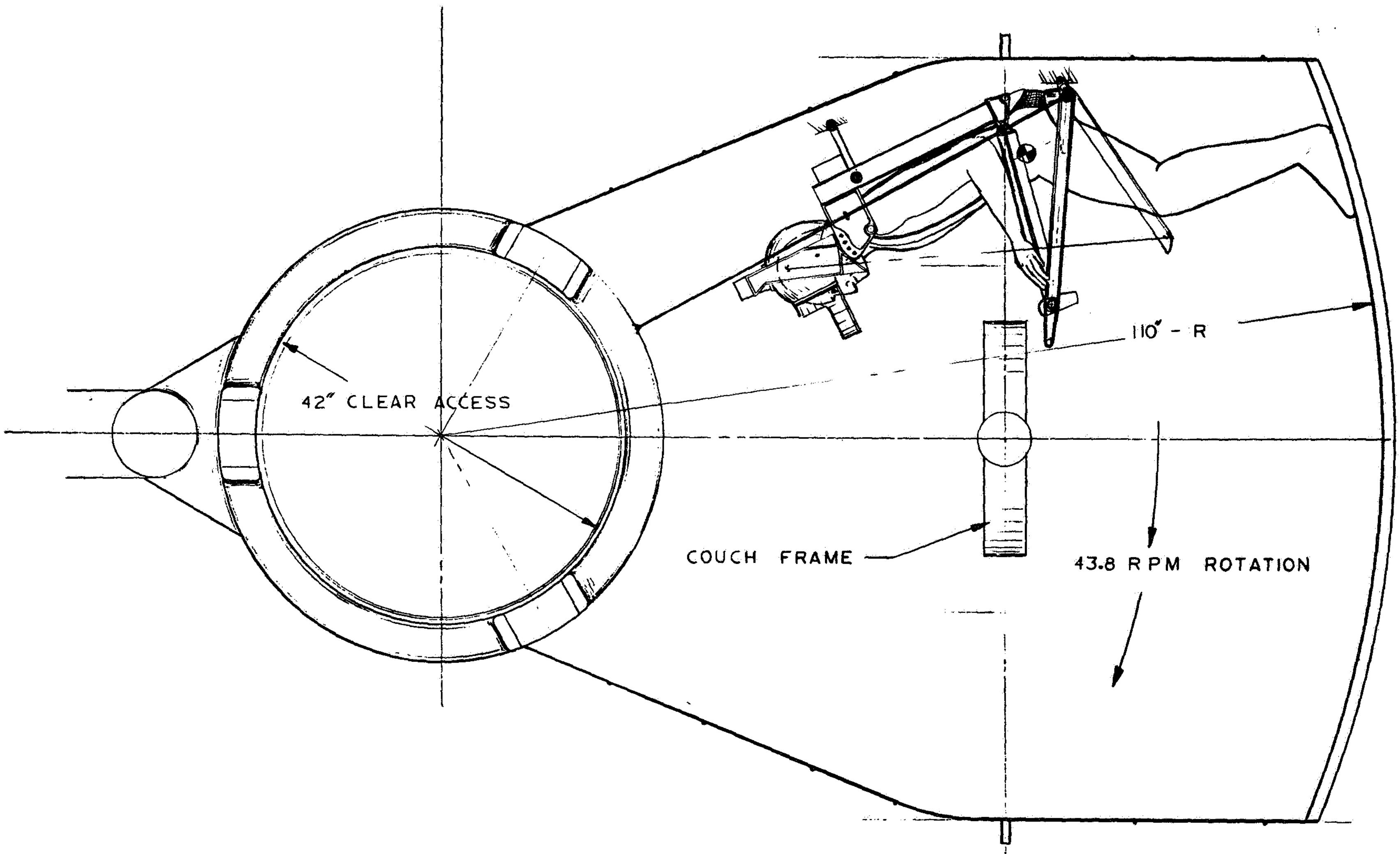


Figure 12. Grayout Sensitivity Threshold (6.0 g at Feet)

b. (Continued)

in the centrifuge couch and is positioned along an arc of constant radius. The centrifuge is brought to proper speed. The subject is then tilted outboard from the center of spin (Ref. Figure 13).

c. Threshold Levels of Sensitivity for Angular Acceleration - This experiment will involve two astronauts on days 2, 9, 19, 23, 30, and 37 of an assumed 45-day crew rotation period. Time required for the experiment will be 103 minutes per day per astronaut. During the test period, thresholds for acceleration will be determined about the X, Y, and Z body axis. The astronaut will be positioned in the couch such that the corresponding axis will coincide with the roll axis of the couch. The subject will then be subjected to angular acceleration by rolling the couch while the centrifuge radius arm remains stationary (Ref. Figure 14).

d. Threshold Levels of Sensitivity to Linear Acceleration - This experiment will involve three astronauts, one on days 2, 9, and 30, a second on days 2, 16, and 37, and a third on days 2, 23, and 44. Time required will be 335 minutes per day per subject. The experiment will be performed in two ways. The subject's response to various combinations of g-level and pitch angles while facing tangential will be measured. The experiment will be repeated with the subject facing axially, the response to various g-levels and roll angles being measured. (Ref. Figure 15)

e. Cross Coupled Semicircular Canals Stimulation - This experiment will involve one astronaut on days 2, 10, 17, 24, 31, and 38, and a second astronaut on days 4, 11, 18, 25, 32, and 39. Time required will be 440 minutes per day per astronaut. The experiment will involve measurement of subject response to various head motions and hand dexterity at various rates of centrifuge rotations. (Ref. Figure 15)

Operational Constraints - For the orthostatic and angular acceleration experiments (a and b), in order to eliminate the possibility of artifactual disorientation and performance loss, stabilization of the spacecraft must be maintained such that the cross product of angular velocities remains below $100^{o}/sec^{2}$.

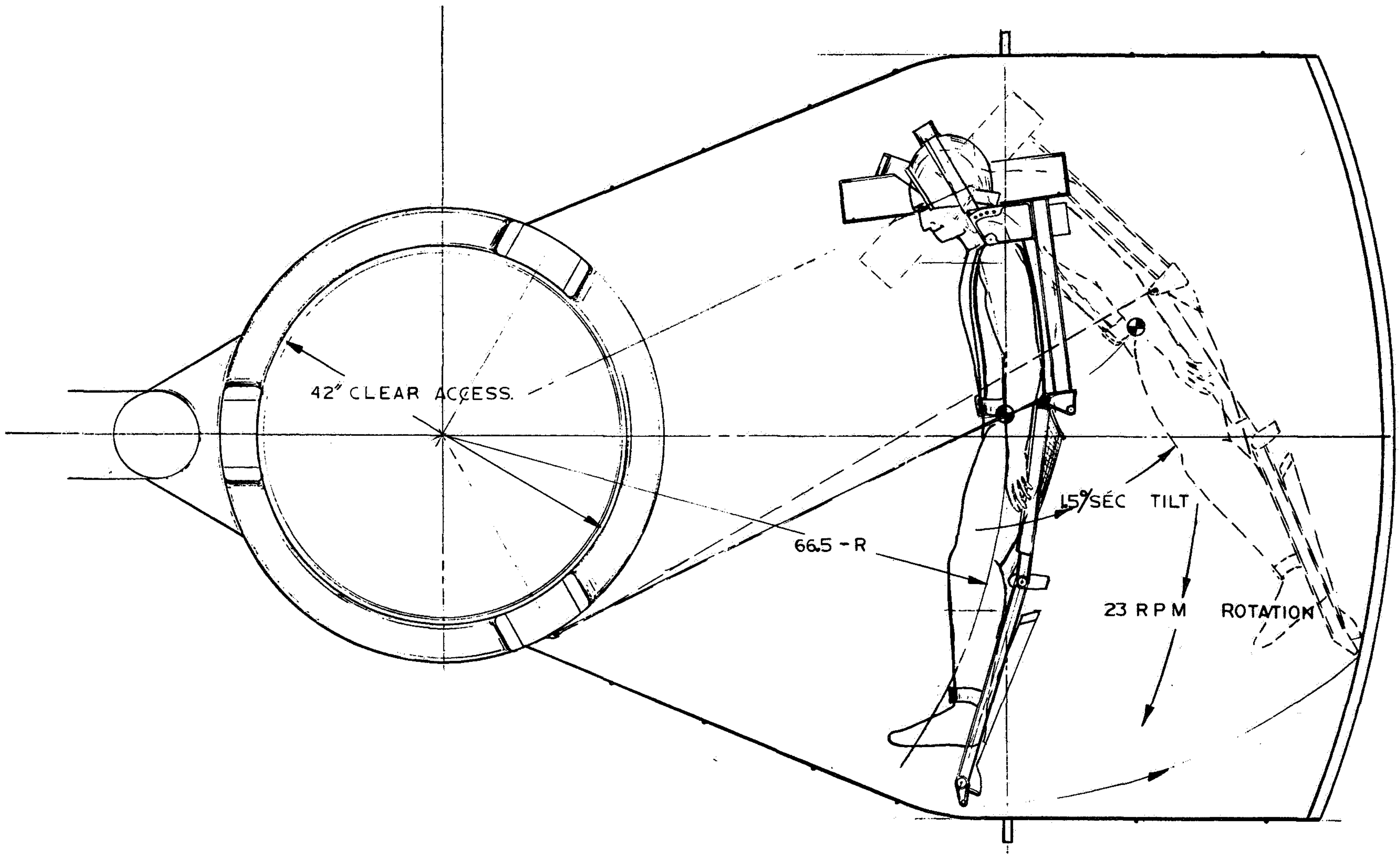


Figure 13 . Tolerance To Tilt Simulation (1.0 g at Head)

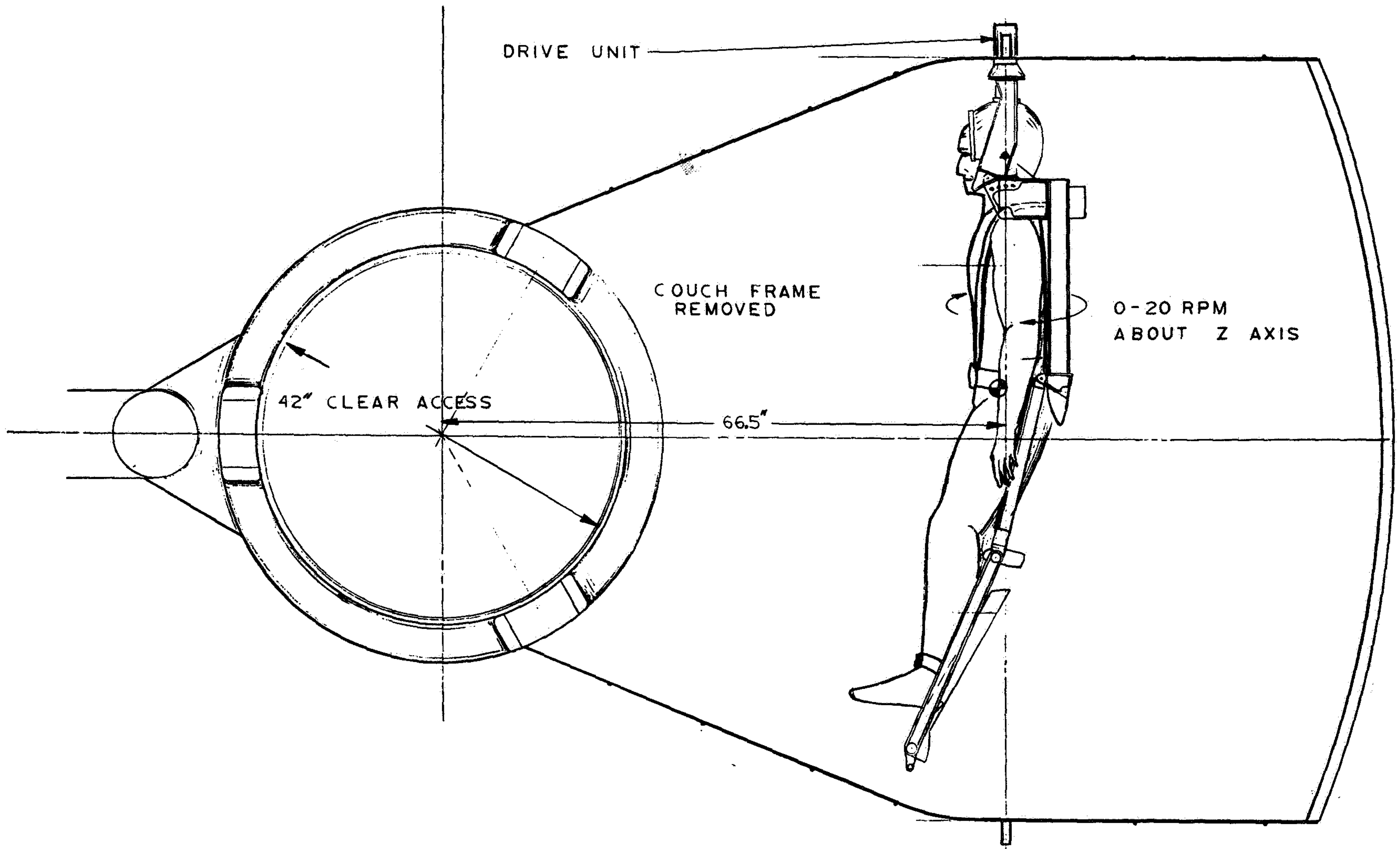


Figure 14. Angular Acceleration Thresholds

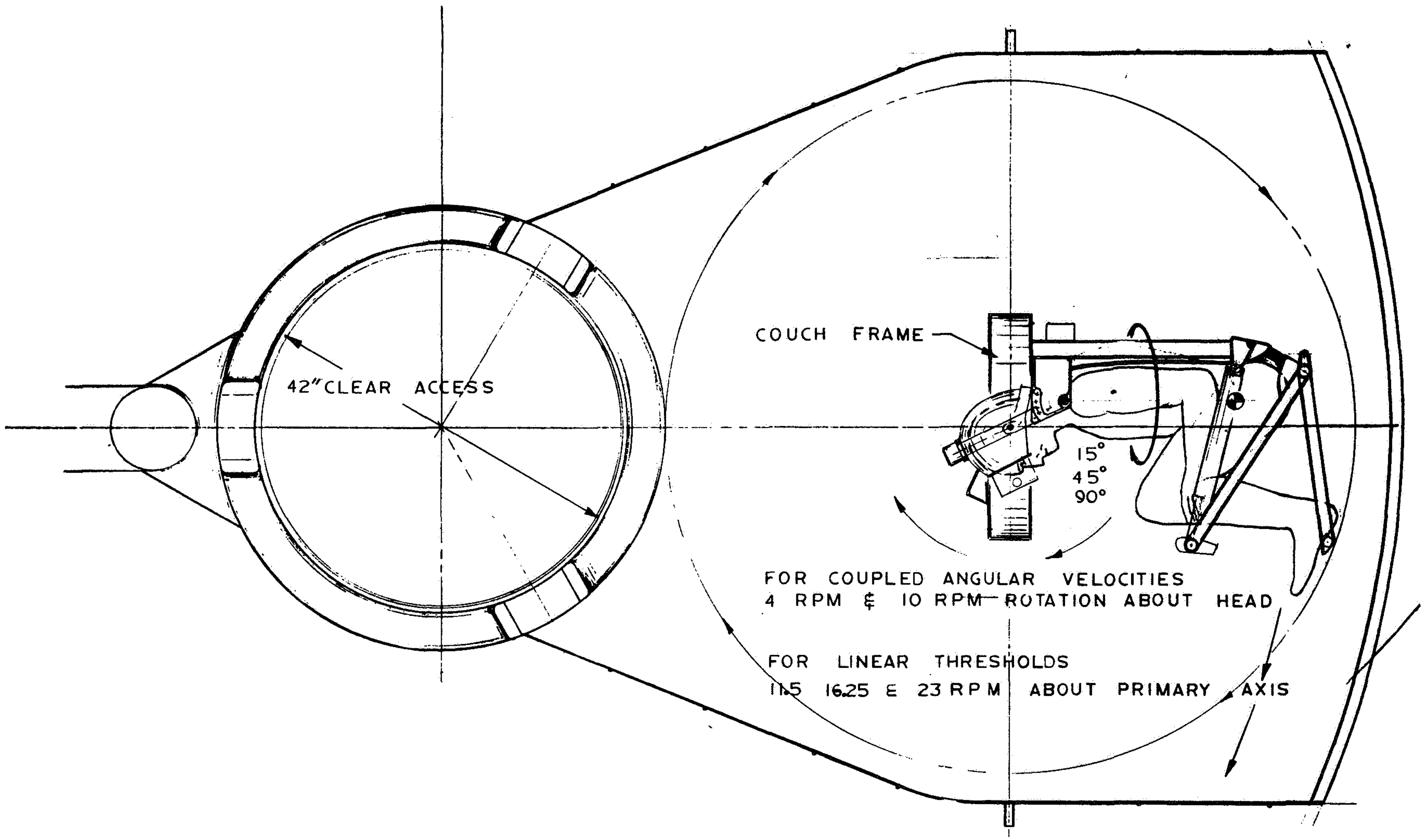


Figure 15. Coupled Angular Velocity and Linear Acceleration Thresholds

Due to the nature of the threshold experiments (c, d, and e), the spacecraft must be stabilized such that the motions of the spacecraft are an order of magnitude below the threshold values to be measured. Consequently, stabilization of the spacecraft must be maintained such that for the linear acceleration threshold experiment (d), spacecraft linear accelerations are $\leqq 0.002$ g, and for the angular acceleration threshold (c) and semicircular stimulation (e) experiments, spacecraft angular accelerations are $\leqq 0.03 \text{ deg/sec}^2$.

Mode of Operation - Generally, for each experiment the subject couch is manually positioned at the required radius and the couch is manually positioned into the proper position. The centrifuge will operate in automatic mode during rotation.

Tilt table operation for the tilt table simulation experiment (b) is programmed. For the angular acceleration threshold experiment (c), the centrifuge will be manually locked in position, the roll drive on the experiment support frame will be manually engaged. The couch rotation will then be programmed through the prescribed experiment cycle.

Crew Support - Special training will be required for operation of the facility by the experiment monitor. Crew skills will be required for the application of biomonitoring and experimental instrumentation sensors to the test subject and for medical monitoring during the test. Test subjects for the semicircular canal stimulation experiment (e) must be trained to baseline proficiency in a perceptual motor test.

Therapeutic Support Evaluation

Specific Objective - Exposure of the astronaut to zero-g over prolonged missions is expected to result in increasing habituation to that environment and corresponding decrease in orthostatic tolerance for gravity, i.e., cardiovascular debilitation. Ground-based studies have demonstrated the value of a centrifuge as a device to allay and reverse the physiological adaptation to simulated weightlessness (by bed rest or immersion). The specific objective of this experiment is to establish the extent to which onboard centrifuge acceleration exposure has therapeutic value on the adaptation of man to weightlessness.

General Description - One astronaut will be centrifuged on days 4, 7, 11, 18, 23, 27, 32, 38, and 42 of an assumed 45-day crew rotation period. A second astronaut will be centrifuged on each of the last 10 days of the crew rotation period days 36 through 45. More subjects may be used if crew work schedule permits. Each subject will ride the centrifuge four times each day for a period of 20 minutes each day. Time required per experiment would include 36 minutes of preparation, 20 minutes of testing, and 15 minutes of cleanup. The maximum radius (Ref. Figure 16 will be used with a rate of rotation to give 1.78 g accelerations at the heart. The inflight studies, as well as pre- and post-flight examinations will be used to determine the effectiveness of such exposure. Subject body orientation on the centrifuge will be axial, facing tangential.

Operational Constraints - Due to divergent physiological effects, test subjects involved in this experiment should be different from those utilized in the centrifuge reentry acceleration profile simulation.

To eliminate the possibility of artifactual disorientation and performance loss, stabilization of the spacecraft must be maintained such that the cross product of angular velocities remains below $100^{o}/sec^{2}$.

Mode of Operation - The centrifuge facility will be configured so that the experiment couch is positioned on the experiment chamber floor and oriented in a sitting position with the torso oriented parallel to the radius vector. The centrifuge will operate in automatic mode during rotation.

Crew Support - Special training will be required for operation of the facility by the experiment monitor. Crew skills will be required for the application of biomonitoring instrumentation sensors to the test subject and for medical monitoring during the test.

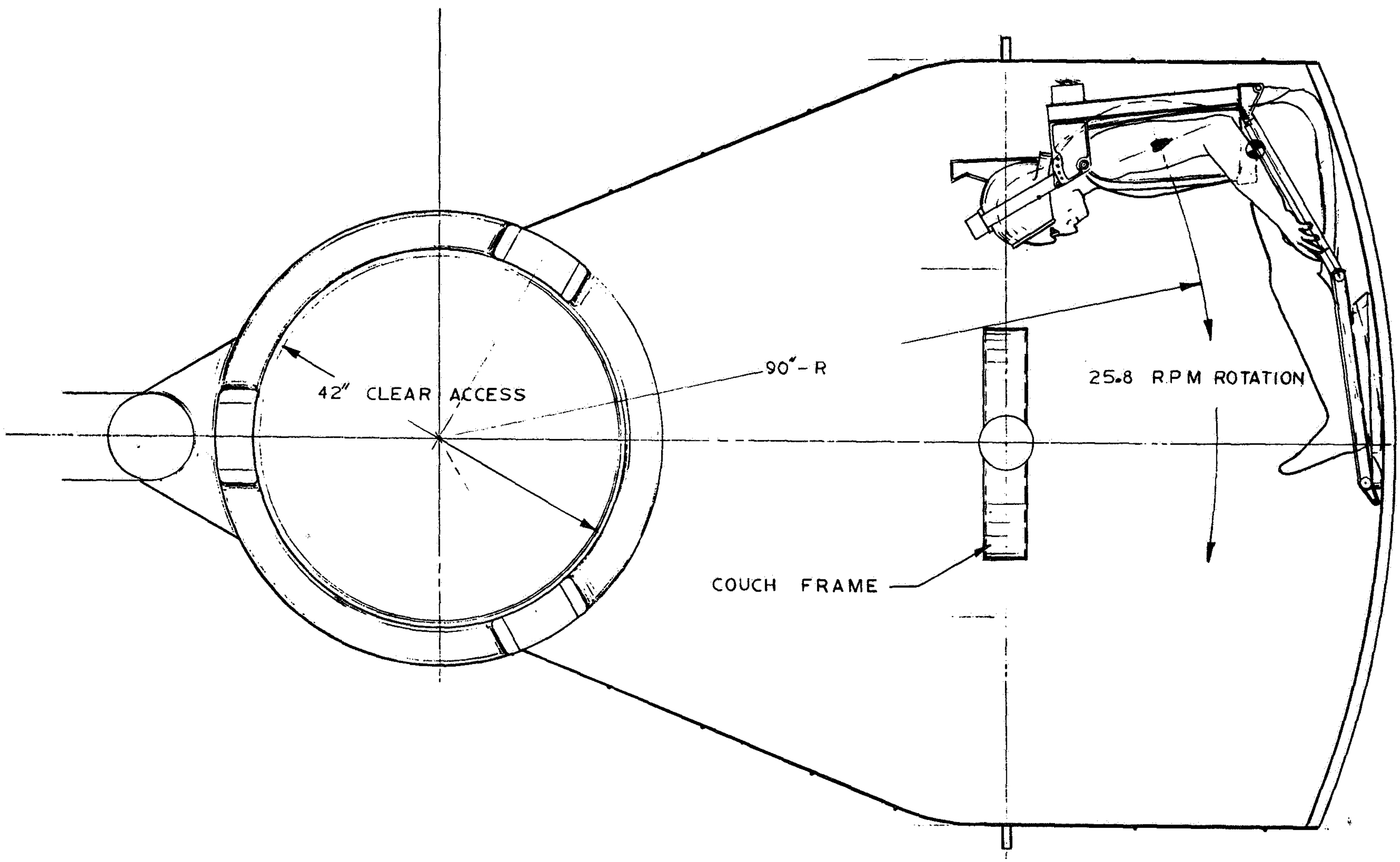


Figure 16. Therapeutic Experiment (1.7 g at Heart)

CENTRIFUGE DESIGN

Structural Design

The centrifuge can be considered as having three distinctive structural and functional entities. These are the experiment chamber, the center hub and the counterweight frame. In this section the structural details of each of these elements will be discussed. Major structural members will be defined along with their design rationale. Supporting data for the selection of materials will be given to substantiate the weight and mass properties generated in a later section. The major considerations of stiffness and structural resonance will also be discussed. Structural design criteria will be presented as will some illustrative stress analysis solutions for the major elements.

The Experiment Chamber - A symmetrical shell has been designed to provide the minimum envelope to perform the vestibular, mobility and hygiene experiments. The outboard (63.0 inches from the spin axis) portion of this shell has a constant section 48.0 inches high and 88.0 inches wide. The top and the bottom are flat and the sides are semi-circular. The outboard end of this shell is closed off with a curved floor with a radius of 112.0 inches concentric with the spin axis. The inboard portion of the chamber is made with a regular tapered section with the walls blending to the hub changing section from semi-circular to flat and vertical with a small corner radius. Thus, the edge of the shell blends with a conical section.

The shell of the experiment chamber, Figure 17, is made from several layers of graphite/epoxy to make a skin of .040 thick. The shell is stiffened longitudinally to carry both the axial and the bending loads with four stiffeners on the bottom and four on the top surface of the shell. The stiffeners have a hat shaped cross section and are made from .032 thick unidirectional graphite/epoyx, making use of that material's high modulus. These stiffeners are bonded to the shell except where they are attached to the hub ring and the floor frame and spliced at the main frame where they are mechanically attached. The outer stiffeners also act as a splice between the semicircular side walls and the flat top and bottom skins. The shell is stiffened circumferentially with an aluminun alloy frame 66.5 inches from the hub center line, which also acts as the hard point for reacting the loads and mounting the couch frame for various experiment configurations. This frame has the shape of an I-beam. There are three locations for the mounting of experiments. These are parallel to the X axis for the vestibular experiments. Here, a splined fitting is provided for the couch frame. Also, a fitting is provided on the Y axis for a drive motor for the "Z-axis roll".

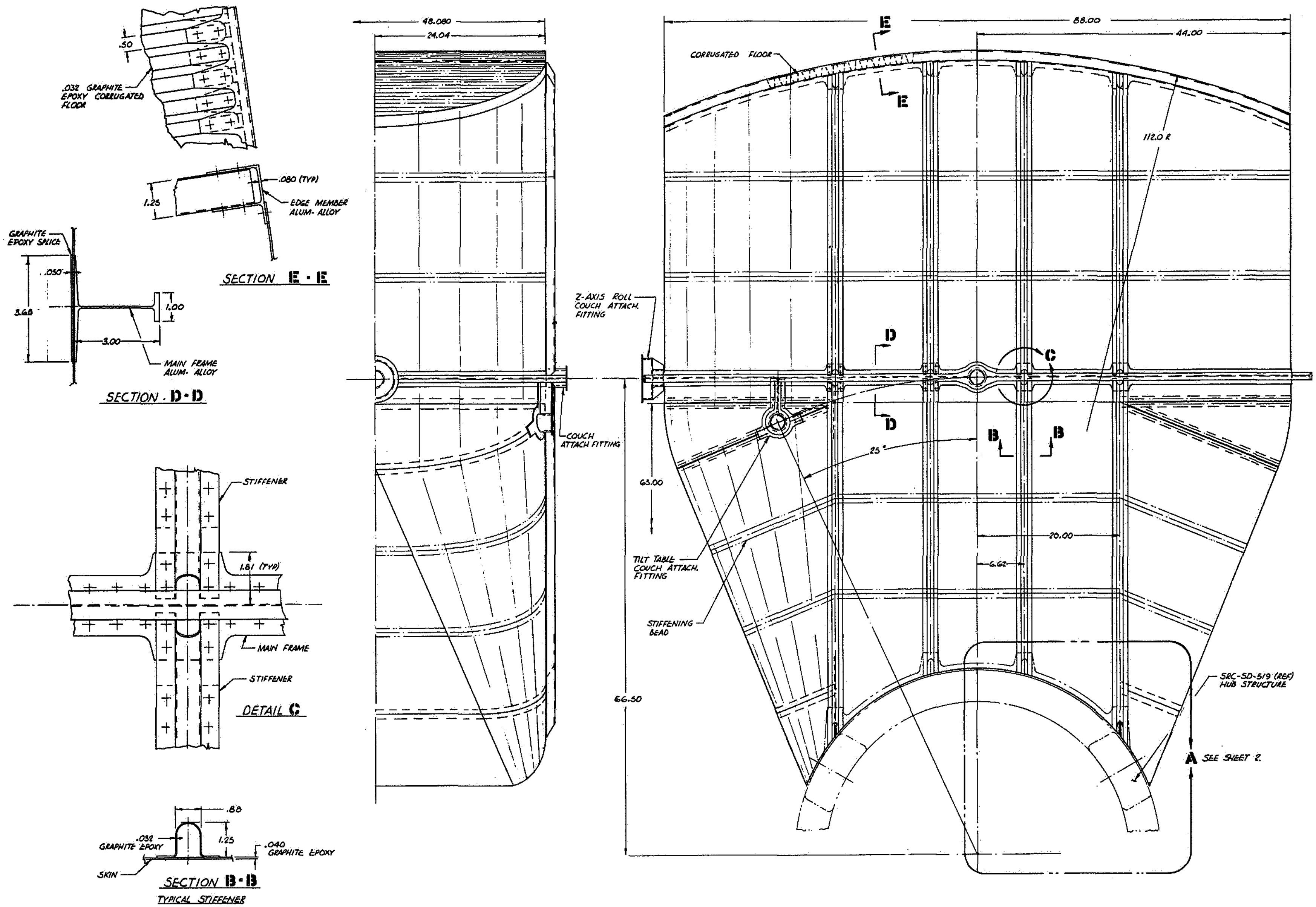


Figure 17. Experiment Chamber Structure (SRC-SD-520)

experiments. Slightly to one side of and parallel with the Z-X plane, another splined fitting is provided for the tilt table experiments. The frame also acts as a stiffening ring for the stiffeners, reducing their column length.

Additional stiffening is provided in the shell skin by bead stiffeners which may be an additional layup. These beads are spaced approximately 12.0 inches apart and run circumferentially around the shell.

The radial floor is designed primarily for the mobility experiment but was found ideal for the placing of the couch for the reentry and the therapeutic experiments. It also provides an excellent closure for the shell. It consists of a corrugated skin layup of graphite/epoxy with a scalloped channel edge member. This edge member is made from aluminum alloy and is used to mechanically attach the floor to the chamber shell. It also serves to react the centrifugal loads into the stiffeners. The inner surface is covered with a non-metallic material to give a smooth non-slip floor.

Figure 18 shows the geometry and details of the intersection of the experiment chamber and the hub. It shows also how the vertical edge of the chamber is mechanically attached to the hub by aluminum alloy angles.

The Hub Structure — The hub structure is the major central element of the centrifuge to which is attached the experiment chamber and the counterweight swing frame. It houses the main rotational drive system. It also contains the balance sensing and the power and communication systems.

It consists of two concentric sheet metal cylinders, Figure 19 with large symmetrical cutouts leaving three posts spaced at 120°. One post is lined up with the swing frame on the Z axis. The cutouts provide access from either side of the hub or from the experiment chamber to the hub. The cylindrical sections are separated by a pair of rings, one pair at the lower and the other at the upper ends of the hub. The rings are spaced 4.62 inches apart. The primary rings, the extreme upper and lower ones, are continuous and machined from aluminum alloy in a channel section. A web is extended from the flange to form tabs and an attachment area for the experiment chamber. The secondary rings are made from three segments and six intercostals which are also machined from aluminum alloy, these rings are interrupted by the center posts and the support channel. The post assembly is designed to react vertical loads and to form a very stiff reaction path for the balance sensors. The center post assembly consists of a machined fitting, a web and two angles that shear out the loads into both cylindrical shells. Lateral forces and torques are reacted out of the sensors into vertical support channels that are spaced 3.95 inches from the center post. The channels also shear out vertical loads into both cylindrical shells. The balance sensor system is attached to both the lower primary ring, the center post

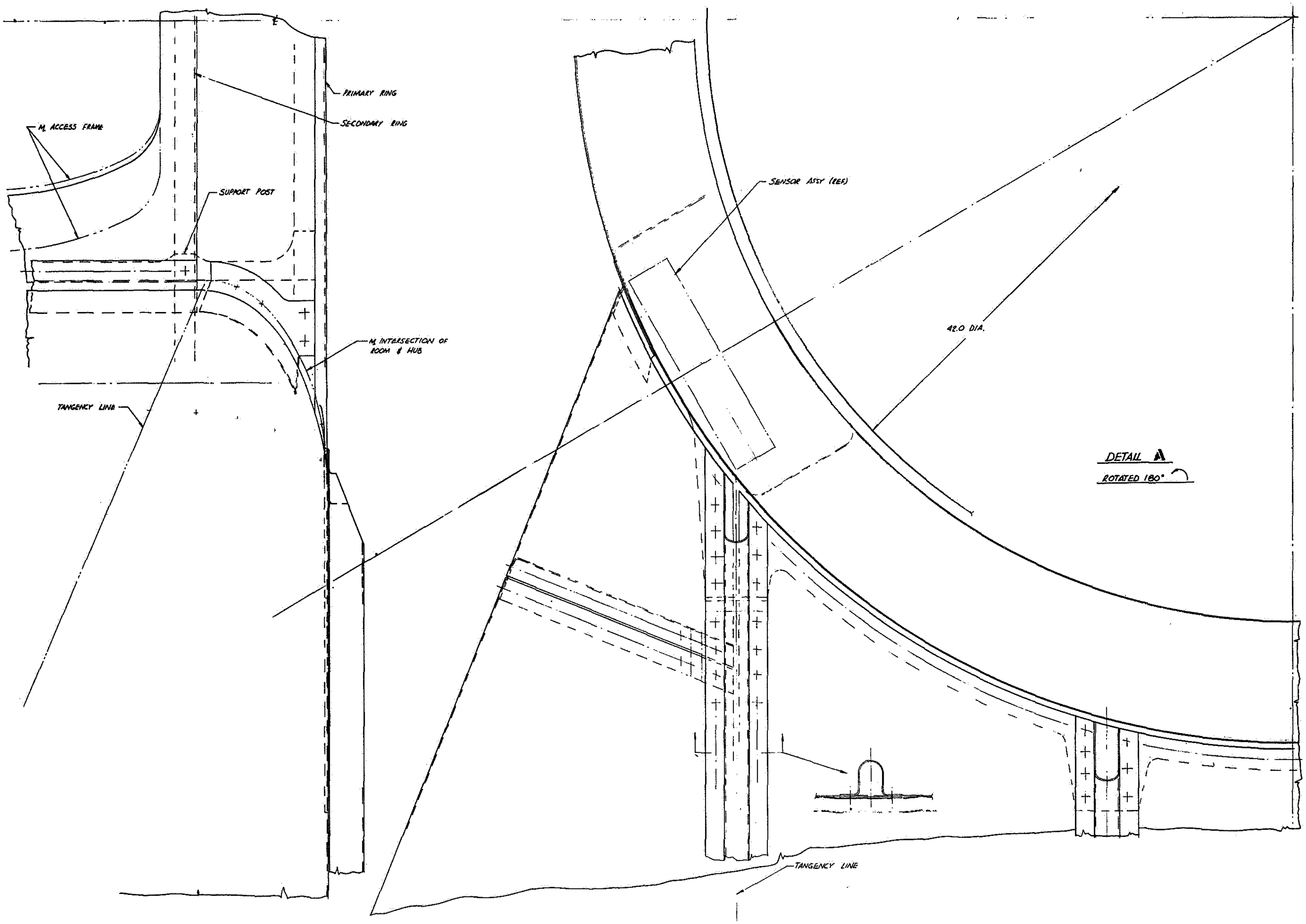


Figure 18. Experiment Chamber/Hub Intersection (SRC-SD-520)

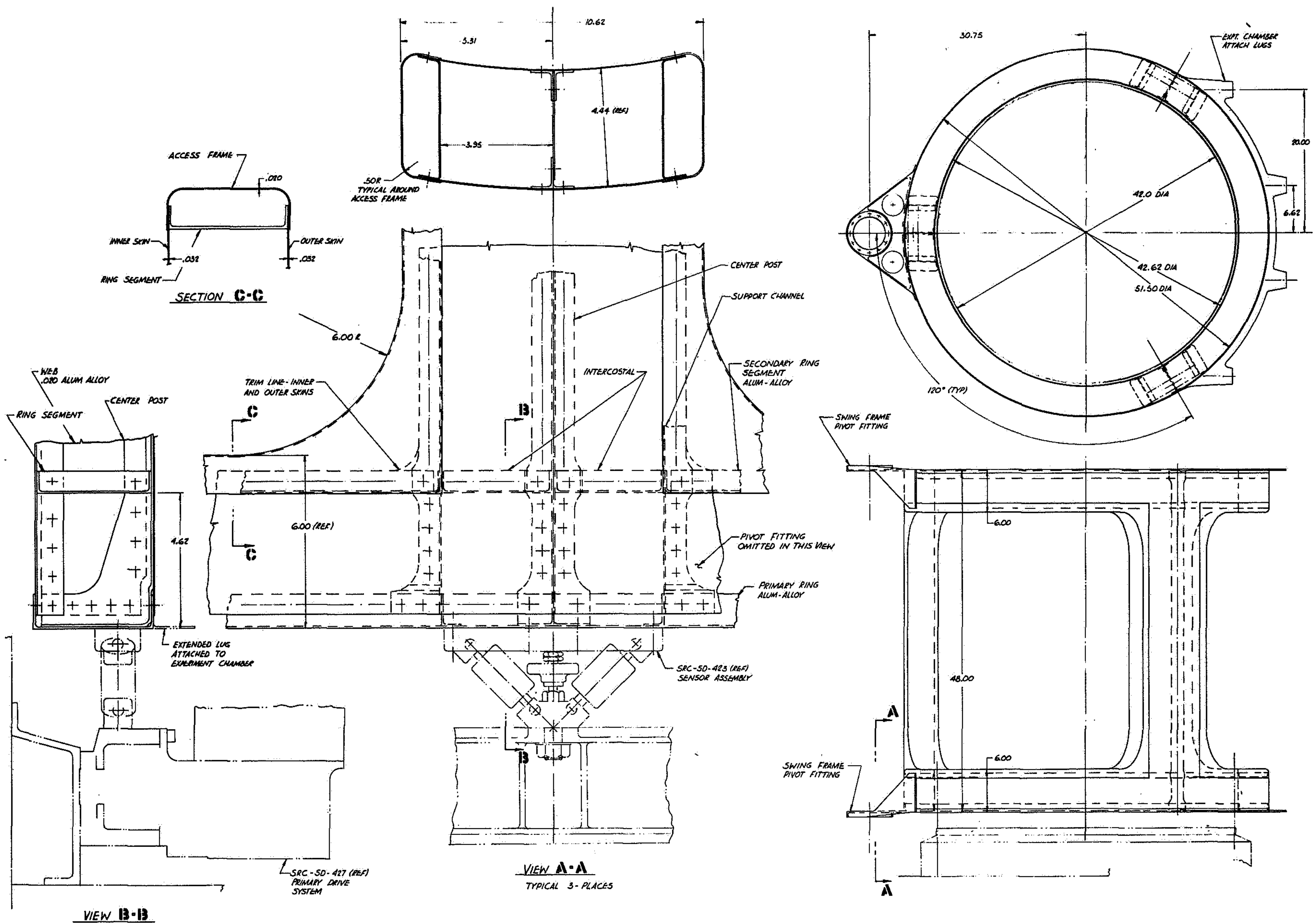


Figure 19. Hub Structure (SRC-SD-519)

and both support channels with a machined fitting. The lower end of the sensors are attached to the rotating ring of the main drive system.

The counterweight swing frame is hung from two pivot fittings that straddle both the primary and the secondary rings. These fittings are machined aluminum alloy. The bending moment loads are reacted into both rings while shear loads are taken out only in the primary ring.

