REPORT NO. GDC-DCL-68-004
CONTRACT NAS 1-7309

FINAL REPORT

FEASIBILITY STUDY OF A CENTRIFUGE EXPERIMENT FOR THE APOLLO APPLICATIONS PROGRAM

VOLUME IV

MANNED CENTRIFUGE TEST REPORT

GENERAL DYNAMICS
Convair Division

15 August 1968

NASA CR- 66684
GDC-DCL-68-004
(SRC-MS-302)

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VOLUME IV

MANNED CENTRIFUGE TEST REPORT

Prepared under Contract NAS 1-7309

by

CONVAIR DIVISION OF GENERAL DYNAMICS

For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER

ACKNOWLEDGMENTS

This Volume was prepared by members of the Life Science Laboratory at the Convair division of General Dynamics. The report preparation was under the direction of Dr. B. D. Newsom, Senior Staff Scientist. Major contributors include Messrs. J. F. Brady and D. L. Kemper of the Aerospace Medicine Section, J. E. Stumm (Appendix A) and A. Greensite (Appendix B)

Security Classification Approved per Requirements of Paragraph 10, DOD 5520.22-M

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Program Manager
Centrifuge Study

CONTENTS

FIGURES

TABLES

SYMBOLS & ABBREVIATIONS

AMP	-	Amplifier
CEVAT	-	USAF Centrifuge Facility located at Convair
CNS	-	Central Nervous System
CRT	-	Cathode Ray Tube
CV	-	Check Valve
CYL	-	Cylinder
deg.	-	Degrees
EKG	-	Electrocardigram
EOG	-	Electro-Oculogram
F	-	Farenheit degrees
g	-	Acceleration Load Factor, gravities
gpm	-	Gallons per Minute
HYD.	-	Hydraulic
LRC	-	Langley Research Center
NASA	-	National Aeronautics and Space Administration
OGI	-	Oculogyral Illusion
rad	-	Radian
RATER	-	Response Analysis Tester
REST.	-	Restrictor
rpm	-	revolutions per minute
SCUBA	-	Self Contained Underwater Breathing Apparatus
sec	-	Seconds
SRC	-	Space Research Centrifuge
VOG	-	Vectoroculogram
X	-	Test Subject axial reference (front to rear)
Y	-	Test Subject axial reference (side to side)
Z	-	Test Subject axial reference (head to foot)
α	-	Cross-coupled acceleration or "Angular Coriolis" defined as the cross product of angular velocities, radians/sec^2
ω	-	Angular velocity, radians/sec

Note: A bar over a quantity (such as $\overline{\alpha}$) denotes average value.

INTRODUCTION

The tentative experimental program for utilization of an on-board orbital centrifuge as a means for research into human physiology was described in Volume III. These experiments, designated as the T-010 series, will require numerous motions of the human subjects according to the protocol developed by the principal investigator. The original plan was to simulate the motions involved in each orbital experiment on a ground-based centrifuge so as to determine the acceptability of the motion; however, the dynamics to be encountered depend on the presently unfinalized vehicle/ centrifuge configuration and experiment plan. Without final definition of these factors, the list of possible motions becomes very extensive, and would require considerable time and expense if each motion were examined individually. A study of a more general nature was selected which investigates the threshold sensitivities and the performance effects related to cross-coupled angular motion. From the results of such a study, predictions can be made concerning the T-010 experiment stability control requirements and subject tolerance limits.

Table 1 lists candidate experiments of the type likely to be proposed for the space centrifuge. The motions of each experiment are confined to the plane of spin except when cross-coupling is required, as in the test of semicircular canal stimulation. The intraplanar orientation of motions reduces the incidence of anticipated cross-coupled (gyroscopic) stimulus to the labyrinth. Vehicle motion and subject positioning, however, could still impose such artifacts on any physiological measurements being made. Such cross-coupling is the product of angular velocities ($\alpha = \omega_1 \times \omega_2$) and becomes more difficult to control at the higher spin rates because the vehicle angular motion (ω_1) must be more closely controlled to compensate for the spin rate (ω_2) increase.

The orbital centrifuge concept is being developed for experimentation in vestibular physiology as well as for physiological support and body mass measurement. The degree to which the vehicle must be stabilized during such experimentation to prevent stimulus artifacts resulting from vestibular cross-coupling is not known. Also, there are insufficient data available as to the relative weighting of the two angular velocities in determining the effective cross-coupled stimulus. The only data found to be pertinent are those of Clark and Stewart (1967) where the subjects were exposed to the same product but for different durations. Six-second tilts produced a consistently lower threshold than three-second tilts when the cross-coupling angular velocities were the same. The motions to be encountered in the

Table 1. Proposed Space Experiments for T-010

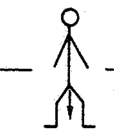
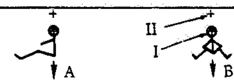
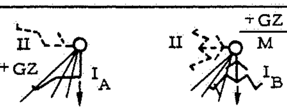
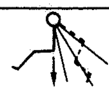
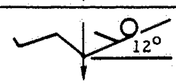
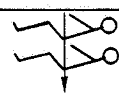
EXPERIMENT	BODY COORDINATE EFFECT	R	RPM	TORSO ORIENTATION WITH RESPECT TO SPIN PLANE	ACCELERATION	DEGREE OF FREEDOM (MOTION)
GRAYOUT	+GZ 	MAX		RADIAL FACING NORMAL	UP TO 6 g AT FEET - INITIAL g ONSET .1 g/sec	NOT REQUIRED
THERAPEUTIC	+GZ	MAX		SAME	4 g AT FEET	NOT REQUIRED
ANGULAR ACCELERATION		MAX	ZERO TO 20	SAME FOR INITIAL AND FINAL	10 SEC BURSTS OF .01 TO 1 DEG/SEC^2	AROUND Z AXIS WITH PARTIAL CHANGE OF SPEED AND DIRECTION
TILT TABLE	+GX 	29.6 in		I - PERIMETRIC FACING CENTER II - ALONG DYNAMIC CURVE	1-g AT HEAD	I - INITIAL K. SPEED AND DIRECTION II - REACHED WHILE ROTATING EQUIVALENT SPEED
SEMICIRCULAR CANAL STIMULATION		ZERO & MAX	4 to 10	I, IIA - RADIAL FACING TAN I, IIB - RADIAL FACING NORM	0 to 1 g AT EARS	I-A, B, HEAD AT CENTER II-A, B, HEAD AT MAXIMUM RADIUS
SENSITIVITY TO LINEAR ACCERATION		MAX		IA RADIAL FACING TAN IIA SEC FACING CENTER IB RADIAL FACING NORM IIB RADIAL FACING NORM	.002 g, .01 g and 1g AT EARS	THRESHOLD FROM-0° to 90° SENSITIVITY AT 0-1°, 15°-16°, 30°-31°, 45°-46° A. - PITCH AT EARS Y B. - ROLL AT EAR X
OCULOGRAVIC ILLUSION	+GZ 	MAX		RADIAL FACING TAN & NORM	1.0 g AT EARS	+ PITCH AT EARS Y TO 15, 30 & 45° ± .5°
EYE COUNTER ROLLING	+GZ 	MAX		RADIAL FACING NORMAL	SAME	+ ROLL AT EARS X TO 15, 30 & 45° ± .5°
REENTRY SIMULATION	+GX 	MAX		PERIMETRIC - 12° FACING CENTER	UP TO 9 g's	NOT REQUIRED
MASS DETERMINATION	+GX 	INTER & MAX		PERIMETRIC FACING CENTER	@ 1 g	2 RADII WILL BE SELECTED AND MAINTAINED THROUGH ALL EXPERIMENTS

Table 1 candidate experiment programs could be characterized by various durations and rates of couch angular movement which are superimposed upon various angular velocities of the centrifuge. As a result, it was considered important to determine not only the subject's perceptual and performance thresholds, but also to determine the physiologic effect of varying the individual values of ω_1 and ω_2 at a constant value of α.

Table 2 generalizes the possible motions the subject may encounter on the centrifuge in space. Orientation along a radius or a cord produces the same magnitude of α from the cross-coupling of the given angular velocities; however, differences in the radial components of the semi-circular canal movements for a given head turn in the two different body orientations pose the possibility for an alteration in comparative physiologic effect and must be considered in justifying such a comparison.

Summarizing the above, it was felt that the initial ground-based testing should provide the following information pertinent to T-010:

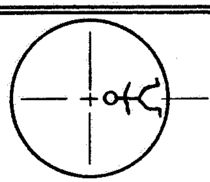
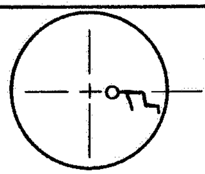
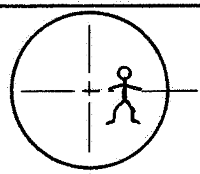
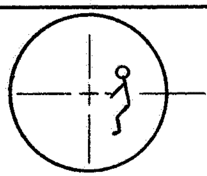
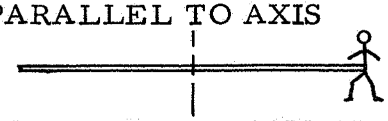
a. Vestibulo-ocular and performance sensitivities to angular acceleration produced by the cross-coupling of two angular velocities.

b. Response to a given cross-coupled angular acceleration as a function of quantitatively varying the two multiplied angular velocities while keeping their product constant.

c. Response to a given angular acceleration, resulting from the cross-coupling of the same angular velocities, as a function of subject orientation within the dynamic system.

The procurement of this information was the objective of the test program.

Table 2. Possible Subject Orientations In Experiment T-010

LONG BODY AXIS ALIGNED WITH :	IN PLANE		RESULTANT
	GAZE	AXIS OF TURN	
 RADIUS	AXIAL	PITCH Y YAW Z ROLL X	YAW Z PITCH Y
 RADIUS	TANGENTIAL	PITCH Y YAW Z ROLL X	ROLL X YAW Z
 CORD	AXIAL	PITCH Y YAW Z ROLL X	YAW Z PITCH Y
 CORD	TANGENTIAL	PITCH Y YAW Z ROLL X	ROLL X YAW Z
	OUT OF PLANE		
PARALLEL TO AXIS 	RADIAL	PITCH Y YAW Z ROLL X	ROLL X PITCH Y
PARALLEL TO AXIS 	TANGENTIAL	PITCH Y YAW Z ROLL X	ROLL X PITCH Y

TEST PREPARATION

Simulator

To facilitate simulation of the space centrifuge, the Langley Research Center Immersion Tank designed by Stone and Letko, was obtained on loan from Arizona State University*. The tank was originally designed to rotate continuously at high rates about its transverse axes. It was decided early in the planning of this initial study of cross-coupled effects that there were too many "unknowns" to justify sealing the test subject in a water-filled tank and rotating the tank continuously while it was being revolved by the centrifuge. Instead, the tank was tilted by means of hydraulic pistons through an arc of 90°. Figure 1 shows the LRC tank on the centrifuge and Figure 2 shows a subject oriented within the tank for the performance degradation test. The details of construction and operation of the tank are described in Appendix A. The tank tilt operator rode the centrifuge outside the tank and controlled its operation from a restraint seat mounted adjacent to the tank. The entire tank and trunnion assembly was constructed so it could be rotated 90° with respect to the centrifuge arm. In this way the tank tilt axis could be aligned radially or tangentially within the plane of centrifuge spin. The trunnion mount was tied together to ensure assembly stability in either the radial or tangential alignment of the tank axis. The couch was positioned with its long axis either coaxial with (position b) or a normal bisect of (position a) the tank tilt axis. All tilts started at 45° off center and ended at 45° off center in the opposite inclination. All tilts were in the same direction with the return rate to the cocked position being at approximately 2°/sec.