The three rectangular access holes in the hub are bounded with a smoothly shaped channel frame. These access frames probably would be a non-metallic and have some resiliance to give smooth safe access to any part of the centrifuge.

The Counterweight Swing Frame — The counterweight swing frame is a beam type of structure that can pivot 30° out of plane. It has tracks to allow the counterweight carriage to move in and out. It is also designed to carry the water storage tanks that are part of the balance system and the hygiene experiment.

Both upper and lower sections of the swing frame, Figure 20, consist of a pair of channel shaped tracks assembled to and separated for a distance of 15.0 inches by a bead stiffened web. Both sections form a beam 47.38 inches deep that has a shear connection at the outboard end formed by the water tank fittings. The inboard end of the beam has a shear connection with the use of two vertical angles and a stiffened web, the web lies in a plane 90° to the Z axis. A pivot fitting is mechanically attached to both the upper and lower webs and tracks. These fittings are machined aluminum alloy and are also designed to accommodate the drive mechanism.

Figure 20. also shows how the slides are installed in both the main, the horizontal and the carriage, the vertical tracks. The slides are made from aluminum alloy and have inserts of teflon, or some similar material. The slides are made in two sections and nest within one another. They are separated by a stepped off-center bolt, that can be rotated to get a cam action on the slides. The bolt has serrations at the stepped end and can be locked in place with a serrated tab washer. The flange end of the bolt has a recess for an insert of teflon to act as a slide on the side of the channel during the imposition of lateral forces. A wrenching flat is provided on the stepped end of the bolt for adjusting the slides to a snug fit. This flat can be held while installing the tab washer.

The water tank support fittings are integral machined plate fittings stiffened vertically and longitudinally. Clevis fittings are machined into the longitudinal stiffeners, four per tank, two of these will be a tight fit to carry vertical loads while the others will be designed to carry the bending moments. The water storage tanks are made from a weldable aluminum alloy and are designed for a limit operating pressure of 60.0 psia. They are cylindrical with semi-elliptical bulkheads,

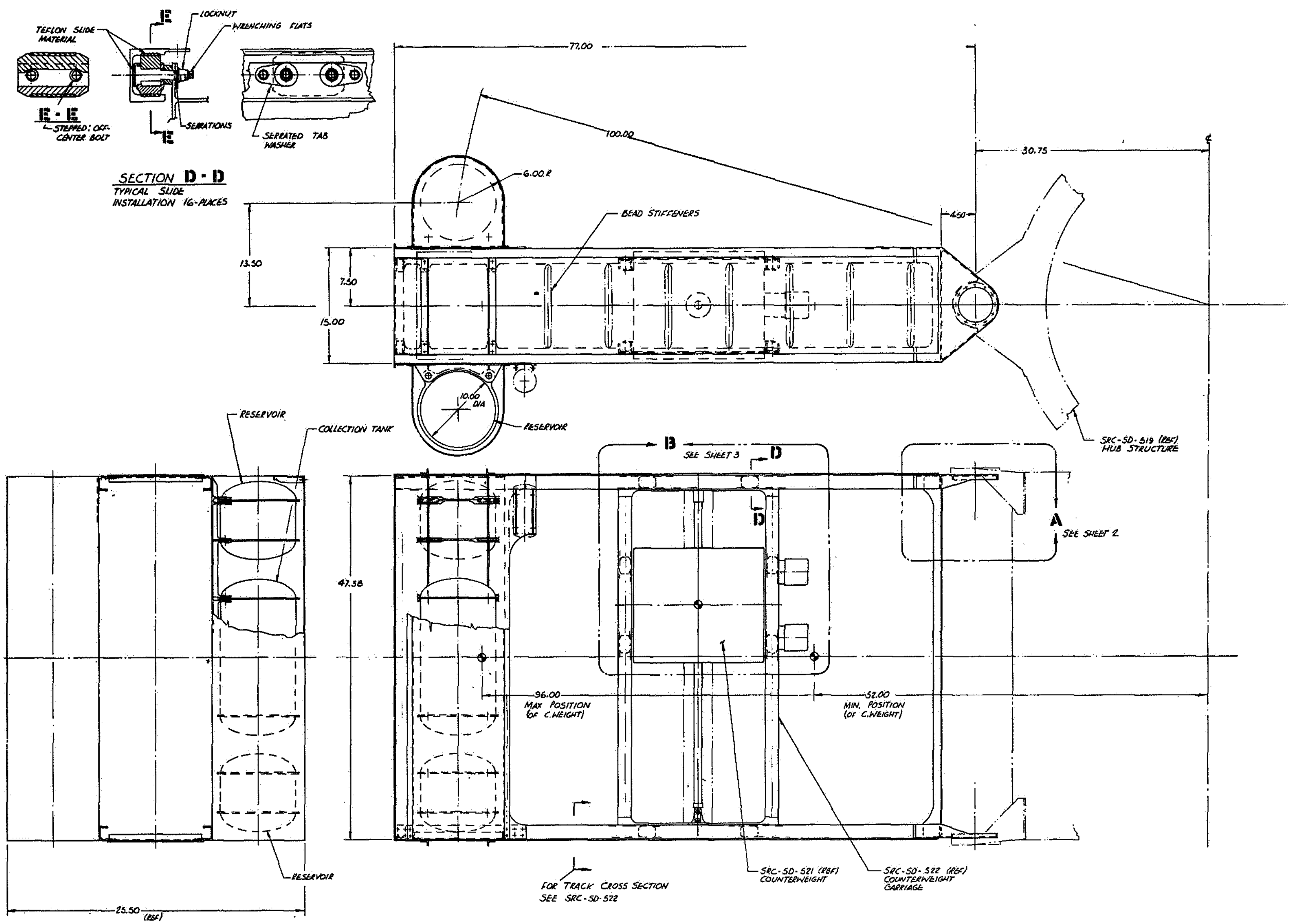


Figure 20. Swing Frame Structure (SRC-SD-518)

tee shaped rings join the bulkheads to the cylinder. Lugs are machined in these rings to attach them to the clevis fittings on the swing frame. A simple non-structural shroud covers the tanks and fittings.

Figure 21 shows the details of the swing frame pivot. It shows how the pivot mechanism is attached to the pivot fitting and how the drive screw for the counterweight carriage is attached through a transfer box. This figure also shows the extreme upper and inboard positions of the counterweight and the corresponding clearances.

The counterweight and the counterweight carriage is shown assembled in the swing frame in Figure 22. The drive mechanism for raising and lowering the counterweight and the access door to this mechanism is shown on the inboard side of the counterweight. Clearances for the drive screw, the carriage track and the counterweight are also shown.

The Counterweight Carriage — The counterweight carriage is a structure to carry the counterweight axially inboard and outboard under control of a drive screw. It also carries the mechanism for moving the counterweight vertically for dynamic balancing of the centrifuge.

The carriage, Figure 23, is made from four vertical channel shaped tracks attached at their upper and lower extremities to a large machined fitting. These tracks have the same cross section as the swing frame tracks and are designed to accommodate the slides described in the <u>Swing Frame</u> section. Both upper and lower fittings are integrally machined from a plate and have mounting provisions for the ball nut for moving the counterweight axially. The upper fitting has a mounting pad for flange mounting the actuator while the lower fitting has a lug for the lower end attachment.

The Counterweight — The counterweight is a box type structure that contains the batteries and electronic equipment that can be moved vertically in the carriage tracks.

The counterweight, Figure 24 is a sheet metal box that straddles the drive mechanism. It has two inner vertical webs with tee shaped fittings that are the attachment to the drive mechanism. Provisions are made for nineteen batteries to be stored in the structure, eight on either side and three outboard of the mechanism. The batteries are mounted in compartments, and above and below them are shelves for equipment mounting. Both sides of the structure are hinged to provide access to the batteries and the equipment. Additionally, the outboard end hinges for access to that section.

Access to the drive mechanism is provided by a wrap around panel on the inboard end of the box.

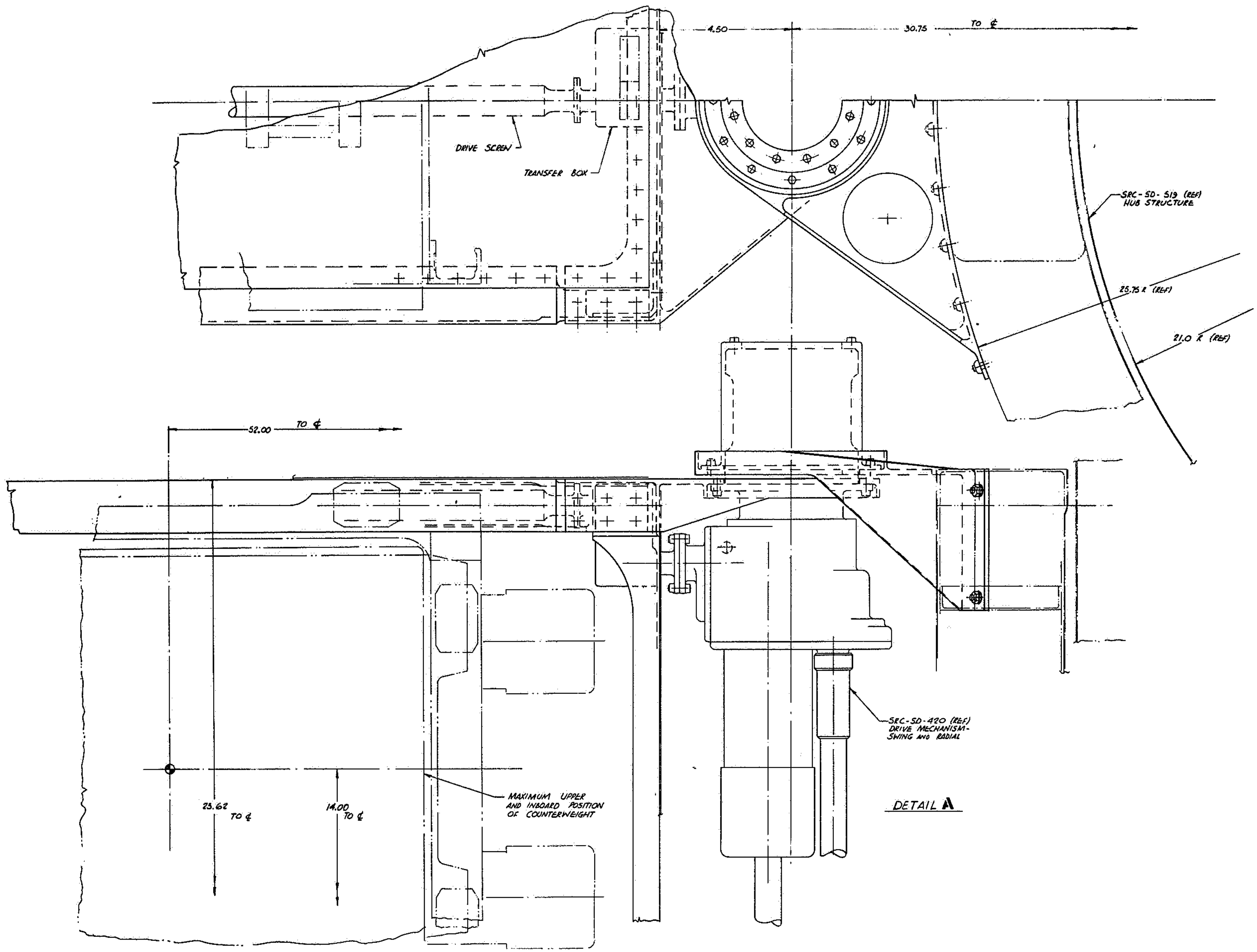


Figure 21. Swing Frame Structural Detail (SRC-SD-518)

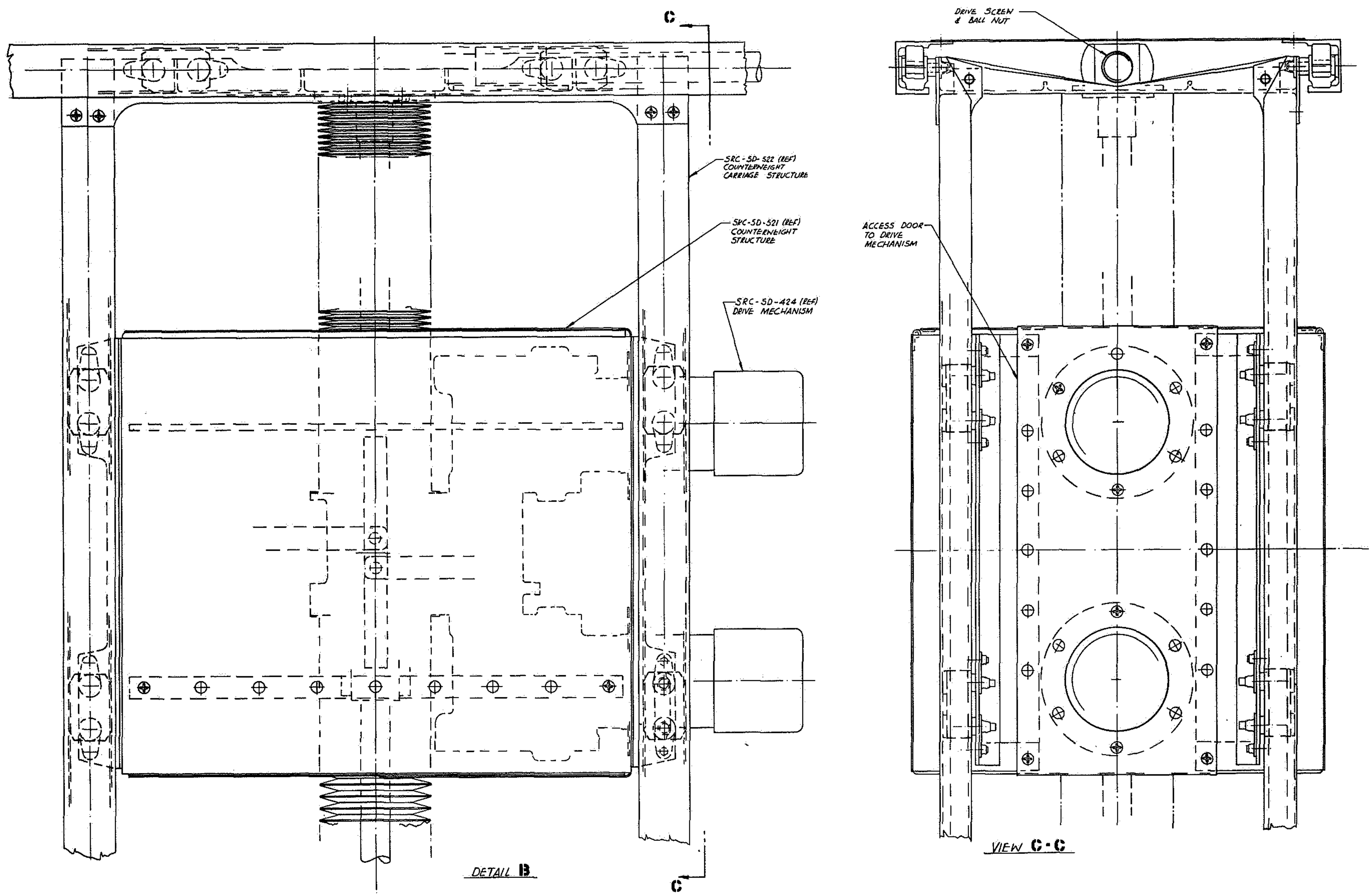


Figure 22. Swing Frame Structural Detail (SRC-SD-518)

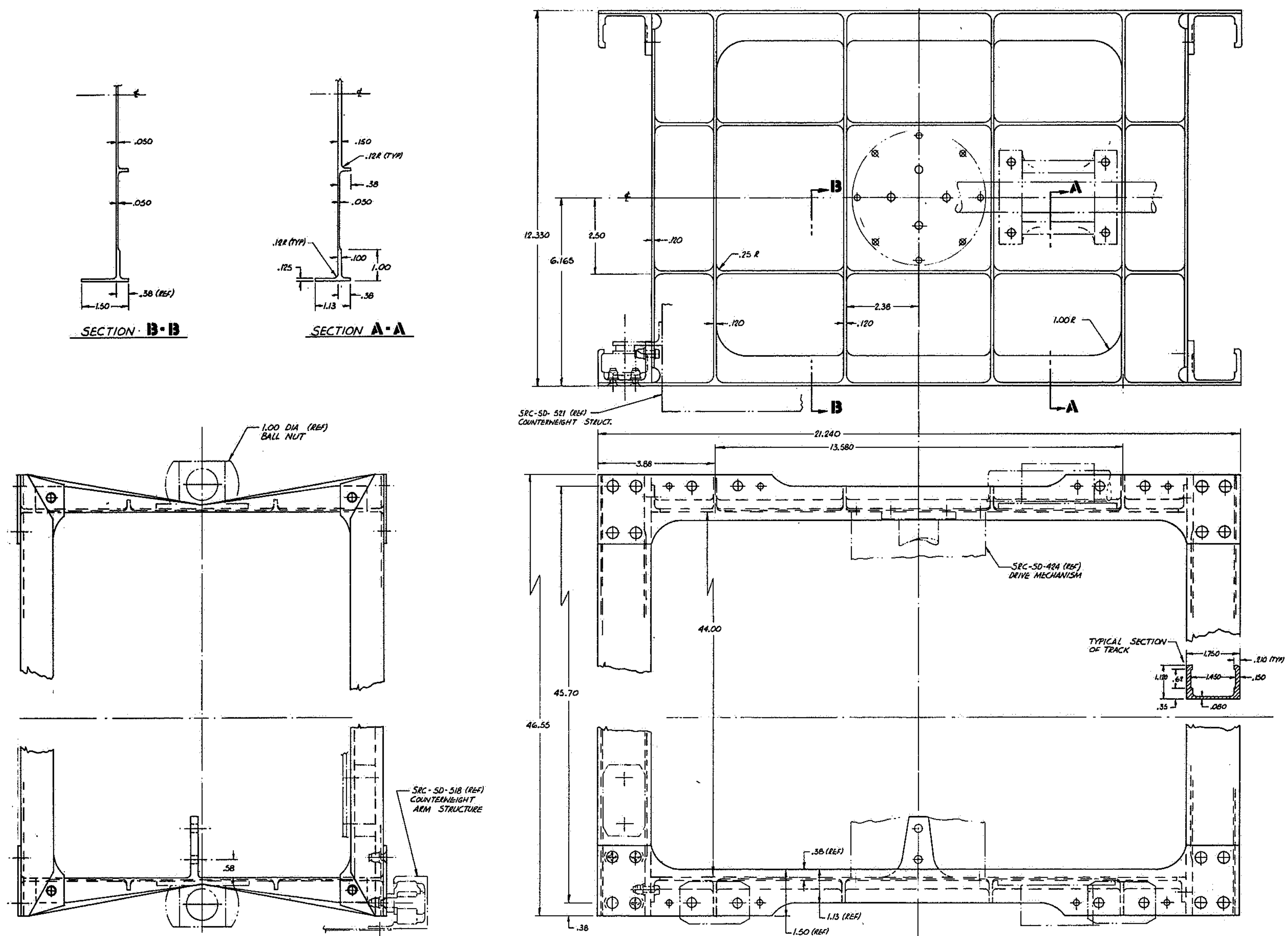


Figure 23. Counterweight Carriage Structure (SRC-SD-522)

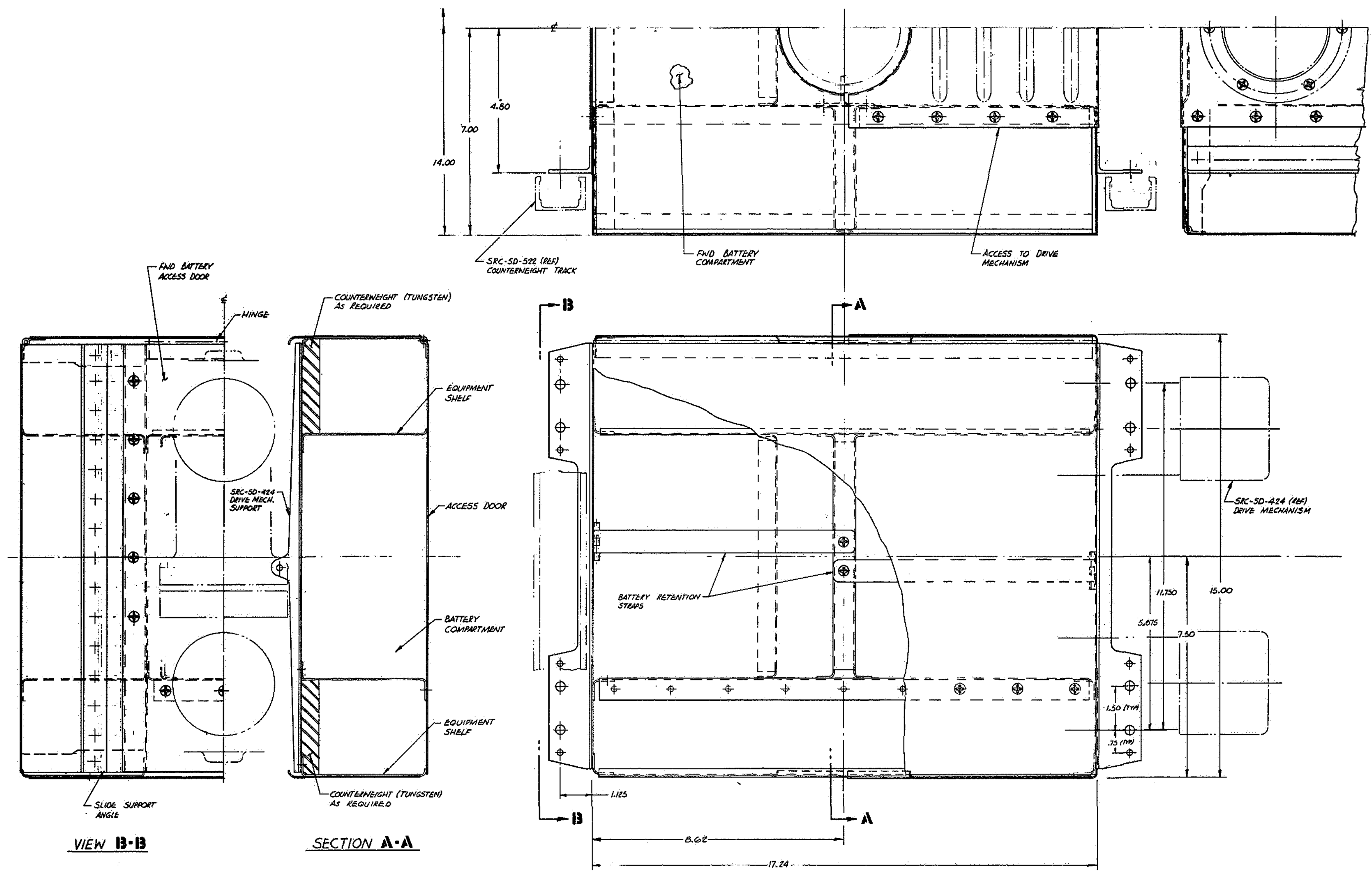


Figure 24. Counterweight Structure (SRC-SD-521)

Provisions are also made for the addition of tungsten weights if the mass of the counterweight must be increased to accommodate possible mass distribution changes.

Material Selection - The structural loads imposed on the centrifuge by the ground tests or during orbital operation are small. Therefore, only small advantages can be gained by the use of high strength alloys. However, the requirements of stiffness and high structural resonance do influence the selection of material. Other influences in the selection process that must be considered are fabricability, weight and total costs.

The experiment chamber is a large thin shell structure subjected to fairly small bending and axial loads, but probably critical for stiffness. Here, high modulus materials can be used to advantage. For high natural frequencies in bending, the parameter $(E_c/W)^{1/2}$, modulus over density, determines the better materials. The higher the number, the better the material. For a given component weight, the stiffness varies directly as the modulus. As it is desirable to keep the rotating weight, and the momentum, as low as possible the material with the highest value for this parameter is most desirable. Table 3 shows some candidate materials that could be used for fabricating the centrifuge. It can be seen that the parameter $(E_c/W)^{1/2}$ is essentially the same for the three common materials, aluminum, titanium and steel and no advantages can be gained with any of these materials. The stiffest material is beryllium, but it is expensive and is difficult to fabricate. Boron/aluminum has good properties but has some fabrication limitations, mainly in the attachment and forming operations. Forming limitations are due to the high inherent stiffness of the boron fibers and are dependent on their orientation. The forming operation limitations also apply to the boron/epoxy, but with this material the attachment problems are less severe. The material with the best combination of properties for this application is the graphite/epoxy, Reference 5. It is available as broad goods and can be draped or layed up to form shapes like the standard fiberglass materials. It can be attached to other structures either by bonding or with mechanical attachments. The cost of the material is approximately the same as boron/epoxy when fabricated.

The hub structure is a large circular structure subjected to large torsional loads. It is also required to be stiff axially. By its size and geometry it has high inherent stiffness. For cost and fabrication considerations aluminum alloys have been selected for this element.

The swing frame is essentially a beam structure and is subjected to bending, axial and torsional loads. It requires a high degree of stiffness to be responsive to balance control requirements. The travel requirements of the counterweight establish the geometry of the frame. The size of the tracks and their spacing are to keep the bearing stresses low and to ensure stable tracking of the counterweight. From these

constraints the structural characteristics are pre-determined and adequate for the stiffness requirements if the aluminum alloys are used.

Table 3 - Candidate Materials

MATERIAL	%V FIBER	w LBS/IN^3	F_{tu} $\times 10^3$	F_{cy} $\times 10^3$	E_c $\times 10^6$	F_{su} $\times 10^3$	$\sqrt{E_c/w}$ $\times 10^3$	$/LB INSTALLED EST.
7075 - T6 Al Alloy		0.101	78.0	70.0	10.5	47.0	10.2	80
6 Al-4V Titanium		0.160	145.0	154.0	16.0	80.0	10.0	120
4340 Steel		0.283	150.0	145.0	29.0	95.0	10.2	120
Beryllium (Cross Rolled)		0.066	85.0	70.0	42.0	40.0	25.2	750
Boron/Aluminum U.D.	50.0	0.096	162.0	115.0	34.0	10.1	18.8	1130
Boron/Aluminum C.P.	50.0	0.096	80.0	78.0	19.2	20.0	14.1	1130
Boron/Epoxy U.D.	64.0	0.066	179.0	275.0	28.1	12.0	20.6	500
Boron/Epoxy C.P.	64.8	0.066	70.2	67.0	17.0	33.6	16.1	500
Graphite/Epoxy U.D. (Morganite I)	70.0	0.054	84.0	62.0	29.5	4.5	23.4	500
Graphite/Epoxy C.P. (Morganite I)	70.0	0.054	39.0	36.0	15.0	22.5	16.0	500

U.D. = Unidirectional
C.P. = Cross Ply

Structural Stiffness — Separation of the natural frequency of the structural assembly from all operating frequencies has been recognized as a major structural requirement during the design of the centrifuge structure. This separation is necessary to prevent resonant conditions occuring while performing the experiments. The maximum rotational speed of 46.9 RPM results in a .781 cps (cycles per second) forcing or operating frequency. This occurs during the reentry experiments, the lowest operating frequency is in the mobility series of experiments and is .230 cps.

A conservative frequency separation ratio ($\omega_{natural}/\omega_{operating}$) of approximately 13 has been adopted to give a $\omega_{natural}$ of 10 cps at the maximum operating frequency. This value has been used for the design of those single structural components that are clearly identifiable. It is recognized that the overall natural frequency of the entire rotating centrifuge structure assembly will be less than the 10 cps value. However by taking the conservative approach to structural design it is felt that adequate separation has been achieved. This design study, like the one previously conducted by Convair (Reference 1), has not resolved all the problems of structural stiffness or mass distribution. But, it has recognized these problems exist. Further study is required to establish complete analytical models for study of the actual structural system. Also analytical methods are required for determining structural element stiffness requirements.

One particular area where stiffness is critical is in the structure that supports the balance sensors. The hub structure, the drive ring and the spacecraft structure all have to be stiff enough so that sensor sensitivity is not compromised. Thus, the spring rate, the stiffness, of these items has to be higher than that of the sensors.

Stress Analysis — Structural loads are imposed on the rotating portion of the centrifuge for a variety of environmental conditions. These include ground handling and checkout, launch, boost to orbit and all of the orbital or experimental operations. The loads will be of various magnitudes and will act in different planes dependent on the operating mode and the experiment requirements.

During rotational accelerations, forces will be produced in the spin plane normal to the Z axis while centrifugal forces will produce axially loads along that axis. During ground checkout, inertia forces can add a third direction of loading. These ground test loads can be eliminated if the test subject and his equipment is artificially supported. A thorough analysis is required to determine if the maximum design loads on the structure are caused by ground loads or by other criteria. At the present time it has been assumed that the ground loads produce no structural penalties and have been used in the design of the structure. It will be shown that by using these loads for the design of axial members results in stiffeners of good proportions for resonance stiffening of the experiment chamber.

External loads to the centrifuge, from launch and boost for example, have been neglected. It has been assumed that during these operations the centrifuge will be configured so that minimum loads result. The counterweight will be retracted, the couch and frame will be stored near the hub or attached to some other rugged structure. Non-permanent devices will be used to react launch loads from the experiment chamber and the counterweight swing frame to the spacecraft structure.

The following groundrules have been observed during the design of the selected baseline configuration.

- Sign convention will be as shown in Figure 25.
- Emergency stop from maximum speed, 1.0 seconds
- Design life, 5,000 hours
- Operating environment — mixed gases at 10.0 psia & $70^{\circ}F$

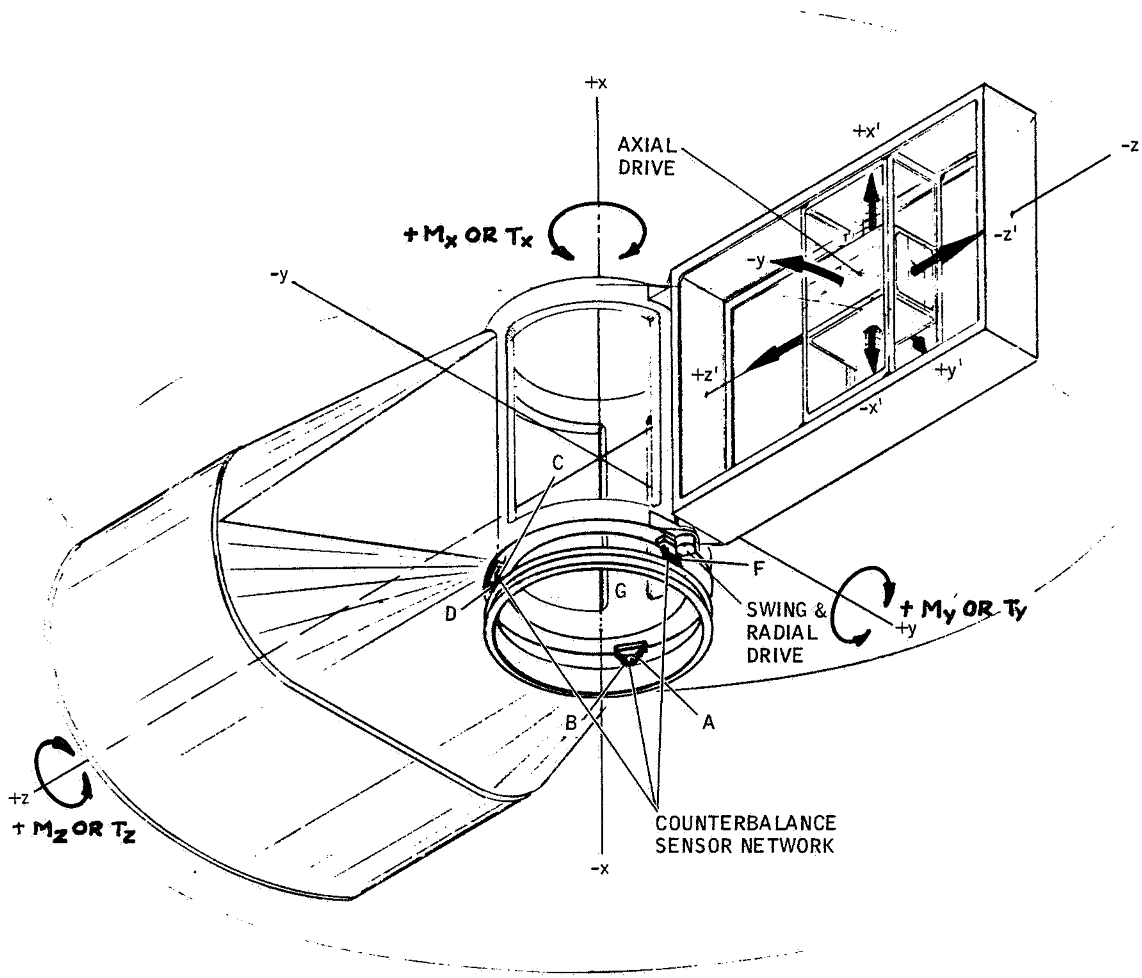


Figure 25. **Centrifuge** Orientation and Sign Convention

- First bending mode frequency for the structure, 10.0 cps
- Ultimate loads are 1.5 time the limit or operating loads

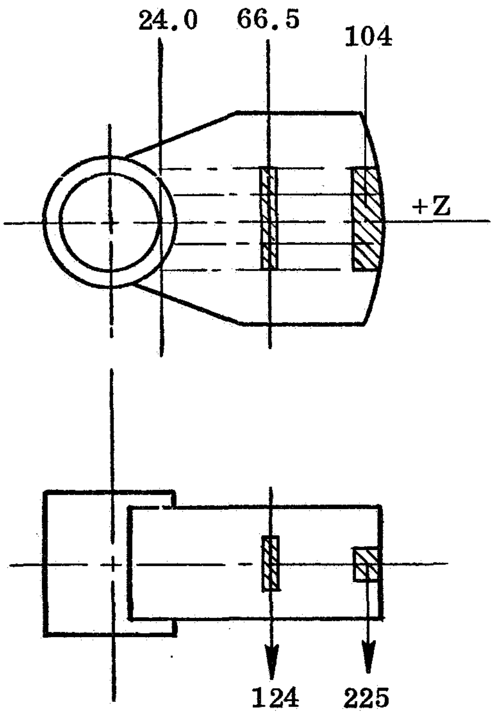
Other detailed groundrules or assumptions will be defined in the following sections.

The following calculations show the major loads on the experiment chamber for six of the seven experiments. The mobility experiment produces significant loads only on the floor and that is shown in a subsequent section.

In this section the first subscript on a load indicates the direction, and the second, the station at which the load is applied; e.g. $P_{Z\ 24.0}$ indicates an axial load in the +Z direction at a station 24.0 inches from the center of spin.

Table 4 summarizes the maximum loads on the experiment chamber.