The CEVAT centrifuge at Convair was used as the prime rotation device. The Langley Immersion Tank was mounted upon the CEVAT centrifuge. For Series A experiments the tank was mounted at a four-foot radius from the centrifuge spin axis with the hydraulic drive mechanism providing the desired tilt rate. The subject dynamics shown in Table 3 were executed to produce the required cross-coupled angular accelerations. All of these were accomplished by tilting the tank with the subject oriented within the tank so that his motion was a pitch, yaw or roll. To accomplish these positions the tank was oriented as shown in Figure 7 with its plane of motion in either a radial or tangential direction. The subject's orientations then produced cross-coupled angular accelerations about each of the axes shown in Table 3. The simulation thereby allowed tentative conclusions to be made about approximate oculogyral illusion (OGI) threshold levels for resultant cross-coupled stimuli about the X, Y and Z axes and allowed comparison of

*Obtained through the courtesy of R. Mayne, Electrical Engineering Department.

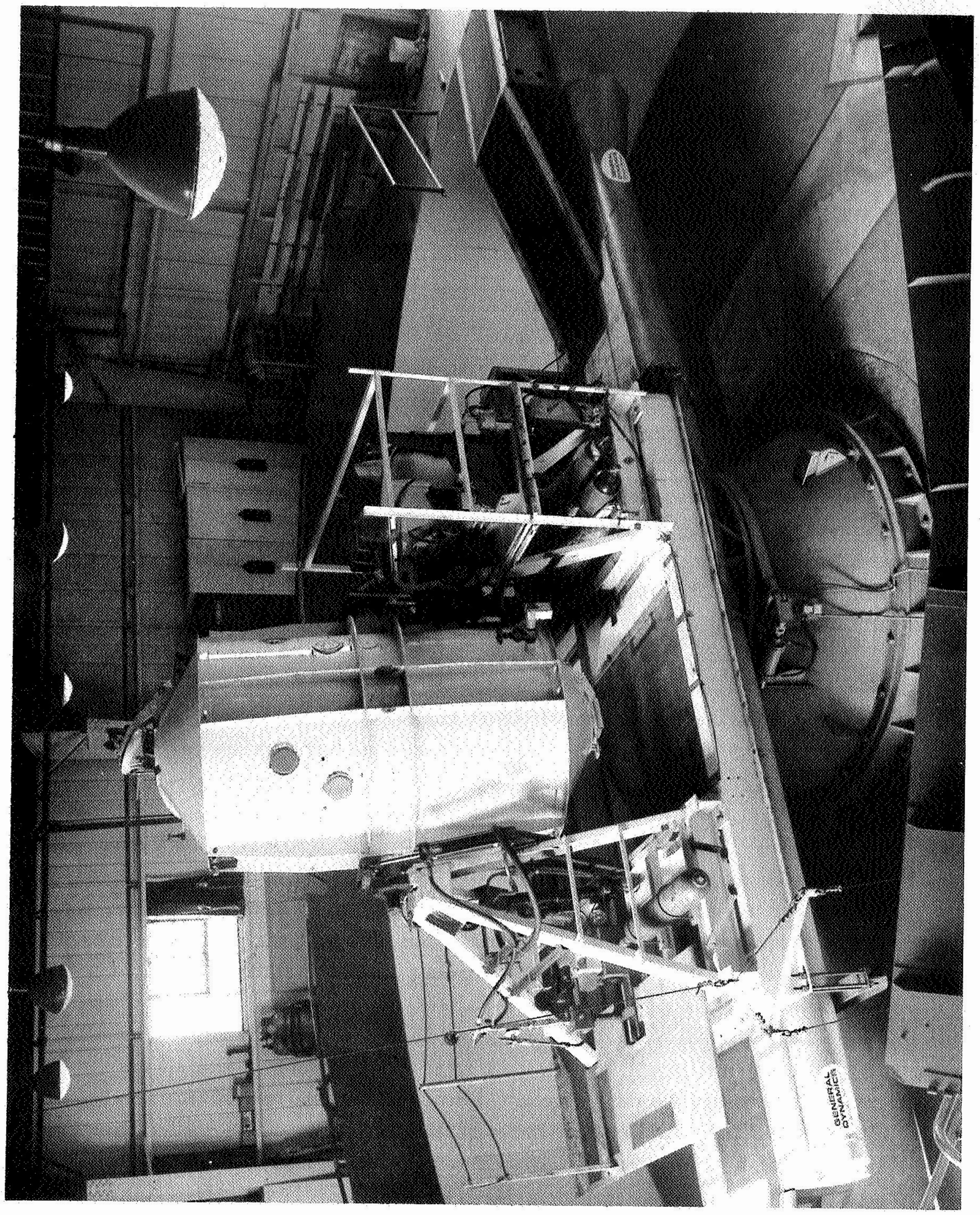


Figure 1. Langley Research Center Immersion Tank Modified for Operation on the CEVAT Centrifuge.

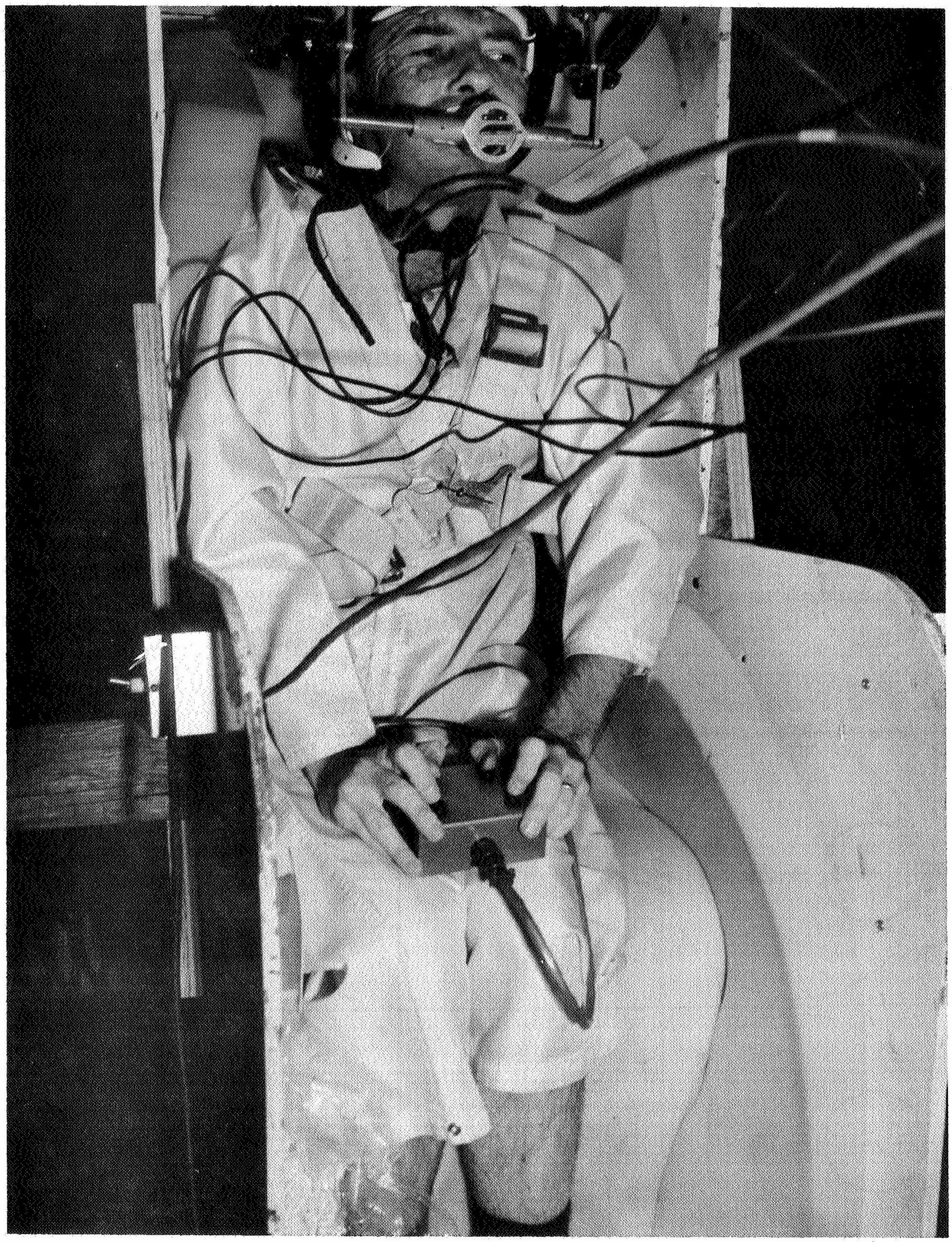
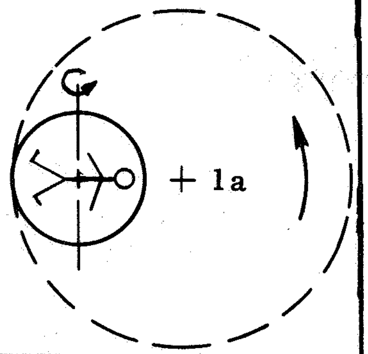
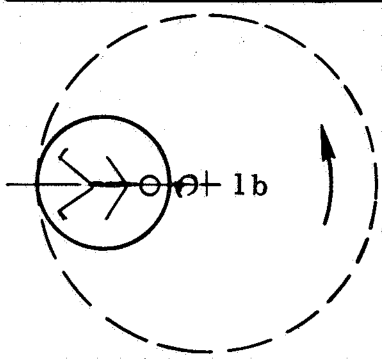
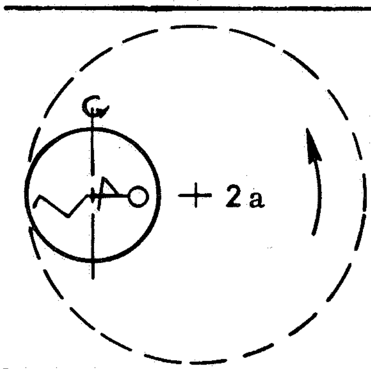
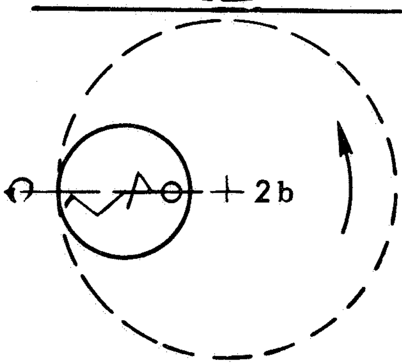


Figure 2. Subject on Couch Within the LRC Tank and Operating the RATER. (Head is Restrained by Helmet and Bite Bar.)

Table 3, Series A, Experiment 1 - Subject Motions and Stimuli

Subject Orientation	Subject Eccentric Rotation	Subject Tilt	Turn Axis of Tank	Resultant Stimulus (Illusion)
	x axis	y axis (pitch)	Tangential	z axis (apparent yaw)
	x axis	z axis (yaw)	Radial	y axis (apparent pitch)
	y axis	x axis (roll)	Tangential	z axis (apparent yaw)
	y axis	z axis (yaw)	Radial	x axis (apparent roll)

the results of the same cross-coupled accelerations when produced by different combinations of angular velocities.

Orientation 1a and 2a both produced a Z axis gyroscopic resultant but involved rotation about different body axes. It was reasoned that if the 1a and 2a threshold values were found to be the same, it would suggest that the resultant axis stimulated was the only important factor, but, if they differed, it would indicate that the axes of the cross-coupling angular velocities were also significant. The latter situation would restrict the applicability of a threshold determination.

Qualitative Dynamics

The large number of variables involved in cross-coupling required a somewhat arbitrary decision on approach. For this preliminary test the arc through which the tank was tilted was kept constant, with the centrifuge spin rate and the tilt rate of the tank being the only experimental variables. Ideally this limitation would be controlled by experimental design, repeating the exposure in each of the following modes and determining the differences:

1. Tilt the tank through the 90° arc at various rates of velocity change from zero to peak and peak to zero (See Figure 3), with the time for traversing the arc being a variable and a different peak velocity being reached for each acceleration. Three variables would be involved: duration of stimulus, peak angular velocity, and acceleration.

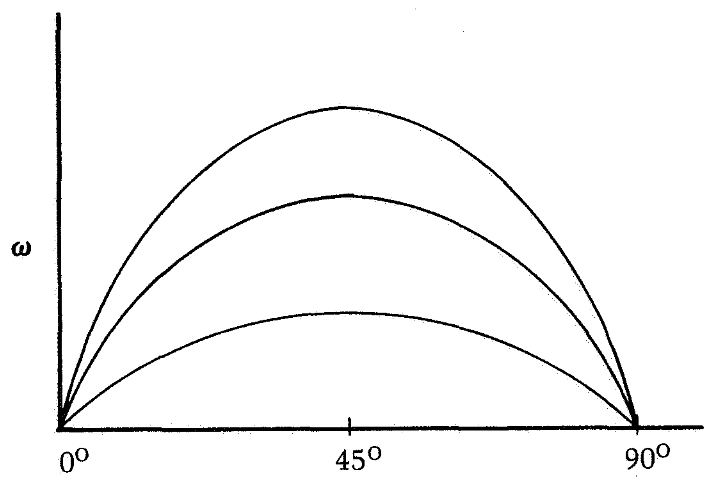


Figure 3. Tank Tilt Mode No. 1

2. Keep the tank peak velocity constant and vary the rate of acceleration (See Figure 4). Two variables would be involved: duration of peak velocity and g-onset.

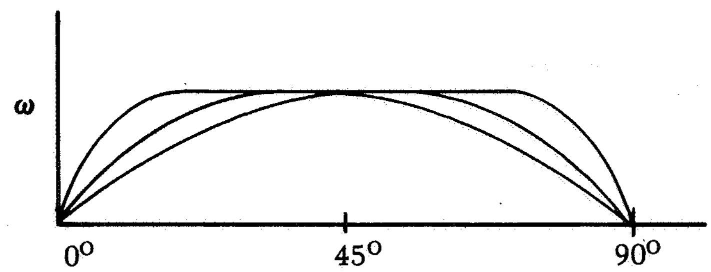


Figure 4. Tank Tilt Mode No. 2

3. Vary the arc through which the motion is made,to keep the peak velocity and duration of peak velocity constant (See Figure 5). Two variables would be involved: onset and total tilt time for each exposure.

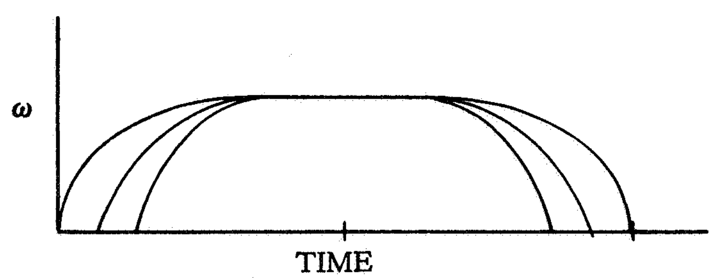


Figure 5. Tank Tilt Mode No. 3

4. Vary the tilt as to peak velocity, g-onset and tilt time for a given arc (See Figure 6).

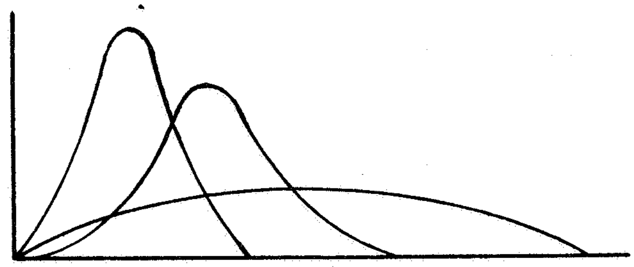


Figure 6. Tank Tilt Mode No. 4

The first three experimental modes presented above offer greater control in interpreting and relating data to semicircular canal dynamics, but are academic to the engineering problem and are difficult to achieve. The fourth mode is easier to achieve experimentally and is of the most pragmatic value to the centrifuge design. It is anticipated that the motions due to positioning the space centrifuge or to vehicle angular perturbation will be in this mode. Such motions have usually been expressed in the literature as average angular velocity, disregarding velocity distribution on the basis that the vestibular time constants favor response to an integrated impluse. The fourth mode, therefore, was selected for the conduct of this test.

Quantitative Dynamics

Semicircular canal angular acceleration threshold levels for the normal population range from $0.03^{\circ}/sec^2$ to $8^{\circ}/sec^2$ with the mean at $1^{\circ}/sec^2$, (Reference 4). These values were primarily determined for rotation about the Z axis. Cross-coupled angular acceleration thresholds have been assumed to be in the same range, but that assumption has not been validated. Gillingham (1966) used a selected group of subjects and rotated them about their Z axis at rates ranging from .1 to .4 rpm. Following rapid pitching head turns while rotating, these subjects reported the direction of any illusory rotation. The results were used to express a threshold in radians per second of environmental spin. Using Gillingham's threshold turning rates of 0.13 to 0.16 radians/sec and assuming a head turn time of 0.5 sec., Clark (1967) computed the cross-coupled threshold to be $1.5^{\circ}/sec^2$. There is, however, considerable room for error in the rate of head turn assumed. Clark and Stewart (1967) have also published a study expressing cross-coupled acceleration thresholds on the basis of environmental rpm. This

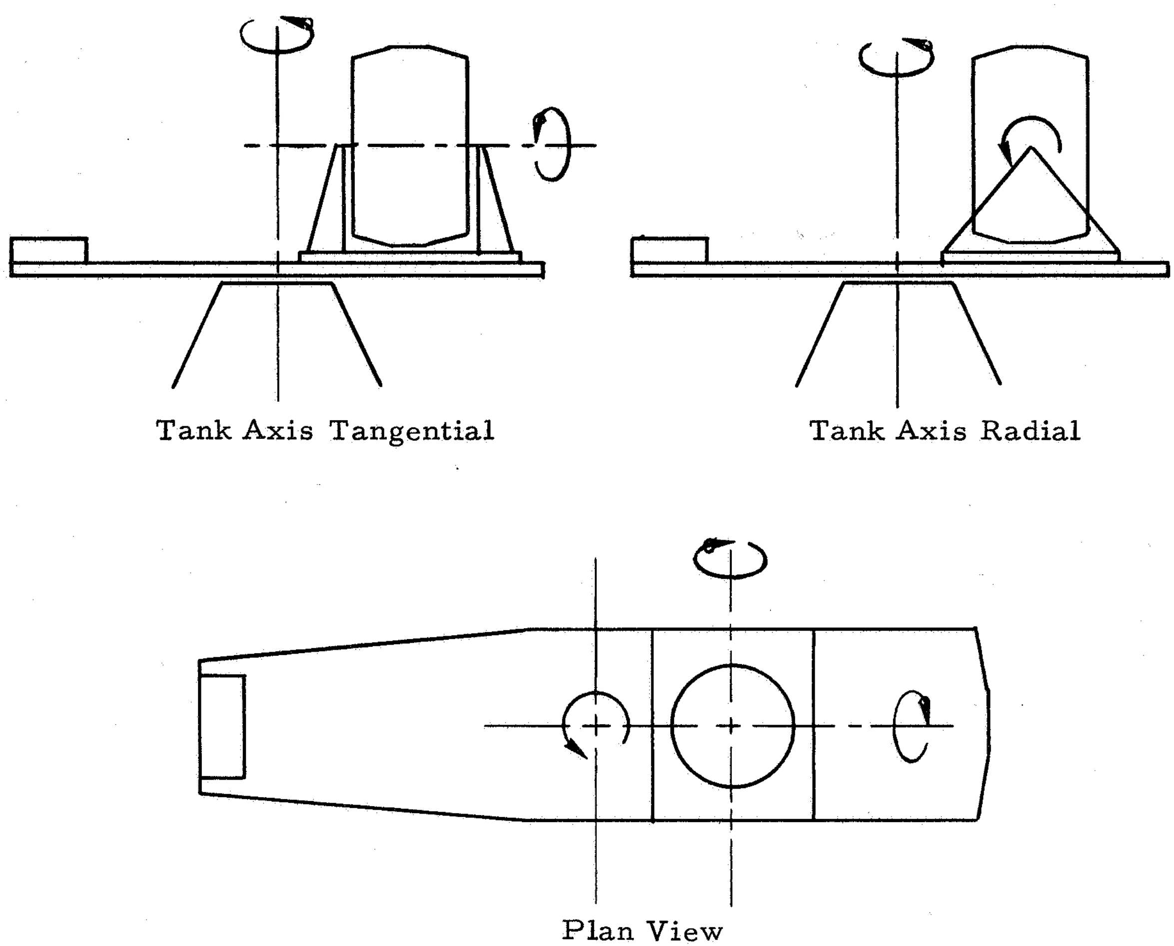


Figure 7. Orientation of LRC Tank On Centrifuge

form of expression, it should be noted, leads to considerable confusion, as the effect is a cross-coupled phenomenon that should always be identified as to both angular velocity factors. Computing the α (angular acceleration) threshold values from Clark and Stewart's passive tilting results in $7.28^\circ/\text{sec}^2$ for 35° tilts (lasting 3 seconds) and $5.23^\circ/\text{sec}^2$ for 70° tilts (lasting 6 seconds), values that are much higher than those calculated from Gillingham's values but based on fewer assumptions. The tilting motions were in the pitch plane in both studies only.

Performance degradation in previous General Dynamics studies began when the cross-coupled α was around $70^\circ/\text{sec}^2$ (Newsom and Brady, 1966).