1. Experiment — Reentry



6.0 g on Subject

$\omega = 4.911$ rads/sec

$- M_{Y\ 66.5} = 1.5 \times 225 \times 37.5 = 12,700$ in lbs

$- M_{Y\ 24.0} = 1.5\ (225 \times 80 + 124 \times 42.5)$

$\doteq 35,000$ in lbs

$P_{Z\ 66.5} = 1.5 \times 225 \times 6 = 2020$ lbs

$P_{Z\ 24.0} = 1.5 \times 349 \times 6 = 3120$ lbs

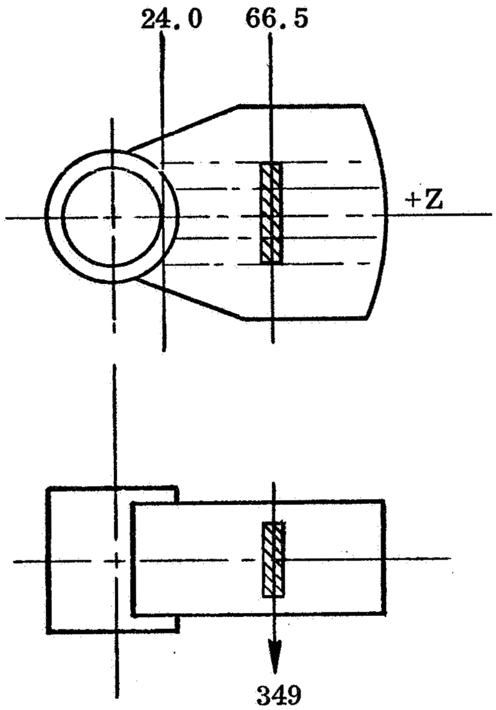
During emergency stop:

Inertia load between couch and floor

$$P_Y = \frac{\text{Momentum}}{\text{Arm x time}}$$

$$P_{Y\ 104} = \frac{1.5 \quad 225 \times 104 \times 4.911}{32.2 \quad 12 \quad 1.0} = 374 \text{ lbs}$$

2. Experiment — Vestibular



1.0 g on Subject

ω = 2.41 rads/sec

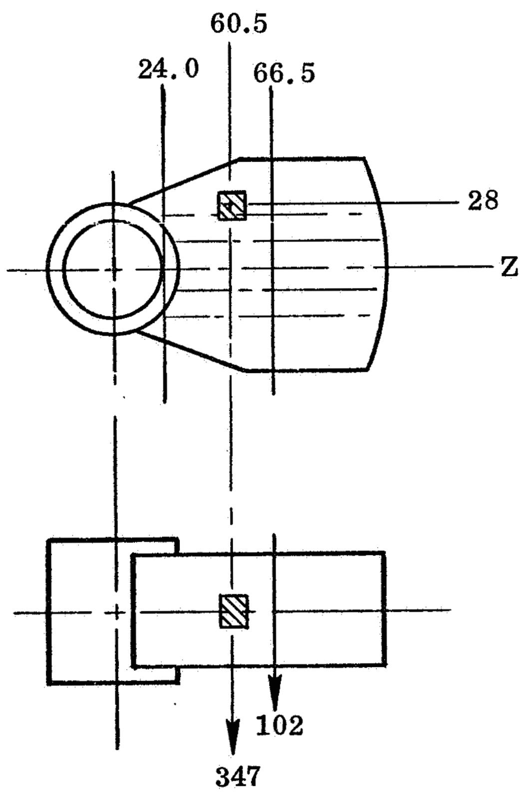
$$-M_{Y\ 24.0} = 1.5 \times 349 \times 42.5 = 22{,}200 \text{ in-lbs}$$

$$P_{Z\ 24.0} = 1.5 \times 349 \times 1.0 = 525 \text{ lbs}$$

During emergency stop:

$$P_{Y\,66.5} = \frac{1.5 \times 349 \times 66.5 \times 2.41}{32.2 \times 12 \times 1.0} = 216 \text{ lbs}$$

3. Experiment — Tilt Table



1.0 g on Subject

ω = 2.41 rad/sec

$$-M_{Y\ 24.0} = 1.5\ (247 \times 35.5 + 102 \times 42.5)$$

$$= 19{,}700 \text{ in-lbs}$$

$$-T_{Z\ 60.5} = 1.5 \times 247 \times 28 = 10{,}400 \text{ lb-in}$$

$$P_{Z\ 24} = 1.5 \times 349 \times 1.0 = 525 \text{ lbs}$$

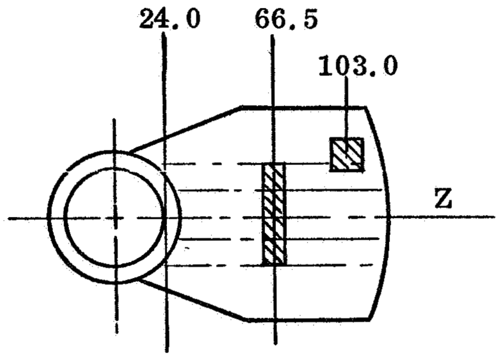
During emergency stop:

$$P_{Y\ 60.5} = \frac{1.5 \times 225 \times 60.5 \times 2.41}{32.2 \times 12 \times 1.0} = 127 \text{ lbs}$$

4. Experiment — Therapeutic

2.0 g on Subject

ω = 2.7 rad/sec



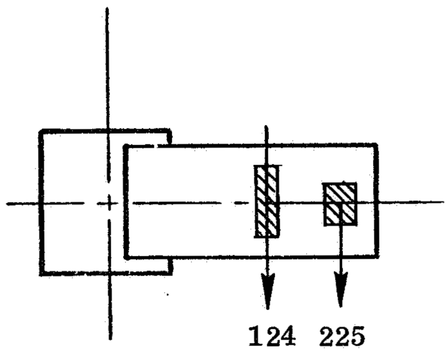
$$-\ M_{Y\ 66.5} = 1.5 \times 225 \times 36.5 = 12{,}400 \text{ in-lbs}$$

$$-\ M_{Y\ 24.0} = 1.5\,(225 \times 79 + 124 \times 42.5) = 33{,}700 \text{ in-lbs}$$

$$-\ T_{Z\ 103} = 1.5 \times 225 \times 35 = 11{,}800 \text{ lbs-in}$$

$$P_{Z\ 66.5} = 1.5 \times 225 \times 2.0 = 675 \text{ lbs}$$

$$P_{Z\ 24.0} = 1.5 \times 349 \times 2.0 = 1040 \text{ lbs}$$



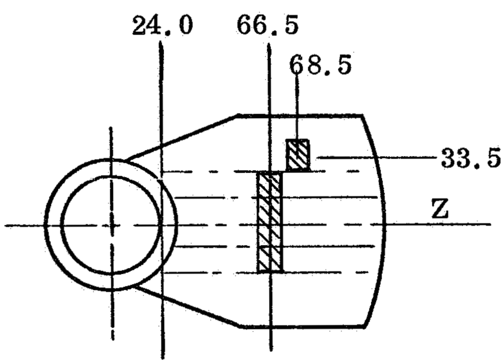
During emergency stop:

$$P_{Y\ 103} = \frac{1.5 \times 225 \times 103 \times 2.7}{32.2 \times 12 \times 1.0} = 242 \text{ lbs}$$

5. Experiment — Grayout

4.20 g on Subject

ω = 4.6 rads/sec



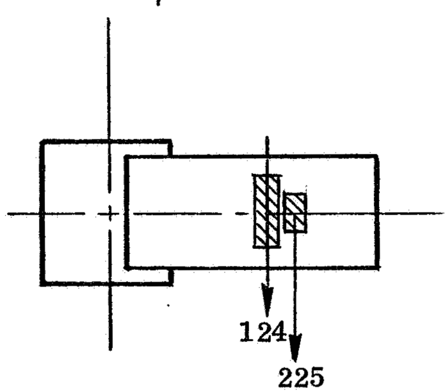
$$-\ M_{Y\ 24.0} = 1.5\,(124 \times 42.5 + 225 \times 44.5)$$
$$= 23{,}000 \text{ in-lbs}$$

$$-\ T_{Z\ 68.5} = 1.5 \times 225 \times 33.5 = 11{,}300 \text{ lbs-ins}$$

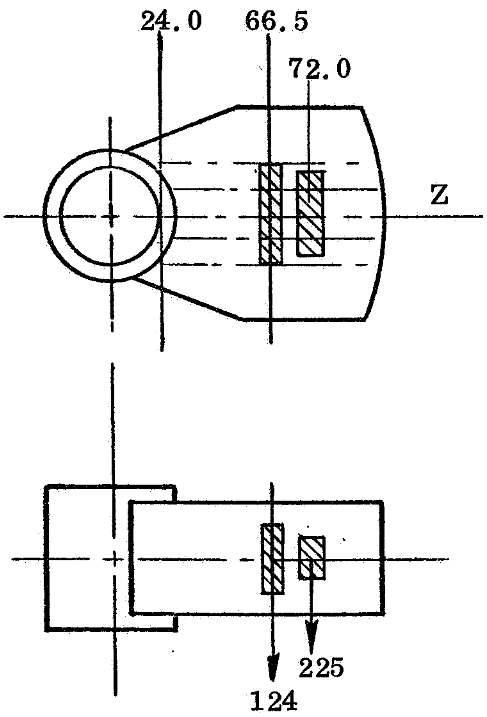
$$P_{Z\ 24.0} = 1.5 \times 349 \times 4.2 = 2200 \text{ lbs}$$

During emergency stop:

$$P_{Y\ 68.5} = \frac{1.5 \times 225 \times 76.5 \times 4.6}{32.2 \times 12 \times 1.0} = 309 \text{ lbs}$$



6.0 Experiment — Hygiene



0.40 g on Subject

ω = 1.46 rads/sec

$$-M_{Y\,24.0} = 1.5\,(225 \times 48 + 124 \times 42.5)$$

$$= 24,100 \text{ in-lbs}$$

$$P_{Z\,24.0} = 1.5 \times 349 \times .40 = 210 \text{ lbs}$$

During emergency stop:

$$P_{Y\,72.0} = \frac{1.5 \times 225 \times 72 \times 1.46}{32.2 \times 12} = 92 \text{ lbs}$$

Table 4. Load Summary - Experiment Chamber

EXPERIMENT	STATION + Z INS	$-M_Z$ IN LBS	$-P_Y$ LBS	$-T_Z$ LBS INS	P_Z LBS
Reentry	24.0	35,000			3120
	66.5	12,700			2020
	104.0		374		
Vestibular	24.0	22,000			525
	66.5		216		
Tilt Table	24.0	19,700			525
	60.5		127	10,400	
Therapeutic	24.0	33,700	242		1040
	66.5	12,400			675
	103			11,800	
Greyout	24.0	23,000			2200
	68.5		309	11,300	
Hygiene	24.0	24,100			210
	72.0		92		

Condition — Ground Test + 1.0 Second Stop.

All Loads Ultimate.

A. EXPERIMENT CHAMBER STIFFENERS Dwg. No. SRC-SD-520

Max load during Reentry Experiment ground tests

Material: Graphite/Epoxy ~ Unidirectional

$$\left.\begin{aligned} -\ M_Y &= 35,000 \\ P_Z &= 2020 \end{aligned}\right\}\ \text{acting concurrently}$$

$$P_{NOM.} = \frac{35000}{48.99 \times 4} = 1800/\text{stiffener}$$

$$P_Z = \frac{3120}{8} = 390/\text{stiffener}$$

Lower Stiff Load - Compression

$$P_{Stiff} = 1800 - 390 = 1410 \text{ lbs compression}$$

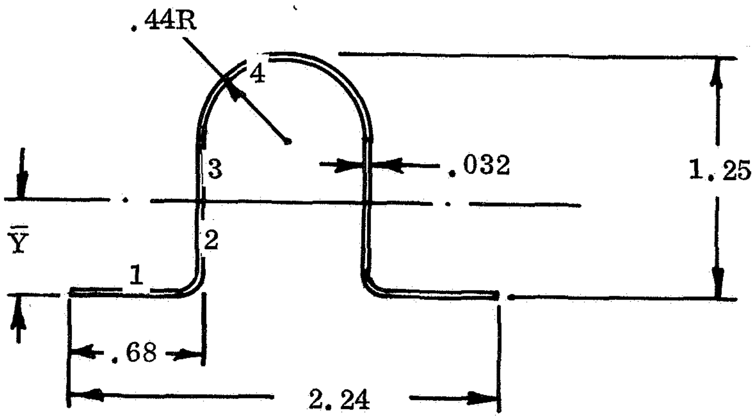
$$\sigma_c = \frac{1410}{.14} = 10,200 \text{ psi}$$

Upper Stiff Load - Tension

$$P_{Stiff} = 1800 + 390 = 2190 \text{ tension}$$

$$\sigma_t = \frac{2190}{.14} = 15,600 \text{ psi}$$

The selected stiffener is as follows



$$\bar{Y} = \frac{2 \times .032 \times .68 \times .016 + 2 \times .032 \times .81 \times .405 + \pi \times .44 \times .032 \times 1.07}{2 \times .032 \times .68 + 2 \times .032 \times .81 + \pi \times .44 \times .032}$$

$$= \frac{.000695 + .021 + .0472}{.0435 + .0518 + .044} = .495$$

No.	A	Y	Y^2	AY^2	I_o
1	.0435	.480	.230	.010	.0
2	.0316	.2475	.061	.0019	.00324
3	.0202	.157	.0247	.0005	.00067
4	.0440	.575	.330	.0145	.00055
$\Sigma A =$	.1393			$\Sigma AY^2 =$ .0269	$\Sigma I_o =$ .00446

$$I_{XX} = \Sigma AY^2 + \Sigma I_o$$

$$= .0314$$

$$\rho_{XX} = (.0314/.1393)^{1/2} = .51$$

Stiffener properties are:

$A = .1393 \text{ in}^2$

$\bar{Y} = .495 \text{ in}$

$I_{XX} = .0314 \text{ in}^4$

$\rho_{XX} = .51 \text{ in}$

$$F_c = \frac{C\pi^2 E}{(L/\rho)^2}$$

For unidirectional graphite/epoxy stiffeners where:

$C = 1$

$E = 29.5 \times 10^6 \text{ in}^2$

$L = 48 \text{ in}$

$\rho = .51 \text{ in}$

$$F_c = \frac{\pi^2 \times 29.5 \times 10^6}{(48/.51)^2}$$

$$= 32,000 \text{ psi}$$

Margin of Safety

$$\text{Tension} \quad \frac{84,000}{15,600} - 1 = +4.4$$

$$\text{Compression} \quad \frac{32,000}{10,200} - 1 = +2.1$$

B. EXPERIMENT CHAMBER WALLS. Dwg. No. SRC-SD-520

Material: Graphite/Epoxy ~ Cross Plied

Consider the natural frequency of the upper and lower flat wall panels.

$$f_n = \frac{\pi}{2} \left(\frac{g\,E\,t^2}{W\,12\,(1-\mu^2)} \right)^{1/2} \left(\frac{m^2}{A^2} + \frac{n^2}{b^2} \right) \text{ cps} \qquad \text{Reference 6}$$

where $a = 40$ ins = width of plate

$b = 80$ ins = length of plate

$E = 29.5 \quad 10^6$ lb/in^2 = modulus

$W = .054$ lbs/in^3 = material density

$t = .040$ ins = plate thickness

$\mu = .25$ = Poisson's ratio

m and n = 1 = integers describing mode of vibration

$g = 386$ ins/sec^2

$$f_n = \frac{\pi}{2} \left(\frac{386 \times 29.5 \times 10^6 \times .040^2}{.054 \times 12\,(1 - .25^2)} \right)^{1/2} \left(\frac{1}{40^2} + \frac{1}{80^2} \right) \text{ cps}$$

$f_n = 6.9$ cps

This is acceptable for this element, the longitudinal stiffeners and the transverse bead stiffeners may raise this value.

C. MOBILITY EXPERIMENT FLOOR Dwg. No. SRC-SD-520

Material: Graphite/Epoxy Cross Plied

Assume 200 lb subject & .4 g acceleration

Ult. Load = 1.5 x 200 x .4 = 120 lbs

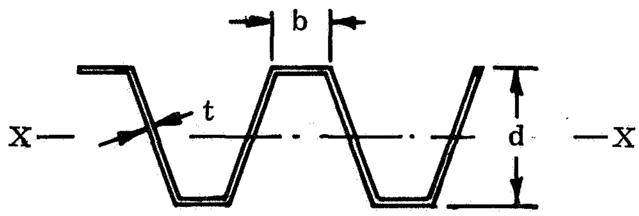
Assume subject applied point load across two corrugations.

I_{XX} for two corrugations

$$I_{XX} = t\left[b\,D^2 + \frac{D^3}{3}\right]$$

$$= .032\left[.50 \times 1.25^2 + \frac{1.25^3}{3}\right]$$

$$= .046 \text{ in}^4$$



b = .50

d = 1.25

t = .032

If two corrugations act as a simple beam

$$\text{Moment} = \frac{PL}{4} = \frac{120 \times 48}{4}$$

$$= 1440 \text{ in-lbs}$$

Then $\sigma_C = \dfrac{1440 \times .62}{.046}$

$$= 19,400 \text{ psi}$$

$$\text{M.S} = \frac{39,000}{19,400} - 1 = 1.01$$

To check long element for crippling

$$\sigma_{cc} = KE\left(\frac{t}{b}\right)^2$$

$$= 3.62 \times 29.5 \times 10^6 \left(\frac{.032}{1.31}\right)^2$$

$$= 62{,}500 \text{ psi}$$

This is higher than σ_{c} so the element will not cripple.

If corrugations act as simple supported beam then deflection

$$\delta = \frac{PL^3}{48\,EI}$$

$$\delta = \frac{120 \times 48^3}{48 \times 29.5 \times 10^6 \times .046}$$

$$= .204 \text{ ins}$$

Actual deflection will be less than this value due to partial end fixity and biaxial effects and it should be acceptable to the test subject.

The natural frequency of these elements can be determined from

$$f_n = \frac{1}{2\pi} \left[\frac{g}{\delta}\right]^{1/2}$$

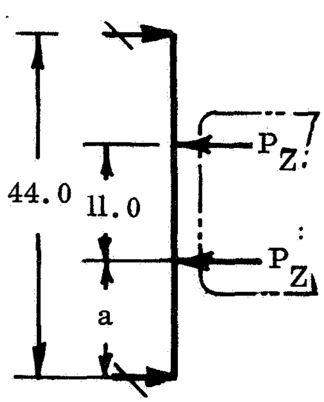
$$= \frac{1}{2\pi} \left[\frac{32.2 \times 12}{.204}\right]^{1/2}$$

$$= 7.0 \text{ cps}$$

For these elements this is an acceptable value.

D. COUNTERWEIGHT CARRIAGE TRACK Dwg. No. SRC-SD-522

Material: 2024-T4 Alum Alloy extrusion



For Reentry Experiment

P_Z is maximum and rotational speed is highest.

Check for maximum bending stresses and for natural frequency.

Maximum bending stress:

For Reentry Counterweight is 77.0 inches from ℄ and rotational speed is 4.91 rads/sec.

$$P = \frac{200 \times 77 \times 4.91^2}{32.2} = 1150 \text{ lbs limit}$$

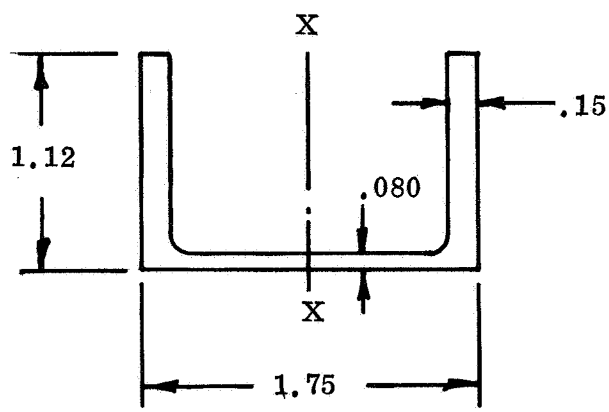
This load is shared with two tracks then

$$\text{MAX } P_Z = \frac{1.5 \times 1150}{4} = 430 \text{ lbs ult}$$

The maximum on the track

$$M = 430 \times 15.5 = 6650 \text{ in-lbs ult}$$

Track cross section is



$$\text{Moment of inertia, } I_{XX} = 2 \times 1.12 \times .15 \times .88^2 + \frac{.08 \times 1.45^3}{12}$$

$$= .306 \text{ in}^4$$

$$\sigma = \frac{6650 \times .88}{.306} = 19,300 \text{ psi}$$

Margin of safety

$$\text{M.S.} = \frac{57,000}{19,300} - 1 = +1.95$$

Natural frequency:

Maximum deflection will occur at maximum rotational speed

$$\delta = \frac{P_Z \; a \; (3\ell^2 - 4a^2)}{24 \; E \; I_{XX}}$$ where $\ell = 44.0$, $a = 15.5$

$$\delta_{MAX} = \frac{430 \times 15.5\ (3 \times 44.0^2 - 4 \times 15.5^2)}{24 \times 10.5 \times 10^6 \times .306}$$

$$= .087 \text{ ins}$$

Natural frequency

$$f_n = \frac{1}{2\pi} \left(\frac{32.2 \times 12}{\delta} \right)^{1/2}$$

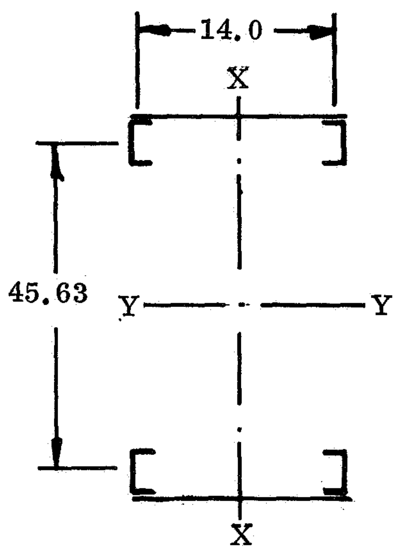
$$= \frac{1}{2\pi} \left(\frac{32.2 \times 12}{.087} \right)^{1/2}$$

$$= 10.6 \text{ cps}$$

This is an acceptable value for this component.

E. COUNTERWEIGHT SWING FRAME Dwg. No. SRC-SD-515

Material: 2024-T4 Aluminum Alloy



For Reentry Experiment consider maximum stress during emergency stop.

Check for natural frequency during ground checkout.

Swing frame weight = 326.5 lbs

Position of c.g. during reentry = 74.0

Distance from pivot = 43.0

Rotational speed = 4.91 rads/sec

Total side force during emergency stop

$$P_Y = \frac{1.5 \times 326.5 \times 74 \times 4.91}{32.2 \times 12} = 458 \text{ lbs ult}$$

Bending moment about the pivot

$$M_Z = 43 \times 458 = 19,700 \text{ in-lbs ult}$$

Maximum axial load on track is due to moment and centrifugal force.

$$P_Z = \frac{19700}{2 \times 14} + \frac{1.5 \times 6.0 \times 326.5}{4} = 1440 \text{ lbs ult}$$

Max Stress

$$\sigma_t = \frac{1440}{.44} = 32,800 \text{ psi}$$

Margin of Safety

$$\text{M.S.} = \frac{57000}{32800} - 1 = + .74$$

Check on natural frequency during ground checkout tests.

Moment of Inertia, $I_{YY} = 2 \times .88 \times 22.8^2$

$$= 915 \text{ in}^4$$

Maximum deflection

$$\delta = \frac{W\ell^3}{3\,EI}$$

$$= \frac{326.5 \times 43^3}{3 \times 10.5 \times 10^6 \times 915} = .001$$

Natural Frequency

$$f_n = \frac{1}{2\pi}\left(\frac{32.2 \times 12}{.001}\right)^{1/2} = 98 \text{ cps}$$

EXPERIMENT SUPPORT EQUIPMENT

Package Concept

It was determined, during the experiment development portion of the study, that the concept of making maximum utilization of the experiment chamber structure, and creating separate experiment packages, was not only feasible, but was a desirable way to proceed. By creating an interface between the baseline centrifuge, and the experiment oriented equipment, a considerable improvement in flexibility of the centrifuge can be realized.

Consistant with the presently defined experiment program, four experiment packages would be required.

Walking Mobility and Balance - Since the major element of equipment involved in this experiment is the centrifuge chamber, the experiment package would include only the specialized apparatus required to support the test subject and monitor his performance. Present estimates envision an experiment package with the following contents.

a. Specially marked subject clothes

b. Head gear and safety restraints

c. Special wide angle photographic equipment

d. Subject instrumentation

e. Special apparatus (not defined)

The estimated weight of this experiment package is 8 lbs. and the stored volume is 2 cubic ft.

Bench Task Performance Experiment - By utilization of the experiment chamber floor as the support structure the experiment package can be confined to the following.

a. Bench structure - This would attach to the floor and could probably serve as the experiment package container.

b. <u>Seat pads and back pads</u> - The subject would sit on the floor with his back supported by a side wall.

c. Headgear and safety restraints.

d. <u>Performance evaluation consoles</u> - Two consoles would be required (subject and monitor's).

e. Special apparatus (not defined).

The estimated weight of this experiment package is 20 lbs and the stored volume is 2 cubic feet.

<u>Cardiovascular and Vestibular Effects Experiment</u> - This experiment package will be somewhat more complex than the other packages thus far described. The package is designed to support six different, but closely related, experiment areas.

a. Gray out experiment

b. Reentry experiment

c. Therapeutic experiment

d. Vestibular experiment

e. Tilt table experiment

f. Angular and linear acceleration experiments

Two basic elements of hardware, a subject couch and a couch support frame, are required to integrate these experiments into the centrifuge test chamber. Since the couch support frame (Ref. Figure 26 , CV/A Drawing SRC-SD-425) is also designed to support the hygiene experiment. It is considered to be a loose piece of equipment associated with the basic centrifuge.

The couch support frame is a circular structure with a channel section. A series of mounting holes are provided circumferentially around the ring section to provide for the variable couch mounting configurations. At each end of the support frame a splined fitting is provided which interfaces with matching fittings in the experiment chamber. The spline portion of one end fitting can be retracted

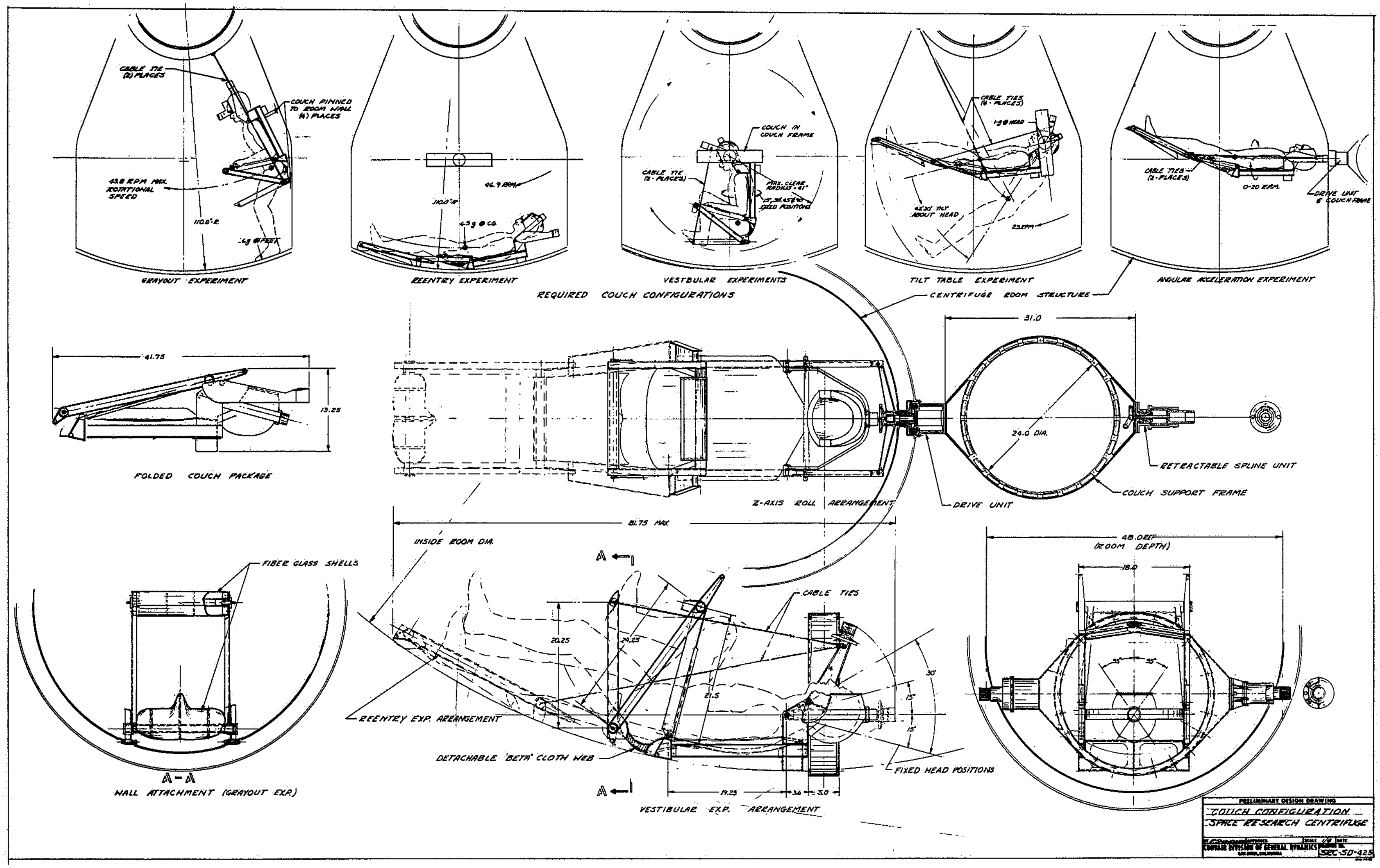


Figure 26. Experiment Couch Configuration

by a manually operated mechanism housed within the fitting. Incorporated into the opposite fitting is a small harmonic drive unit which provides rotation of the support ring around the fixed splines. This mode of rotation is required for both the Z-axis rotation experiments, (angular acceleration) and for the experiments requiring subject rotation about his head. The drive unit is powered by a fractional HP, brushless DC motor which is integrated into the harmonic drive unit. A battery unit is mounted on the support frame to provide power during these experiments.

The subject couch is a foldable framework which provides all of the necessary body restraints required to support the test subject during the various experiments. The major element of the couch structure is the back frame. This consists of two channel sections tied together by a box section at one end and a tube at the other. Affixed to the frame is a contoured fiberglass shell to which the body restraints are attached. On the upper portion of the frame, provision is made for an adjustable head restraint and the couch mounting frame. The lower section of the couch is composed of folding frames which can be configured to the five basic positions required by the experiment program (Ref. Figure 26 CV/A Drawing SRC-SD-425).

Incorporated into the couch mounting frame is a spline fitting which mates with the support frame to provide Z-axis rotation. On the front of the head restraint helmet is a mounting flange to facilitate the various experiment instruments and monitoring equipment. As presently configured, the couch package will include the following:

a. Basic couch frame and its attachments.

b. Body support pads and restraints, cables, etc.

c. Emergency first aid and medical monitoring apparatus.

d. Specialized experiment instrumentation packages - one for each of the 6 experiments.

NOTE: It is assumed that the experiment chamber will be equipped with a television monitoring system.

The estimated weight of the couch package is 40 lbs. and the stored volume is 6.8 cubic feet.

Hygiene Experiment Package - Since the collection of human waste and the shower experiment require substantially the same type of equipment and enclosure requirements, they have been integrated into a common experiment package (Ref. Figure 27, GD/C Drawing SRC-SD-426). The package is installed in the experiment chamber utilizing the couch support frame as the mounting platform. The package can thereby be rotated about the couch frame axis to provide the desired body positions.

Power and the water storage and transfer system, supporting the experiment, are provided on the centrifuge and interface with the experiment package through a disconnect panel located in the experiment chamber. Waste water and urine are transferred directly, during the test, to a collection tank on the centrifuge. Fecal waste is collected in a disposable bag which is sealed in the fecal collection container during the test period. At the conclusion of a test period the waste water is transferred to the space station, for processing, through a disconnect panel which interfaces the centrifuge with the station. The fecal collection container is removed manually from the experiment package and interfaced with the station waste collection system for processing and container decontamination. The fecal collection container is then reinstalled on the experiment package for reuse.

The hygiene experiment facility is an inflatable, water tight, fabric enclosure which is affixed to the seat frame which mounts to the couch support frame. Installed on the seat frame are the following system elements which are required to support the experiment.

a. Water drain and transfer pump

b. Air exhaust system

c. Desiccant canisters

d. Hot air blower

e. Urine collection system

f. Fecal collection system

g. Folding foot rest

h. Safety restraints

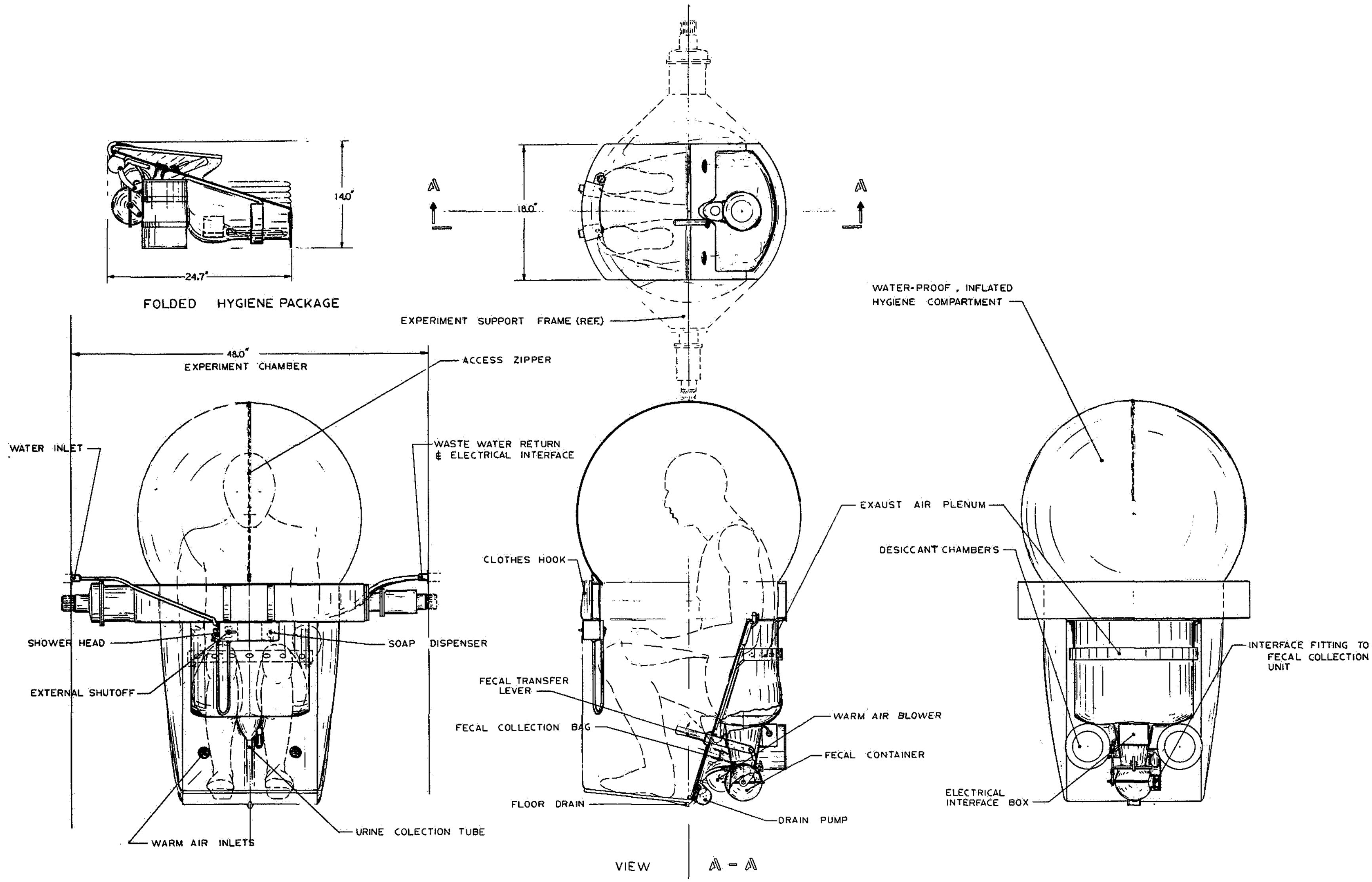


Figure 27. Hygiene Experiment Package

Mounted opposite to the seat frame, and also affixed to the fabric enclosure, is a shower console. This unit provides:

a. Shower head and hose assembly

b. Shower shutoff (internal and external)

c. Soap dispenser

d. Wash cloth

e. Clothes holder (external of enclosure)

Access to the enclosure is through a water tight zippered opening in the top of the enclosure. Ingress and egress are accomplished in zero g while the enclosure is deflated.

The hygiene experiment package is expected to weigh a total of 30 lbs and will require a stored volume of 3.5 cubic feet.

Counterbalance System

The necessity of minimizing imbalance during centrifuge operation has been established in previous parametric studies [1] and, as a requirement, is independent of any particular centrifuge configuration. For installation in spacecraft having fairly large moments of inertia (in the order of 3×10^6 slug ft^2), prior work indicated that centrifuge experiment objectives can be achieved if imbalance forces do not exceed 10 lbs. While this limit was conservitively arrived at and may be revised upward as a result of sensitivity threshold reported in Ref. 4, this value was maintained as a system objective during the present study. This was done considering that the inertial properties of the interfacing spacecraft are still arbitrary and the stability requirements of other experiments aboard the spacecraft are not defined.

Observing that the 10 lb. imbalance limit is of the same order of magnitude as forces resulting from crew motion, the assumption is that if human activity can be tolerated by zero-g experiments aboard the spacecraft, then centrifuge operation will introduce no additional problem in this respect.

Meeting this objective for the range of experiments now contemplated will require a system with increased response and much lower threshold than previously envisioned. This is caused by the greater range of activity of the test subject especially in the case of the mobility experiments. As a consequence, redesign of the counterbalancing system included lowering the sensing threshold to approximately 1 lb., increasing the mass translation rates to correspond to those of normal walking rates and re-establishing the geometry of the system to accommodate the required center passageway. In addition, provisions for both static and dynamic balancing were incorporated to increase balancing capability for the larger range of test subject activity.

General Description. - The principle elements of the counterbalance system are the force sensors, the control network (including computation, signal conditioning and monitoring circuits), the counterweight drives, and the counterweight and supporting structure. The force sensors are installed so that they form the only mechanical interface between the spacecraft and the rotating portion of the centrifuge. As a consequence, all loads acting between centrifuge and spacecraft can be measured and interpreted in terms of required counterweight motion. The control network distinguishes between forces due to centrifuge imbalance and forces introduced by spacecraft motion, subject activity and counterweight dynamics. In addition, circuits are included which monitor the validity of the sensor signals and permit rapid and automatic assessment of system operational status. In the recommended centrifuge design, the counterweight is installed in a guide frame which can be swung about an axis parallel to the centrifuge spin axis. The combined effect of rotating the guide (or swing) frame and translating the counterweight in a radial direction within this frame is used to minimize static imbalance produced by experiment activity. Dynamic imbalance is reduced by translating the counterweight within the swing frame in a direction parallel to the centrifuge spin axis.

Imbalance Sensors. - The dynamic condition of the centrifuge may be completely described if torques and forces acting on it in three orthogonal planes can be determined. This requires that a minimum of six force measurements to taken in order to provide sufficient information for solution of the problem. The use of a six sensor minimum is most desirable in as much as any additional information is extraneous, resulting in cross-talk and complicating the problem of resolution. However, an additional consideration arrises from the observation that if all forces acting on the centrifuge pass through the sensors, then the sensor arrangement must have sufficient stiffness to keep the overall natural frequency of the device far enough above its operating frequency to preclude problems of amplification and dynamic instability. A six-sensor arrangement having inherent stiffness in all planes while maintaining the fundamental requirement that only tensile or compressive loads can be accepted by the sensors (no bending), is obtained if the sensors are arranged symmetrically about the spin axis in three pairs with each pair forming a triangle which can accept loads only in the plane of the triangle. For optimum load sharing, each sensor pair should form a 45° right triangle and should be equally spaced around the spin axis with the plane of the sensor triangle normal to a radius from the spin axis. In addition, the least complexity in load resolution is obtained if the sensor pairs are arranged symmetrically about the major reference axis of the centrifuge and are installed in a plane which is normal to the centrifuge spin axis. Such an arrangement is illustrated by Figure 28, which shows the three sensor pairs located at 120° intervals around the centrifuge spin axis. This tripod attachment has the additional advantage of preventing distortion or loading of the elements during installation if the attachment surface is not a true plane, or if there are some differences in height between the sensors. (The advantages of a three leg vs a four leg stool on an irregular surface is a good illustration). The force sensor pair is shown realistically by Figure 29. Each load cell is mounted at 45° to the other by means of ball sockets which prevent bending loads from being transmitted by the individual elements. In the event that sufficient stiffness cannot be achieved with the ball socket arrangement, an all welded assembly with flexures at both ends of the load cells may be substituted. For the present, however, the ball socket appears to be a reasonable approach and allows easy assembly, adjustment or replacement of individual load cells. The gravity compensator actuator is part of a separate system introduced for ground operation only and will be removed prior to orbital operation.