Stone and Letko have reported performance tolerance levels for cross-coupled α (1964, 1965) and found subjects tolerated 4.0 rad/sec^2 (229°/sec^2) at 10 rpm and that subjects reduced their head turn rates at higher angular velocities to maintain cross-coupling below 5.1 rad/sec^2). The rotational velocities of Stone and Letko's centrifuge varied between 1 rpm and 10 rpm. This is the anticipated operating rpm range of the space centrifuge during vestibular studies.

The performance test (RATER) used in this and previous studies (Newsom and Brady, 1966) can be adjusted for difficulty in task and is believed to be more sensitive to the environment than the task used by Stone and Letko. The highest cross-coupled α anticipated for the required positioning of the SRC would be considerably below that necessary to produce a cross-coupled α of 70°/sec^2, but with a very sensitive test there might still be some degradation in performance.

It should be emphasized when considering quantitative threshold determinations that threshold values for semicircular canal sensitivity for either the constant force field of angular acceleration or the varying force field encountered by each canal in cross-coupling of angular velocities are dramatically dependent upon the response indices used. Vestibulo-ocular response to angular acceleration, for example, is contingent upon ambient illumination, visual fixation and CNS arousal. Similarly, the level of stimulus required to degrade performance depends upon the complexity of the required task.

The oculogyral illusion (OGI) is considered to be the most sensitive quantitative index of semicircular canal stimulation and it was used to determine the perceptual threshold. The OGI is experienced by a subject with functional vestibular organs when exposed to an angular acceleration level that exceeds his sensory threshold. The OGI consists of an apparent movement of a target fixed relative to the viewer.

Perceptual-motor performance is the category of psycho-motor function which is the most kinematically sensitive. A perceptual-motor device, the Response Analysis Tester (RATER), was used to determine the threshold for performance degradation. The RATER task requires that the subject press the correct one-of-four microswitches in response to each one-of-four colored light signals as it is presented on a 1° of visual angle display screen. The signals are presented randomly at a rate dependent upon how fast the subject responds correctly (self-paced mode). Both total responses and total correct responses are recorded as well as time for correct response (response latency) to each signal.

Based on the above consideration of data in the literature, anticipated space centrifuge dynamic profiles and the sensitivities of the selected threshold indices, the mean cross-coupled accelerations resulting from rotation through the 90^{o} arc, at obtainable tilt rates and acceptable rpm, were selected ranging from $0.3^{o}/sec^{2}$ to $90^{o}/sec^{2}$. The ceiling for OGI testing was nominally set at $4.8^{o}/sec^{2}$, with the RATER testing ranging from 18^{o} to $90^{o}/sec^{2}$.

Ancillary Equipment

For the OGI Test (Experiment #1), the subject was submerged four feet below the water surface and used hookah breathing gear and a full face mask. The immersion, together with ballasting of the subject to provide neutral buoyancy, provided a simulation of the weightlessness that would be experienced in the space centrifuge environment by attenuating exteroceptive cues to orientation. The wet (intra-tank) monitor used identical breathing support equipment. The tank was filled daily with heated water pumped from an adjacent swimming pool. The water was passed through the heater to obtain a temperature of $95^{o}F$. This gave a mean temperature of $94^{o}F$ throughout the test day. The use of swimming pool water was necessary to ensure the required clarity for the OGI measurements. Figure 8 indicates the immersed subject in the supine test position. He was also tested while positioned on his left side.

For the RATER Test (Experiment #2), the subject was tested only in the supine position and with the tank dry.

EKG and EOG sensing electrodes were applied in accordance with recommended Beckman Instrument Company procedures. Three EKG electrodes were applied transthoracically - one each three to four inches below each armpit and the indifferent over the sternum at the same level. Five EOG electrodes were applied as follows:

2 vertical electrodes	1 cm. directly above the right eyebrow and 1 cm. below lower right eyelid
2 horizontal electrodes	1 each at right and left temporal canthi
1 indifferent electrode	1 positioned on the forehead, a cm. above bridge of nose.

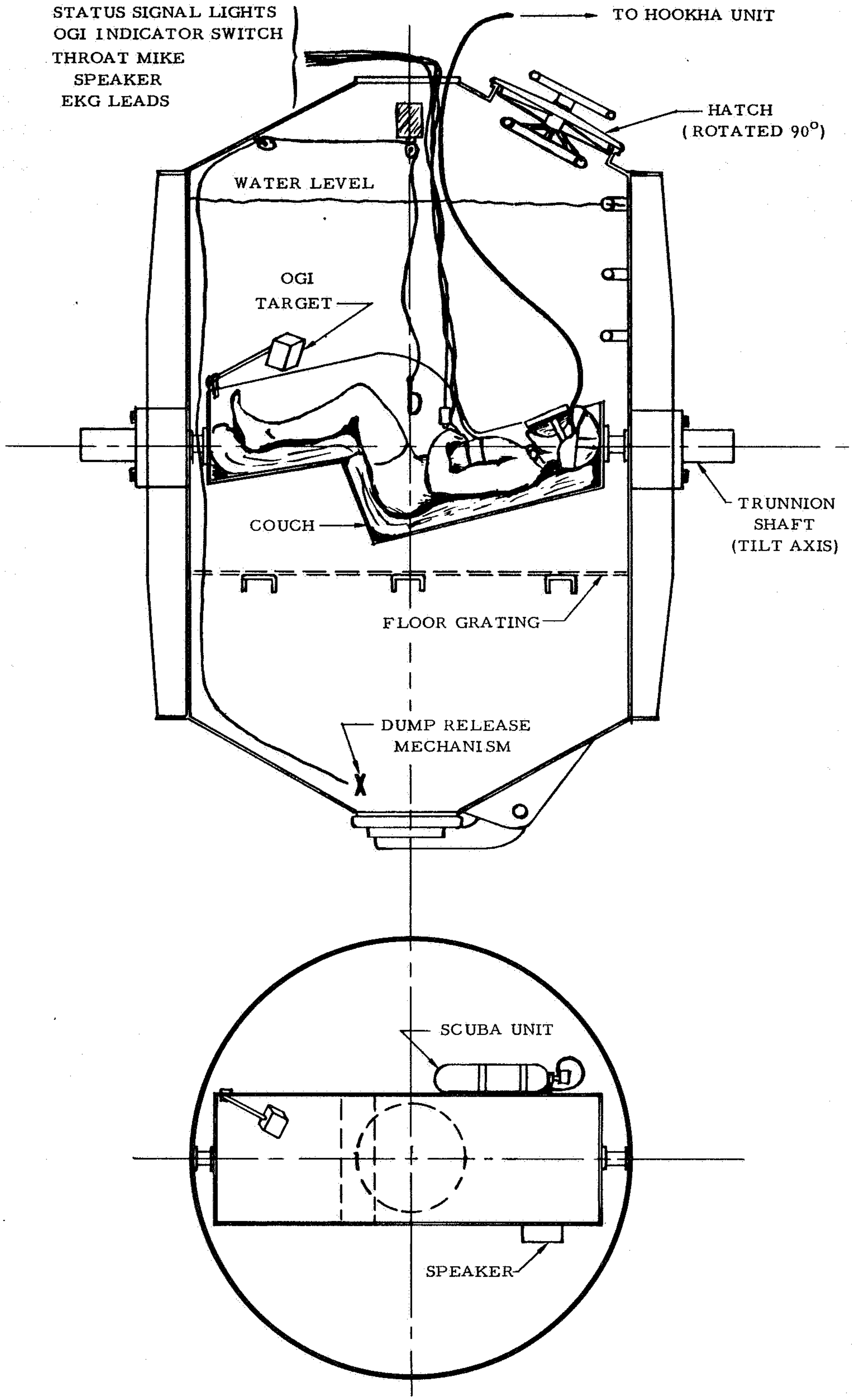


Figure 8. Langley Immersion Tank Conversion for Experiment 1.

Figure 9 shows amplifiers and recording equipment, and gives a detailed picture of system integration as it was related to each measurement.

RATER total responses and total correct responses were registered by counters incorporated in a console positioned on the tank platform (the number of leads to the console precluded transmitting through the slip rings of the centrifuge). Scores were relayed by the tank tilt engineer thru the intercom to the examiner in the centrifuge control room.

The signals of all the other parameters recorded were electrically transmitted directly to instrument display. The centrifuge position signal was hardwired directly to a Sanborn 150 recorder in the centrifuge control room. The remaining signals (personnel EKG, subject EOG, RATER response latency, OGI affirmation, and tank position) were transmitted thru the centrifuge slip rings for hardwire to the same Sanborn recorder. The subject's vertical and horizontal EOG were also combined by a Tektronix 503 oscilloscope to produce a single two-dimensional display termed a vectoroculogram (VOG), and combined by a Mosely X-Y plotter for permanent write-out of the VOG.

The OGI affirmation was signaled by the subject using a thumb switch. All electrical power into the wet environment was wired thru a Circuitron for safety.

A preliminary wet run for the purpose of system checkout preceded formal testing. This checkout effort required that all three test conductors complete at least one performance test sequence as a test subject in the immersed mode. Such static testing of the tank involved application of all biosensors and collection of complete data from subjects in the wet environment. Data collection and communication equipment received final qualification at that time.

Final centrifuge modifications, including checkout, involved:

a. Removal of slip ring and boom supports.

b. Installation of small 15-line slip ring and leads.

c. Water-tight enclosure of electric box located in centrifuge pit.

d. Checkout of tank water dump release mechanism offering either subject or on-board monitor release capability during rotation and tilt.

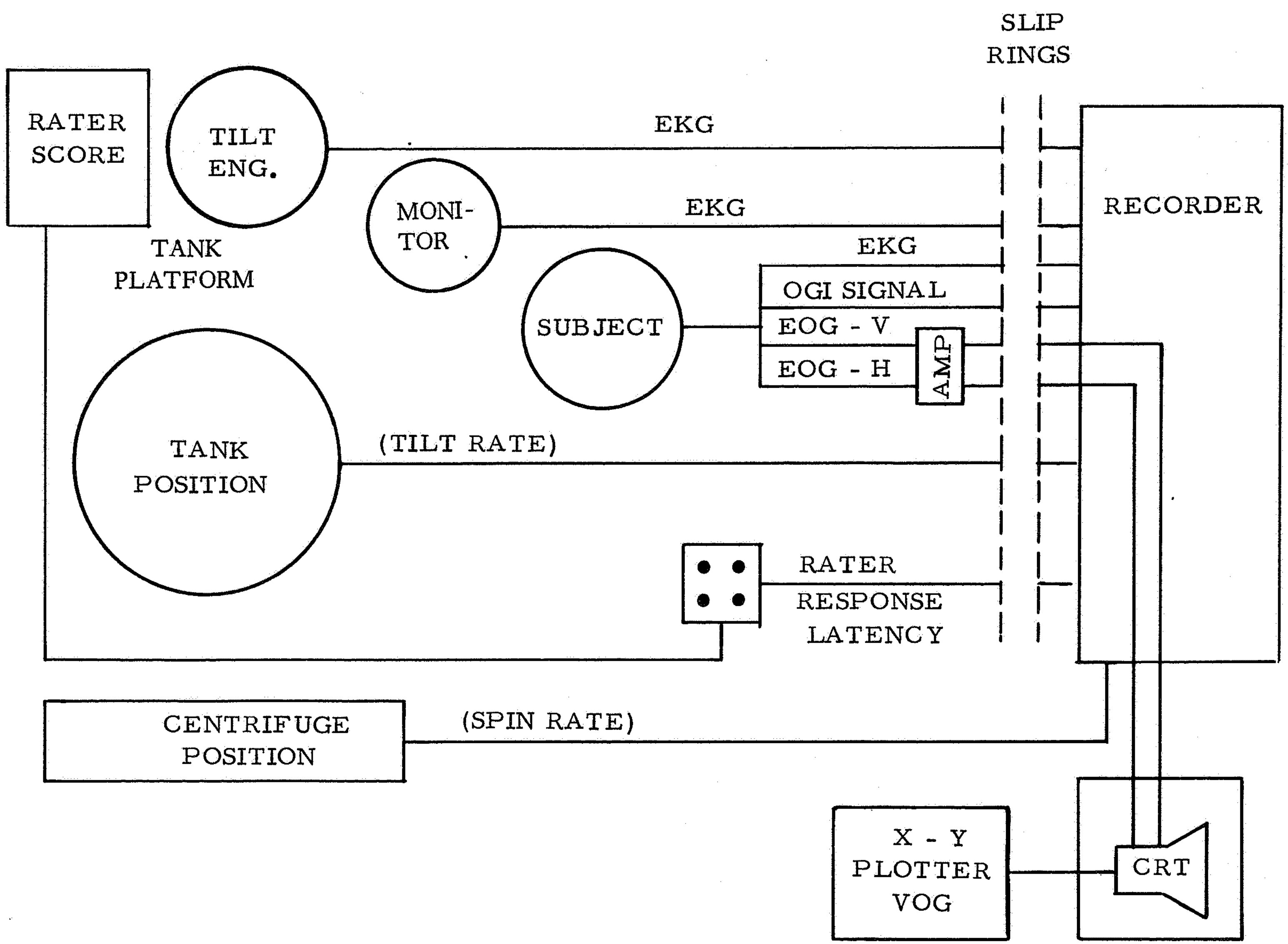


Figure 9. Data Collection System Schematic

TESTING

Experiment 1 (OGI Threshold)

Purpose: - To determine threshold for cross-coupled acceleration (α) and the dependence upon velocity factors, ω, in the expression $\alpha = \omega_1 \times \omega_2$.

Method: - The method employed was to measure duration and magnitude of oculogyral illusion for eight subjects when they were exposed to cross-coupled accelerations. The primary rotation was imposed by centrifuge rotation (ω_c) and the secondary angular motion was imposed by tilting the submerged subject through 90^o at a four-foot radius (ω_t).

Procedure: - Ten subjects (two acted as alternates) qualified in SCUBA techniques were required to pass a Class III Flight Physical. Each subject was exposed to a single static (0 rpm) practice tilt preceding formal testing at each new tilt rate. The practice tilt was used to acquaint subjects with the wet environment and the sensation of tilting to which they would be exposed during the test. During the practice runs the subjects were advised of their starting position and the dynamics to follow. During the practice trials they were asked to note post-acceleration and post-deceleration effects to assist them in recognizing the motion sensations involved in this study.

The ten subjects were exposed to the α accelerations shown in Table 4. The tilt rate of 5.7^o/sec (0.1 rad/sec) was selected as a reasonable rate at which the space centrifuge couch might be positioned during rotation. Five subjects were exposed first to a constant ω_c and a varying ω_t and then to a constant ω_t with a varying ω_c. The second five subjects were tested in a reversed order.

Exposures were repeated in each of the orientations: (a, 1 and 2; and b, 1 and 2.

The OGI were indicated by a hand switch (duration) and by intercom (magnitude) in terms of units of target deflection from its original position. Direction of apparent target movement was expressed in clock-face terminology. The OGI target was a four-inch illuminated cube painted black with transparent edges.

Table 4. - Cross-Coupled Accelerations In $^{o}/Sec^{2}$

(ω_c) Centrifuge		(ω_t) Tank ^{o}/sec									
RPM	^{o}/sec	0	0.7	1.4	2.1	2.9	4.3	5.7	11.5	17.2	22.9
0	0							0			
.25	1.5							.15			
.5	3.0							.3			
.75	4.5							.45			
1.0	6							.6			
1.5	9							.9			
2.0	12	0	.15	.3	.45	.6	.9	1.2	2.4	3.6	4.8
4.0	24							2.4	(α) $^{o}/sec.^{2}$		
6.0	36							3.6			
8.0	48							4.8			
10.0	60							6.0			

Experiment 2 (Performance Degradation)

Purpose - To determine the vestibular cross-coupled acceleration threshold for RATER performance degradation with the resultant acceleration in the pitch plane.

Method - Each of four subjects were tested by being required to perform the RATER perceptual-motor task immediately following their being passively yawed about their long body axis while being continuously rolled by the CEVAT centrifuge. The passive yaw was produced by tilting the dry LRC tank which contained their restraint couch. All subjects were tested through a matrix of cross-coupled accelerations resulting from a product of four tank tilt rates (6, 15, 30 and 45^{o}/sec) and three centrifuge spin rates (10, 15 and 20 rpm). At each point in the matrix five tilts and associated performance trials were performed.

Procedure - Each subject was processed as follows:

He was instrumented for EKG, EOG and fitted for bite bar. During this period the subject memorized the RATER response pattern.

His EOG was calibrated by requiring him to make 10^{o} - 20^{o} eye excursions relative to a clinical perimeter in vertical and horizontal orientations. Gain adjustments were made to yield convenient stylus and eyespot excursions.

He was trained to asymptotic level on the RATER.

He was placed in the test couch, which was heavily padded and included a restraint harness to augment the restraint due to a fixed helmet and bite bar.

A baseline sequence of testing was performed with the centrifuge static. Each sequence of test trials (static and perrotatory) consisted of five trials, each trial including a 45-second cocking period, a 15 second waiting period, and a 30 second testing period consisting of a variable (ranging from 2 to 15 seconds in duration) tilt period and a subsequent post-tilt testing period lasting until the 30 seconds were completed.

Each subject was tested through the dynamic matrix with a five-trial sequence at each of the twelve matrix points shown in Table 5.

Table 5. Cross-Coupled Accelerations in Degrees/sec^2

Tank Tilt Rate (^{o}/sec)	Centrifuge Spin Rate			
	10	15	20	rpm
	60	90	120	^{o}/sec
6	6.3	9.4	12.6	
15	15.7	23.0	31.4	(α)
30	31.4	47.3	62.8	$^o/sec^2$
45	47.1	70.7	94.2	

Tilt rates were always presented in an increasing order, with the spin rates being varied in an increasing order at each tilt setting.

The subject was in a dry environment with ample air circulation and ambient lighting provided. He had voice communication and three electrical status switches, in addition to the previously described bio-sensors, to indicate his condition. All subjects were instructed to announce the first sign of stomach awareness. The bite bar was mounted to permit quick removal by the subject. The only other person on the centrifuge was the operator outside the tank who tilted the tank and relayed RATER scores to the control room.

The RATER performance test was conducted in the usual manner with the subject's signal display console being situated directly in front of the subject with a lead connecting it to the remote response button unit in his lap. The examiner's console was placed outside the tank, its counters being monitored by the tank tilt operator. He reported total responses and errors to the control room. Response latency was transmitted directly to the control room.

Biomonitoring and centrifuge and tank position recording were continous throughout both Experiment 1 and 2.

Conflict in centrifuge priorities required a delay and subsequent shortening of Experiment 2. It had originally been proposed to perform Experiment 2, as well as Experiment 1, using submerged subjects. The accelerations involved were found to be less stressful within the tank than had been anticipated, however, and as exteroceptive cues should not be expected to affect perceptual motor performance as it would the OGI threshold, there was little justification for complicating the procedures of Experiment 2 with the problems of immersion.

RESULTS AND SRC IMPLICATIONS

Experiment 1

Ten subjects were scheduled and evaluated in the test series. Data of one subject were discarded because he never reached a liminal level. He reported illusions when tilted with the centrifuge static and no cross-coupling involved. He was reporting sensations due either to the angular acceleration of the tilt phase, or was perceiving an illusion due to otolith stimulation. One other subject (D.K.) developed an ear infection after the first test and was excluded from further testing. A third subject's data were not complete due to equipment malfunction.

Useful data were obtained from the remaining seven subjects. These subjects were also tested with aural caloric stimulation to determine the consistency of their vestibular response. On the day of the caloric testing one subject was not available. The responses of the six remaining subjects are shown in Table 6. All showed active labyrinthine response that was duplicated by the second response when retested four hours later.

Table 7 presents the data accrued during Experiment 1. The α value shown for the threshold is the first stimulus which evoked an OGI but is not necessarily the lowest effective value possible as a substantial range separated the positive response value from its closest negative, especially for the higher values of α used for test points.

The preliminary test objectives, however, can be derived from these results. The values for all three axes stimulated are very close and if a difference exists between these values it is doubtful if it has practical importance to the design and experimental planning of the Space Research Centrifuge (SRC). The values are in good agreement with those calculated from Clark and Stewart's published figures of $5.23^{\circ}/sec^2$ for 70° tilt (1967).

The information relaxes the control problem considerably as the previous threshold envelope for cross-couplings had to be based on the angular threshold value of $.03^{\circ}/sec^2$ and it had, therefore, been tentatively decided

Table 6. Duration Of Oculogyral Illusion Resulting From Caloric Stimulation*

No.	Subject	Ear	First Stimulation Response	Second Stimulation Response	Difference
1	WGT	L	3.02 min.	3.18 min.	+0.16
		R	2.83	2.88	+0.05
2	RLW	L	0.98	0.83	-0.15
		R	1.38	1.97	+0.59
3	JES	L	3.15	3.28	+0.13
		R	2.07	1.93	-0.14
4	BDN	L	0.68	0.90	+0.22
		R	0.97	1.00	+0.03
5	JFB	L	2.95	3.25	+0.30
		R	2.60	2.75	+0.15
6	DLK	L	2.77	3.10	+0.33
		R	1.98	2.40	+0.42

Mean ± 1 S.D.	Diff(in min.)	Diff(% of First)	Age	Height	Weight
	+0.17± 0.21	±8.2±10	36±6.1	5.88 ± 0.1	163±15

\+ indicates increase   - indicates decrease   L indicates left ear   R indicates right ear

* 50 cc of 25°C water at 1 cc/sec.

Table 7. Results Of Experiment 1

Orientation		Subject Axes Motion Due To:			Subject	Threshold**	Illusion at Equivalent α with Increased Tilt Rate		
Tank	Couch	Cent.	Tank	α*		α = $^{o}/sec^{2}$	$11.5^{o}/sec$	$17.2^{o}/sec$	$22.9^{o}/sec$
a	1	X	Y	Z	RB	4.8	neg.	-	neg.
					RW	3.6	-	neg.	neg.
					EC	3.6	-	pos.	pos.
					RS	3.6	neg.	pos.	-
					CM	4.8 ($\bar{\alpha}$ = 3.6, N = 7)	pos.	-	-
					BN	2.4	-	-	-
					DK	2.4	pos.	-	-
a	2	Y	X	Z	RB	5.7	-	neg.	-
					RW	4.8	-	neg.	neg.
					EC	4.8	-	-	neg.
					RS	4.8	neg.	neg.	pos.
					CM	5.7 ($\bar{\alpha}$ = 4.5, N = 7)	neg.	neg.	neg.
					BN	2.4	-	-	-
					DK	3.6	neg.	-	neg.