Sensor Loads. - In addition to system performance requirements for resolution, dead band, hysteresis and similar characteristics, the sensing

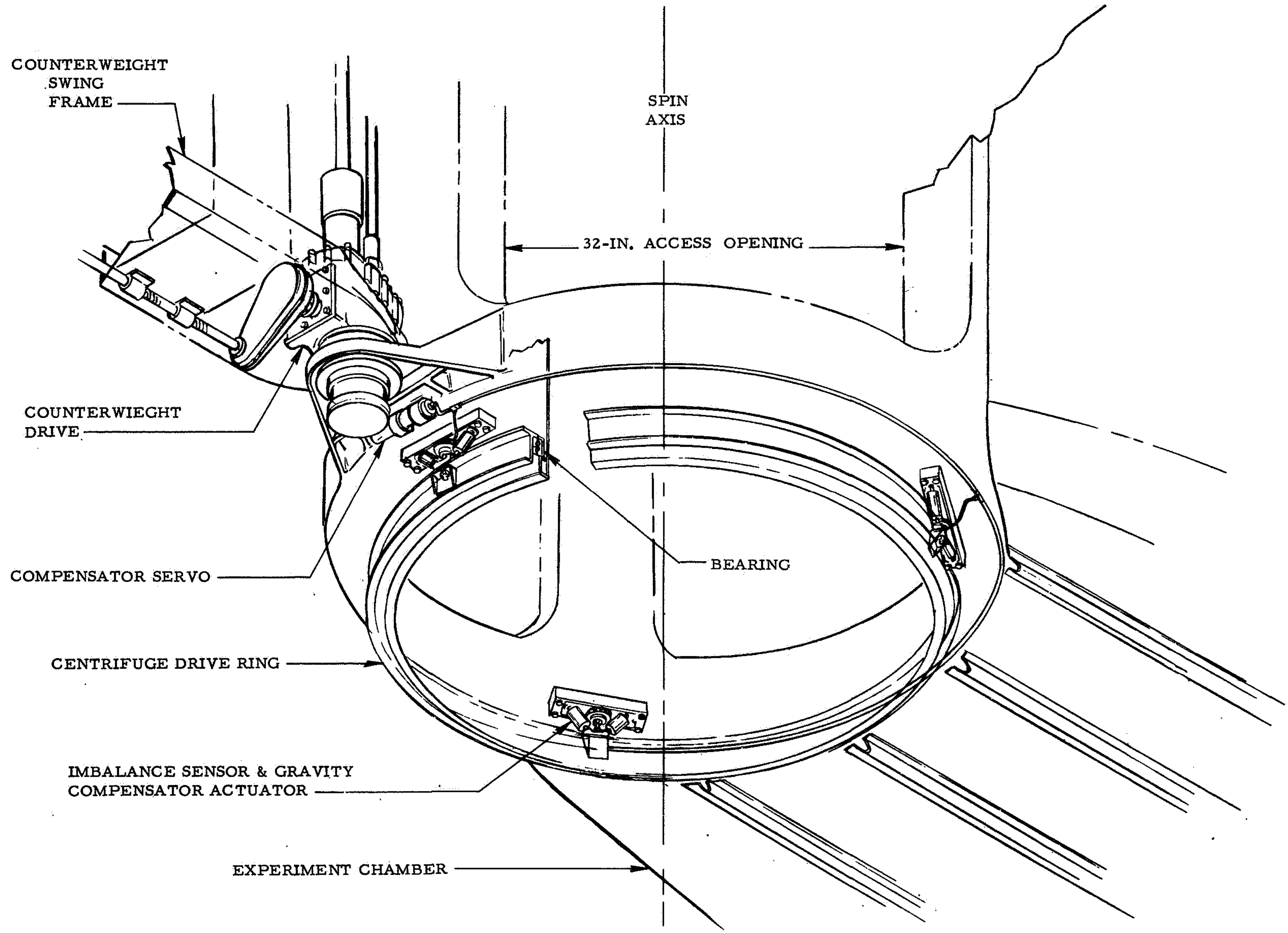


Figure 28. Centrifuge Hub and Balance System Arrangement

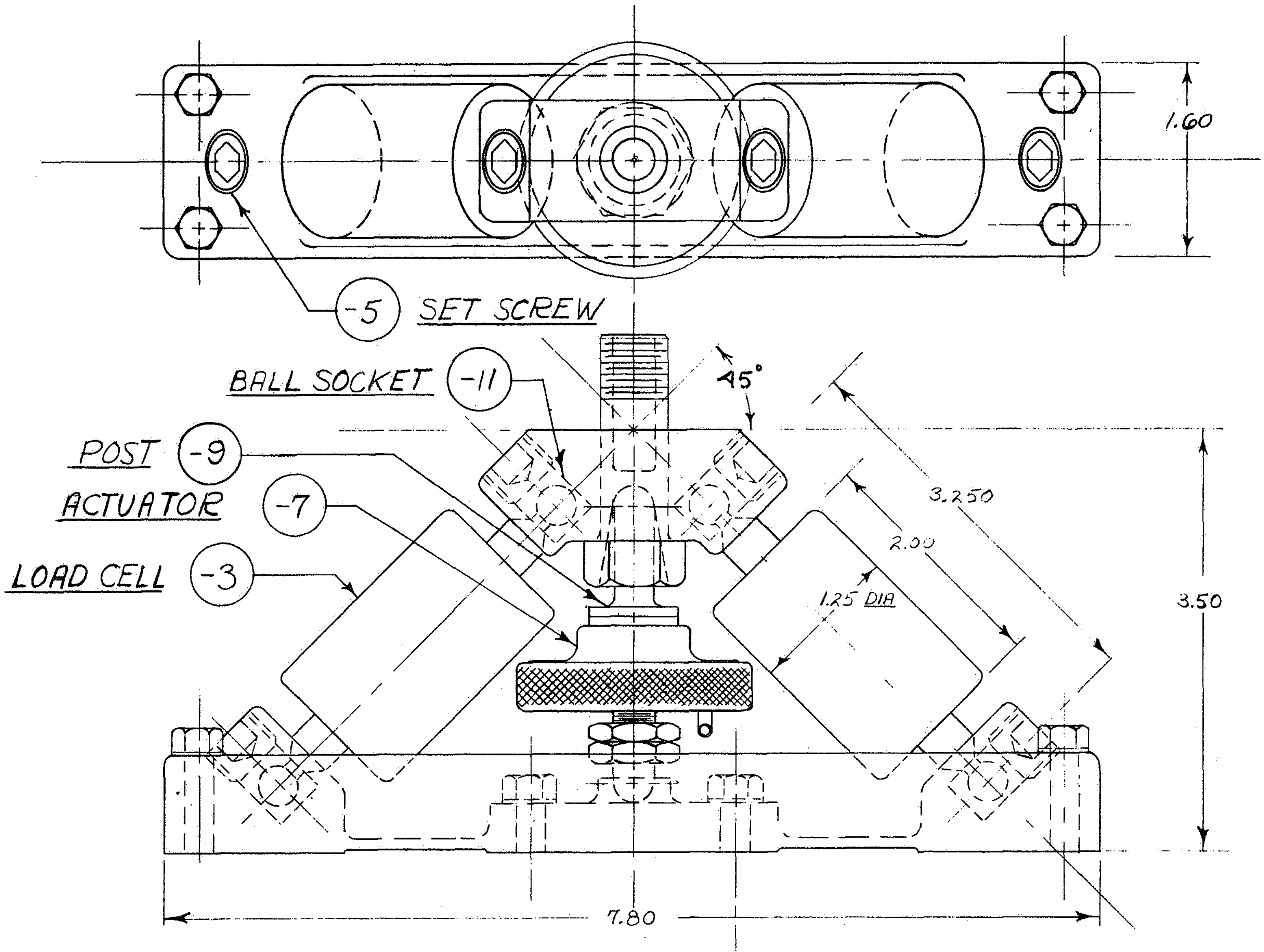


Figure 29. Counterbalance System Force Sensor Pair and Gravity Compensator Actuator

element design is highly influenced by load characteristics and stiffness requirements. The sources of loadsimposed on the sensors are identified as gravity, imbalance, torque due to spin up or stopping and spacecraft loadsduring launch and orbital operation. Each of these loads is examined in the following discussion to determine their influence on sensor design, and a summary of the loading conditions presented in Table 5.

Assuming a rotational mass of 1200 lbs and a moment of inertia of 1500 ft/lb/sec. for the centrifuge, the static load per sensor element on the ground will be:

$$\frac{1200}{3}\left(\frac{\sqrt{2}}{2}\right) = 283 \text{ lbs.}$$

Considering that we are interested in measuring imbalance loads in the order of 1 lb (.235 lbs per sensing element) operating against such a large bias would mean that the useful signal would be in the vicinity of .1% of cell output. This would seriously compromise the sensitivity of the system and generates the requirement for a gravity compensation system which will remove the gravity load during ground operation. An overload capability (mechanical stop) should be provided to prevent over-loading the cell in the event of a failure of the gravity compensator.

Maximum imbalance loads can occur under the following conditions:

a. The test subject kneels or falls to the floor during the mobility experiment.

b. The counterweight is driven to an extreme position by a system failure at high g.

For condition (a), consider that a 200 lb man rotating at 1.408 rad/sec undergoes a c.g. radius change of (106"-78"). The resulting imbalance force will be 28.8 lbs.

For condition (b), consider that a 200 lb counterweight rotating at 4.66 rad/sec. (grayout) is translated from 109" to 60". The imbalance force for conditions (b) will be 551 lbs. which results in the maximum imbalance load per sensor element of 130 lbs.

Maximum operating torque loads that must be transmitted across the sensor system during spin-up are introduced by the re-entry experiment and reach a peak of approximately 166 ft-lbs. Assuming that the sensors are located at a radius of 2.04 ft, the maximum load per sensor element becomes 19.2 lbs.

If emergency stopping loads are taken across the sensors, the torque resulting from a one second stop from 5.04 rad/sec. (Re-entry) will be

TABLE 5.- FORCE SENSOR LOAD SUMMARY

	Maximum Load Per Sensor Element							
	Without Gravity Bias				With Gravity Bias & Disconnect			
	Failed Operation		Normal Operation		Failed Operation		Normal Operation	
	Ground	Orbital	Ground	Orbital	Ground	Orbital	Ground	Orbital
Gravity	283.00	0.0	283.00	0.0	283.00	0.0	0.0	0.0
Max. Imbalance	130.00	130.00	.44	.44	130.00	130.00	.44	.44
Torque	872.00	872.00	19.20	19.20	872.00	872.00	19.20	19.20
Spacecraft	0.0	6.78	0.0	6.78	0.0	6.78	0.0	6.78
Launch & Transport	1700. +	0.0	1700. +	0.0	0.0	0.0	0.0	0.0

7550 ft-lbs and will result in a force of 872 lbs applied to each sensor element. This represents an ultimate condition which is introduced only as a result of failure of some part of the drive mechanism. A similar operating condition, which may be introduced if mechanical brakes are employed, may be avoided if the brake is applied directly to the rotating mass at a point which transmits the load around the sensor network.

Some appreciation of the magnitude of load which may be introduced into the sensor by spacecraft disturbance can be gained by the following argument.

Assume a spacecraft natural frequency of 1.0 H_Z. If maximum accelerations are $A\omega^2$, then

$$F_{max} = \frac{1200}{32.2} (6.28)^2 A = 1470 A$$

where A is the amplitude of off-set disturbance (ft). Assume that F_{max} is the same as the maximum imbalance load of 551 lbs due to counterweight misposition. The amplitude would then have to be 551/1470 = .375 ft. in order to result in a load equal in magnitude to the maximum counterweight imbalance load. As it is safe to assume that such an amplitude will not be induced by any spacecraft activity, the maximum imbalance force will be the governing factor in sensor design. A more reasonable representation of the forces which may be expected to result from spacecraft motion would be given by considering test subject c.g. shift. Spacecraft amplitude corresponding to this magnitude of load becomes

$$A = \frac{28.8}{1470} (12) = .235 \text{ inches.}$$

This is more the order of amplitude which might be involved in a spacecraft disturbance input.

During launch or transportation operations, the high g loads and vibration conditions involved make it mandatory that the sensing system be disconnected or locked out during these periods, and that separate provisions be made to support the centrifuge rotating assembly.

<u>Sensor Stiffness Requirements</u>. - The centrifuge may be represented simply as a rigid mass connected by three springs (the sensor pairs) to a rigid base. To keep the overall natural frequency of the device well above the operating frequency of .8 cps., a natural frequency of this simple model is specified at 10 cps.

Using the relationship:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{I_o}}$$

Where f_n = Natural Frequency, cps

K = Spring rate, ft-lbs/rad.

I_o = Moment of Inertia, ft-lb-sec^2

$$K = \left[2\pi\,(10)\right]^2 (1500) = 5.91 \times 10^6 \text{ ft-lbs/rad.}$$

Converting this to the stiffness required by each sensor element results in:

$$\frac{5.91\,(10)^6}{2\,(2.04)^2} = .71 \times 10^6 \text{ lbs/ft or } .591 \times 10^5 \text{ lbs/in}$$

Sensor Specifications - From the load estimates and system performance requirements previously outlined, the main characteristics of the sensing element are stated as follows:

Operating Load	-	± 35 lbs per sensing element
Limit Load	-	±283 lbs per sensing element (overload requirement)
Ultimate Load	-	±872 lbs per sensing element (structural requirement)
Linearity	-	.05% of full scale (± 35 lbs)
Repeatability	-	±.01%
Hysteresis	-	.05% of full scale
Null Dead Band	-	0
Threshold	-	.0025% of full scale
Operating Temp.	-	+ 60° to + 80°F.
Non Operating Temp	-	-65° to + 160°F
Excitation	-	10 volts for full scale output of ±10 MV. (± 1 MV/V.)
Stiffness	-	$.591 \times 10^5$ lbs/in.
Weight	-	.75 lbs/element (Max.)
Operating Atmosphere	-	Air at 14.7 psia or O_2 at 5 psia.

In addition to these characteristics, the element should be a dual-series unit to provide sufficient redundancy for meeting reliability goals.

Contact with prospective suppliers for this type of equipment indicates that the requirements can be met using conventional bonded foil strain gages incorporated in low deflection dual-guided cantilever beam elements.

Gravity Compensator System - A compensation system which counteracts gravity loads acting on the counterbalance system force sensing elements during ground operation of the centrifuge has been shown to be necessary for increasing system sensitivity and accuracy. Such a system can be simply implemented by incorporating small servo controlled hydraulic actuators in each sensor set as shown by figure 29. Ideally, the system acts as an infinite spring which exactly balances the gravity load carried by the sensor pair. As illustrated schematically by figure 30, the three compensator actuators are connected in a closed system to a common gravity compensator pressure cell. Small diameter rigid tubing and tube flexures at each actuator are suggested to prevent extraneous loads from entering the system and to keep system compliance low. Hydraulic actuation rather than pneumatic actuation has been specified to reduce sensitivity to temperature variation. The system has been designed so that it is completely independent and removeable without breaking any of the lines or connections. The actuator, shown in detail by figure 31 is a simple diaphragm and plunger design having an effective area of 1.765 in^2. For normal loading conditions, required fluid pressure will be approximately 227 psi. Removal of the actuator is accomplished by backing-off the -15 cap about 1/16 inch and removing the -17 post, after which the actuator body can be slipped out of the assembly. Actuator pressure is supplied by a spring loaded pressure cell illustrated by figure 32. Spring preload, normally about 11.14 lbs, operates against a .25 inch diameter piston which has a rolling diaphragm seal to reduce friction to a minimum. The spring setting is adjusted to compensate for changes in test subject mass and onboard equipment weight for each experiment by driving a servo motor in response to signals from the force sensing network.

Counterbalance System Control Network - Signals from the three-pair sensor system previously described must be resolved into appropriate centrifuge oriented forces and torques before they can be utilized to command counterweight position.

Individual sensor signals, identified as A, B, C, D, E & F on figure 33 will be produced only by forces acting in the plane of the sensor pair. These forces, designated F_1, F_2 and F_3 for each of the three sensor pairs can be resolved into horizontal force components (in the centrifuge Y-Z plane) and vertical force components (parallel to the centrifuge X or spin axis). For each sensor pair, these force components can be determined from the relationship:

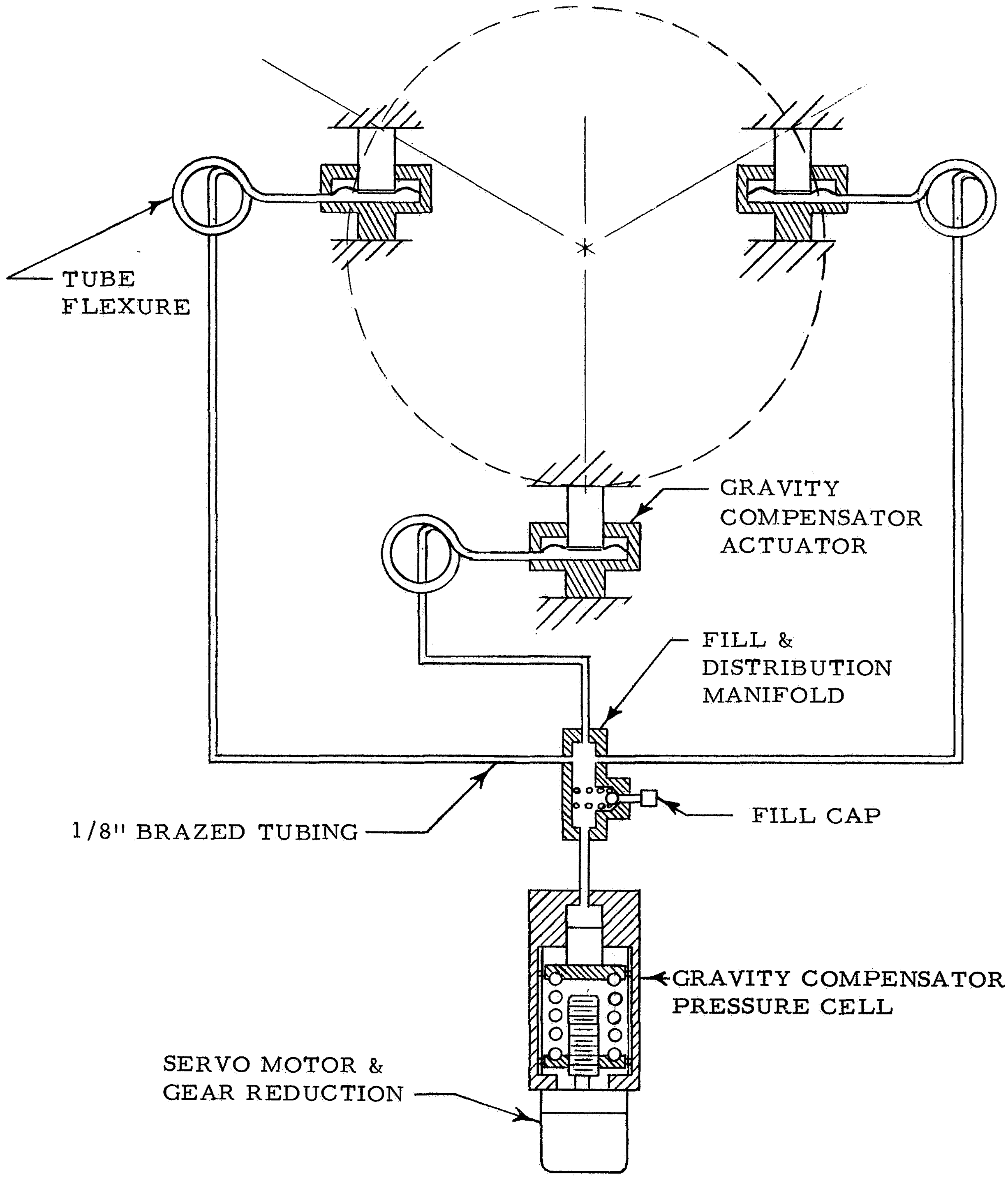


Figure 30. - System Schematic - Detachable Gravity Compensator for Ground Testing and Operation of Imbalance Sensing System

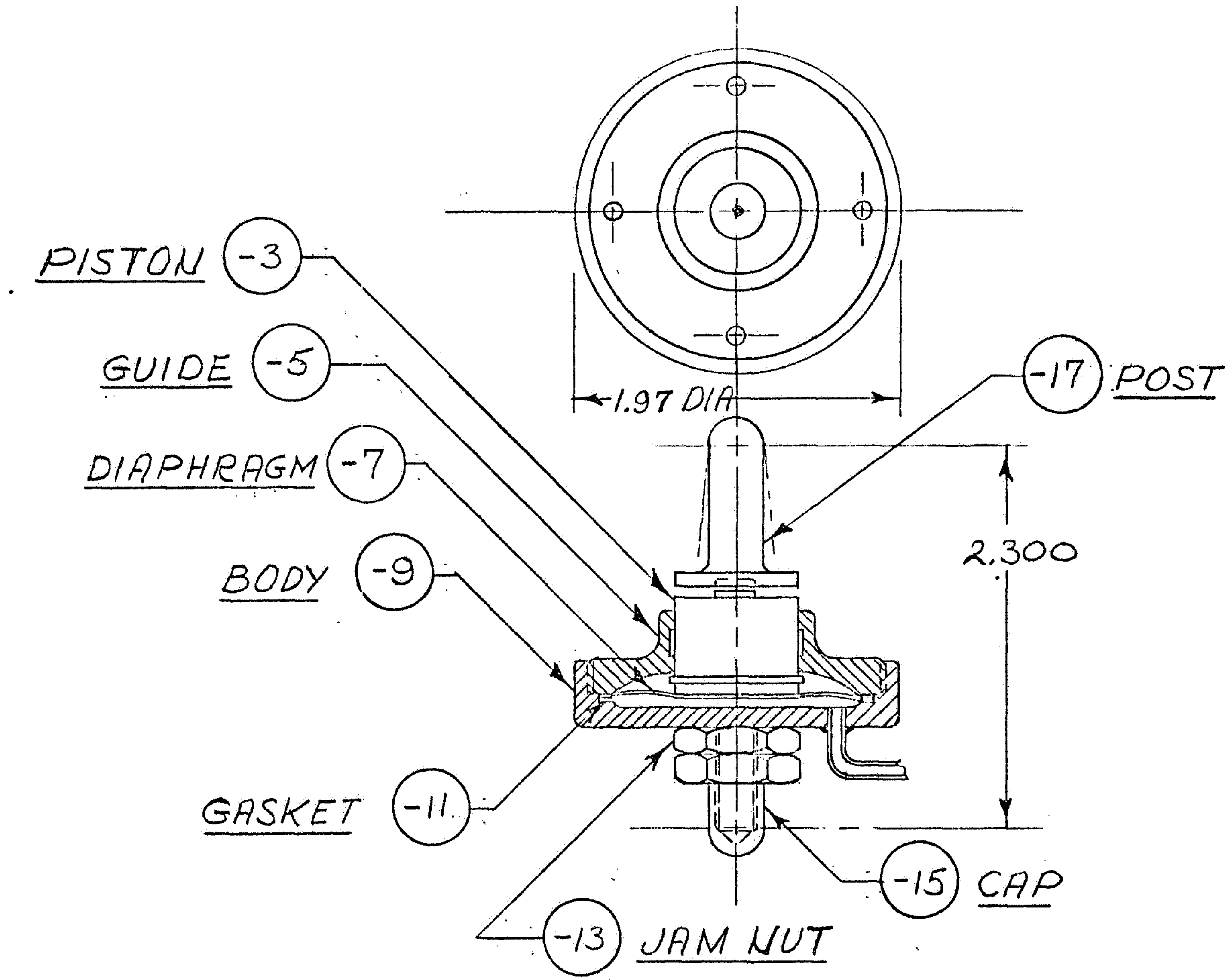


Figure 31. -Gravity Compensator Actuator (SRC-SD-421)

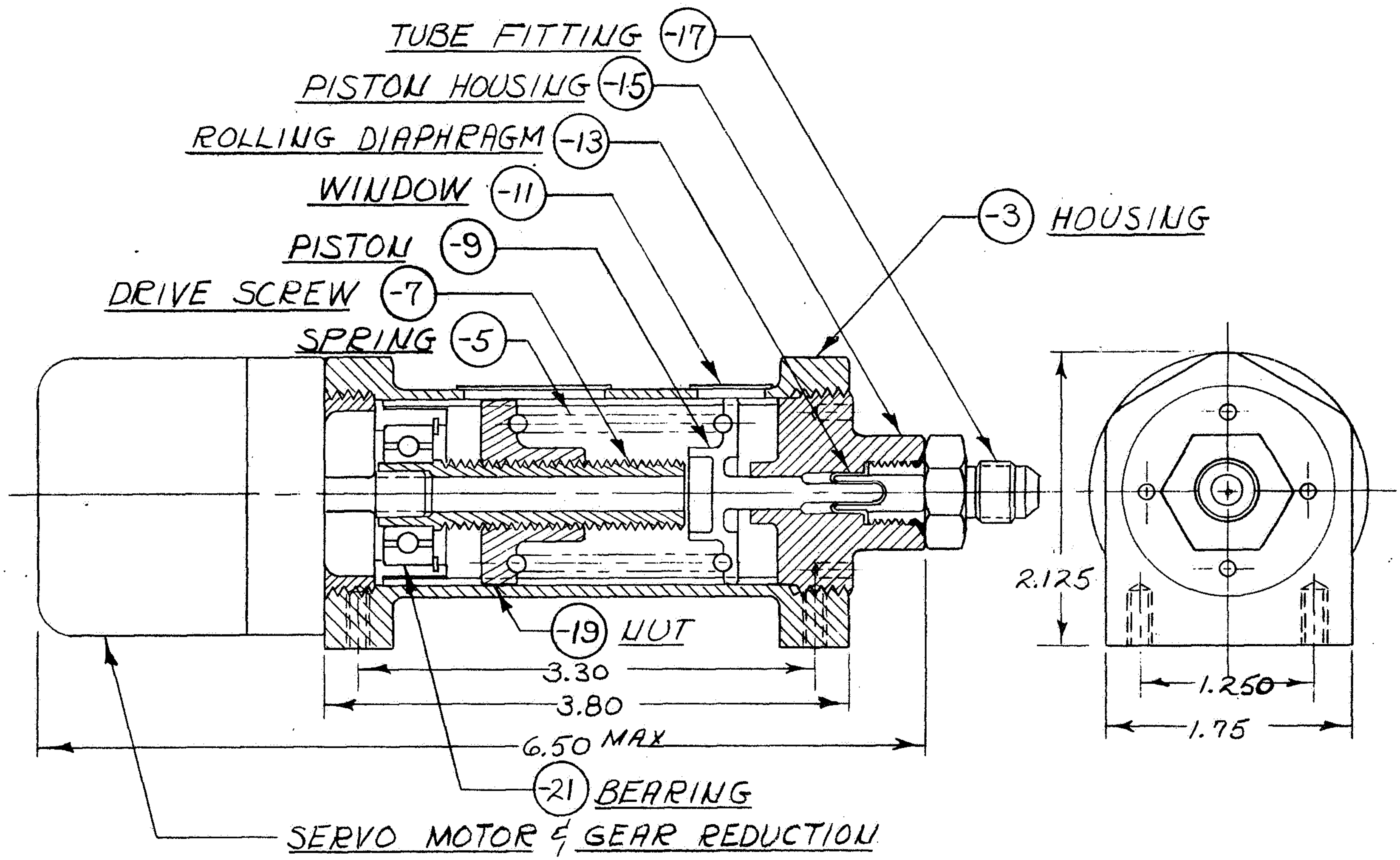


Figure 32. - Gravity Compensator Servo Controlled Pressure Cell (SRC-SD-422)

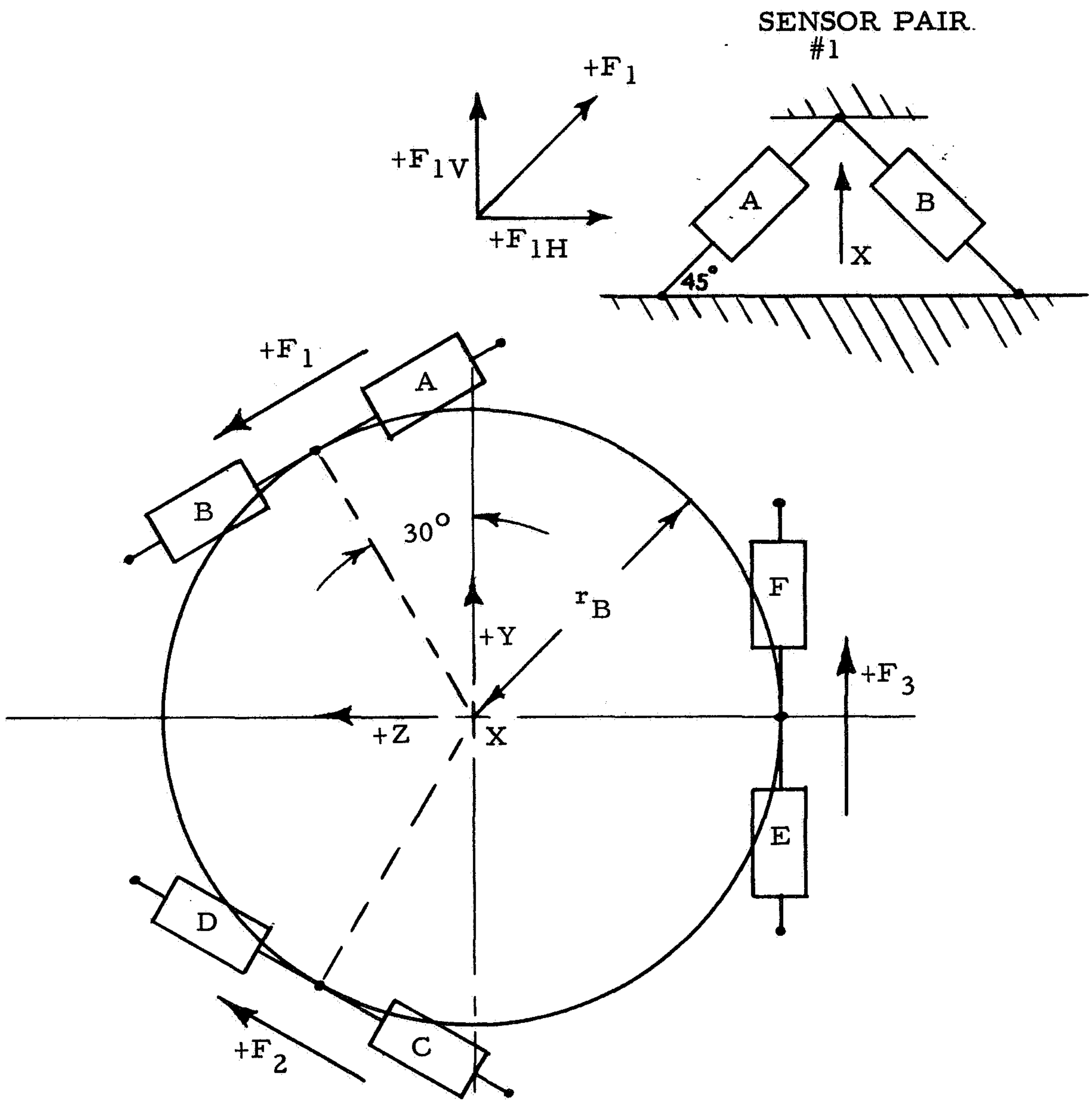


Figure 33, - Sensor Geometry and Nomenclature

$$F_{1H} = (A - B)\ \cos 45^\circ \qquad \text{Set \#1}$$

$$F_{1V} = (A + B)\ \sin 45^\circ$$

$$F_{2H} = (C - D)\ \cos 45^\circ \qquad \text{Set \#2}$$

$$F_{2V} = (C + D)\ \sin 45^\circ$$

$$F_{3H} = (E - F)\ \cos 45^\circ \qquad \text{Set \#3}$$

$$F_{3V} = (E + F)\ \sin 45^\circ$$

These forces are then resolved into forces and moments about the three principle axes of the centrifuge.

$$\sum F_X = F_{1V} + F_{2V} + F_{3V}$$
$$= (A + B + C + D + E + F)\ \sin 45^\circ \tag{1}$$

$$\sum F_Y = -F_{1H}\ \sin 30^\circ + F_{2H}\ \sin 30^\circ + F_{3H}$$
$$= (B - A + C - D)\ \cos 45^\circ \sin 30^\circ + (E - F) \cos 45^\circ \tag{2}$$

$$\sum F_Z = F_{1H} \cos 30^\circ + F_{2H} \cos 30^\circ$$
$$= (A - B + C - D) \cos 45^\circ \cos 30^\circ \tag{3}$$

$$\sum M_X = (F_{1H} - F_{2H} + F_{3H}\ \ r_B$$
$$= (A - B - C + D + E - F)\ r_B \cos 45^\circ \tag{4}$$

$$\sum M_Y = -F_{3V}\ r_B + F_{1V}\ r_B \sin 30^\circ + F_{2V}\ \ r_B \sin 30^\circ$$
$$+ (E + F)\ r_B \sin 45^\circ - (B + A)\ r_B \sin 45 \sin 30^\circ$$
$$-(D + C)\ r_B \sin 45^\circ \sin 30^\circ$$
$$= \left[-(E + F) + (A + B + C + D) \sin 30\right] r_B \sin 45^\circ \tag{5}$$

$$\sum M_Z = F_{2V}\ r_B\ \cos 30^\circ - F_{1V}\ r_B\ \cos 30^\circ$$
$$= (D + C - B - A)\ r_B \sin 45^\circ \cos 30^\circ \tag{6}$$

Testing of the individual equations with pure torque and force inputs in each axis indicates that the solutions are uncoupled.

Utilization of the force sensor signals in a logic and control circuit is illustrated by figure 34. Dual-redundant signals are taken from each sensor and fed into the comparator and switching unit. Dual signals from each sensor are compared and a fault is indicated at the control panel if their difference is greater than some selected percentage (characteristically 5%). If the signals are within tolerance, the low-value signal is selected and fed to the summing and control network where the computations indicated by equations 1-6 are performed. Force signals used in the direct control of the counterweight system (F_Y, M_Y & F_Z) are passed through a signal conditioning and discriminating circuit which modifies the signal by eliminating those components which are the result of spacecraft motion, test subject motion and counterweight motion. The ability to distinguish between space craft inputs and imbalance forces is provided by signals from the spacecraft stabilization system accelerometers and by the phase relationship and frequency of the force. For example, forces with the same frequency as the natural bending frequency of the spacecraft will probably be from that source and can be filtered out. Forces with the same frequency as the centrifuge rotation period can be identified as externally caused because the sensor network travels with the rotating portion of the machine. The reaction produced by motion of the counterweights appears as a negative feedback to the system and must be eliminated by computation of the counterweight accelerations (differentiation of velocity measurements) and provision of a negating signal. In addition to these functions, the incorporation of BIT (Built-In Test) provisions is suggested which will permit the measurement of system response to a programmed command input. Comparison of actual response with a standard response will allow rapid assessment of control system functional status.

In each counterbalance axis, the servo loop is closed through the sensor element, i.e., the counterweight is driven in such a way as to reduce the resolved sensor signals to zero. Imbalance forces in the "Y" direction are compensated for by rotating the entire counterweight swing frame toward one side or the other depending on the sign of the imbalance signal. Forces in the "Z" direction, along the radius of symetry of the experiment chamber, are balanced by driving the counterweight radially within the swing frame until the F_Z force signal is reduced to zero. The combined displacement of the counterweight by swing and radial motion results in static balancing of the centrifuge in the Y-Z plane

Dynamic balance is achieved by driving the counterweight within the swing frame in a direction parallel to the spin axis until the M_Y signal is reduced to zero. This results only in a partial dynamic balance of the system as presently concieved because the M_Z imbalance is uncompensated. This compromise is suggested in order to simplify the system and will probably be acceptable because the imbalance moment around the Z axis will be small. In any event, only monitoring of the M_Z imbalnce is recommended for initial system implementation. If M_Z imbalance is shown to be a problem, full dynamic balancing can be achieved by using the M_Z signal to modify swing frame position.

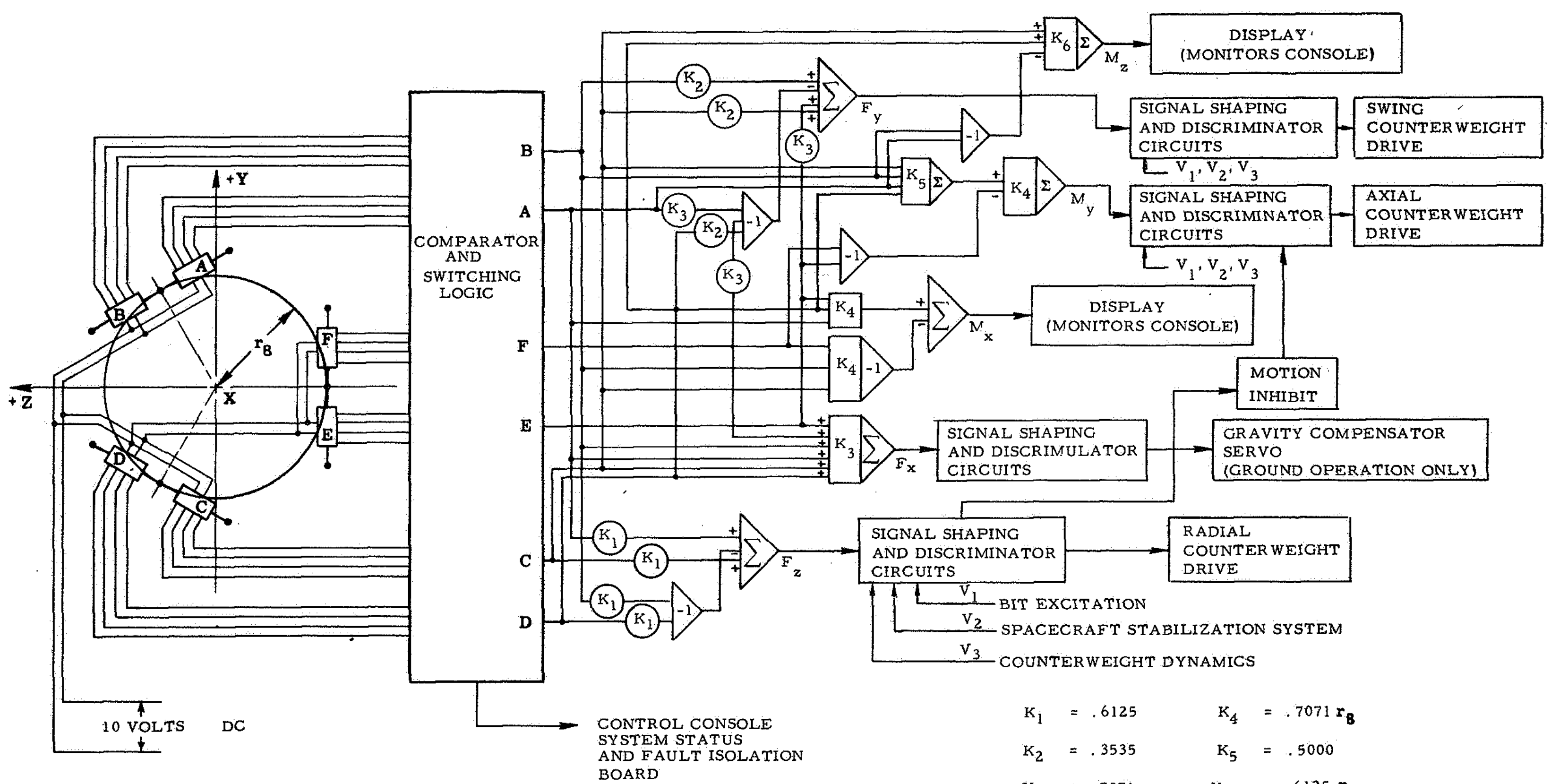


Figure 34. - Counterbalance System - Sensing and Control Network Schematic

The M_X signal represents the spin-up or spin-down torque acting on the centrifuge and is not required for counterbalance command. This signal may have some application in centrifuge acceleration control but, at present, it is recommended that it merely be monitored.

The F_X signal represents forces normal to the spin plane and for ground operation is a measure of the gravity forces acting on the sensors. For this reason, it is convenient to use this signal to drive the gravity compensator servo until the net F_X force is zero. Once compensation is achieved for a particular experimental set-up, it should not vary unless some mass loss occurs.

One problem arises from the fact that,for ground operation, the system is unable to distinguish between static imbalance in the Z direction and dynamic imbalance around the Y axis. As a tentative solution, it is suggested that progressive balancing be used during ground operation. This can be accomplished by inhibiting motion of the axial counterweight drive until radial counterweight motion drives the F_Z signal to zero or to some minimum value. Radial counterweight motion will reduce the M_Y signal as well as the F_Z signal. When the F_Z signal is reduced to zero, the residual M_Y signal will represent dynamic imbalance around the Y axis and can be compensated for by axial motion of the counterweight. This condition does not occur during orbital operation so that the motion-inhibit circuits can be bypassed at that time.

In addition to these considerations, aerodynamic loads acting on the centrifuge will affect the sensing system to some extent. This fact argues for a design which is aerodynamically balanced and reasonably symetrical, and indicates the need for enclosing the engineering development (ground based) centrifuge model in a manner which will duplicate the eventual module or spacecraft condition.

Counterbalance Drives - The mechanisms for positioning the centrifuge counter weight are a major subsystem and considerable effort was devoted to their detail description during the study. This was necessary in order to arrive at a realistic estimate of their weight, size, efficiency and reliability and to allow their proper integration with centrifuge structure.

For this initial study, a simple, direct, approach to mechanizing the drives was selected. This approach consists in utilizing battery driven brushless DC motors for the power source, gear and screw power transmission and intermittent clutching for on-off positioning rather than proportional control. Additional specifications used in the design study are as follows:

a. The units shall be powered to drive the counterweights under maximum centrifugal and inertial loads imposed by each experiment.

b. Rates and accelerations of the counterweight:

Swing Drive: 4 rpm max. in 50 sec. for the mobility experiments up to .5 g. .4 rpm max. in .50 sec. for high g experiments which do not involve large changes in the test subjects cg position.

Radial Drive: .5 ft/sec. in .50 sec. for the mobility experiments up to .5 g. .05 ft/sec for the high g experiments in .50 sec.

Axial Drive: Same as for the Radial Drive.

c. The counterweight drives shall be irreversible.

d. The drives shall be designed to fail operational with reduced performance for a first failure and fail safe with a second failure in the same drive axis.

e. The mechanism shall withstand maximum deceleration loads without catastrophic failure.

Counterweight Swing & Radial Drive - A preliminary analysis of power requirements and drive geometry indicates that combination of the swing and radial drive units is expedient with respect to weight, envelope and commonality of motor size with the radial drive.