* α is product of angular velocities.

\- Not Run.

** Tank Tilt = $5.7^{o}/sec$ at 0-12 rpm

Table 7. Results Of Experiment 1 (Cont'd)

Orientation		Subject Axes Motion Due To:			Subject	Threshold**	Illusion at Equivalent α with Increased Tilt Rate		
Tank	Couch	Cent.	Tank	α*		$\alpha = {}^{o}/sec^2$	$11.5^{o}/sec$	$17.2^{o}/sec$	$22.9^{o}/sec$
b	1	X	Z	Y	RB	4.8	-	-	neg.
					RW	7.2	-	-	neg.
					EC	1.2	-	-	-
					RS	5.7	-	-	neg.
					CM	7.2 ($\bar{\alpha} = 5.3$, N = 8)	-	-	neg.
					BN	4.8	-	-	neg.
					DK	-	-	-	-
					JS	5.7	-	-	neg.
					JB	5.7	-	-	neg.
b	2	Y	Z	X	RB	5.7	-	neg.	neg.
					RW	‡	-	-	-
					EC	1.2	-	-	-
					RS	7.2	-	-	neg.
					CM	‡ ($\bar{\alpha} = 5.3$, N = 6)	-	-	‡
					BN	4.8	-	-	neg.
					DK	-	-	-	-
					JS	5.7	-	-	neg.
					JB	7.2	-	-	neg.

- Not Run. ‡ No illusion at maximum rpm and tilt. * α is product of angular velocities.

** Tank tilt = 5.7^{o}/sec 0-12 rpm.

that the space operation should not impose more than $.03^{\circ}/sec^2$ extraneous acceleration by cross-coupling. The fact that in all planes the values are an order of magnitude higher for cross-coupling than they are for pure angular acceleration ensures minimal interference from passive vehicle rotation during SRC operation.

Another question answered concerned the possible difference in α threshold for a given vestibular axis when the same resultant force is created by different angular velocity combinations. An α_z stimulus was imposed first (Test 1a) by tilting the subject about his Y axis while spinning about an eccentric X axis. The average threshold was found to be $3.6^{\circ}/sec^2$. This is significantly lower than the $4.5^{\circ}/sec^2$ that was found when the reverse dynamics were used (Test 2a), i.e. tilt about the Z axis while spinning about the Y. Again, the difference is of physiological interest and warrants confirmation with additional experimentation, but it is doubtful if it is of practical significance operationally. All seven subjects were tested in the a tank orientation for both positions 1 and 2 and all but one were consistent in the higher threshold for the 2a orientation. The starting position, 1 or 2, was alternated between subjects to balance possible bias due to cumulative effects.

The literature cites the Z axis rotation as having a lower threshold and a longer time constant than X or Y for pure angular acceleration detection (Meiry 1966, Jones 1964). This appears to also be true for the cross-coupled acceleration sensitivity. One subject (E.C.), however, demonstrated a much lower threshold about the X axis. As the OGI response is a subjective test, this kind of variation and possible error could reasonably be anticipated.

The results of Experiment 1 again demonstrate the importance of the relative time (tilt angle/angular rate) it takes for the tilts producing equivalent α values. Clark found higher rpm thresholds when subjects were tilted 35° than when tilted 70° at the same rate. In that experiment both the amount of tilt (degrees arc) and time varied. The present experiment kept the arc constant but varied the time. Angular acceleration thresholds are known to be time dependent ("Mulder Product" Van Egmond et al, 1949) and, from the results obtained, the cross-coupling appears to be similarly sensitive as would be expected. Because of the varied vector dynamics during the tilt in cross-coupling it might be anticipated that the time constant dependent on the damping to cupula deflection ratio would have a greater effect than in pure angular acceleration. Equivalent α stimuli to those found to be threshold frequently evoked no response when the tilt rate was increased and the centrifuge rpm decreased. This is probably a function of cupular stimulation which in the case of gyroscopic stimuli would be of a continually varying direction and strength to each receptor throughout the motion and, as such, very complex to describe for all six receptors. Practically, it confirms the hypothesis that the two ω (angular velocities) involved do not produce an equivalent effect and that, therefore, a constant tilt rate should be used for positioning subjects on the SRC if any control over experimental design is to be achieved. The dynamics of the present experiment are developed in Appendix B.

Experiment 2

The initial concept for Experiment 2 was to describe a dynamic envelope for use in the T-010 experiments that would just exceed the nausea threshold. This was seen as a requirement to ensure that no experimental condition would approach that critical level. The nausea threshold, however, is highly variable and difficult to quantify because of its lability, the reticence of subjects to participate in such testing, and the attendent difficulties for the experimenter. A performance threshold can be used to assess the same problem, as the association of performance degradation with stomach awareness has been a consistent observation in previous experiments done on this centrifuge. The complexity of the performance task can be selected to show degradation at that level of vestibular stimulus that will elicit vegetative response. The RATER test used in these experiments had been previously found to show a degradation in performance following rapid active head turns that exceeded an α of approximately $70^{\circ}/sec^2$.

The objective of this testing was therefore altered to one of determining the threshold angular acceleration level produced by the cross-coupling of two angular velocities (those of the centrifuge and tank-restraint couch system) that would cause the test subject to experience a significant decrement in perceptual-motor performance.

Testing was restricted to orientation 1b only. Four of the subjects used in Experiment 1 made up the sample for Experiment 2, being selected essentially on the basis that they represented the full range of labyrinthine sensitivity observed in the previous experiment. Approaching this pilot study in a conservative manner, the decision was made to run the subjects in the dry state so as to reduce possible complications due to nausea and to eliminate the need for an intra-tank monitor. The final format consisted of each of the four subjects being placed in the simulator, being trained to an asymptotic level on the perceptual-motor testing device, and then being processed through the entire testing matrix. The matrix consisted of performing a five-trial testing sequence at 0, 10, 15 and 20 rpm at each of the tilt rates (6, 15, 30 and $45^{\circ}/sec$). As an additional safeguard in this initial test, all subjects were tested in the same order, from the lowest α of $6.3^\circ/\mathrm{sec}^2$ through the matrix to the highest α of $94.5^\circ/\mathrm{sec}^2$. The matrix exposed the subjects to ω(α x tilt duration) values of approximately 90, 140 and 190°/sec for the three ω_c at each ω_t. Each trial started with the tank in the cocked position, with the command of "start" over the intercom being the signal for the subject to start performing his RATER task of pressing the appropriate buttons in response to the displayed colors, and the signal for the engineer to tilt the tank. The subject would continue to perform for 30 seconds, irrespective of the duration of tilt, at which time the test conductor would command "stop", signaling the subject to quit responding and the engineer to return the tank to the cocked position at the rate of approximately 2°/sec. Five trials were completed in each sequence, at which point the tank would be centered and the dynamics transferred to the next position in the testing matrix.

The most significant point established by Experiment 2 was the very benign nature of the exposure. Even the most severe dynamics did not cause any appreciable degradation in overall test performance, and absolutely no nausea or stomach awareness was detected even by the one subject who had a history of susceptibility to motion sickness. The passive tilting, with the RATER task display being fixed relative to the subject, appeared to give adequate visual stabilization to discourage spatial disorientation. The 20 rpm, 45°/sec tilt exceeds any motion contemplated for the SRC couch and, under the conditions tested, there was no indication that the α of $94.5^\circ/\mathrm{sec}^2$ was any problem.

It was observed, on a pilot basis, that active head motions roughly equivalent to the 45°/sec tilt rate caused more pronounced disorientation at 20 rpm. The subject making the observation had difficulty fixating on the target, a problem that was not noticeable when passively tilted.

It should be emphasized at this point that the small sample size and the decision not to use balanced orders of testing must necessarily reduce the pertinence of the results. However, the recorded data and their initial evaluation have demonstrated points of interest that are of inherent value in addition to providing a useful basis for the performance of a similar test in a wet environment.

Observation of the raw trial data suggests that in the majority of the matrix test points the initial trials showed some decrement in performance with quick recovery preventing an overall significant sequence decrement. This again demonstrates the rapid adjustment of task performance to force field changes that has been demonstrated in previous, but similar, tests run in this laboratory's rotating simulator.

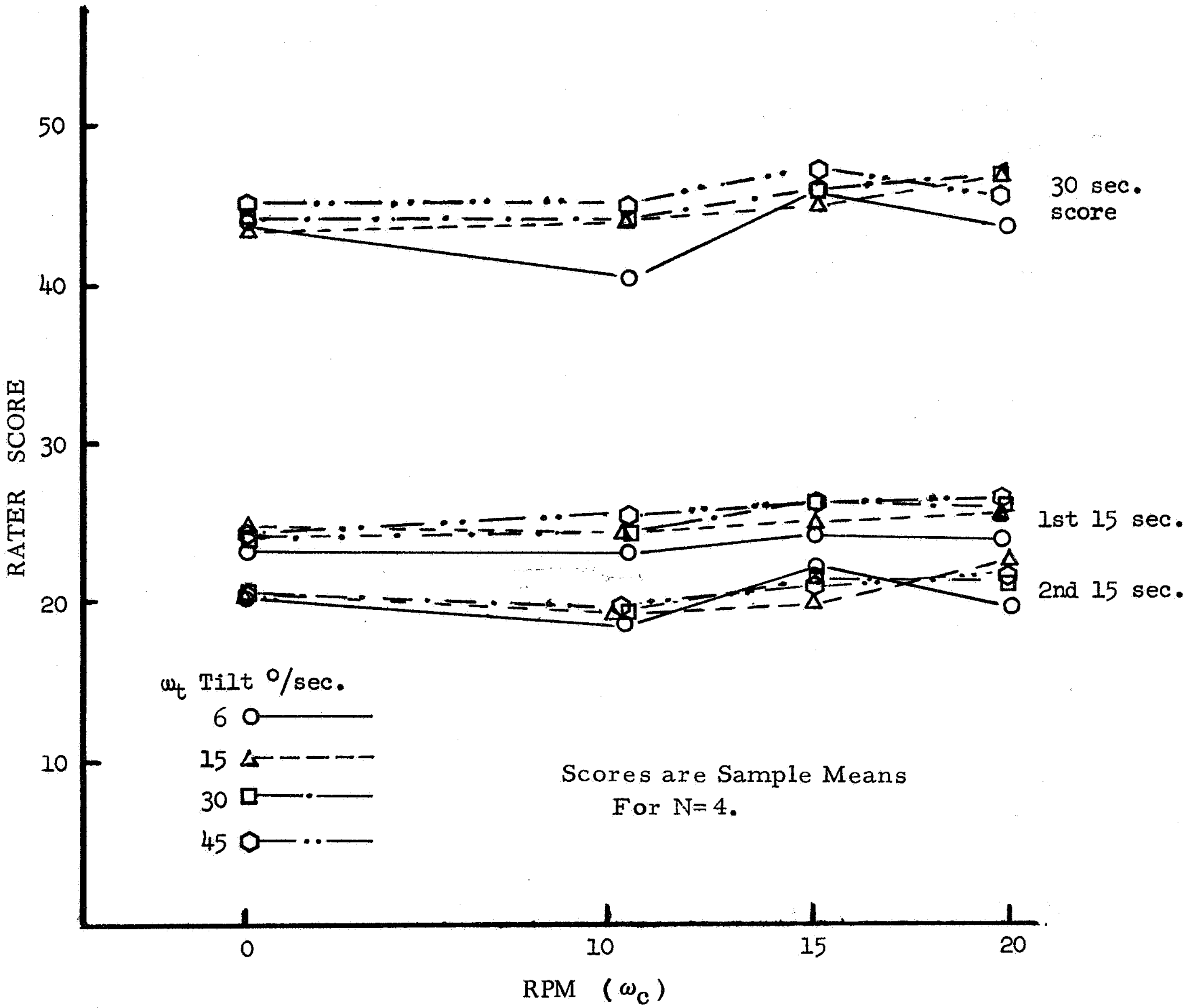


Figure 10. Performance During Cross-Coupled Acceleration Exposure (all tilts completed within first 15 seconds of trial).

In considering the sample means for scoring versus the parameters of cross-coupling, as in Experiment 1, the parameter that most pertinently relates to the apparent stress of the testing points is ω (α integrated over the tilt duration). Evaluating the score as a function of ω throughout the 30 sec. trial and during its first and second halves (Figure 10), there is no demonstration of significant performance decrement. However, the period during tilt of the tank does demonstrate some significant effect. Figure 11 illustrates the mean performance rate for the test sample during each tilt. For tilts of 6^{o}/sec and 15^{o}/sec there is no significant decrement, while the 30^{o}/sec tilt shows significant decrement at 10 rpm with subsequent recovery, and the 45^{o}/sec tilt shows significant decrement at 10 and 15 rpm with some recovery at 20 rpm. Although the lack of balanced testing orders reduces the freedom with which the above data may be interpreted, it appears that there is evidence of marginal performance decrement followed by rapid recovery. This is evident on a trial-to-trial basis as well as on a sequence-to-sequence basis. For performance during tilts of 30^{o}/sec and 45^{o}/sec respectively, initial decrements occur at $\alpha = 32^{o}/sec$ and $\alpha = 45^{o}/sec^2$.

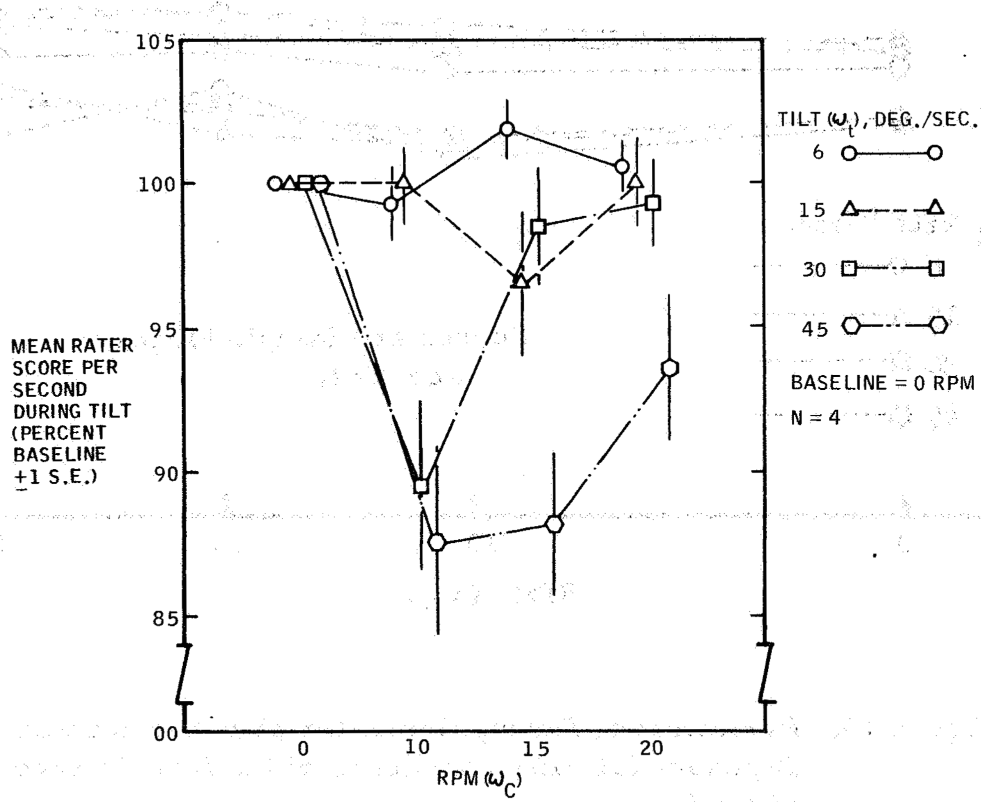


Figure 11. RATER Performance During Tilt

PHYSIOLOGICAL IMPLICATIONS

During the early stages of OGI testing it was observed that the duration of tank tilt (the time during which the cross-coupled α was being produced) was more critically important in effecting an adequate vestibular stimulus than had been anticipated during experimental design. In a majority of the subjects it was necessary to progress through a changing ω_t to a maximum tilt rate of $22.9^{\circ}/sec$ and then increase the ω_c to reach a threshold α level. This procedural modification bore the advantage of maximizing the numerical differences of the ω_t and ω_c values making up the two threshold α values, thereby amplifying any inherent differences in the weighting of their velocity contributions to a given cross-coupled α. The data are listed in Table 8.

Although the results tend to be higher than had been expected, they are consistent with the range of values that have appeared in the literature, all of which have been determined in the dry state.

The $T(\Delta\omega_c)$ values defined in Table 8 are well within the range of $0.035^{\circ}/sec^2$ to $8.2^{\circ}/sec^2$ published in a recent survey paper on angular acceleration perception by man (Clark, 1967,). Though the survey's median value is somewhat lower than this study's, the latter's figures do not exceed the values determined in several individual studies surveyed.

The similarity of the pitch and roll thresholds and their significant elevation above the yaw thresholds are consistent with the findings of other workers and have been logically attributed by them to the differences in the time constants for stimulus decay in the involved semicircular canals (Benson and Bodin, 1966; Guedry, 1965). Some studies which have used vertical subject orientations have demonstrated an even greater disparity between the yaw and the pitch and roll thresholds (Clark, 1967). The horizontal orientations of the subject for this study reverses the coplanarity of the involved canals to the linear force field, which is a relationship recently demonstrated to be effective in elevating the coplanar canal's threshold (Benson and Bodin, 1966).

The significantly higher yaw threshold that was determined when the subject was oriented on his side rather than on his back may be due in part to the similarity in direction of the OGI resulting from the angular acceleration inherent in the tilting of the tank to the direction of the OGI resulting from the cross-coupled angular acceleration. In testing position 1a any illusion of target movement due to the tilting alone was in the pitch plane, 90° to the plane of the illusion produced by cross-coupling. In the 2a testing position, any illusion due to tilt alone was in the roll plane and may have

Table 8. OGI Threshold Versus Subject Orientation and Cross-Coupling

SD						$T(\Delta\omega_t)$		$T(\Delta\omega_c)$	
						ω, Deg/Sec	α, Deg/Sec^2	ω, Deg/Sec	α, Deg/Sec^2
TO	CO	N	ω_c	ω_t	α	$\bar{x} \pm 1$ S.E.	$\bar{x} \pm 1$ S.E.	$\bar{x} \pm 1$ S.E.	$\bar{x} \pm 1$ S.E.
a	1	7	X	Y	Z	33.6 ± 5.8	6.5 ± 1.6	52.7 ± 7.8	3.6 ± 0.3
	2	7	Y	X	Z	51.2 ± 9.8	11.2 ± 2.8	65.6 ± 7.9	4.5 ± 0.4
b	1	8	X	Z	Y	56.1 ± 9.1	14.0 ± 2.8	79.6 ± 10.2	5.3 ± 0.6
	2	6	Y	Z	X	70.4 ± 10.8	18.6 ± 3.2	80.1 ± 12.4	5.3 ± 0.8

Note:
TO = tank orientation (a = tank tilt axis tangential, b = tank tilt axis radial).
CO = couch orientation (1 = subject supine, 2 = subject on left side).
N = sample size.
SD = subject dynamics due to ω_t, ω_c and α (X = roll, Y = pitch and Z = yaw). In the case of the α the dynamics are illusory.
$T(\Delta\omega_t)$ = OGI threshold determined using an ω_t other than 5.7°/sec.
$T(\Delta\omega_c)$ = OGI threshold determined using 5.7°/sec ω_t and varying the ω_c.
α = threshold angular acceleration resulting from cross-coupling the two angular velocities, ω_c and ω_t.
ω = impulsive angular velocity thought to be the output of the cupulo-endolymph system in its normal operating range. It represents the integration of α over the time period of the cross-coupling.

Table 8. OGI Threshold Versus Subject Orientation and Cross-Coupling(Cont'd)

$\pm$ 1 S.E. = means plus and minus one standard error of the mean for the entire sample. It should be emphasized that in the interest of simplifying the above table, some liberty was taken in listing the threshold values, In all cases the mean threshold value is equal to or slightly less than the figure shown, depending upon the range separating the lowest positive α and the highest neg. α at each $\Delta\omega_c$ and $\Delta\omega_t$ determination. Those ranges varied from approximately $1.2^\circ/sec^2$ for the $T(\Delta\omega_c)$ to 3 deg/sec^2 for the $T(\Delta\omega_t)$. The values for ω are subject to the same qualification.

caused some confusion in the perceiving of the illusion due to cross-coupling which appears in the yaw plane as they share some commonality of direction. All subjects were tested with zero ω_c at each change in ω_t to prevent this sort of confusion, but it remains as a possible explanation for the higher threshold in the 2a orientation. This explanation is given support by the even greater disparity in the $T(\Delta\omega_t)$ determinations, where the higher ω_t created a higher incidence of baseline OGI.

In considering the values for the various thresholds expressed as both ω and α, results are consistent with present hydrodynamic theory and empirical evidence concerning the vestibule as a dynamic sensor. All ω values lie within the range of stimuli in which the cupula-endolymph system is thought to transduce imposed angular velocities in a linear fashion (Jones, 1965). The threshold values, ranging from 33^o/sec to 84^o/sec, are on the high side but within the range of values in the literature. The higher ω values for $T(\Delta\omega_c)$ are in line with current thought and evidence that as the duration required to produce the impulsive angular velocity is prolonged beyond five or six seconds, the ratio of increase in velocity sensed to increase in imposed velocity decreases (Bornschein, 1962; Guedry, 1959). Therefore, with the $\Delta\omega_c$ tilt cutoff point at 15 seconds, the decreased cross-coupled α input is not completely compensated for by the increased tilt duration relative to the 3.8 seconds duration, and a higher ω is required to surpass the threshold. Though this reduced effect for the longer period may be due partly to an increase in cupular tension, a neural adaptive response is thought to be the primary cause (Guedry, 1959).