Assuming the geometry shown by figure 35 for the counterweight swing static torque, T_S, will be given by,

$$T_S = 300\ (g)\ (2.75)\ \sin\left[\arc\tan \frac{7.0 \sin\phi}{2.75 + 7.0 \cos\phi}\right]$$

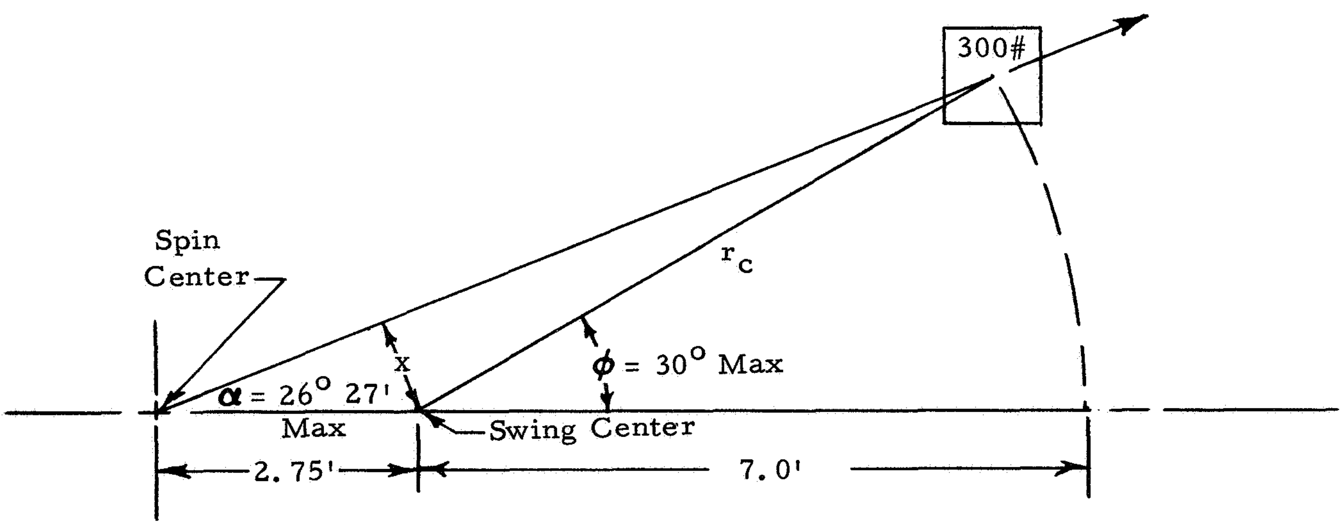


Figure 35 - Representative Counterweight Swing Geometry

Assuming that maximum operating torque occurs during the grayout experiment with the test subject sitting in a corner of the experiment chamber (this will be conservative as the counterweight will not be fully extended radially) the values of g = 4.18, ϕ = 30° and x = 1.227' produce a T_s of 1540 ft-lbs. Based on an estimated carriage/counterweight moment of inertia of 456 ft-lb-sec^2, an additional 38.2 ft-lbs will be required to accelerate the counterweight swing. The resulting swing drive torque requirements for the high-g experiments will be 1578 ft-lbs.

For the mobility experiment, assume that maximum operating torque occurs with the counterweight at 30° and 2/3 full radial extension at .50 g. Static torque will be 134 ft-lb, and acceleration torque 169 ft-lbs based on a moment of inertia of 202 ft-lb-sec^2. Total torque requirements will be 303 ft-lb.

The power requirement, assuming 80% transmission efficiency will be

$$HP = \frac{TN}{5250\eta} = \frac{(303)(4.0)}{5250(.8)} = .288 \text{ horsepower}$$

If the power requirement of the mobility experiment is used to size the system and a 10/1 gear reduction introduced to account for the rate difference between the high-g and mobility experiments, then a torque capability of 3030 ft-lb will be available at low rate (.4 RPM).

For the radial counterweight drive, assuming a 200 lb counterweight and a 10/1 gear ratio change, the following forces and power levels must be provided.

High Rate

Holding Force	=	100 lbs
Acceleration Force	=	6.21 lbs
Total Force	=	106.2 lbs
Power (η =.80)	=	.121 Horsepower

Low Rate

Holding Force	=	1300 lbs
Acceleration Force	=	.621 lbs
Total Force	=	1300.6 lbs
Power (η = .80)	=	.148 Horsepower

Integration and mechanization of the swing and radial counterweight drive is shown by figure 36. Completely redundant units operating in parallel are suggested for this application. Drive power is provided by two identical 1/4 horsepower brushless DC motors operating at a continuous 8000 rpm. Spur gears with a ratio of 2:1 transfer power from the motor to the swing and radial drive trains through electromagnetic

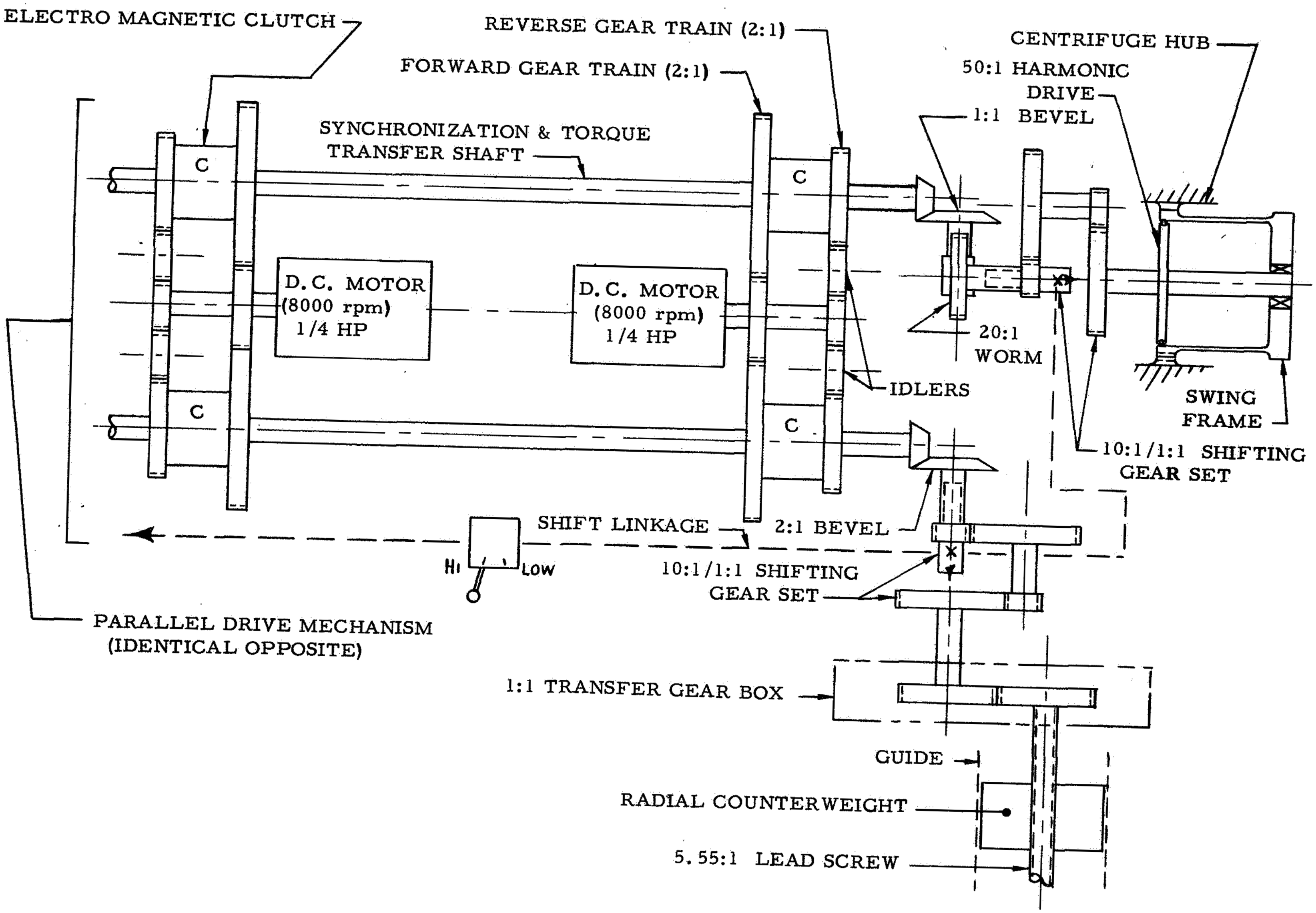


Figure 36.-Schematic Diagram - Combined Swing and Radial Drive Mechanism for the Counter weight

clutches which select either forward or reverse motion in response to the command direction of counterweight travel. Clutch output from each of the units is mechanically summed by a torque transfer and synchronizing shaft. For the swing drive, clutch output is fed through a 1:1 right angle hypoid bevel gear and 20:1 worm to a 10:1/1:1 shiftable spur gear set. The final reduction is provided by a 50:1 harmonic drive whose output is grounded to the centrifuge hub structure. In operation, the swing and radial drive travels with the swing frame. For the radial drive, clutch output is transferred through 2:1 right angle hypoid bevel gear to a 10:1/1:1 shiftable spur gear set. An additional transfer gear (1:1) is required to align the radial drive lead screw with the center line of the swing frame.

A preliminary design of the drive unit was developed to establish internal arrangement and envelope requirements and is shown by figure 37. Sufficient analysis was performed to assure that gearing, clutches and shafting were adequately sized and realistically represented. Weight estimates based on this design resulted in a weight of 18.4 lbs for each drive unit (2 required) and 2.36 lbs for the common interconnecting shafting and other hardware.

Counterweight Axial Drive. - The force and power requirements of the counterweight axial drive change drastically for the ground and orbital operating conditions. For ground operation, the static load is the full 200 lbs of the counterweight. Acceleration loads are minor and are identical to those of the radial drive. Power requirements are maximum for the high rate operation and are found by:

$$HP = \frac{.5\ (206.2)}{550\ (.80)} = .2345 \text{ Horsepower}$$

If the same 1/4 HP, 8000 rpm motor is employed in this unit as is required for the swing and radial drive, the torque at the motor will be 1.54 ft-lbs. This is somewhat larger than the clutch torque requirement of the swing/radial drive so that common clutches cannot be effectively employed. A schematic representation of the axial counterbalance drive is shown by figure 38. Axial motion of the counterweight is achieved by driving a ball nut (connected to the counterweight) on a threaded shaft which is stationary with respect to the counterweight carriage. Dual redundant motors are also used for the axial drive unit. Because of the peculiar installation requirements of the axial drive and the necessity of keeping the drive package fairly short so that as much axial travel as possible may be obtained, the motors are mounted in line with the direction of radial travel.

Power is taken from the motor to the clutch forward/reverse input gear through a 1:1 right angle bevel gear. Clutch outputs are tied through a common shaft which permits either or both of the motors to feed power to the ball nut. Transmission from the common clutch output shaft to the ball nut is through either a 2:1 spur gear set or a 10:1 gear set which can be selected by manual shift. Enclosure of the ball nut screw by a metal bellows allows normal lubricating practices to be employed in this assembly.

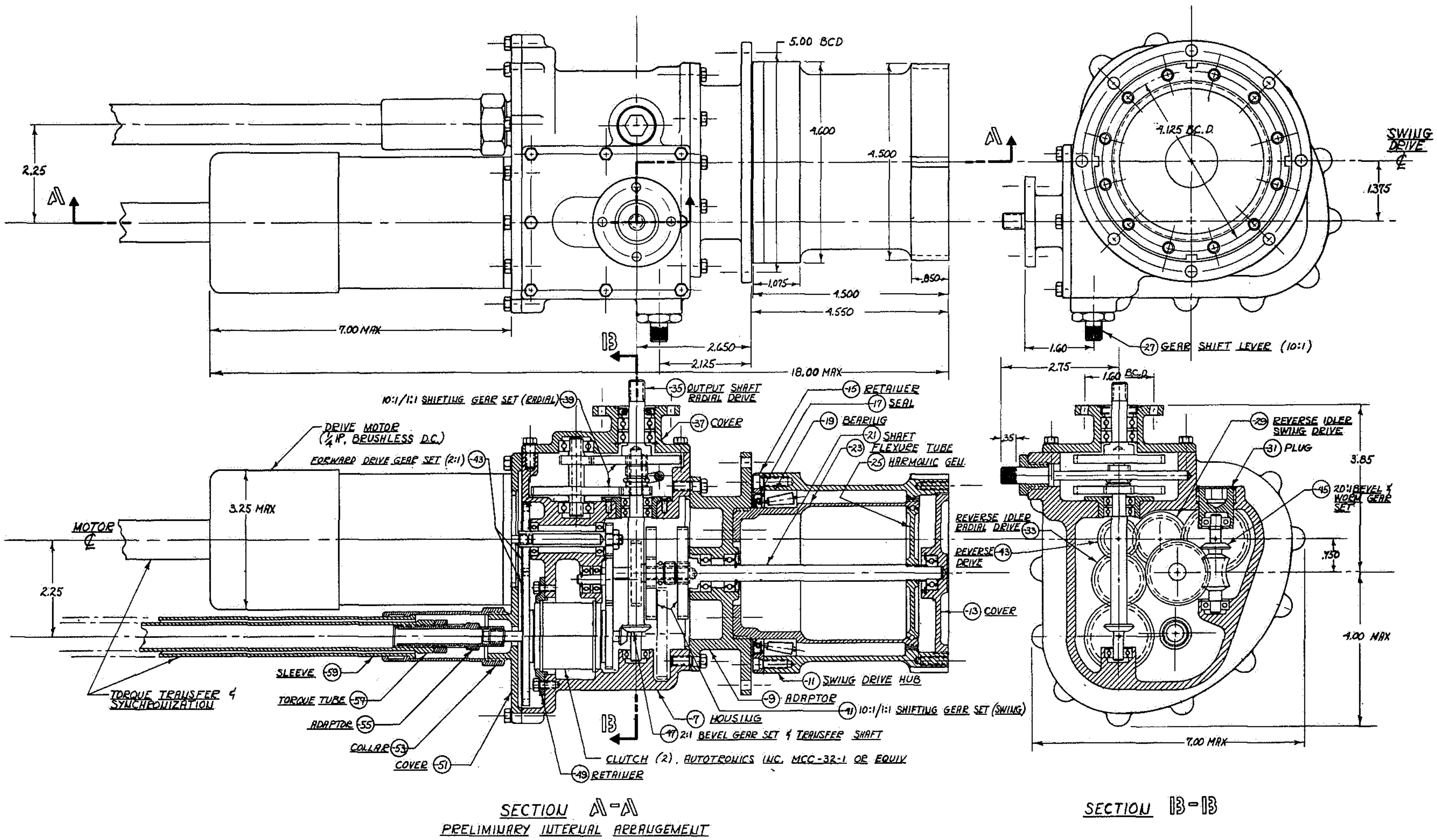


Figure 37 - Counterbalance System - Counterweight Swing and Radial Drive Mechanism

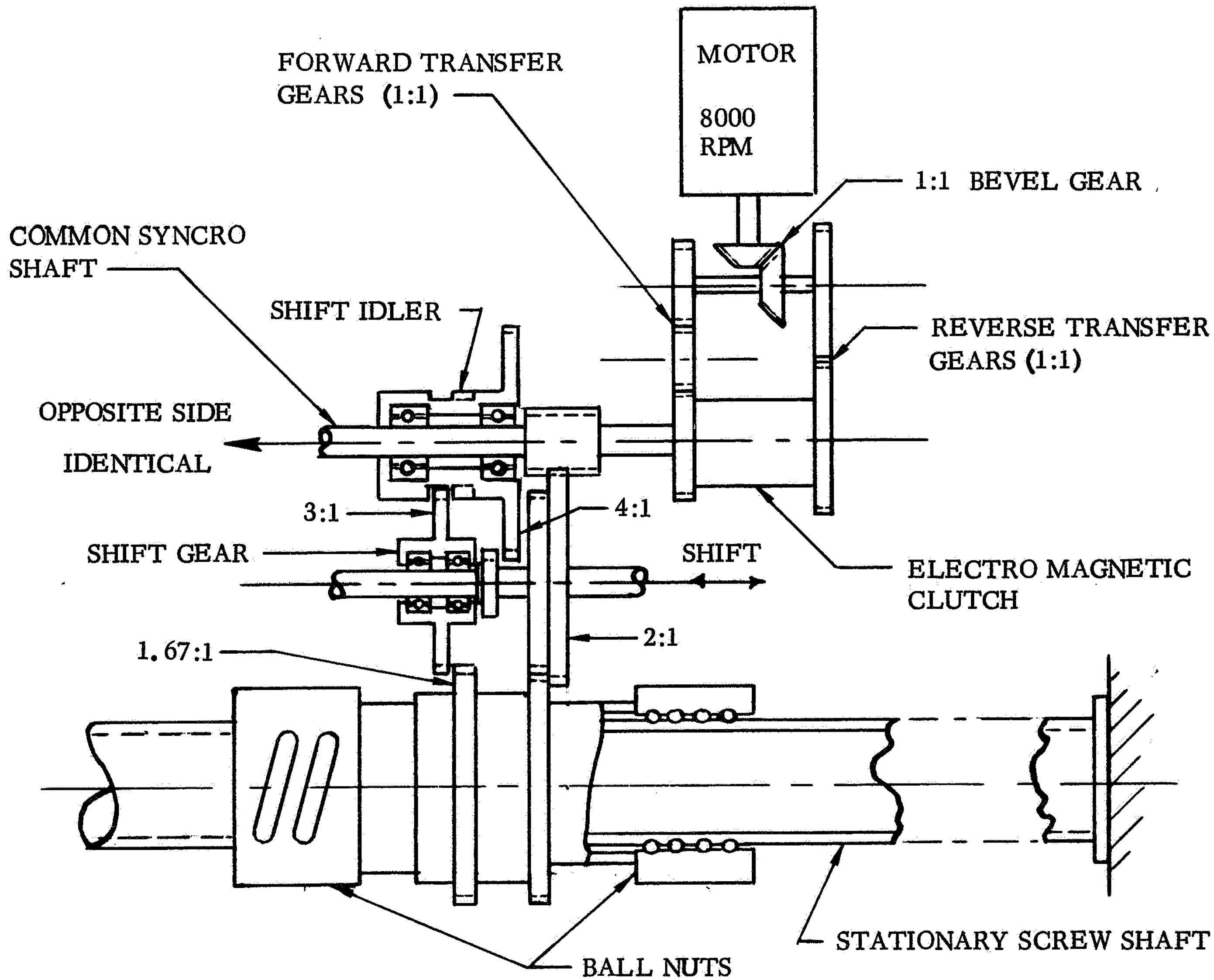


Figure 38 - Schematic Arrangement - Counterweight Axial Drive

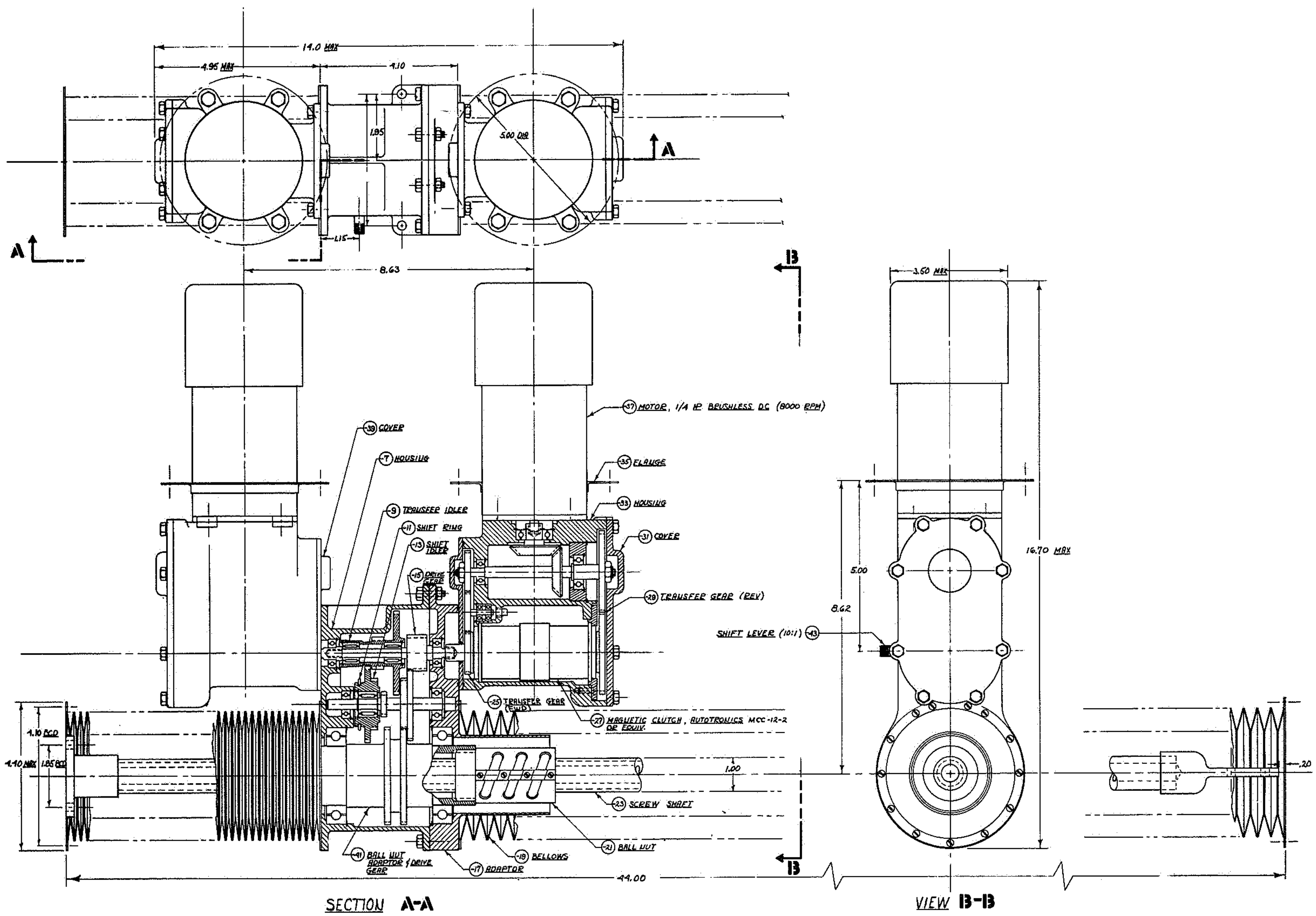


Figure 39 - Counterbalance System - Counterweight Axial Drive Mechanism

The physical envelope and internal arrangement of the counterweight axial drive is illustrated by figure 39. The weight estimate based on this design is 41.0 lbs for the total assembly.

Water System

A water system is required on board the centrifuge to supply fluid for the shower and hygiene experiments. Present system design is based on an estimated minimum requirement for ten gallons of fluid which can be replenished after each experiment run. It is recommended that the systems equipment be permanently installed rather than a packaged supplementary application due to its mass and complexity which would make temporary installation time consuming and compromising to the overall balance of the machine.

General Description. - The water system is shown schematically by figure 40 Six containers, four supplying fresh water and two receiving waste water, are located at the maximum radial position on the counterweight swing frame. Multiple containers are required in order to maintain the center of mass of the fluid on the swing frame centerline and at a relatively constant radial position. Fairly constant mass distribution is achieved by keeping the mass of circulating fluid small and returning the expended fluid to a radial position identical with that of the supply fluid. Location of the water tanks on the swing frame arm allows the water and component mass (approximately by 100 lbs) to serve as a passive part of the counterbalance system. In operation, water is transferred from the counterweight side of the centrifuge to the experiment chamber through permanently installed lines. Either plastic or .020 in wall thickness stainless tubing is applicable in tube sizes of 3/8 inch for the supply and 1/2 inch for the return circuit. After its use in the experiment, the water is pumped back to the collection tank with a minimum mass accumulation being allowed to build up between utilization and return.

Expulsion of water from the supply reservoir is accomplished on demand by a simple pneumatic blowdown. Expulsion gas is supplied by a replaceable 50 cubic inch capacity bottle containing dry air or nitrogen at 3000 psia. Alternate approaches using a small compressor may be substituted if a high pressure gas source is not available or if the high pressure gas becomes objectionable from a safety standpoint. The supply gas is regulated down to 60 psia before entering the reservoir expulsion bladder, providing a new fluid supply pressure of 50 psi if a 10 psia spacecraft environmental pressure is assumed. Bladder construction of both supply reservoirs and collection tanks is specified to eliminate sloshing and mass shifts due to free fluid surfaces. For the collection tank a separate regulator supplies pressurant gas at 15 psia to provide a net 5 psi back pressure.

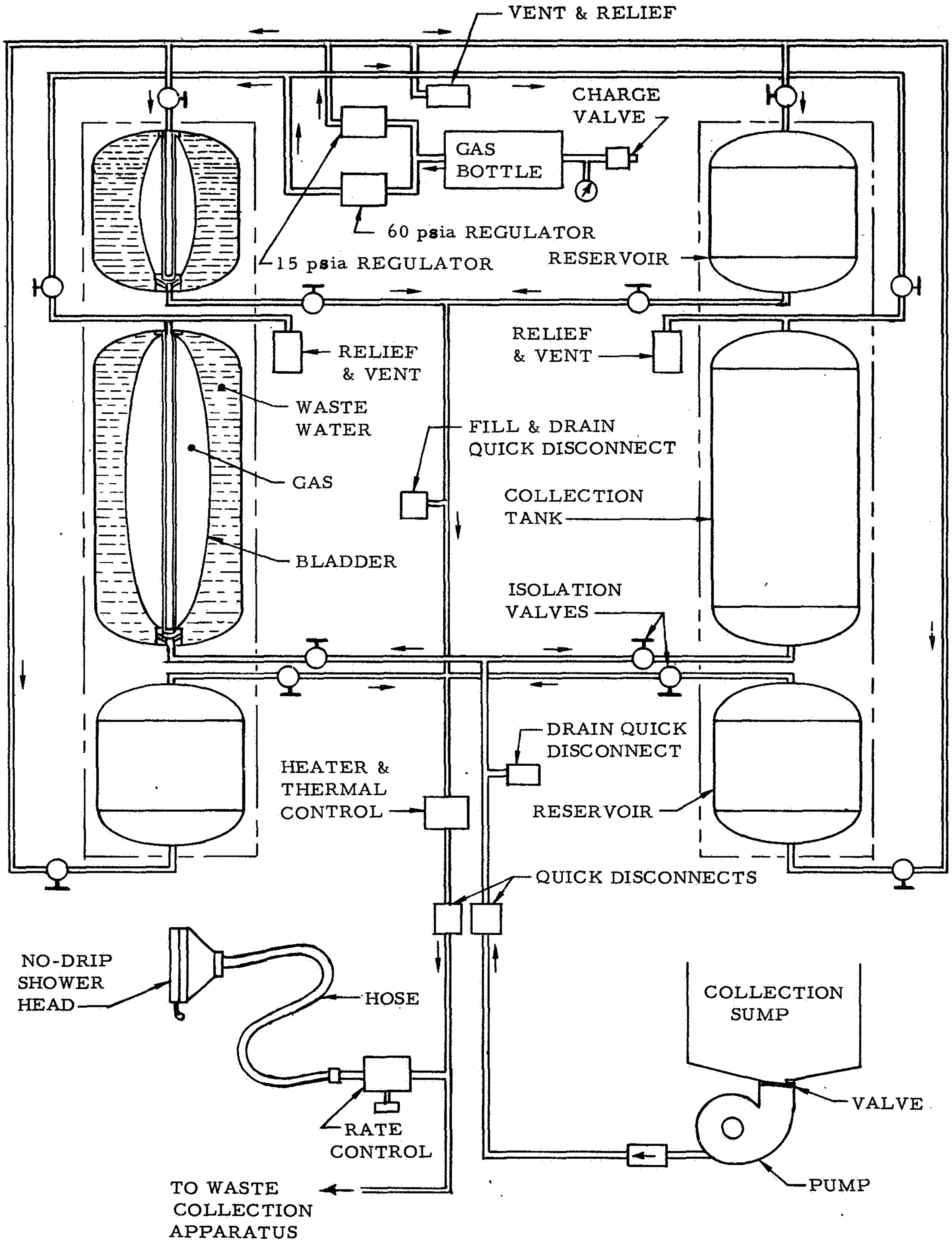


Figure 40 - Schematic Diagram - Centrifuge Water System

All tanks are provided with manually operated isolation valves to allow their removal for maintenance such as bladder replacement or cleaning. In the event that one of the tanks malfunctions, sytem operation can be continued at reduced fluid capacity by isolating the faulty unit.

Relief valves are provided to allow collapse of the bladder during tank filling and to prevent over pressurization in the event of regulator failure.

Quick disconnect fittings are provided for servicing operations such as filling and draining, and for connection of the system to the hygiene experiment package.

Control of water temperature can be achieved either by filling the system with water at an appropriate temperature just prior to the experiment run or by introducing a heater into the circuit. The use of a heater is presently recommended in order to achieve greater flexability and control accuracy and to eliminate the need for heating at the resupply source.

An electrically powered unit with integral manually set temperature controls will be located in the water feed line as indicated. Assuming that the maximum water flow rate is 2 gal/min and the water temperature is increased from a mean of 70°F to 110° F, power requirements will be in the order of 1.5 KW (including losses) for a 5 minute shower period.

Operation and Servicing. - The centrifuge is designed to operate with a full charge of water in the water system for maintaining proper balance. Once the initial charge of water is expended in an experiment, the used water must be drained off and a fresh charge loaded. The procedure suggested is to provide lines to the spacecraft fresh and waste water systems in the centrifuge chamber. The fresh water line is connected to the centrifuge water system "fill" quick disconnect. If water pressure is sufficiently high (70-80 psia) the supply reservoirs will fill directly. If spacecraft water system pressure is low, filling must be preceded by venting of the reservoir bladder. Discharge of the centrifuge waste water into the spacecraft waste water system is accomplished in a similar manner through the "drain" quick disconnect. If the spacecraft waste water system operates at a pressure higher than the collection tank bladder pressure (15 psia), then the collection tank pressure will have to be in-increased to effect the transfer. This can be accomplished by temporarily diverting the 60 psia regulated pressurant to the collection tank bladder and locking out the low pressure relief valve. In both cases, the same procedure will vent entrained air which must not be allowed to accumulate in the system. Air trapped on the supply side of the system will reduce the volume of available water and change the balance of the machine. Air trapped in the collection tank will decrease its capacity and may block drainage of waste water.

In addition to servicing the water supply, the tank pressurant must be replenished between each operating period. Replacement of the entire gas bottle with a fully charged unit is the most convenient method. Spent gas supply bottles may then be recharged at a high pressure source on the spacecraft or recycled through the logistics system.

Connection of the hygiene experiment package with the water system is accomplished by coupling hoses from the experiment package with the supply and return quick-disconnect fittings. No other interface with the experiment package is required as the system operates on demand and water will be furnished until the supply is exhausted.

Main Drive System

Parameters - Provision of a 42-inch access tunnel through the centrifuge hub dictated that a new concept for the primary drive system would be required. An evaluation of the redefined experiment requirements, as related to the mass properties of the selected centrifuge configuration is shown in Table 6.

Table 6

Experiment Requirements

Experiment	I Slug ft^2	ω Rad/Sec	α Rad/Sec^2	T Ft. Lbs.	Mo Ft. Lb. Sec	HP	Peak Power (Watts)
Mobility	1040	1.44	.036	37.4	1500	.098	73.1
Work Bench	1450	1.18	.0245	42.7	1710	.092	69.3
Hygiene	1140	1.47	.0368	41.9	1678	.12	89.5
Reentry	1475	4.9	.123	181.1	7225	1.62	1205
Grayout	1120	4.58	.0763	85.5	5130	.71	532
Tilt Table	1175	2.4	.12	141	2820	.62	462
Vestibular	1280	2.4	.24	307.5	3075	1.35	1009
Therapeutic	1450	2.7	.159	230	3918	1.13	844

Reflecting these data and the previously established design requirements, the following design parameters were established for the primary drive system.

a. The centrifuge will provide a range of inertial environment from .1 g to 9 g.

b. The drive system will be capable of producing accelerations duplicating the g-onset profile of an Apollo reentry.

c. Angular velocity of the centrifuge will remain constant within 1% of any selected control setting.

d. Both manual and programmed angular velocity control will be provided in the drive control system.

e. An emergency stop capability, overriding all other control commands will be provided for both the test subject, in the experiment chamber, and the test monitor at the control console.

f. Since the drive system must be mounted upstream of the counterbalance sensing system, careful consideration must be given to the dynamic balance of the drive system and the support ring assemblies.

g. A positive braking system, capable of bringing the centrifuge to a full stop from 9-g simulation within 30 sec, will be provided.

Drive System Velocities - As determined from the experiment definitions, the radial point at which a specified g level is required will vary with the test subjects position. It has been determined, however, that by providing a .1 g to 9 g environment at the floor radius, (110 in.) all of the experiment g requirements can be met.

$$\text{Min. RPM} - \sqrt{\frac{.1\ g}{2.84 \times 10^{-5} \times 110}} = 5.65\ \text{RPM}$$

$$\omega_{min} = \frac{2\ \pi\ \times\ 5.65}{60} = .59\ \text{Rad/Sec}$$

$$\text{Max. RPM} - \sqrt{\frac{9\ g}{.00312}} = 53.75\ \text{RPM}$$

$$\omega_{max} = \frac{6.28 \times 53.7}{60} = 5.62\ \text{Rad/Sec}$$

Accelerations - The largest power requirement is established by the reentry experiment (i.e. 6.5 g in 40 sec). Since the 6.5 g-requirement is related to the test subject's c.g., which is located approximately 6 inches above the floor level, the radius is 104 inches.

$$\text{RPM} = \sqrt{\frac{6.5}{2.84 \times 10^{-5} \times 104}} = 46.9 \text{ RPM}$$

$$\omega = \frac{6.28 \times 46.9}{60} = 4.9 \text{ Rad/Sec}$$

$$\alpha = \frac{4.9 \text{ Rad/Sec}}{40 \text{ Sec}} = .123 \text{ Rad/Sec}^2$$

From Table 14, it will be seen that the maximum acceleration requirement is related to the vestibular experiments, ω .24 Rad/Sec^2. This results from a .1 g/sec, g-onset rate required for these experiments. The mass moment of inertia during the experiments, however, is relatively low and the velocities are also small, so the overall power requirement is below that of the reentry experiment.

Deceleration - The deceleration requirement was arbitrarily set by selecting 30 seconds as the maximum stopping time from a 9-g rotation.

$$\alpha = \frac{5.62 \text{ Rad/Sec}}{30 \text{ Sec}} = .187 \text{ Rad/Sec}^2$$

Drive Torques - The highest mass moment of inertia of the centrifuge, based on the experiment protocols and selected design concept, is approximately 1500 slug ft^2. The maximum acceleration torque is therefore:

$$T \quad I\alpha_{acc} = 1500 \times .123 = 184.5 \text{ ft. lbs.}$$

or 2214 in. lbs.

Deceleration Torque:

$$T = I\alpha_{del} = 1500 \times .187 = 280 \text{ ft. lb.}$$

or 3365 in. lbs.

Horsepower Requirements - For the maximum operating condition (reentry experiment):

$$\text{System HP} = \frac{2214 \times 46.9}{63025 \times \text{Eff.}} = 1.64 \text{ (100\% Eff.)}$$

Drive Efficiencies:

Motor	70%
Gearing	95%

$$\text{Eff. Factor} = \frac{1}{.7 \times .9} = 1.59$$

$$\text{Motor HP Required} = 1.64 \times 1.59 = 2.5 \text{ HP}$$

Braking Requirement:

$$\text{Brake HP} = \frac{3365 \times 53.7}{63025 \times \text{Eff}} = 2.9$$

Brake Eff 85%

$$\text{HP} = \frac{2.9}{.85} = 3.4$$

Motor Selection - The centrifuge requires a variable speed drive with a control range from 0 to 55 RPM. From a review of available off-the-shelf hardware, and recent motor development programs, it was determined that an AC motor with a variable frequency, variable voltage speed controller would meet these requirements. On this basis the following motor parameters were selected.

a. 4-pole, 120-cycle, 3-phase, induction type

b. HP rating: 3 HP @ 3500 RPM

c. Variable speed control from 64 RPM to 3500 RPM

d. Continuous duty - with thermal overload protection and

e. Automatic reset

f. Control signal 0-10 volts

<u>Drive Transmission</u> - The drive train is composed of a segmented ring gear mounted on the stationary support ring (Ref. Fig. 41 (SRC-SD-427). The drive unit is installed on the drive ring which is attached to the rotating portion of the centrifuge through the counterbalance sensing system. Stability between the drive ring and the stationary support ring is provided by a system of 12 equally spaced roller assemblies mounted on the support frame and riding two angular tracks on the drive ring. Incorporated into the gear housing is a magnetic brake assembly and tachometer unit.

<u>Segmented Ring Gear</u>:

Pitch Diameter	-	48 inches (P.D.)
Diametral Pitch	-	16 (D.P.)
Number of Teeth	-	768 (N)
Pressure Angle	-	14 1/2°
Circular Pitch	-	.1963 (C.P.)
Tooth Load (W)	=	$\frac{2 \times \text{Torque}}{\text{PD}}$

$$T_{max} = 3365 \text{ In. Lbs. (Deceleration)}$$

$$W = \frac{2 \times 3365}{48} = 140 \text{ lbs.}$$

$$\text{Face Width} = \frac{W \times (600 + V)}{S \times C.P. \times Y \times 600}$$

S = 20,000 (Alum)
Y = .124 = Form Factor
V = .262 x 48 x 55 = 688 ft/min
CP = .1963 Circular Pitch

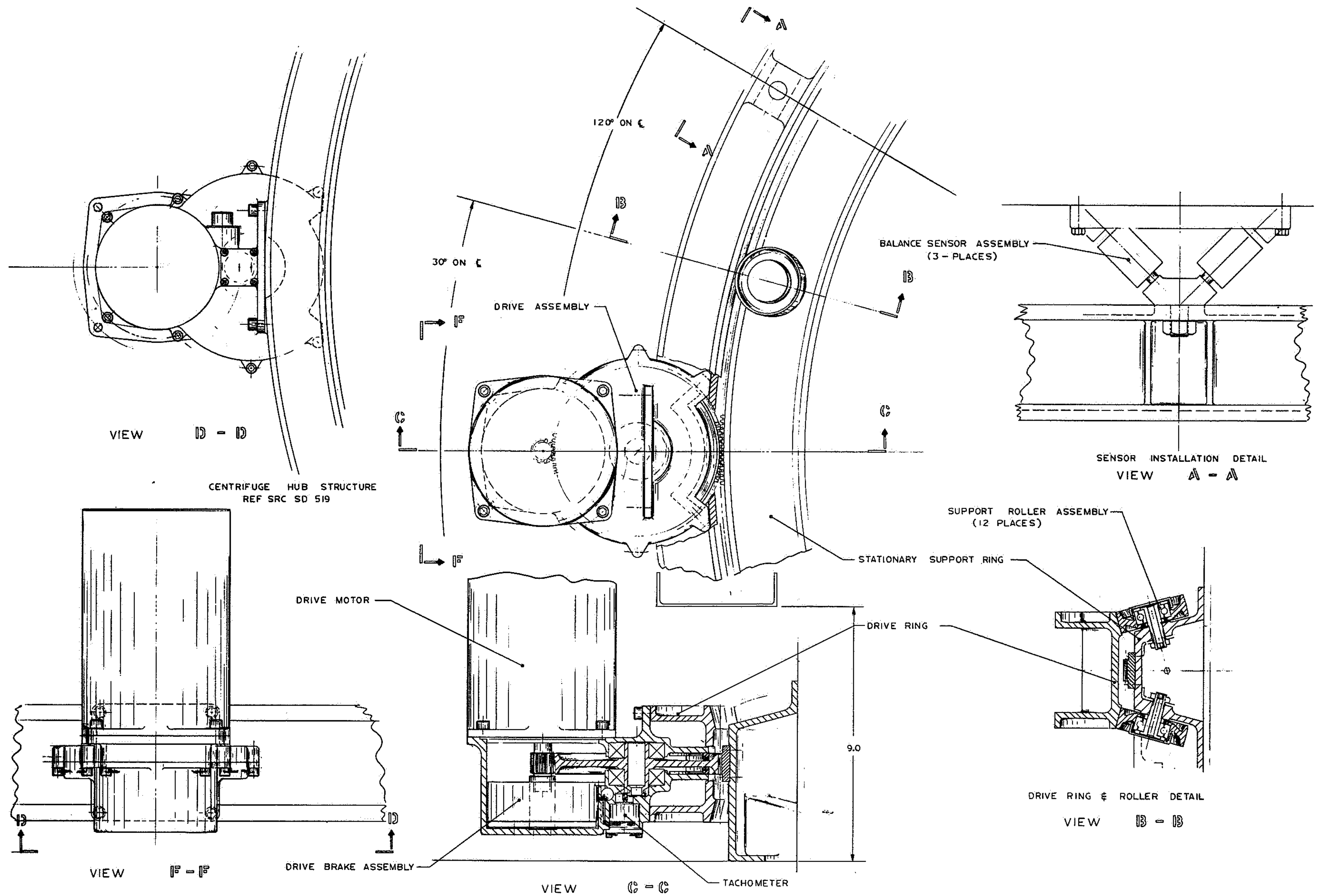


Figure 41. Primary Drive System (SRC-SD-427)

$$F.W. = \frac{140 \times 1288}{20,000 \times .1963 \times .124 \times 600}$$

F.W. = .612 Inches (Use .75)

Gear Weight = 3.5 Lbs.

Primary Drive Gear:

P.D. - 6 Inches (8:1 Reduction)
D.P. - 16
N - 96
Press Angle - 14 1/2^{o}
C.P. - .1963
W - 140 lbs.
V - 688 Ft/Min (440 RPM)

$$T_{max} = \frac{140 \times 6}{2} = 420 \text{ in lbs.}$$

S = 20,000
Y = .116

$$F.W. = \frac{140 \times 1288}{20,000 \times .1963 \times .116 \times 600}$$

F.W. = .66 - (Use .75)

Gear Weight = .7

Drive Pinion Gear:

P.D. - .75 Inches (8:1 Reduction)
D.P. - 16
N - 12
Press Angle - 14 1/2^{o}
C.P. - .1963
W - 140 Lbs.
V - 688 ft/min

$$T_{max} = \frac{140 \times .75}{2} = 52.5 \text{ In. Lb.}$$

MASS PROPERTIES

From the mechanical and structural designs and the materials selected in the previous sections of this study, detailed weight calculations were made for each item on the rotating portion of the centrifuge. The weight of each item is shown in Table 7 which groups the items by functional areas or assemblies. Additionally, a subtotal is shown for the moveable portion of the counterweight system.

Table 8 shows a summary of the total rotating and the fixed weight items. It also shows the total weights that comprise the complete centrifuge experiment package.

The requirements generated by the experiment program result in out-of-balance conditions that have to be compensated by the counterweight system. The static out-of-balance for the seven major experiments is shown in Table 9. Using this data the centrifuge can be balanced with the counterweight system. Table 10 shows the static balance for each of the experiments. It shows that water is not required for balance during the grayout and the mobility experiments. This table was compiled assuming that the hub structure was statically and dynamically balanced.

Table 11 shows the individual weights of the four experiment packages.

From this data the mass moment of inertia of the centrifuge was generated. The centrifuge was broken down into fairly large section. Then, the I_{xx} about the spin axis was calculated along with I_0, the moment of inertia about the section's own center of gravity. The items that were fixed or not changed by the experiment's requirements were calculated first. Then to this was added the inertias generated by the variable items for each experiment. The total of each of these for each experiment is shown in Table 12.

Table 7 — Detailed Weight Statement

Experiment Chamber		(102)
Stiffeners	6.6	
Skin	55.0	
Main Frame	20.0	
Beaded Stiffeners	5.0	
Stiffener Splice	1.8	
Misc. Splice	4.6	
Hub Attach.	4.0	
Misc.	5.0	
Floor		(30)
Corrugated Skin	15.0	
Side Frame	6.0	
Skin (Cover)	4.5	
Misc.	4.5	
Hub Structure		(202.8)
Primary Ring	24.2	
Secondary Ring	15.0	
Center Post	6.8	
Support Channel	3.5	
Outer Skin	10.5	
Inner Skin	8.0	
Misc. Angles	1.0	
Access Frames	5.2	
Splices	2.0	
Sensors	6.0	
Outer Ring and Track	31.5	
Motor and Gear Box	32.0	
Shrouds	3.0	
Pivot Fitting	4.5	
Pivot Mechanism	39.2	
Misc.	10.0	
Swing Frame		(81.5)
Tracks	16.0	
Upper and Lower Webs	4.5	
Inboard Angles	1.6	
Upper and Lower Angles	1.1	
Pivot Fitting	3.5	
Tank Supports	12.0	
Inboard Web	2.5	
Drive Screws	12.0	

Table 7 — Detailed Weight Statement (cont'd.)

Swing Frame (cont'd.)		
Water Storage Tanks	9.0	
Water System	6.0	
Tank Shrouds	4.3	
Pressurant System	4.0	
Misc.	5.0	
Carriage Support Structure		(15.00)
Tracks	10.0	
Webs	3.5	
Stiffs	1.5	
Counterweight Structure		(10.0)
Angles	1.20	
Doors	1.00	
Center Webs	1.00	
Supports	.73	
Equipment Shelves	1.30	
Upper and Lower Skins	1.93	
End Skins	1.60	
Misc.	1.23	
Couch Frame		(22.0)
Ring	4.8	
Arms	2.1	
Flange	.9	
Mechanism	12.0	
Misc.	2.2	
Couch		(25.0)
Frames	10.0	
Shells	4.5	
Helmet	1.6	
Pads	1.7	
Comm. and Equipment	3.0	
Restraints	3.2	
Misc.	1.0	

Table 7. — Detailed Weight Statement (cont'd.)

Moveable Counterweight		(200)
Carriage Support Structure	15.0	
Counterweight Structure	10.0	
Drive Mechanism	41.0	
Batteries or Counterweight	121.6	
Electronic Equipment	12.4	

Table 8 – Complete Weight Summaries

Rotating Weight Summary		Operating	Launch
Experiment Chamber Structures		102	102
Experiment Chamber Floor		30	30
Man		200	
Couch		25	25
Support Frame		22	22
Hub Structure & Drive System (Main & Swing)		202.8	202.8
Swing Frame & Water System		81.5	81.5
Moveable Counterweight		200	200
Water		84	
Power & Communication		60	60
Hub Batteries		100	100
Contingency		100	100
	Total	1207.3	923.3
Fixed Weight Summary			
Inner Roller Support Ring		24.5	24.5
Roller System		12	12
Control Console, Lines & Connectors		40	40
Illumination		20	10
CMG System		500	500
Noise & Vibration Damping		110	110
Contingency		70	70
Launch Support Structure			20
	Total	776.5	796.5
Experiment Weight	Total	1983.8	1719.8

Table 9 — Balance Conditions and Experiment Requirements

EXPERIMENT	REQUIREMENTS	WEIGHT X RAD LBS-IN
1. Reentry	Frame at 66.5 Man & Couch on Floor at 104	1,460 23,400 (24,860)
2. Vestibular	Frame at 66.5 Man & Couch at 93.2	1,460 20,900 (22,360)
3. Tilt Table	Frame at 66.5 Man & Couch at 86.0	1,460 19,300 (20,760)
4. Therapeutic	Frame at 66.5 Man & Couch at 103	1,460 23,200 (24,660)
5. Greyout	Frame at 66.5 Man & Couch at 76.5	1,460 17,200 (18,660)
6. Mobility	Frame & Couch at 50.0 Man at 74.0	2,350 15,400 (17,750)
7. Hygiene	Frame at 66.5 Man & Facility at 74.0 Couch on Floor at 104	1,460 16,700 2,600 (20,760)

Table 10 - Static Balance and Counterweight Positions

EXPERIMENT	ITEM	-Z WT LBS	-Z RAD INS	-Z WR LBS IN	+Z ITEM	+Z WR LB IN
1. Reentry	S. Frame	126.5	70.8	8960	Chamber	7900
	Water	84.0	100.0	8400	Experiment	24860
	C. Weight	200.0	77.0	15400		
				(32760)		(32760)
2. Vestibular	S. Frame	126.5	70.8	8960	Chamber	7900
	Water	84.0	100.0	8900	Experiment	22360
	C. Weight	200.0	64.5	12900		
				(30260)		(30260)
3. Tilt Table	S. Frame	126.5	70.8	8960	Chamber	7900
	Water	84.0	100.0	8400	Experiment	20760
	C. Weight	200.0	56.5	11300		
				(28660)		(28660)
4. Thera-peutic	S. Frame	126.5	70.8	8960	Chamber	7900
	Water	84.0	100.0	8400	Experiment	24660
	C. Weight	200.0	76.0	15200		
				(32560)		(32560)
5. Greyout	S. Frame	126.5	70.8	8960	Chamber	7900
	C. Weight	200.0	88.0	17600	Experiment	18660
				(26560)		(26560)
6. Mobility	S. Frame	126.5	70.8	8960	Chamber	7900
	C. Weight	200.0	83.5	16690	Experiment	17750
				(25650)		(25650)
7. Hygiene	S. Frame	126.5	70.8	8960	Chamber	7900
	Water	84.0	100.0	8400	Experiment	20760
	C. Weight	200.0	56.5	11300		
				(28660)		(28660)

Table 11 - Individual Experiment Package Weights

Mobility and Balancing Experiment Package	8
Work Bench Experiment Package	20
Hygiene & Personal Care Experiment	30
Cardiovascular and Vestibular Effects Experiment	40

Table 12 - Mass Properties Of The Rotating Assembly

EXPERIMENT	ITEM	WEIGHT LBS	Z^2 FT^2	Ixx LBS FT^2	Io (LBS FT^2)	MASS MOMENT OF INERTIA Ixx + Io (LBS FT^2)	(SLUGS FT^2)
	Floor	30.0	80	2400	137	2537	
	Room	102.0	40.6	4150	1293	5443	
	Hub + Equip.	373.0	-	-	1420	1420	
	C. Weight Mech.	44.0	6.7	295	-	295	
	S. Frame	81.5	59	4800	250	5050	
			Total for Fixed Items			(14745)	
1. Reentry	Man & Couch	225.0	75.5	17000	710	17710	
	Frame	22.0	30.3	662	35	697	
	C. Weight	200.0	41.0	8400	35	8435	
	Water	84.0	70.0	5880	25	5905	
						(47492)	(1475)
2. Vestibular	Man & Couch	225.0	60.0	13500	710	14210	
	Frame	22.0	30.3	662	35	697	
	C. Weight	200.0	29.0	5800	35	5835	
	Water	84.0	70.0	5880	25	5905	
						(41392)	(1280)
3. Tilt Table	Man & Couch	225.0	51.0	11500	710	12210	
	Frame	22.0	30.3	662	35	697	
	C. Weight	200.0	22.0	4400	35	4435	
	Water	84.0	70.0	5880	25	5905	
						(37992)	(1175)
4. Therapeutic	Man & Couch	225.0	74.0	16600	710	17310	
	Frame	22.0	30.3	662	35	697	
	C. Weight	200.0	40.0	8000	35	8035	
	Water	84.0	70.0	5880	25	5905	
						(46692)	(1450)
5. Greyout	Man & Couch	225.0	40.5	9100	710	9810	
	Frame	22.0	30.3	662	35	697	
	C. Weight	200.0	54.0	10800	35	10835	
						(36087)	(1120)
6. Mobility	Man	200.0	38.0	7600	500	8100	
	Frame	22.0	17.0	374	35	409	
	Couch	25.0	17.0	425	200	625	
	C. Weight	200.0	48.0	9600	35	9635	
						(33514)	(1040)
7. Hygiene	Man & Facility	225.0	38.0	8500	400	8900	
	Frame	22.0	30.3	662	35	697	
	Couch	25.0	75.0	1890	200	2090	
	C. Weight	200.0	22.0	4400	35	4435	
	Water	84.0	70.0	5880	25	5905	
						(36772)	(1140)

POWER REQUIREMENTS

As a supplement to previous power estimates published in Reference 1, the direct drive power requirements of the revised room/hub centrifuge configuration were recalculated for each experiment configuration. These power requirements, which are based on the experiment description time lines outlined in this report, are shown in Figures 42 through 50. Only the drive output power necessary to overcome intertia, bearing friction and aerodynamic losses is illustrated. Electrical and mechanical losses, surge power and power required for operation of all other subsystems are not accounted for in this estimate and should be taken from the Reference 1 data. From this analysis, and the conclusions reached during the initial centrifuge study, Reference 1, there are no significant power demands which could not be easily supported by the presently envisioned space station concepts. From the profile charts it can be seen that in all cases the peak demands are of short duration, and the sustained requirements are relatively small. It is felt that the original approach, Reference 1, of utilizing a system of rechargeable batteries mounted on the rotating portion of the centrifuge, is still valid and will meet the energy requirement of the new configuration. In the event that habituation or other experiments of long duration (several days) are included, a method of battery recharge during rotation must be incorporated.

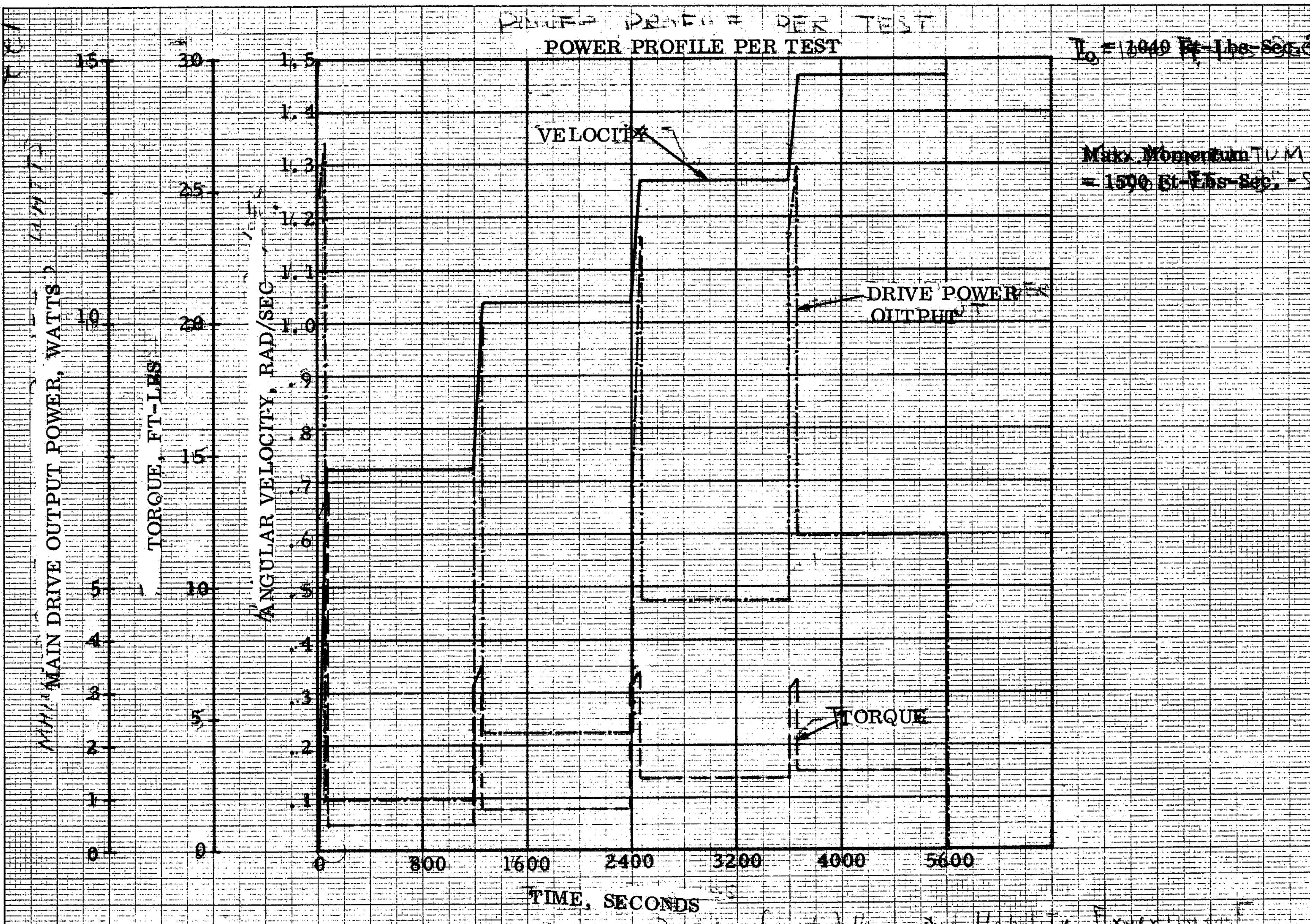


Figure 42. Power Profile for Walking and Mobility Experiment

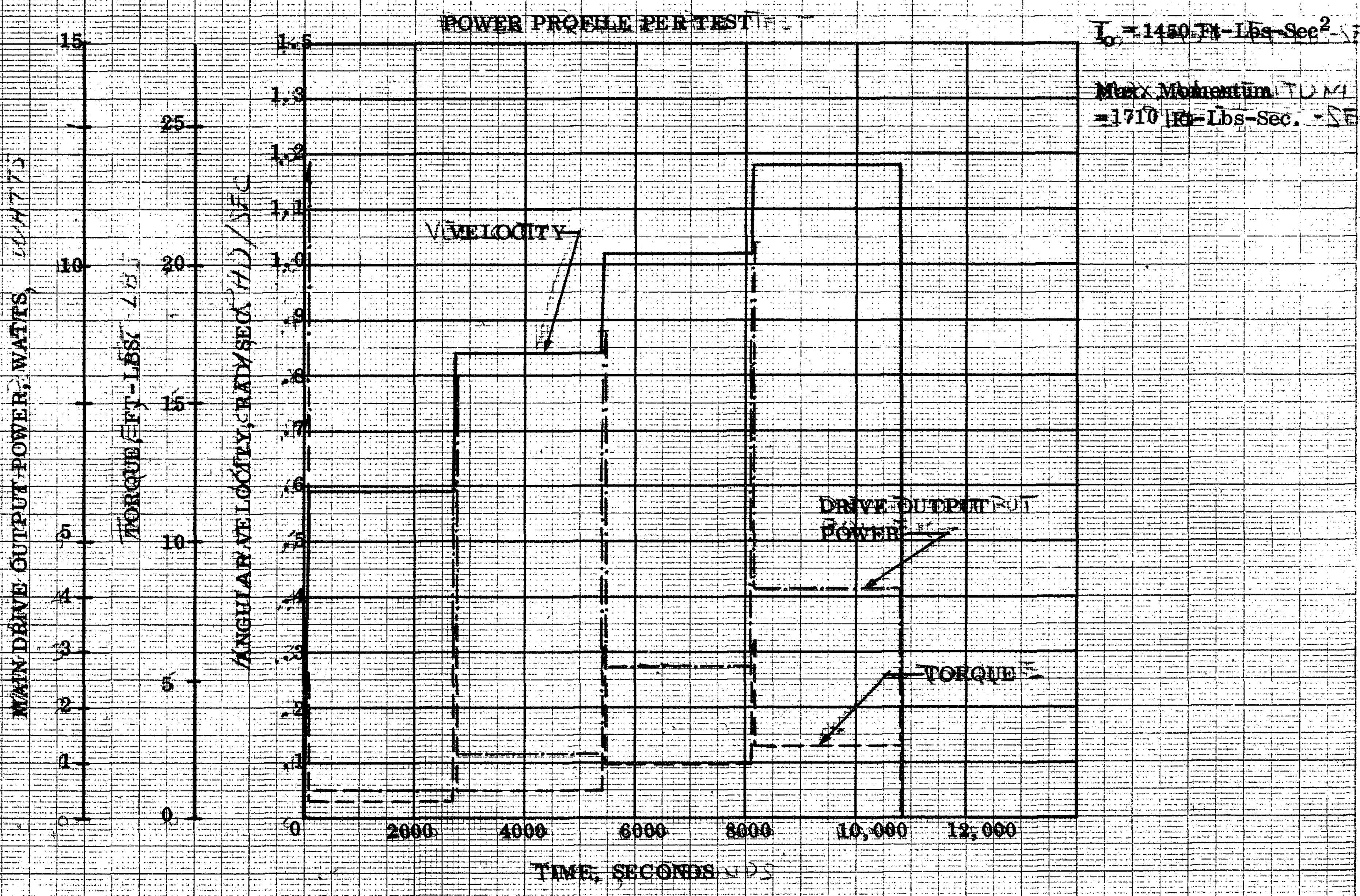


Figure 43. Power Profile for Workbench Experiment

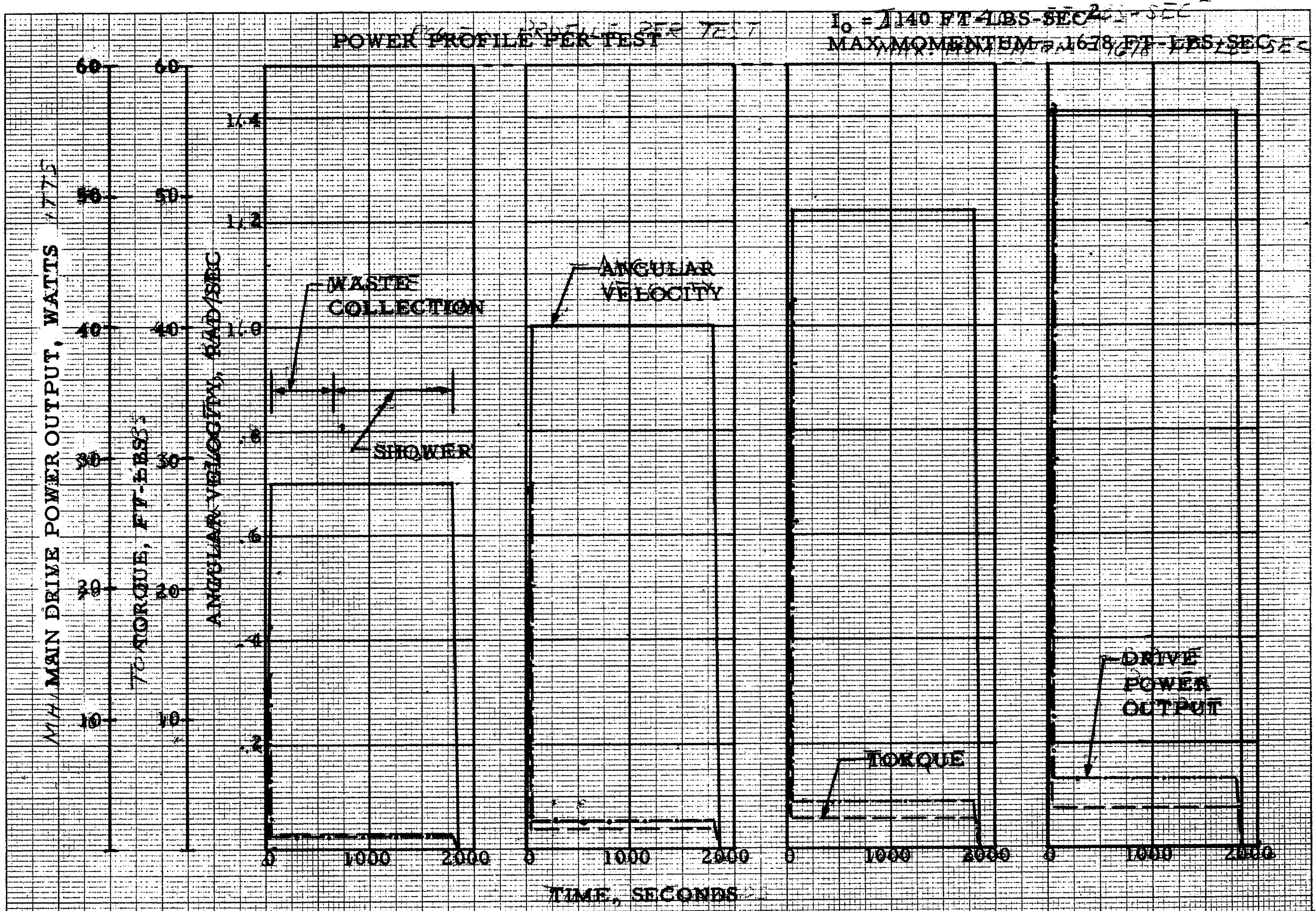


Figure 44c Power Profile for Personal Care Capability Experiment

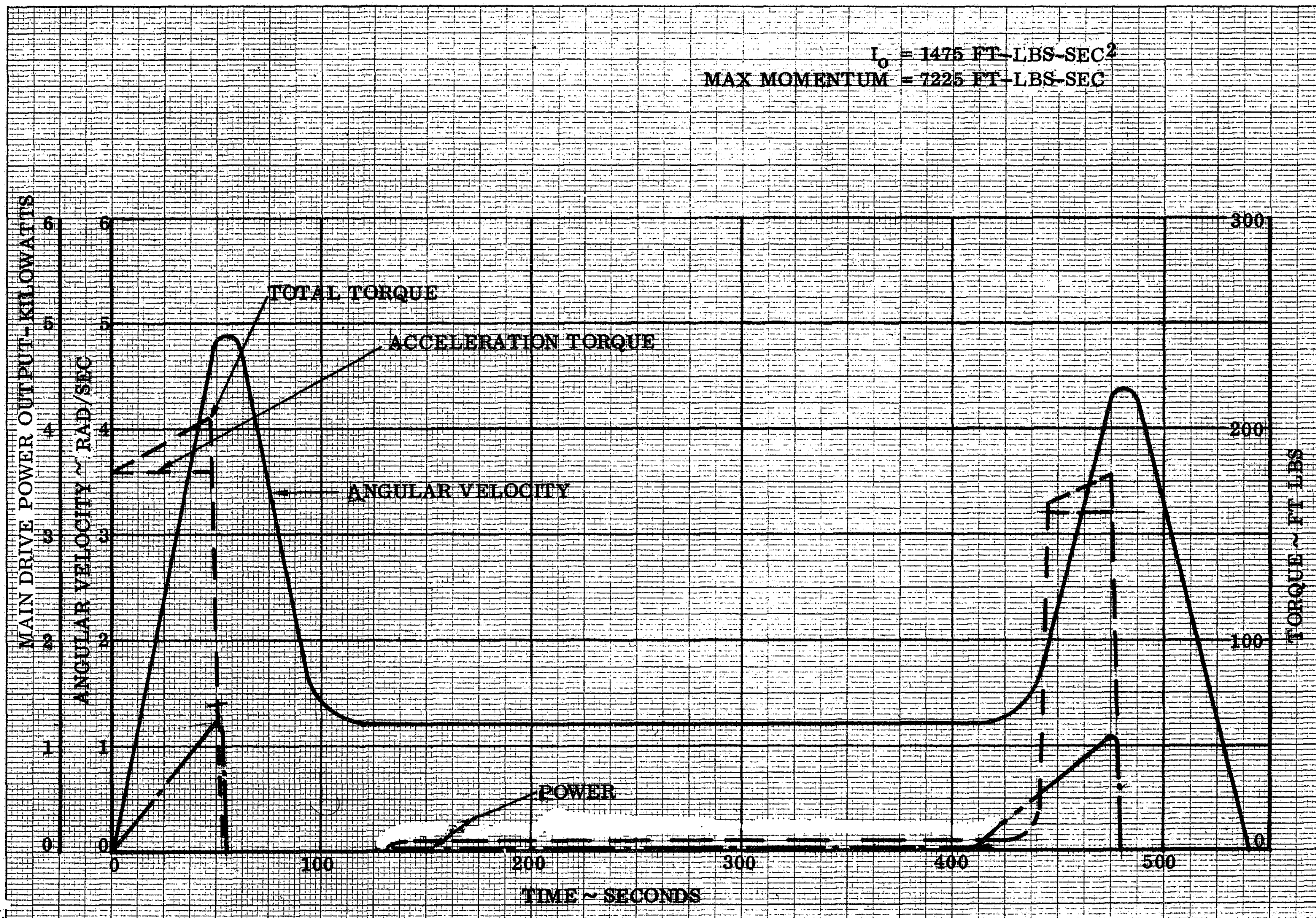


Figure 48. Power Profile for Re-entry Experiment

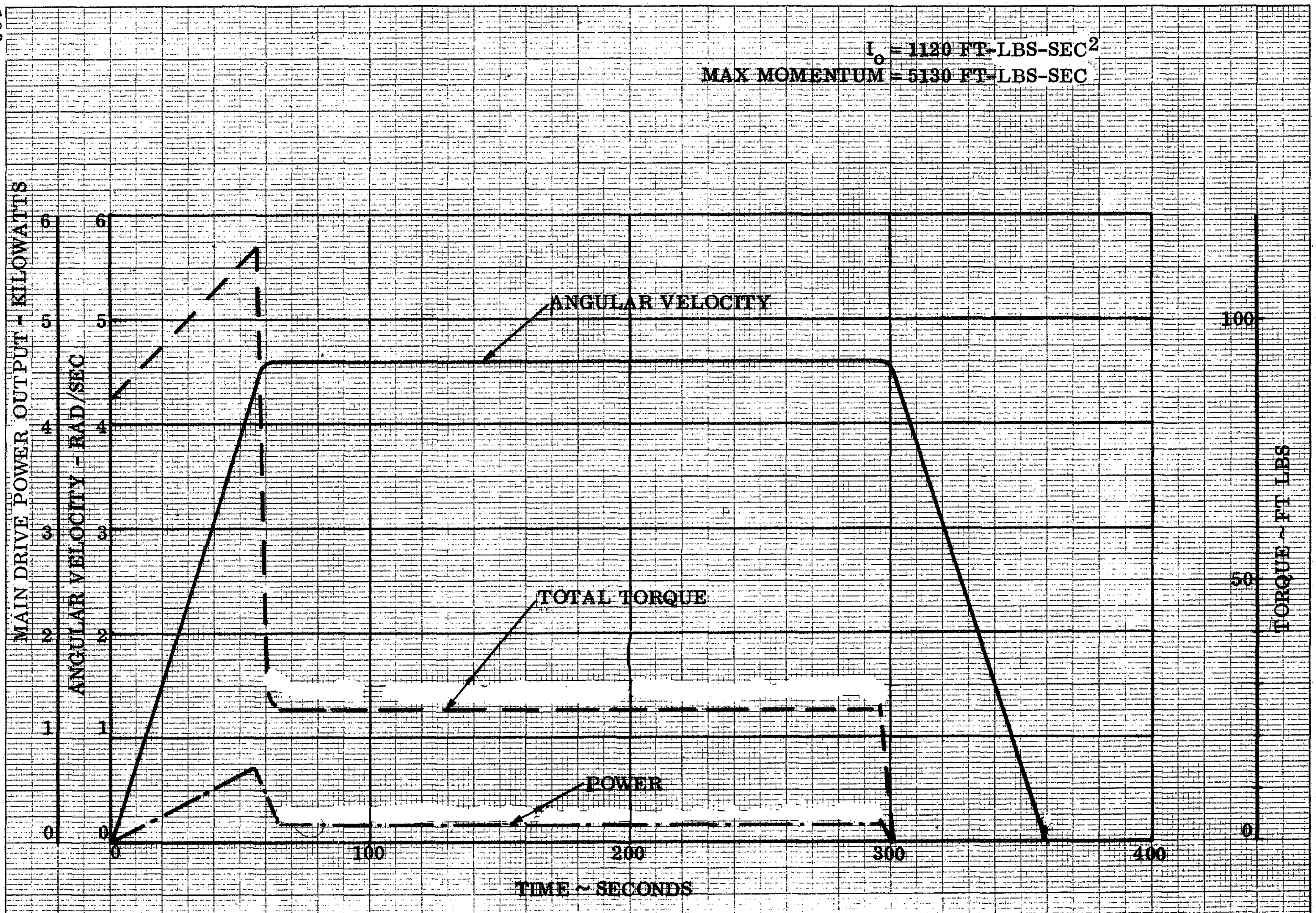


Figure 49. Power Profile for Grayout Experiment

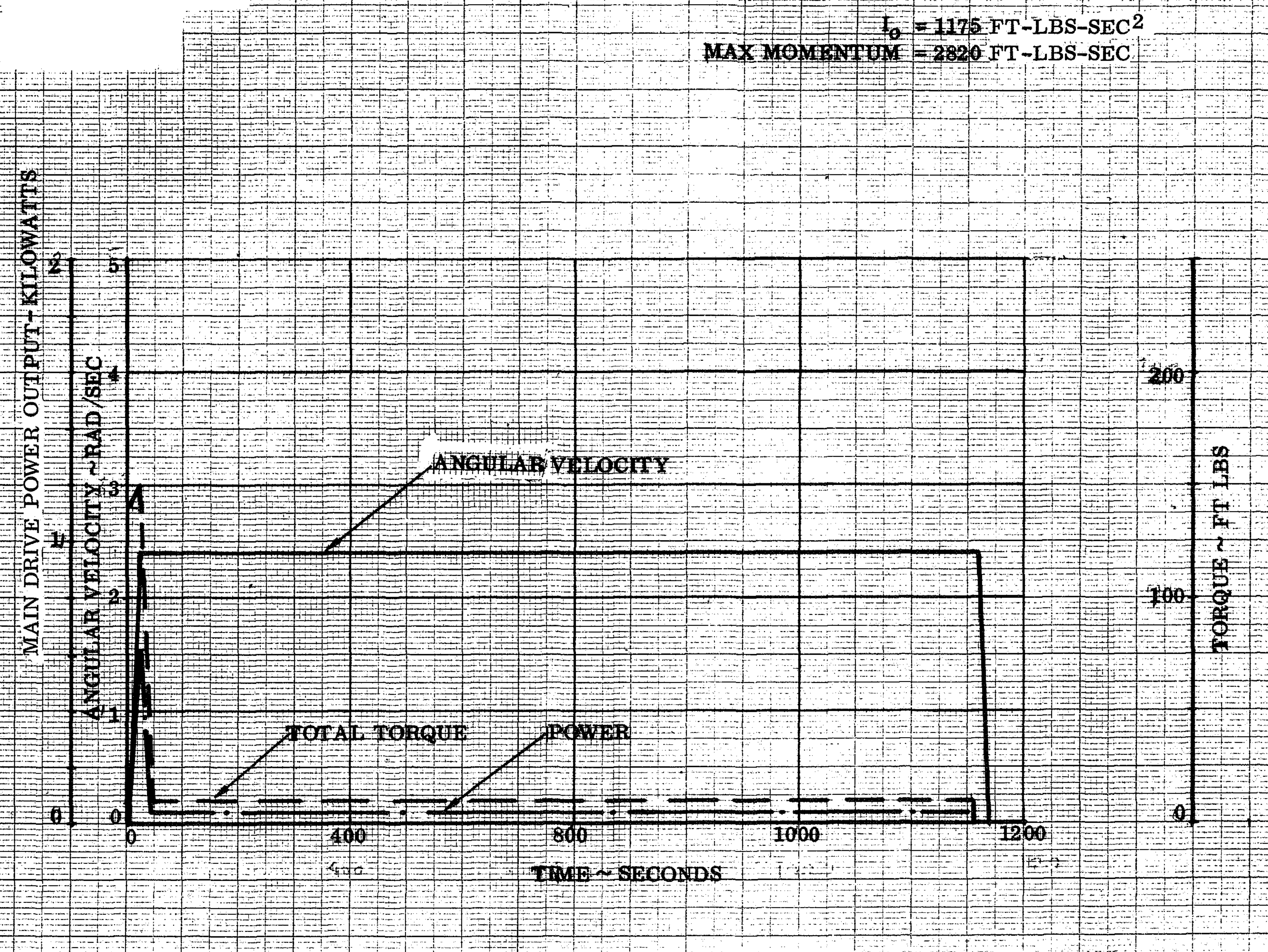


Figure 50. Power Profile for Tilt Table Experiments

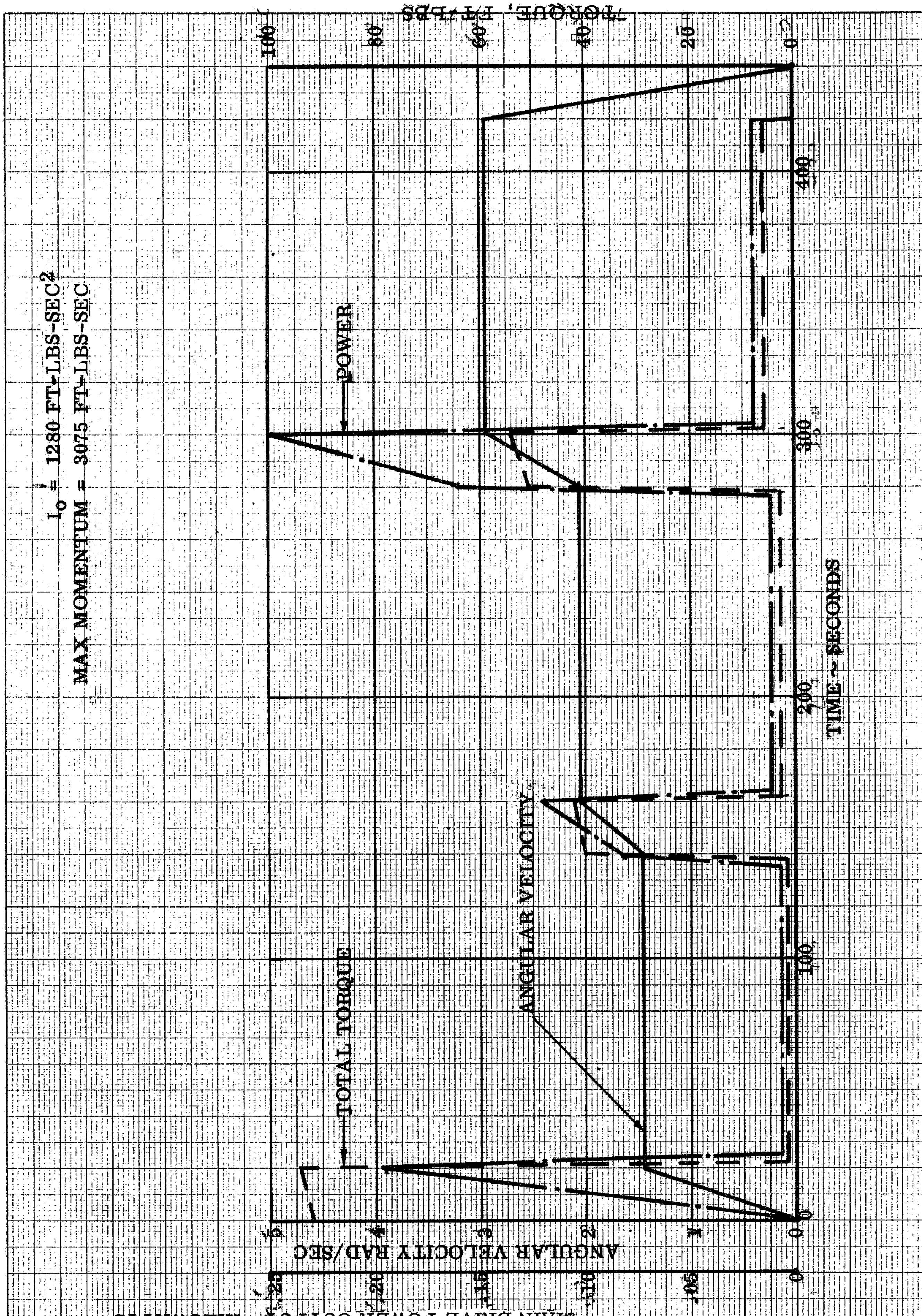


Figure 5_. Power Profile for Sensitivity to Linear Acceleration Experiment

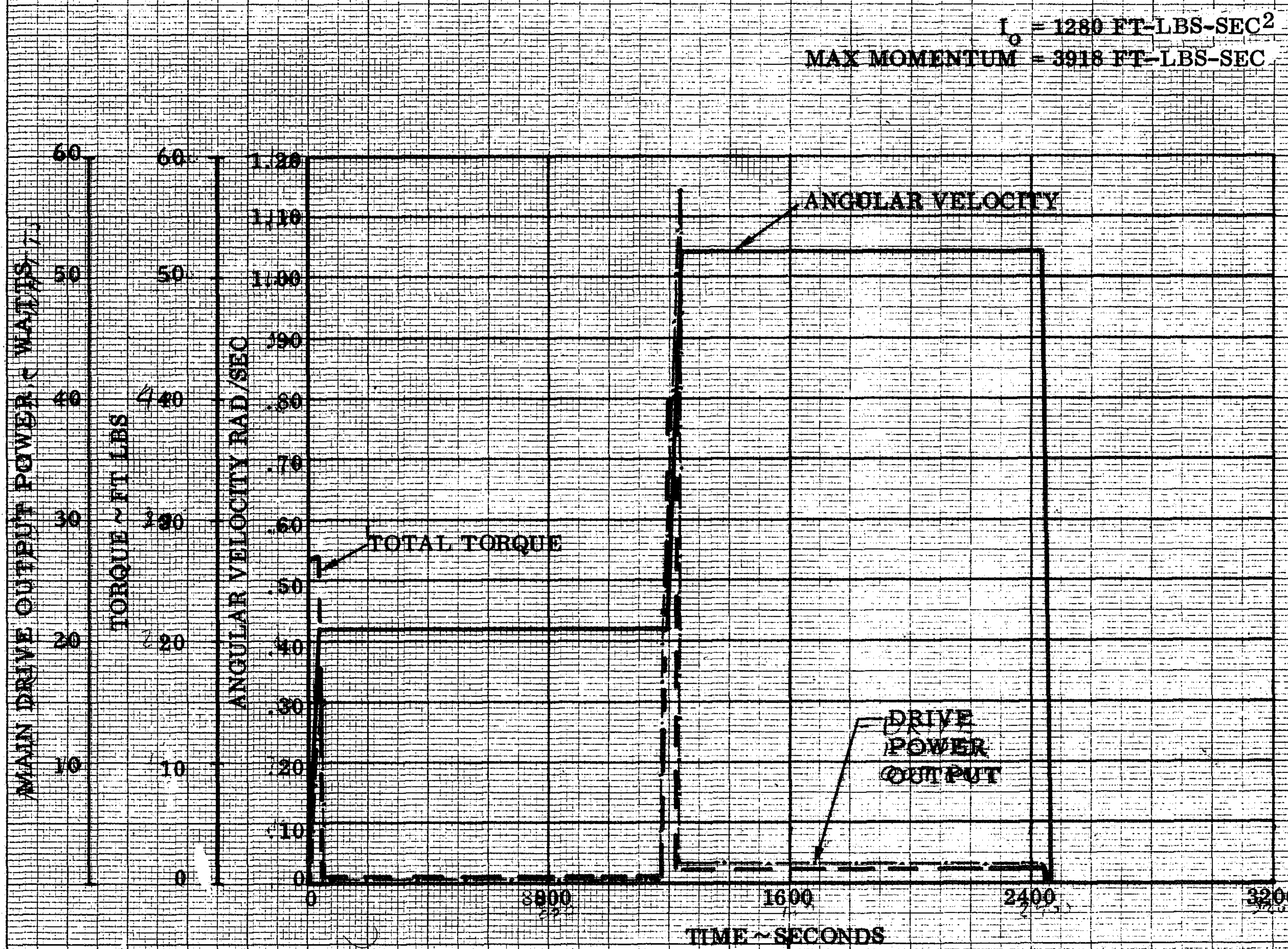


Figure 52. Power Profile for Semicircular Canal and Coupled Angular Velocities

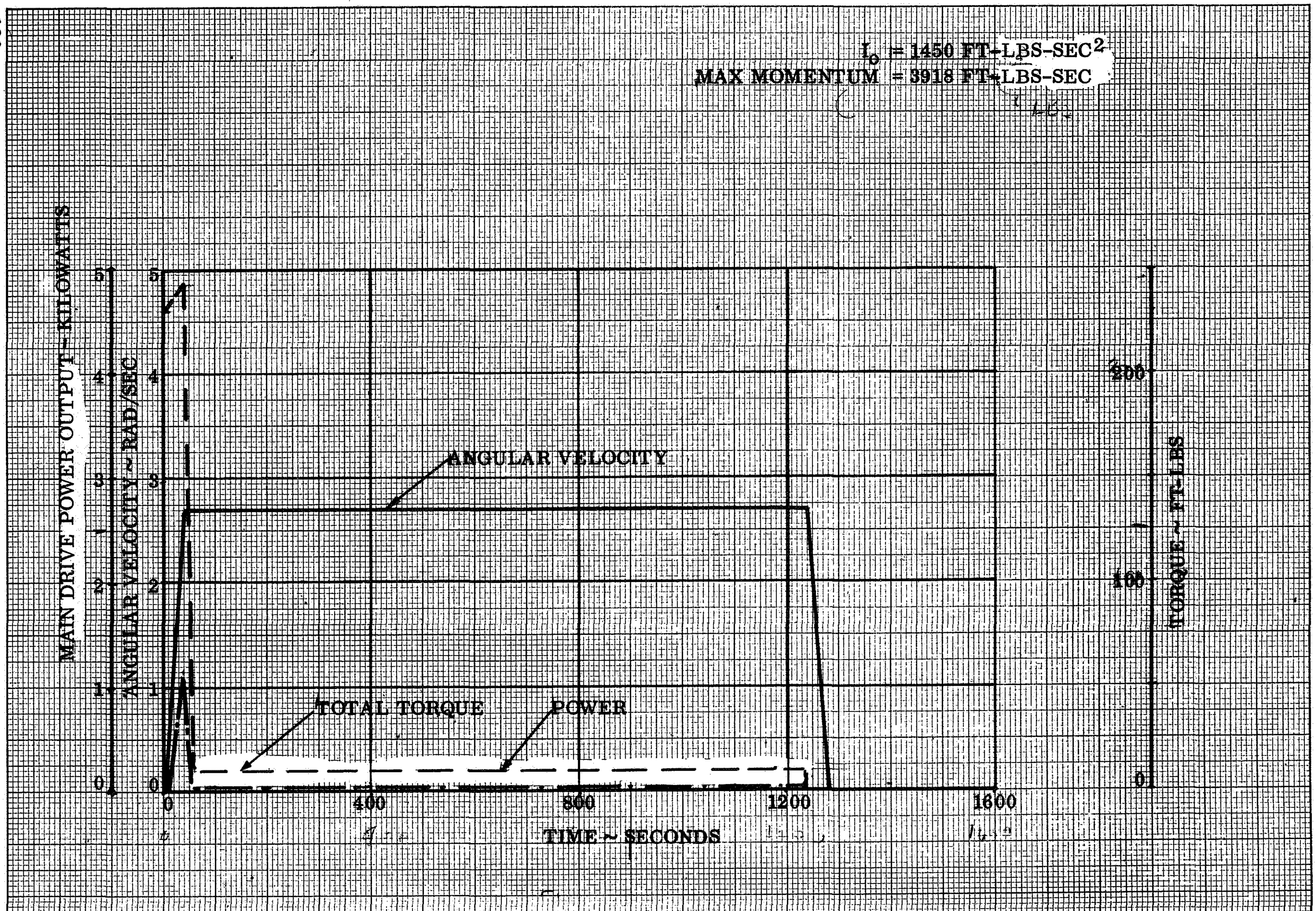


Figure 53. Power Profile for Therapeutic Experiment

ORBITAL CENTRIFUGE INTEGRATION

Space Station

Installation of the selected centrifuge configuration into either the MORL or the EOSS space station concepts does not appear to present a major problem. However, some modification of the existing station designs would be required.

Space Requirement - Location of the centrifuge within these station concepts can be substantially the same as presently shown. The 36-inch height, which is allotted for a centrifuge installation in both configurations, would not, however, be sufficient for a centrifuge having the expanded capabilities defined herein. Two obvious approaches could be taken to solve this problem. One approach would be to slightly reduce floor spacing through the station and of course the other approach would be to lengthen the station by approximately 30 inches.

Center core access can be provided up to a 72 inch diameter, for a 260 inch diameter space station, without materially affecting the baseline configuration (Ref. Fig. 51 (SRC-SD-121). Larger access opening would necessitate increasing the station diameter if the same experiment capability is maintained. Off center access through the centrifuge chamber are not recommended.

Incorporation of the centrifuge into the MORL necessitates the relocation of the lab ECLS equipment and provision for two additional CMG units to react the SRC momentum. No other changes in the equipment arrangement are evident.

MOM Installation

A cursory evaluation of the modular concept was conducted to determine its suitability as a housing for the centrifuge. Figure 52 SRC-SD-120, illustrates a potential module approach.

The module would be initially launched with a baseline of individually packaged experiments. Supplemental experiments could then be launched on a scheduled basis and integrated into the SRC. During inactive periods the SRC module could either remain attached to the Space Station or be undocked and placed into a parking orbit. A standardized automatic docking system, with a manual override, at each end of the module would permit flexibility in space station configuration.

As presently configured, the SRC module would house all of the necessary systems, and provide all the storage space, to support its operation except for power generation and life support. A system of rechargeable batteries, incorporated into the SRC counterbalance system, would provide power to the rotating portion of the centrifuge. These would be recharged from the station power source through

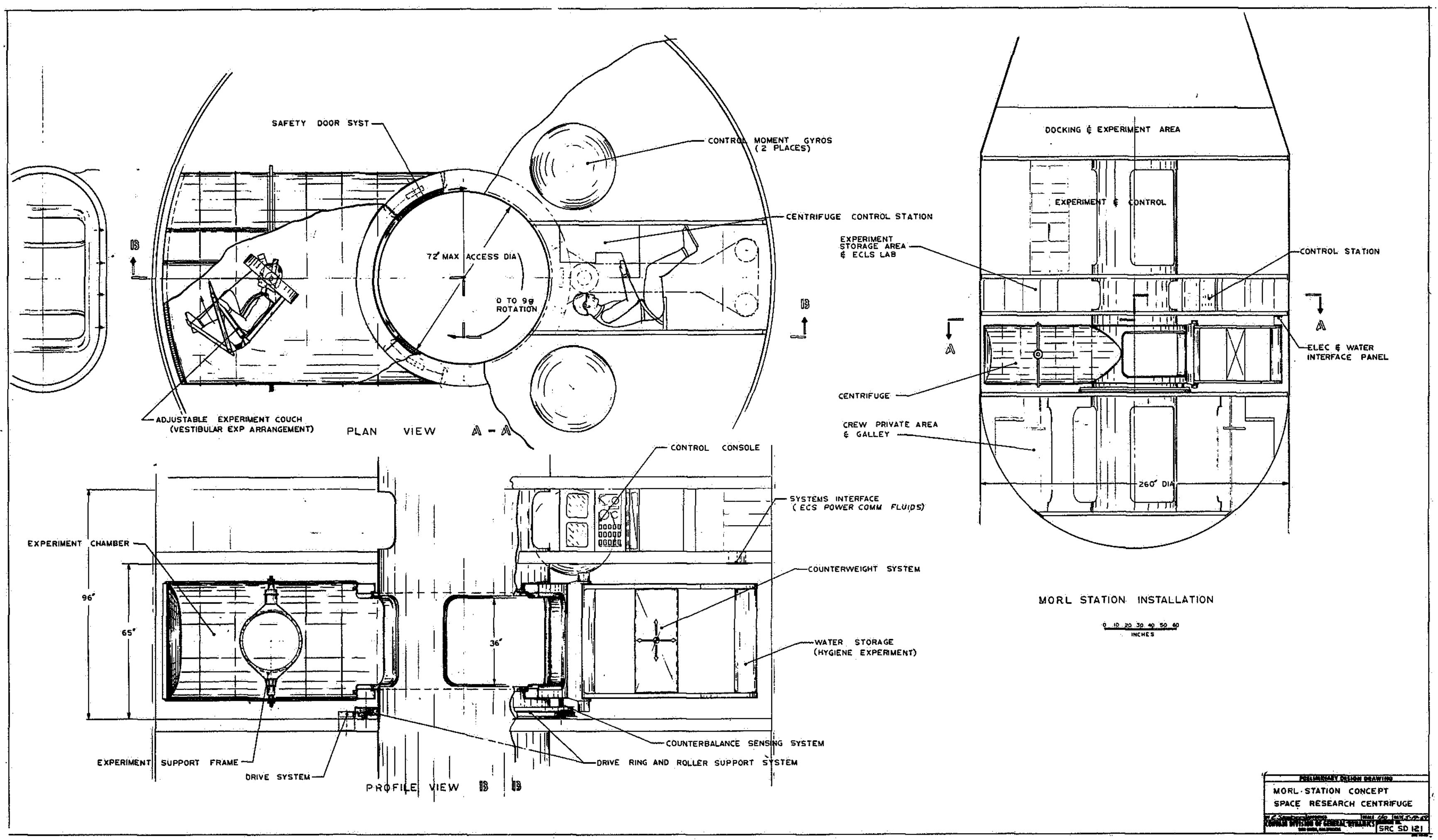


Figure 51 MORL Station Installation Concept (SRC-SD-121)

an interface panel at either end of the module. The balance sensor system coupled with a system of counterweights maintain both static and dynamic balance of the SRC. Two single degree of freedom control moment gyros (CMG) are provided to react the momentum of the SRC during spin-up and spin down. The SRC is controlled by an astronaut at the centrifuge control station. The experiment monitor would also be the safety monitor during SRC operation.

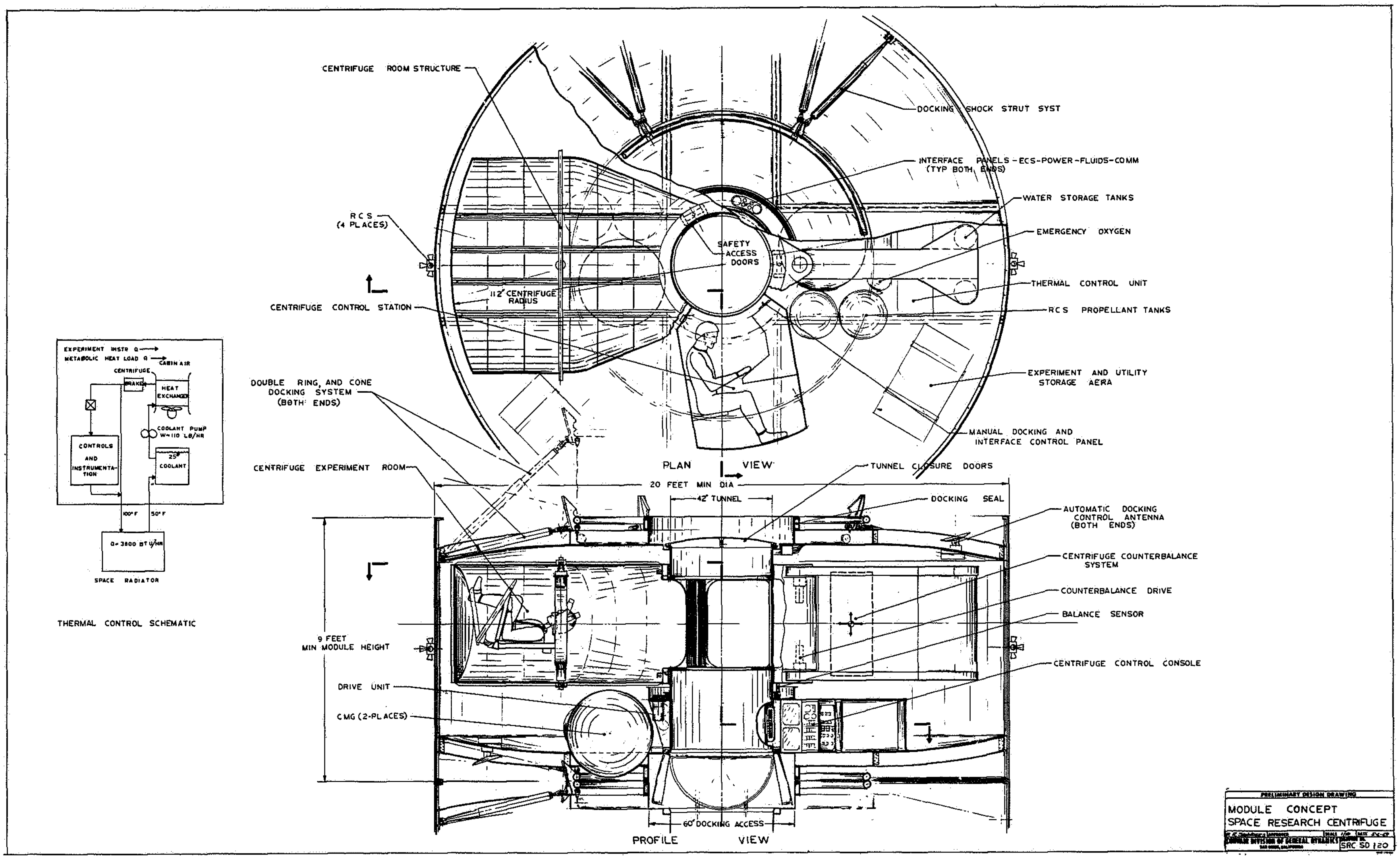


Figure 52 Experiment Module Installation Concept (SRC-SD-120)

GROUND BASED PROTOTYPE CENTRIFUGE

Some changes in design philosophy have been made in defining the present centrifuge which affect the test concepts and procedures for the ground-based engineering development model which were outlined in reference 2. The most important of these is the decision to design the unit only for the loads imposed by orbital operation if the ground based testing, checkout and transport loads and the launch loads can be circumvented or carried by temporary supports and special test equipment. In addition, the introduction of such experiments as the mobility and hygiene experiments impose an additional challenge to direct simulation with the ground based unit because the test subject is not closely restrained and supported by the centrifuge as was the case with the previous experiment series (Ref 3). These factors prompt the following observations.

a. Greater reliance will have to be placed on simulation in verifying experiment procedures and operations.

b. Additional mock-ups will have to be developed which are oriented to the normal g vector.

c. Special support fixtures and systems will have to be developed to relieve loads imposed by ground operation.

Facility Equipment Requirements. - The ground based development centrifuge should be designed and fabricated using the same criteria as the orbital hardware with the exception of space qualification. Mass distribution, structural stiffness, counterbalance and drive systems should be as realistic and complete as possible because dynamic effects and control will be one of the primary areas of test evaluation. This discourages the possible use of a boiler-plate approach for the ground based unit. A realistic centrifuge, mounted on an air bearing platform will be the central feature of the facility and is the same as previously recommended. The orientation and arrangement shown by figure 53 is recommended. In view of the importance of dynamic simulation studies, additional features which should be incorporated are as follows:

1. Control moment gyros should be included on the air bearing platform to allow demonstration of the counter-momentum system capability.

2. A suitable computer tie-line should be available for computation of spacecraft reaction to centrifuge imbalance forces. The computed spacecraft response should be used to drive the air bearing platform so that the problems of coupling between the spacecraft and the counterbalance system may be evaluated.

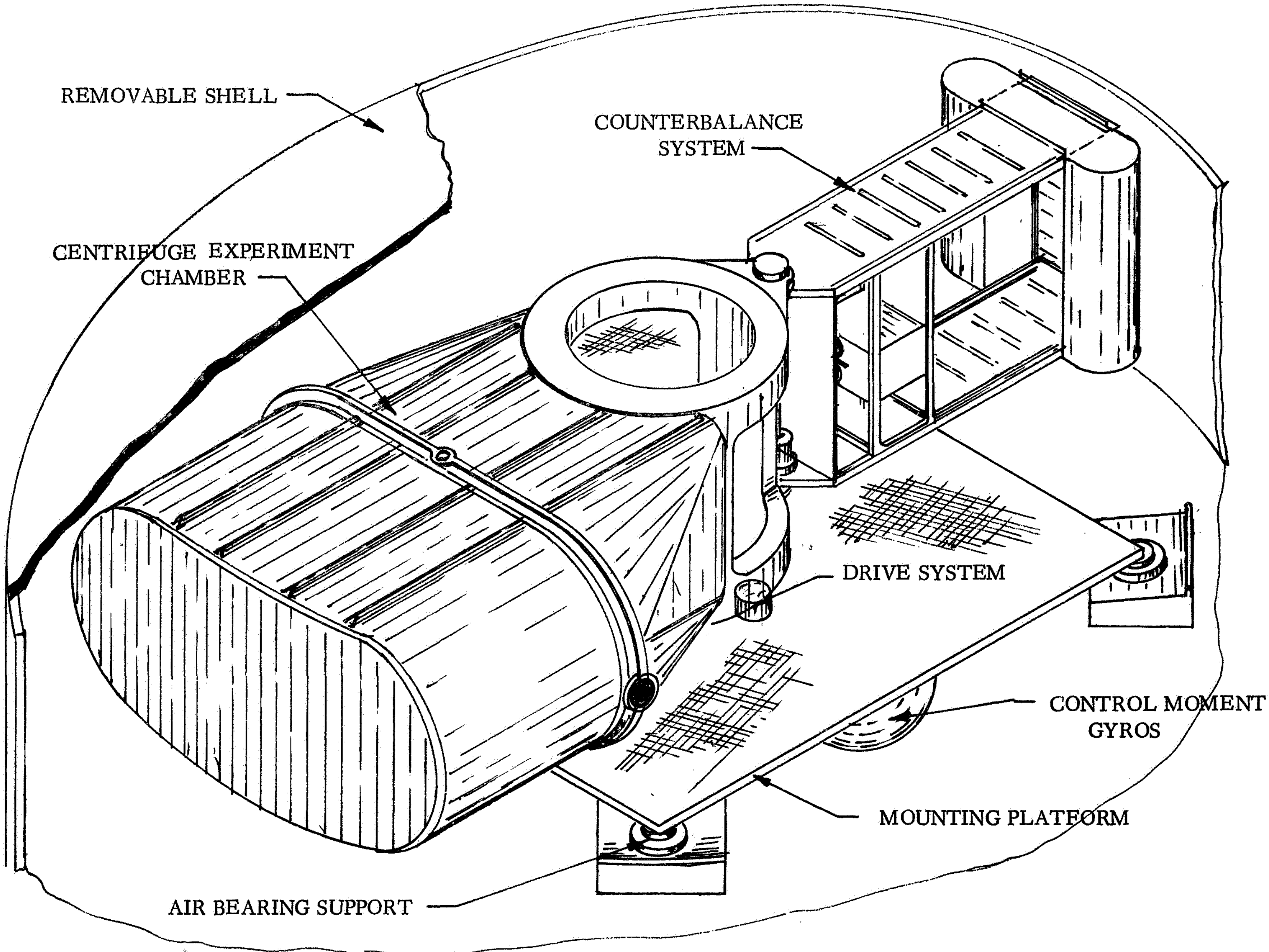


Figure 53 Ground Based Engineering Development Centrifuge Concept

3. An enclosure, representative of the module or spacecraft centrifuge chamber, should be placed around the centrifuge so that aerodynamic effects will be properly duplicated.

4. A fixture must be developed which supports the weight of the test subject from inside the centrifuge experiment chamber but still allows sufficient freedom to permit simulation of mass distribution for the mobility experiments.

For experiment and instrumentation development, the use of a separate, vertically oriented experiment chamber mock-up is suggested. As illustrated by figure 54 , the chamber should be articulated about the spin axis so that a test subject inside the chamber can be aligned with the local vertical. This motion can be servo driven using the test subject as a reference or positioned by an observer watching the location and movement of the test subject. The instrumentation and communication equipment for this facility should be the actual experiment aparatus, allowing realistic simulation of the experiment potocol to be performed. This same mock-up experiment chamber can then be used in accumulating baseline experiment data if the chamber is mounted on a centrifuge with sufficient capacity to accept the equipment and provide the necessary rotational velocity and acceleration for each experiment. It is noted, however, that the axis of rotation of the chamber required for this application is at a right angle to that required for experiment and equipment development. As the cost of such a mock-up chamber is relatively small in comparison to the cost of the instrumentation and experimental hardware, it may be expedient to provide an additional experiment chamber mock-up specifically for performing baseline experiments.

A third mock-up becomes necessary for providing realistic time-line and motion capability data relative to zero-g operations. This includes check-out of servicing procedures, experiment set-up procedures, safety operations, emergency routines, maintenance and repair operations and validation of the location of zero-g mobility aids. This data can best be supplied using neutral boyancy test techniques which generates the need for an immersable geometric representation of the centrifuge and at least a partial mock-up of the centrifuge chamber such as is shown by figure 55. A static (non-rotating) envelope constructed of wire mesh will suffice to represent the centrifuge structure. More detailed representations of the mechanism should be provided at work stations and maintenance points to allow realistic simulation of tasks.

Experiment Equipment Requirements. - For the particular centrifuge configuration recommended, each experiment category requires the use of one or more pieces of support equipment or "experiment packages" as they have been designated. These have been identified as the basic support ring, the couch package, the instrument package, the hygiene package and the work-bench package. Each of these packages must be developed concurrently with the engineering development centrifuge and become an integrated part of the test and development facility.

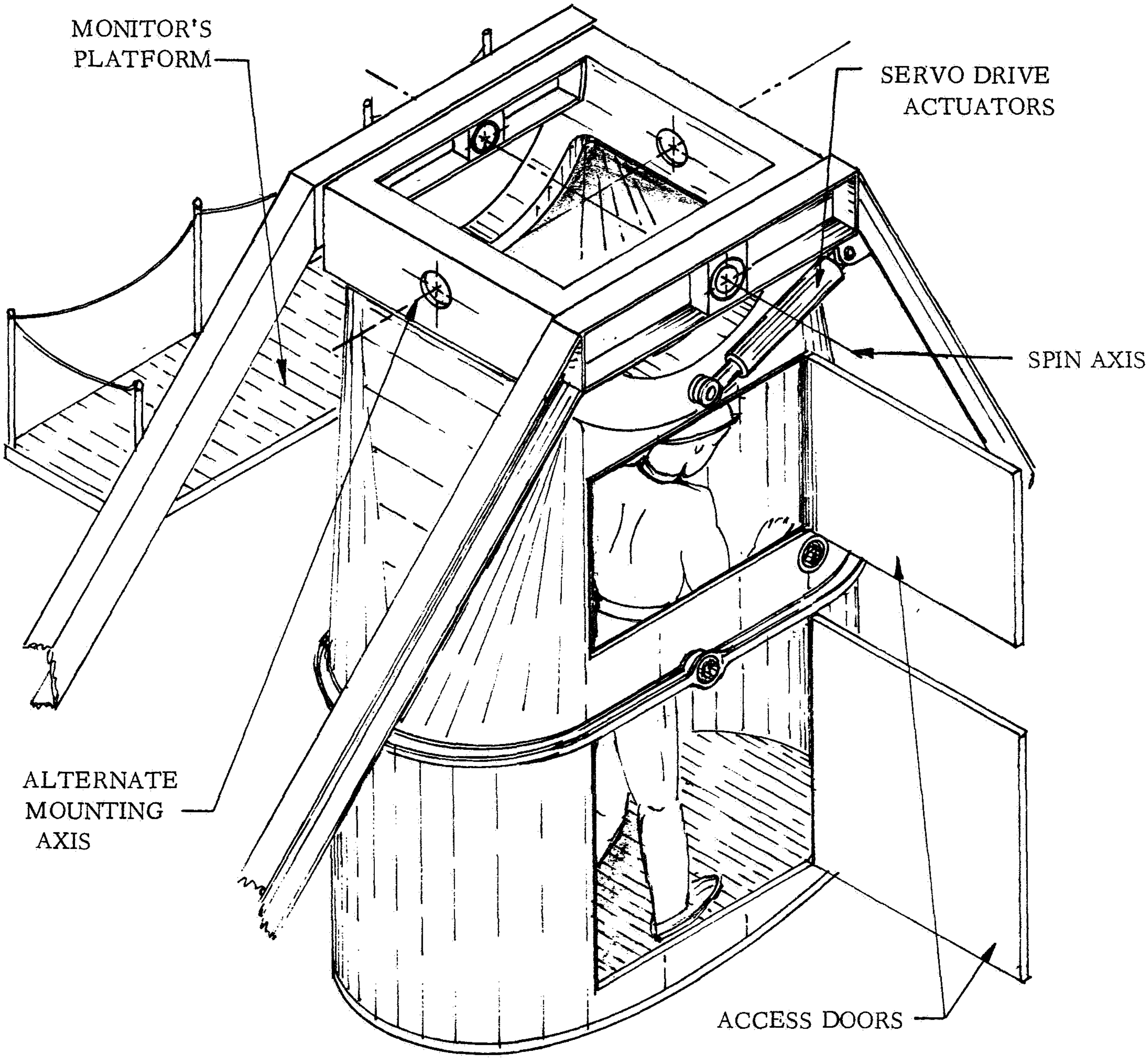


Figure 54. Experiment Chamber Mock-Up Concept for Detail Experiment Development

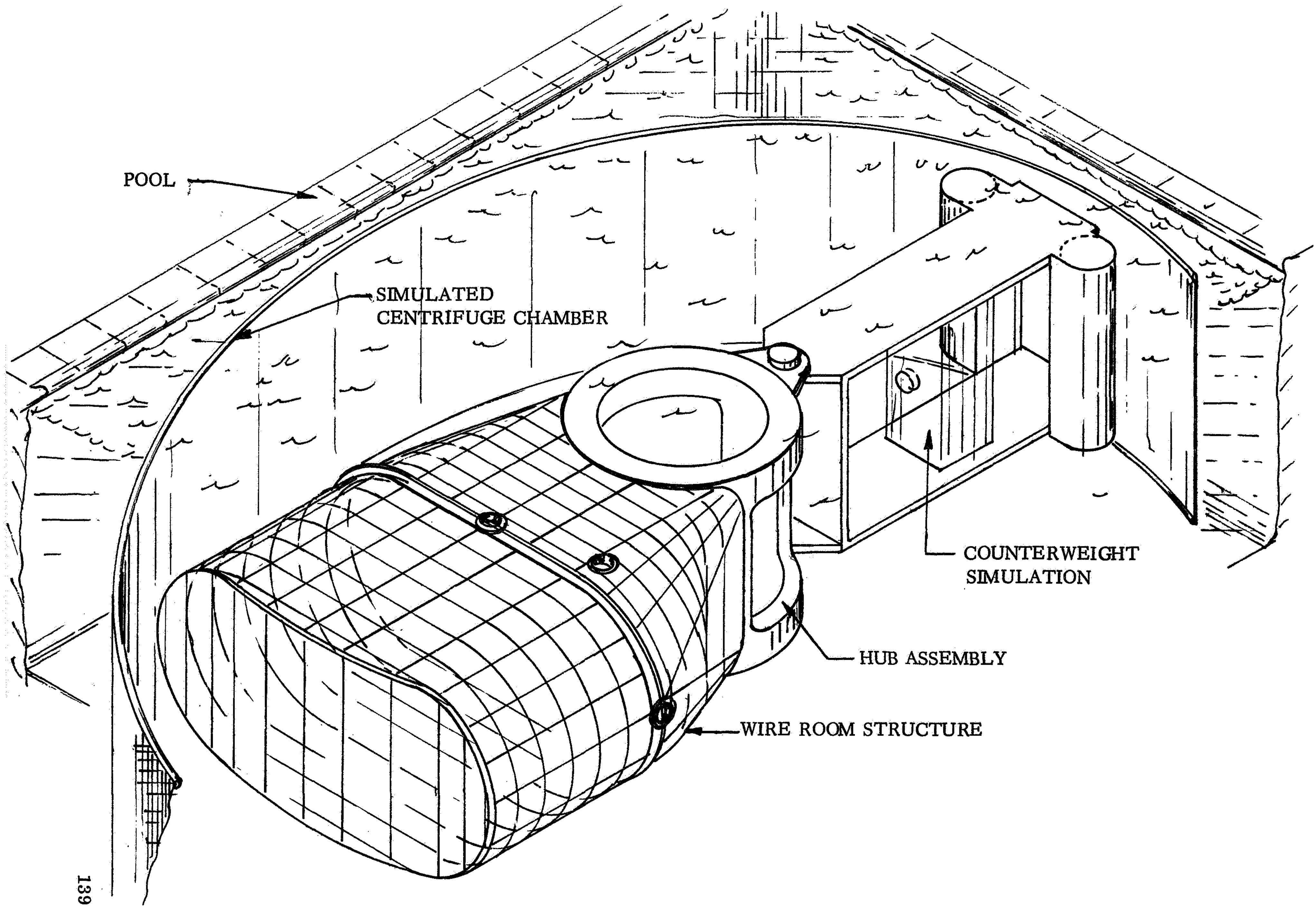


Figure 55. Neutral Boyancy Test Mock-Up Concept

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APPENDIX A
CENTRIFUGE DRAG LOSS ESTIMATES

Forces acting on the centrifuge as a result of aerodynamic effects and bearing friction are of interest in three areas of inquiry. First, these forces contribute to the power requirement of the main drive. Secondly, the aerodynamic forces will be registered by the counterbalance system force sensors and must be considered in the design of that system. The third area of interest relates to the possibility of torquing the centrifuge by using Control Moment Gyros (CMG) or momentum wheels mounted directly on the rotating mass. In this case, aerodynamic drag and bearing friction are the means by which momentum is transferred from the centrifuge to the surrounding spacecraft structure and represent a continuous momentum drain which must be replaced by CMG capacity and reacted by the spacecraft attitude control system. In order to assess the magnitude and influences of these forces, some preliminary estimates of steady state aerodynamic drag and bearing losses have been made.

Stored Aerodynamic Momentum. - As the centrifuge is spun up to some operating angular velocity, the atmosphere in the centrifuge chamber will tend to vortex and will absorb momentum. Assume that as the centrifuge reaches a constant angular velocity, the chamber atmosphere approaches solid body rotation. Then, the momentum of the atmosphere (H_A) may be found by:

$$dH_A = \frac{\rho V v}{g_c} = \frac{\rho\, hr\omega dr.}{g_c} \tag{1}$$

$$H_A = \int_0^r \frac{\rho\, h\omega rdr}{g_c} \doteq \frac{\rho\, hwr^2}{2\, g_c}$$

Using characteristic values for oxygen at 5 psia and a temperature of 70° F,

ρ = density = .028 lbs/ft^3

h = chamber height (cylindrical) 6.42 ft.

r = chamber radius 11.0 ft

ω = centrifuge angular velocity = 2π rec/sec.

Then: H_A is approximately 2.11 ft-1b-sec.

Assuming other atmospheres, such as oxygen rich air at 10 psia, will not alter the observation that the amount of momentum stored in the vortexing atmosphere is small in comparison to the momentum of the machine and other factors.

Bearing Losses. - Assumptions regarding bearing losses were based on a review of available literature which places the frictional forces at 0.2 lbs for the maximum load and velocity involved. At a 22 inch bearing radius, the resulting torque requirement will be .36 ft-lbs. A representative momentum drain for a 20 minute experiment would then be 432 ft-lb-sec due to the bearings alone.

Aerodynamic Drag Losses. - In estimating steady state aerodynamic drag losses the assumption is again made that the atmosphere in the chamber is approaching solid body rotation, and that the same chamber geometry and atmosphere are involved as were used for the aerodynamic momentum estimates. Based on a Reynolds number of 500,000, turbulent boundary conditions will exist above velocities of

$$v = \frac{N_R \mu}{\ell \rho} = 3.475 \text{ ft/sec.} \tag{2}$$

At the outer wall, this velocity will occur at a centrifuge rate of 3 rpm so that turbulent boundary conditions will prevail over most of the experimental regime.

Using a relationship for torque at the outer wall (T_o) of:

$$T_o = C_D \lambda q A r \tag{3}$$

Where: C_D = Coefficient of Drag $= \frac{.074}{(N_R)^{1/5}}$

N_R = Reynolds No.

λ = Factor compensating for the continuity of the plate = .918

q = Dynamic Pressure

A = Area, ft^2

r = radius, ft.

$$T_o = .074 \left(\frac{\mu}{\rho \ell v}\right)^{1/5} (.918)(1/2\, \rho v^2)(6.42)(22\pi)(\pi)$$

Substituting $r\omega$ for velocity

$$T_o = \frac{.906\, \omega^2}{(\omega)^{1/5}} \tag{4}$$

Drag Torque at the side walls (T_S) may be estimated from the relationship

$$T_S = 2\int_{r1}^{r2} C_D q r dA = \tag{5}$$

$$2\int_{11}^{2} .074\ (.918) \left(\frac{\mu}{\rho \ell v}\right)^{1/5} \left(1/2\ \rho v^2\right)\left(2\pi r^2\right)\ dr$$

Letting v = r ω and introducing previously specified values for μ and ρ

$$T_S = \frac{.000335\ \omega^2}{(13100\,\omega)^{1/5}} \int_{11}^{2} r^{18/5}\ dr \tag{6}$$

$$= \frac{.68\,\omega^2}{\omega^{1/5}}$$

In addition to the aerodynamic torques, a linear parametric expression for becoming friction torque (T_B)is taken as:

$$T_B = .0565\ \omega \tag{7}$$

Total torque transferred to the spacecraft (T_T) by drag will then be:

$$T_T = T_O + T_S + T_B \tag{8}$$

Substituting equations 4, 6 & 7 into equation 8, the total drag torque as a function of centrifuge angular velocity in radians per second becomes:

$$T_T = 1.586\ \frac{\omega^2}{\omega^{1/5}} + .0565\omega \tag{9}$$

A plot of equation 9 over the centrifuge operating range is shown by figure A1.

In considerat ion of the possibility of driving the centrifuge by using CMG'S mounted on the rotating member, the resulting momentum drain caused by drag was estimated for each of the proposed experiments. These estimates are summarized in table A1. The results indicate that excessive CMG momentum capability would be required (greater than one order of magnitude increase) if this method of drive is employed.

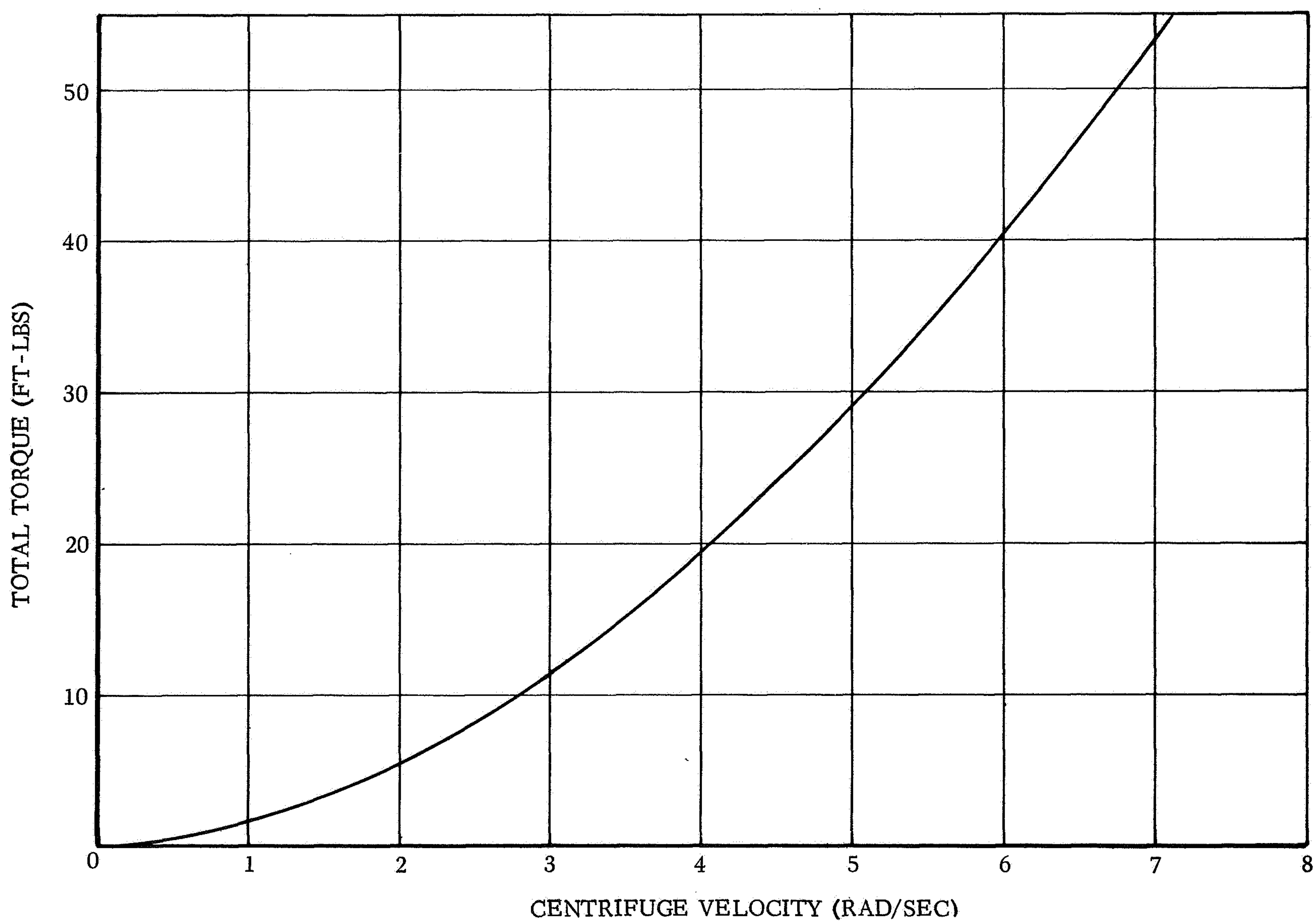

Figure A1 - Centrifuge Drag Torque As A Function of Angular Velocity

Table A1. Experiment Momentum Drain Estimates

Experiment	Radius	g Req.	Description	Time (Sec)	(Rad/Sec)	Drag ft:# Max Torque	Momentum Drain (ft-lb-sec)
Grayout	106"	6.0 at feet (max.)	Spin up Test Spin Down	60 sec. 240 sec. 60 sec.	4.66 4.66 4.66	25.5 25.5 25.5	765 6120 765 7650
Therapeutic	106"	1.7 at Heart	Spin up Test Spin Down	40 1200 40	3.93 3.93 3.93	18.75 18.75 18.75	375 22500 375 23250
Sensitivity to Angular Acceleration							No Primary Rotation Required
Tilt Table	62"	1.0g at head	Spin up Test Spin Down	20 1500 20	2.5 2.5 2.5	8.1 8.1 8.1	81 12150 81 12312
Semicircular Canal and Coupled Angular Velocities	45" to head	.0205g at head	Spin up (4 rpm) Test Spin Up (10 rpm) Test Spin Down Repeat 5 Times	20 1200 20 1200 20	.419 .419 1.047 1.047 1.047	.05 .05 1.8 1.8 1.8	.48 60.0 18. 2160. 9.0 2247.48

Table A1. Experiment Momentum Drain Estimates Cont'd

Experiment	Radius	g Req.	Description	Time (sec)	(Rad/Sec)	Drag ft.-# Max Torque	Momentum Drain (ft-lb-sec)
Sensitivity to Linear Acceleration	45" (at head)	.25	Spin up	20	1.465	3.1	32.
		.25	Test	120	1.465	3.1	372.0
		.50	Spin up	20	2.070	5.8	98.
		.50	Test	120	2.070	5.8	696.0
		1.0	Spin up	20	2.925	11.0	110.
			Test	120	2.925	11.0	1320.
			Spin Down	20	2.925	11.0	55.
			Repeat 7 times each test day				2663.0
Re-entry Simulation	100" (at subject cg.)	Max 6.53g	Test	120	5.03	29.2	1740
		.75	"	300	1.70	4.1	1230
		5.4	"	120	4.57	24.7	1480
							4450
Walking and Mobility	78" to cg. (approx)	.1	Test	1200	.704	1.0	1200
		.2	"	1200	1.00	1.6	1920
		.3	"	1200	1.22	2.3	2760
		.4	"	1200	1.408	3.0	3600
							9480
Bench Task Performance	78" to cg (approx)	.1	Test	2700	.704	1.0	2700
		.2	"	2700	1.00	1.6	4315
		.3	"	2700	1.22	2.3	6210
		.4	"	2700	1.408	3.0	8100
							21,325

Table A1. Experiment Momentum Drain Estimates Cont'd

Experiment	Radius	g Req.	Description	Time (Sec)	(Rad/Sec)	Drag ft. # Max Torque	Momentum Drain (ft-lb-sec)
Personal Hygiene Capability	78" to cg (approx)	.1	Shower	1200	.704	1.0	1200
		.2	"	1200	1.00	1.6	1920
		.3	"	1200	1.22	2.3	2760
		.4	"	1200	1.408	3.0	3600
							9480
	78" to cg (approx)	.1	Waste Collect	600	.704	1.0	600
		.2	"	600	1.00	1.6	960
		.3	"	600	1.22	2.3	1380
		.4	"	600	1.408	3.0	1800
							4740

NOTE: The momentum drain during transient conditions (spin-up/spin-down) for the Grayout, Therapeutic, Tilt Table and Vestibular experiments was based on an assumed rate of change of 0.1 g/sec. For the Mobility, Hygiene and Bench Test experiments, a linear accelration over a period of 60 seconds was assumed for spin-up and spin-down. For the Re-entry Experiment, momentum drain was calculated using the acceleration profile of figure 11.

APPENDIX B

PRELIMINARY DESIGN CONCEPTS

As an initial step in re-configuring the centrifuge, three separate design approaches were selected to serve as models in studying the impact of incorporating the center passageway. These approaches (identified as concept No's 1, 2 & 3 in the following material) were selected to evaluate differences between 1) linear and pivoting radial translation of the test subject and counterweight and 2) peripheral vs. minimum radius suspension and drive installation. The maximum center passage diameter of 42 inches was used in all cases based on the observation that if this condition can be satisfied then the 30 inch passageway can easily be accommodated. Each of the configurations was developed to a point were realistic trade-offs of inertial properties, mechanism and structural requirements, system requirements, safety and reliability could be made.

At this time, the experiment capability requirements of the machine were expanded by contract re-direction to include experiment evaluation of inertial support for mobility, hygiene and work-bench task performance. Features allowing performance of these experiments as well as the T-010 series of experiments (ref. 3) resulted in the "room" or "experiment chamber concept which was evaluated by analysis of concepts designated as 1A and 2A in this section and later optimized in the selected baseline design approach.

Design Ground-Rules and Evaluation Criteria

A series of ground rules and optimization parameters were assembled from the requirements of the statement of work and the proposal and applied as a guide configuring the centrifuge. These are discussed as follows:

Design Ground-Rules. - The primary ground rule is, of course, that the experimental capability of the machine be maintained with respect to subject orientation, motion, rotational velocity, acceleration and g-level. This was essentially achieved in all design concepts, however, some concessions of extra capability not firmly required by present experiment definition were made. An example of this is by position for orientation out of the plane of spin. Previous positioning of the couch with the legs straight out was modified to a bent-knee approach in order to minimize centrifuge chamber height.

Consideration was made in all designs for allowing positioning of the subjects head at the center of spin. This was found to be controlled mainly by spacecraft design rather than centrifuge design. If a spacecraft center passageway is utilized, it is likely that this same area will be used to route power and communication leads, ducts, plumbing and similar continuous components. As such arrangements would obviate the use of the spin center for subject positioning, alternate provisions for performing these experiments were provided. It is now recommended that these experiments be performed using the secondary motion capability provided by the support ring drive.

Configurations were developed so as to take into consideration the interface problems typical of center core access space stations and alternate module installations. Emphasis was placed on arriving at a common design for all applications as far as major system and configuration elements are concerned.

The designs were selected to optimize height as much as possible. Minimum centrifuge chamber height is desirable in order to reduce the amount of spacecraft weight and volume chargeable to the centrifuge and to increase volume utilization.

Minimum clear center core diameters of 30 inches with growth capability to 42 inches were maintained for each design. In order to provide a common basis for comparison of designs, the 42 inch core was used as a standard as previously mentioned. Some additional investigations were carried out which indicate that larger core access diameters (up to 72 inches) can be accommodated if a one-for-one increase in centrifuge radius is allowed and if the added penalty in weight, inertia, spacecraft volume and power can be accepted.

In early studies a ground rule calling for minimum changes to the previous centrifuge design configuration (reference 1.) was imposed. It was soon recognized that this requirement was unduly restrictive and it was discarded in favor of greater design freedom. While commonality with early designs can be maintained with respect to the experiment couch, roll ring, roll frame and instrumentation for the T-010 experiment program, introduction of the inertial support experiment studies calls for a complete re-evaluation of all systems.

Optimization and Evaluation Criteria. - Centrifuge design concepts were implemented in a manner which optimized specific desirable characteristics of the machine. For the overall configuration, weight and inertia were minimized. Close attention was also given to reducing experiment compromise and eliminating operational hazards which may be attributed to the structural or mechanical arrangement selected. In addition to these factors mechanical approaches were taken which will result in optimum reliability, maintainability and performance while structural concepts also emphasized stiffness and mechanisms/systems compatibility. While cost factors are not as influential as other considerations at this time, no approaches were specified which would be disadvantageous from this respect. Technology utilized in all areas is within the existing state-of-the-art.

Loads. - Maximum loads were derived for the rotating portion of the centrifuge using the load factors and conditions specified in table B1. These load factors are identified by the nomenclature shown in figure B1 with respect to orientation and sign. At this time no attempt has been made to study the effect of interaction of loads, combined bending and torque for example. Each load is assumed to act in one plane only. Further study will define the combined load envelope. Table B2 shows the tabulation of the ultimate loads for configurations 1, 2 & 3 based on the load factors of table B1.

Table B1. Load Criteria

Condition Number	Phase of Operation	Condition	Environment	Load Factor & Direction		
				X	Y	Z
1.0	Ground	Fabrication	A			
1.1		Installation	A			
1.2		Check & Test	A	1.0	E	E
1.3		Transportation	A	3.0	3.0	3.0
2.0	Launch	Transportation	A	3.0	3.0	3.0
2.1		Checkout	B	1.0	-	-
2.2		Liftoff	B	1.5*	-	-
2.3		Max q	B	2.0*		
2.4		Max G	B	6.0*		
2.5		Orbit Insertion	B	*		
3.0	Orbital			0	E	E

A. Normal Atmosphere
B. 5.0 PSI O_2
E. Per T-010 Experiment Requirements
* Launch Vehicle Dependent

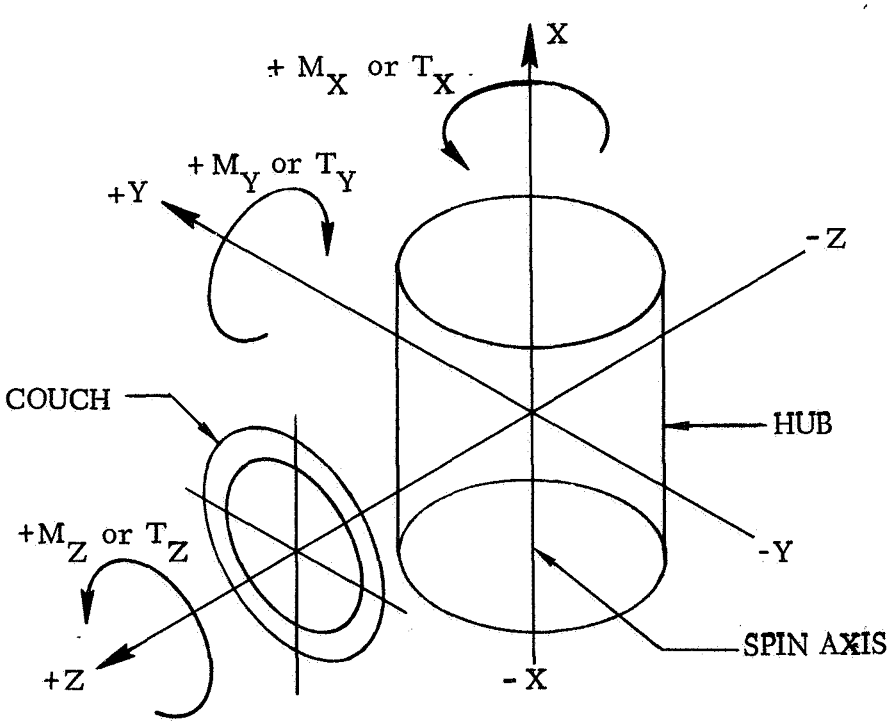

Figure B1. - Load Orientation and Sign Convention.

Table B2 Ultimate Loads.

CONFIG. CONCEPT	POINT OF APPLICATION	CONDITION *	MOMENTS lbs/ins			TORQUES lbs/ins			AXIAL LOADS lbs		
			M_x	M_y	M_z	T_x	T_y	T_z	P_x	P_y	P_z
ALL	Radial Arms	1.2		67,000							
	Radial Arms	1.3	49,000								
	Radial Arms	1.2, 3.0						7,450			1,240
	Hub	1.2, 3.0									
ALL	(1) Pivot Drive (couch)	1.2, 3.0		29,000					413	819	2,480
1.	(2) Slide (couch)	1.3	4,956	9,500					870	413	
	(3) Pivot (C/Wt)	1.2, 3.0		29,000					413	819	2,480
	(4) Slide (C/Wt)	1.3	4,956	9,500					870	413	
2.	(2) Rad. Struct. Pivot	3.0							980		2,900
	(3) Support Struct.	1.3							875		2,640
	(4) C/Wt Pivot Drive	1.2, 3.0		29,000					413	819	2,480
	(5) C/Wt Rad. Struct.								980		2,900
	Pivot	3.0							980		2,900
	(6) C/Wt Support Struct.	1.3									
3.	(1) Pivot Drive	1.2, 3.0		29,000					413	819	2,480
	(2) Sec C/Wt Attach	3.0	30,000						495		990

*For Condition Identification, See Table B1

In general, the loads imposed on the centrifuge are small and most of the structure will be designed by stiffness requirements, operational considerations or geometry constraints. The structure will be designed only for its own operational loading environments, external loads to the centrifuge from launch or boost for example will be handled with non-permanent external structure wherever that is feasible.

Centrifuge Nomenclature and Functions. - For convenience in describing and comparing the various candidate designs, a common nomenclature was adopted as follows:

a. Upper or Lower Support Hub: The structure that attaches the centrifuge to the spacecraft or space station. The bearing system and all associated rings and structure. The main rotational drive system, the out of balance sensors and attendant hardware. All or any of these items may or may not be on the upper or the lower hub depending on the configuration.

b. Passageway Structure: The structure that keeps the hubs apart and provides the main passageway through the rotating centrifuge. This may consist of all or part of the following; a tunnel, a series of rings and longerons. It may also include equipment or experiment support structure.

c. Variable Radius System: The main rotating structure of the centrifuge including the arms or beams that may support the pivot, roll, and counterweight systems. It may also consist of the counterweight support structure depending on the configuration. Bearings, slides and rollers used to mechanize the variable radius of the pivot and couch system will be included in the mechanism. A motor and system may also be included.

d. Pivot System: The structure that attaches the roll frame to the radius arm. The pivot bearing motor and associated systems.

e. Roll System: The roll frame structure with the couch supports. The roll drive mechanism, motor and associated systems.

f. Primary or Secondary Counterweight Systems: May consist of either or both a translating or radial counterweight support structure, mechanisms, motor and associated systems. Any or all of these systems may be duplicated in the secondary system dependent on the configuration.

g. Physiological Experiment Couch: Structure to support the test subject in all of the experimental modes with adequate cushioning and harnesses. A power and distribution system, instrumentation and communication system.

Preliminary Configurations

The three preliminary configurations examined prior to introduction of the inertial support experiments are described as follows:

Concept No. 1. - This configuration is illustrated by figure B2. The design features linear translation of the experiment positioning mechanisms and counterweight system to effect radius changes. Four tapering arms connected to a hollow cylinderical hub hold the pivot and roll frame housing and the counterweight housing. These elements are designed to have approximately equal masses, so that the greater portion of static balance is achieved by driving them to equal radial positions as required by the individual experiments. Imbalance resulting from changes in position of the test subject within the roll frame is then compensated for by movement of the main counterweight and counterweight swing. Additional lateral balance capability is provided by trim counterweights which are necessary because the main counterweight cannot be moved to a short enough radius to balance the "head-on-spin-axis" condition. The arms are aluminum skin/stringer box beams containing guide tracks which react all lateral loads from the pivot/roll frame and counterweight housings. Radial loads are reacted in tension through drive screws running the length of the beam. and operating through ball screws fixed to the individual housings. The translation is powered by dual, fractional horsepower, D. C. motors coupled through a synchronizer shaft.

The main rotation drive also features dual electric motors for redundancy. The motors are attached to spacecraft structure and are mounted 180° apart to avoid side loads during centrifuge acceleration. Drive is accomplished through a friction track which is normal to the spin axis to reduce interference with the force sensing system. Bearings and force sensors are installed at the opposite end of the hub from the drive motors. In the later analysis, this location was found to be impractical and the main drive was applied between the stationary hub and the bearing ring so that all loads affecting the rotating mass would pass through the force sensors.

The pivot and roll frame housing is developed from a cylindrical section and is sized as a waffle stiffened aluminum machined assembly.

The roll frame, couch and other equipment directly associated with the test subject are assumed to be the same as that used in the previous centrifuge design (Reference 1.)

Utilizing the previously described nomenclature, the centrifuge Concept No. 1 weight analysis is summarized in tables B3 and B4.

Concept No. 2. - This configuration is depicted by figure B3. The main feature being evaluated in this design approach is the use of rotational rather than translational motion in accomplishing radial positioning of the test subject and counterweight. The structure is a build-up of integrally machined fittings and mechanically attached sheet

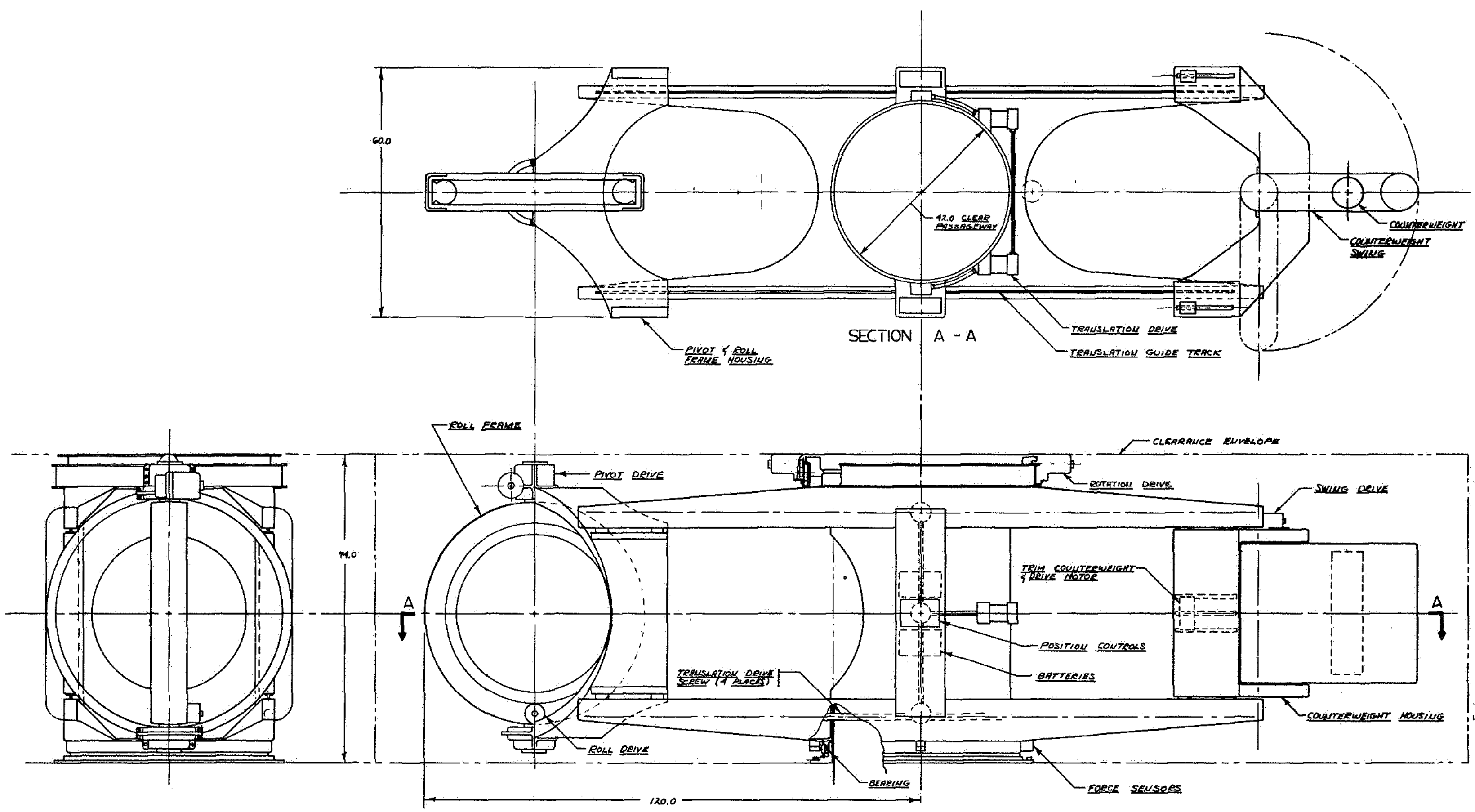

Figure B2 - Centrifuge Preliminary Concept No. 1

Table B3 - Centrifuge Weights

Concept No. 1

		STRUCTURE	MECHANISM
1.0	UPPER SUPPORT HUB	(23)	(87.8)
1.1	Spacecraft Support Struct.	10	
1.2	Bearing Support Ring	13	
1.3	Bearing System		12.8
1.4	Drive or Support Ring		30.0
1.5	Drive Motor & System		45.0
1.6	Balance Sensor Ring		
1.7	Sensors & System		
2.0	LOWER SUPPORT HUB	(23)	(17.6)
2.1	Spacecraft Support Struct.	10	
2.2	Bearing Support Ring	13	
2.3	Bearing System		12.8
2.4	Drive or Support Ring		
2.5	Drive Motor & System		
2.6	Balance Sensor R.ng		.8
2.7	Sensors & System		4.0
3.0	PASSAGEWAY STRUCTURE	(41)	( )
3.1	Rings		
3.2	Shell	36	
3.3	Longerons		
3.4	Equipment Support Struct.	5	
4.0	VARIABLE RADIUS SYSTEM	(277)	(59)
4.1	Radius	202	
4.2	Pivot Support Struct.	75	
4.3	Pivot Radial Struct.	-	
4.4	Counterweight Support Struct.		
4.5	Bearing Slides etc.		
4.6	Variable Radius Mechanism		4
4.7	Motors & Systems		45
4.8	Position Sensor		10
5.0	PIVOT SYSTEM	(35)	(27)
5.1	Pivot Frame Struct.	35	
5.2	Pivot Bearing		7
5.3	Pivot Motor & System		20
5.4	Position Sensor System		

Table B3 - Centrifuge Weights (Cont'd)

Concept No. 1

		STRUCTURE	MECHANISM
6.0	ROLL SYSTEM	(25)	(20)
6.1	Roll Frame Struct.	25	
6.2	Roll Drive Mechanism		15
6.3	Roll Motor & System		5
6.4	Position Sensor System		
7.0	PRIMARY COUNTERWEIGHT SYSTEM	(90)	(40)
7.1	Translation Struct.	50	
7.2	Radial Struct.	40	
7.3	Translation Mechanism		35
7.4	Radial Mechanism		
7.5	Translation Motor & System		5
7.6	Radial Motor & System		
7.7	Position Sensor System		
8.0	SECONDARY COUNTERWEIGHT SYSTEM	(5)	(5)
8.1	Translation Struct.	5	
8.2	Radial Struct.		
8.3	Translation Mechanism		5
8.4	Radial Mechanism		
8.5	Translation Motor & System		
8.6	Radial Motor & System		
8.7	Position Sensor System		
	TOTAL WEIGHTS	(519)	(256.4)

Table B4 Centrifuge Weights Summary

Concept No. 1

Structure	519
Mechanism	256.4
Primary Counterweight (Less batteries)	280.
Secondary Counterweight	70
Power and Communication	120
Batteries	220
Inverters	30
Experiments & Systems	
Couch System	117
Man & Gear	200
Contingency	100
Total	1922.4

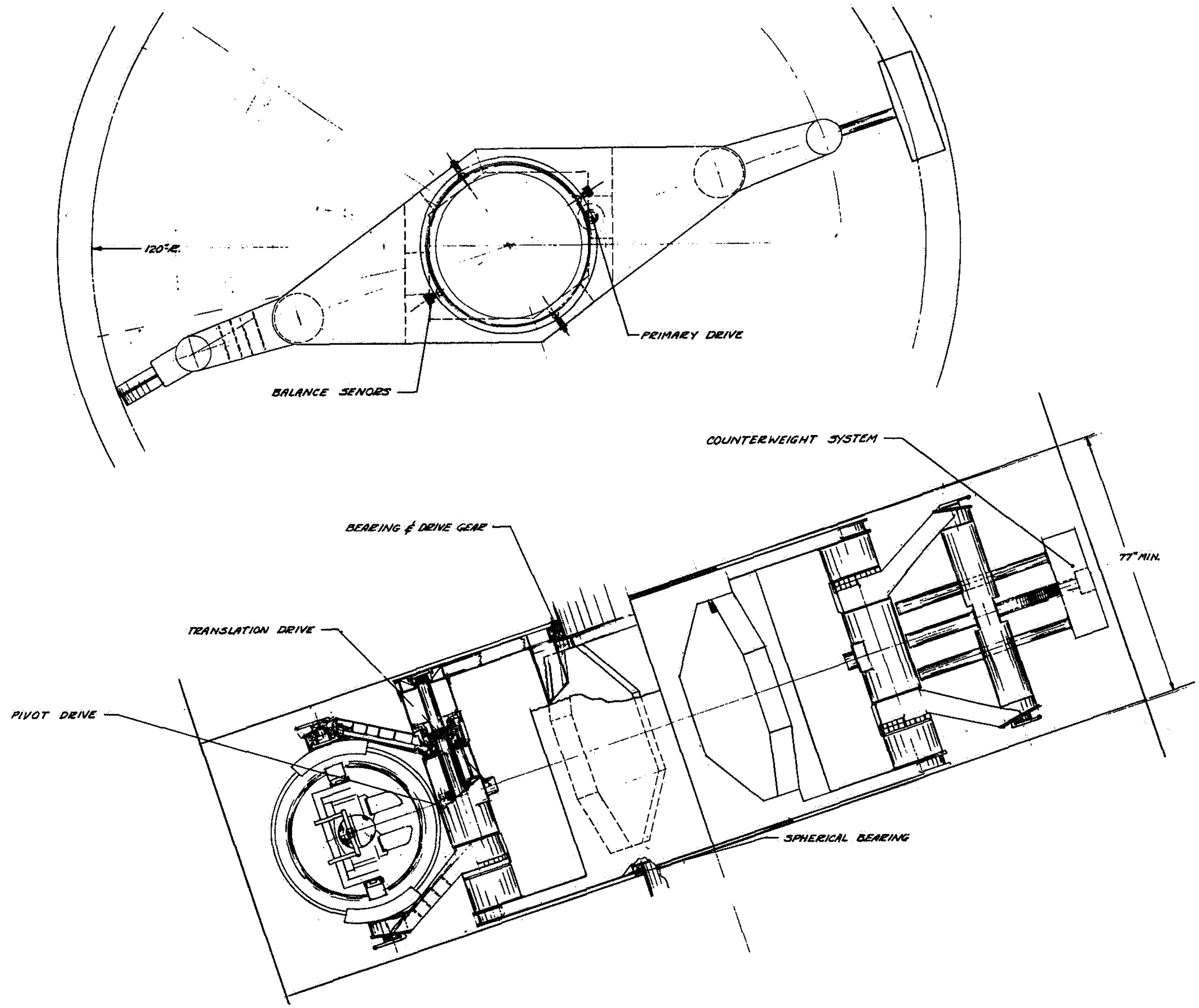

Figure B3- Centrifuge Preliminary Concept No. 2.

metal parts using aluminum alloy as the main structural material. The experiment couch, pivot mechanism, roll ring and associated drives are identical with those of the reference (1) design although, with this configuration, the arrangement would benefit by using more direct load paths in attaching the roll ring to the translation drive hub.

The counterweight suspension is almost an exact duplicate of the experiment roll/pivot suspension. Again, close initial static balancing of the machine is achieved by positioning the experiment and counterbalance carriages in symetrical locations. Incidental motion of the test subject is then followed by the angular and radial motion of the counterweight about its pivot column.

Suspension of the centrifuge is accomplished by placing a spherical bearing at one of the bulkhead interfaces and an axially orientated bearing and sensor ring at the opposite bulkhead. The main drive is also located on the opposite side from the spherical bearing and applies torque through the sensor net. This arrangement was postulated in an effort to increase the rigidity of the installation. Resulting analysis, however, indicated that imbalance sensing could not be reliably achieved because a portion of the load is transmitted through the spherical bearing.

The weight breakdown for this concept is given by tables B5 and B6.

Concept No. 3. - This configuration is illustrated by figure B4. The main features examined in the development of Concept No. 3 are the peripheral drive and the positioning of counterweights by translation alone. As is shown, these features lead to a rather widely dispersed, open mechanism. Again, the previous design configuration of the roll ring and experiment couch were incorporated in the concept. Some of the problems which occurred with this approach were excessive inertias, high weight penalty in achieving adequate stiffness and safety and lubrication problems associated with exposed mechanism. A weight breakdown for this concept is contained in tables B7 and B8. While problem areas arising with this approach are solvable, no strong positive advantage was found. Consequently, this approach was eliminated from further consideration.

Table B5. Centrifuge Weights, Concept No 2.

		STRUCTURE	MECHANISM
1.0	UPPER SUPPORT HUB	(23)	(87.8)
1.1	Spacecraft Support Struct.	10	
1.2	Bearing Support Ring	13	
1.3	Bearing System		
1.4	Drive or Support Ring		12.8
1.5	Drive Motor & System		30.0
1.6	Balance Sensor Ring	10	45.0
1.7	Sensors & System		
2.0	LOWER SUPPORT HUB	(23)	(17.6)
2.1	Spacecraft Support Struct.	10	
2.2	Bearing Support Ring	13	
2.3	Bearing System		
2.4	Drive or Support Ring		12.8
2.5	Drive Motor & System		
2.6	Balance Sensor Ring		.8
2.7	Sensors & System		4.0
3.0	PASSAGEWAY STRUCTURE	(134)	
3.1	Rings		
3.2	Shell	129	
3.3	Longerons		
3.4	Equipment Support Structure	5	
4.0	VARIABLE RADIUS SYSTEM	(378)	(27)
4.1	Radius Arm Struct.	280	
4.2	Pivot Support Struct.	36	
4.3	Pivot Radial Struct.	62	
4.4	Counterweight Support Struct.		
4.5	Bearing Slides etc.		
4.6	Variable Radius Mechanism		20
4.7	Motors & Systems		7
4.8	Position Sensor		
5.0	PIVOT SYSTEM	(35)	(27)
5.1	Pivot Frame Struct.	35	
5.2	Pivot Bearing		
5.3	Pivot Motor & System		7
5.4	Position Sensor System		20

Table B5. Centrifuge Weights, Concept No. 2. (Con't)

		STRUCTURE	MECHANISM
6.0	ROLL SYSTEM	(25)	(20)
6.1	Roll Frame Struct.	25	
6.2	Roll Drive Mechanism		15
6.3	Roll Motor & System		5
6.4	Position Sensor System		
7.0	PRIMARY COUNTERWEIGHT SYSTEM	(35)	(54)
7.1	Translation Struct.	15	
7.2	Radial Struct.	20	
7.3	Translation Mechanism		27
7.4	Radial Mechanism		20
7.5	Translation Motor & System		
7.6	Radial Motor & System		7
7.7	Position Sensor System		
8.0	SECONDARY COUNTERWEIGHT SYSTEM		
8.1	Translation Struct.		
8.2	Radial Struct.		
8.3	Translation Mechanism		
8.4	Radial Mechanism		
8.5	Translation Motor & System		
8.6	Radial Motor & System		
8.7	Position Sensor System		
	TOTAL WEIGHTS	(653)	(233.4)

Table B6 Centrifuge Weight Summary, Concept No. 2

Structure		653
Mechanism		233.4
Primary C/W Secondary C/W	Less Batteries	117
Power & Communications		120
Batteries		220
Inverters		30
Experiments		
Couch System		117
Man & Gear		200
Contingency		100
	TOTAL	1790.4

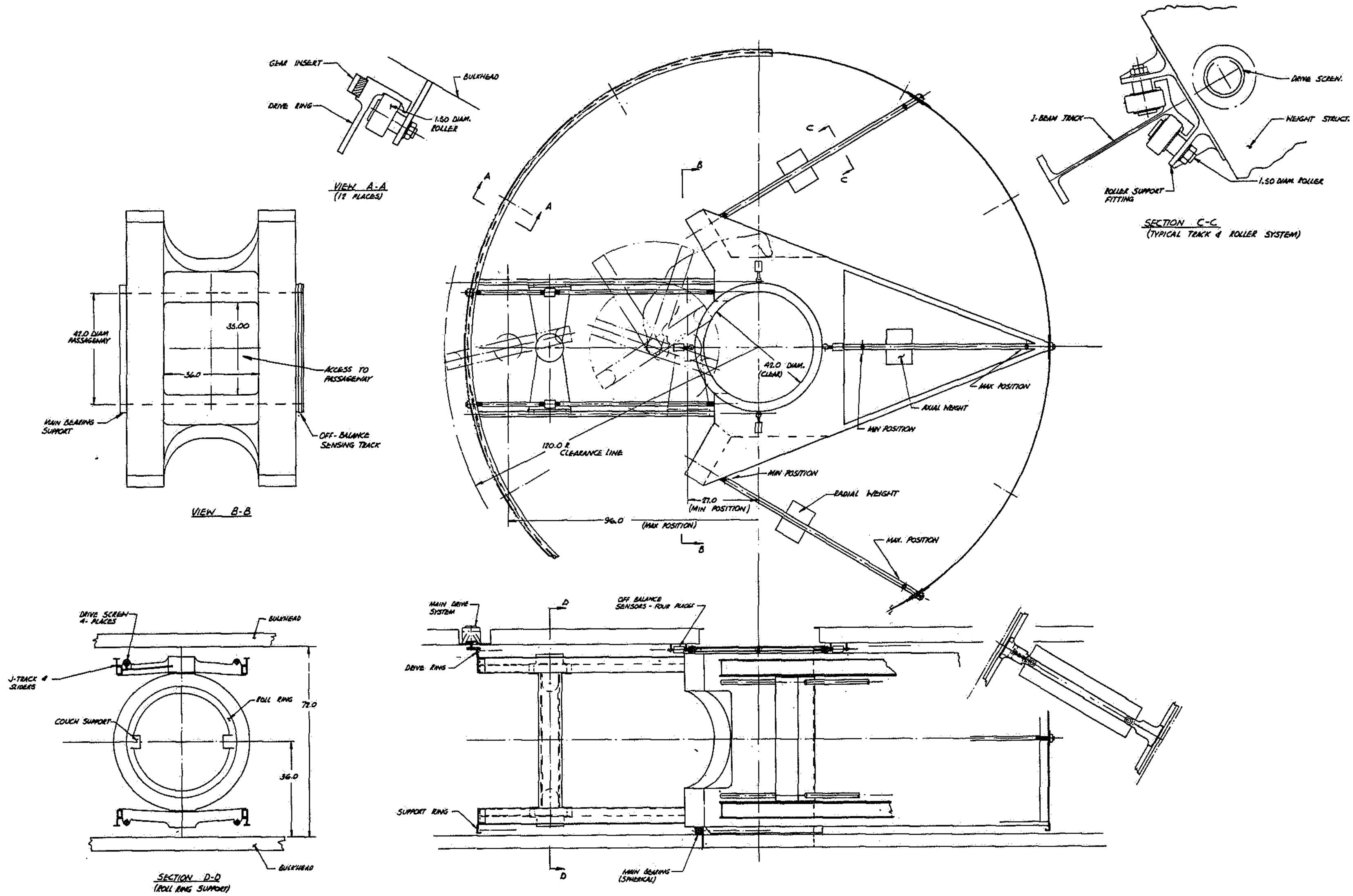

Figure B4. Centrifuge Preliminary Concept No. 3.

Table B7 Centrifuge Weights, Concept No. 3

		STRUCTURE	MECHANISM
1.0	UPPER SUPPORT HUB	(143)	(52.8)
1.1	Spacecraft Support Struct.	10	
1.2	Bearing Support Ring	13	
1.3	Bearing System		12.8
1.4	Drive or Support Ring	120	
1.5	Drive Motor & System		40
1.6	Balance Sensor Ring		
1.7	Sensors & System		
2.0	LOWER SUPPORT HUB	(143)	(31.3)
2.1	Spacecraft Support Struct.	10	
2.2	Bearing Support Ring	13	
2.3	Bearing System		
2.4	Drive or Support Ring	120	
2.5	Drive Motor & System		26.5
2.6	Balance Sensor Ring		.8
2.7	Sensors & System		4.0
3.0	PASSAGEWAY STRUCTURE	(70)	
3.1	Rings		
3.2	Shell	65	
3.3	Longerons		
3.4	Equipment Support Structure	5	
4.0	VARIABLE RADIUS SYSTEM	(186)	(63)
4.1	Radius Arm Struct.	126	
4.2	Pivot Support Struct.	60	
4.3	Pivot Radial Struct.		
4.4	Counterweight Support Struct.		
4.5	Bearing Slides, etc.		8
4.6	Variable Radius Mechanism		45
4.7	Motors & Systems		10
4.8	Position Sensor		
5.0	PIVOT SYSTEM	(35)	(27)
5.1	Pivot Frame Struct.	35	
5.2	Pivot Bearing		
5.3	Pivot Motor & System		7
5.4	Position Sensor System		20

Table B7. Centrifuge Weights, Concept No. 3 (Con't)

		STRUCTURE	MECHANISM
6.0	ROLL SYSTEM	(25)	(20)
6.1	Roll Frame Struct.	25	
6.2	Roll Drive Mechanism		15
6.3	Roll Motor & System		5
6.4	Position Sensor System		
7.0	PRIMARY COUNTERWEIGHT SYSTEM	(30)	(40)
7.1	Translation Struct	30	
7.2	Radial Struct.		
7.3	Translation Mechanism		35
7.4	Radial Mechanism		
7.5	Translation Motor & System		5
7.6	Radial Motor & System		
7.7	Position Sensor System		
8.0	SECONDARY COUNTERWEIGHT SYSTEM	(80)	(80)
8.1	Translation Struct.	80	
8.2	Radial Struct.		
8.3	Translation Mechanism		70
8.4	Radial Mechanism		
8.5	Translation Motor & System		10
8.6	Radial Motor & System		
8.7	Position Sensor System		
	TOTAL WEIGHTS	(712)	(314.1)

Table B8. Centrifuge Weight Summary, Concept No. 3

Structure	712	1026.1
Mechanism	314.1	
Primary c/w (Less Batteries & Inverter)	100	
Secondary c/w	250	
Power & Communications	120	
Batteries	220	
Inverters	30	
Experiments		
Couch Systems	117	
Man & Gear	200	
Misc		
Contingency	100	
Total	2163.1	

ABSTRACT

This document is the final study report prepared under Contract NAS 1-8751, Feasibility Study of the Incorporation of a Center Core Passageway In the Existing Centrifuge Design Developed Under NASA Contract NAS 1-7309. The study was performed for the Langley Research Center, National Aeronautics and Space Administration, Hampton, Virginia.

This design oriented study examines the practicality of incorporating a relatively large passageway (up to 42 inch dia.) through the hub area of an orbital research centrifuge. The study details the configuration required for the evaluation of low-g inertial support for walking mobility, personal hygiene, and bench tasks as well as for performance of a wide range of experimental observation of human physiological response. The work contains preliminary experiment descriptions, spacecraft integration data, performance requirements and a detailed examination of the centrifuge and its systems.

GENERAL DYNAMICS

Convair Division