In conclusion, it is seen that the observed thresholds are higher than had been anticipated, but not unreasonably so. However, by using the OGI as the index of perception one should tend to demonstrate thresholds somewhat lower than those determined by relying on the subjective perception of body rotation as used in many of the surveyed studies (Clark, 1967). In addition, the immersion technique and the use of padded restraints did an excellent job of reducing exteroceptive cues, a factor that should also cause a relative reduction in the vestibulo-ocular threshold by reducing the level of extraneous signals from the lower neural pathways. In opposition, however, any passive rotation would tend to initiate just such extraneous signals through inertial impulses that would be appreciated independent of gravity.

Another possible explanation for higher cross-coupled α thresholds may be inferred from information in an unpublished paper by Jones, Guedry and Benson (1968) describing a waxing and waning of impulses recorded from bilateral vestibular nuclii that are antagonistic during sinusoidal oscillation. The field dynamics of cupular stimulation during cross-coupling are similar to the intensity pattern of a sinusoidal motion, growing from zero in the plane of spin to maximum when normal to it. Central interpretation of such a signal could account for the higher α threshold.

VECTOROCULOGRAPH AND ELECTRO-OCULOGRAPH RECORDINGS

In Experiment 1 it was found that the EOG leads caused a constant leak of the face mask. This was particularly bothersome to the subjects when on their sides or when on their backs in the cocked position (head down 45°). Those recordings were, therefore, omitted from the procedure. In Experiment 2 these complications were absent, as the tank was dry. Figure 12 is the trace of a representative X-Y plot of the vectoroculogram. As in all the X-Y plots recorded, this example shows no evidence of significant oculomotor disturbance. With the initiation of tilt there is a pitch deviation that may be the effect of labyrinthine Coriolis impulse, but the recovery is rapid, with subsequent eye excursions concentrated within a visual cone whose base is 1° of visual angle.

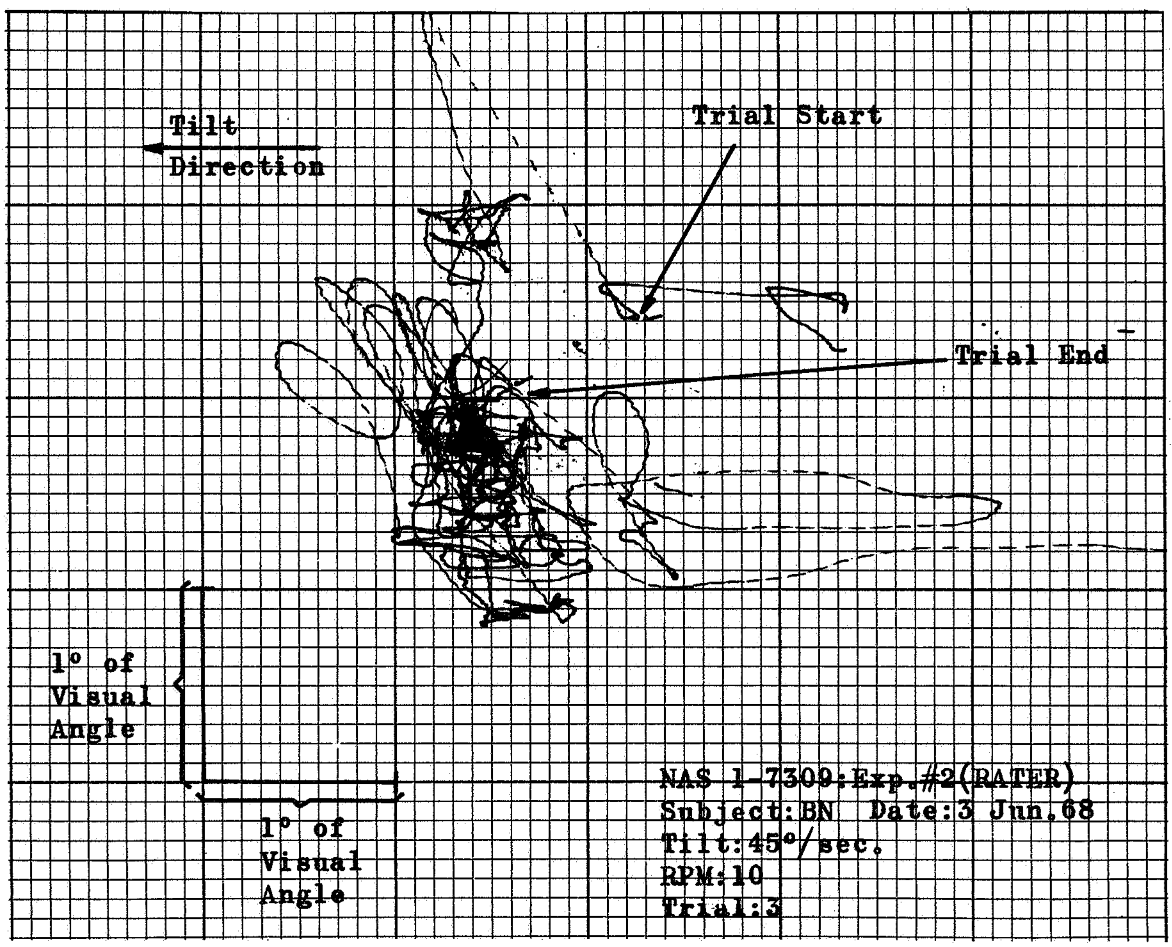


Figure 12. Representative X-Y Plot of Vectoroculogram

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APPENDIX A

TEST EQUIPMENT DESIGN AND OPERATION

In its original concept, the objective of the manned centrifuge test series was to observe the reaction of test subjects to the spacecraft/centrifuge dynamic environment predicted from computer studies. It soon became evident that the wide range of possible dynamic conditions prevented the selection of representative combined motions for the test and that a better approach was to generate stability requirements for the spacecraft/centrifuge by establishing sensitivity and performance degradation thresholds for such motions. From preliminary experiment design it was specified that the facility required to study these thresholds should provide:

a. Full immersion of the test subject in water.

b. The capability of 90° tilt travel orthogonal to a basic rotation.

c. Smooth acceleration and deceleration of the tilting motion.

d. Tilt velocities within the range of a fraction of a degree per second up to a maximum of 120 degrees per second average.

Development of the test facility was then directed toward satisfying these requirements. This appendix deals specifically with defining the CEVAT modifications and the development and operation of the tank tilt actuation system.

Test Equipment Design

The test facility was designed around two major elements. These were the large Air Force centrifuge (CEVAT) located at Convair and a 10' by 5.5' diameter, trunnion mounted, immersion tank which had been designed and fabricated by Langley Research Center in support of a previous program. These basic pieces of equipment are shown in figure A-1. Major tasks consisted in modifying the CEVAT to allow mounting of the Langley tank; providing the tank with an appropriate tilt actuation system; and modifying and instrumenting the tank interior.

CEVAT Modifications - The position of the tank on the centrifuge arm was selected so that a 4.0 foot off-set would exist between the centrifuge spin axis and the center of rotation of the tank. Two positions were required, one position with the trunnion axis normal to the centrifuge radius and a second position with the trunnion axis parallel to the centrifuge radius. These locations are illustrated by figures A-2 and A-3.

The centrifuge arm was first cleared by removing the slip-ring assembly and tubular boom which normally spans the entire machine and carries information

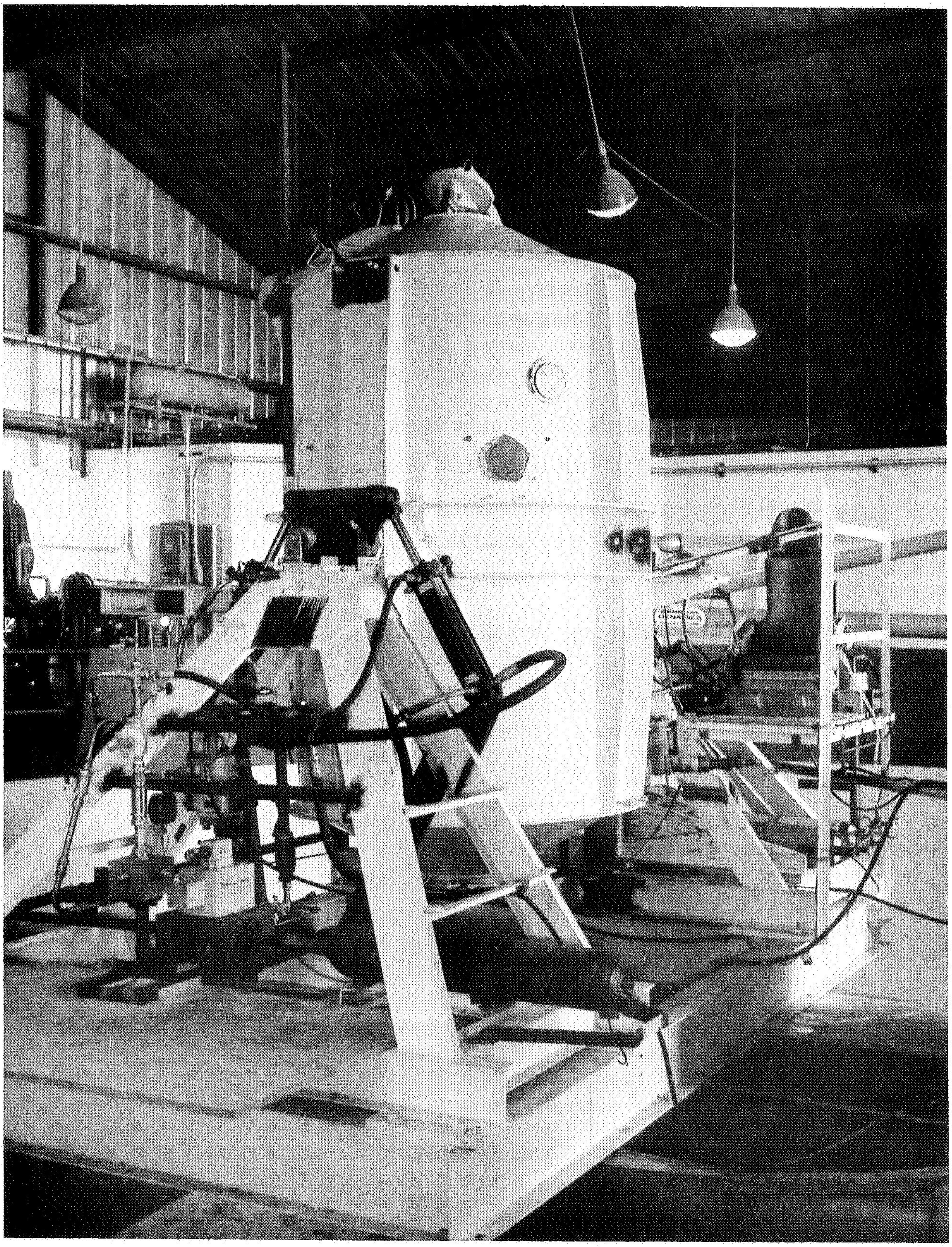


Figure A-1. Immersion Tank and Actuation System
Mounted on Centrifuge

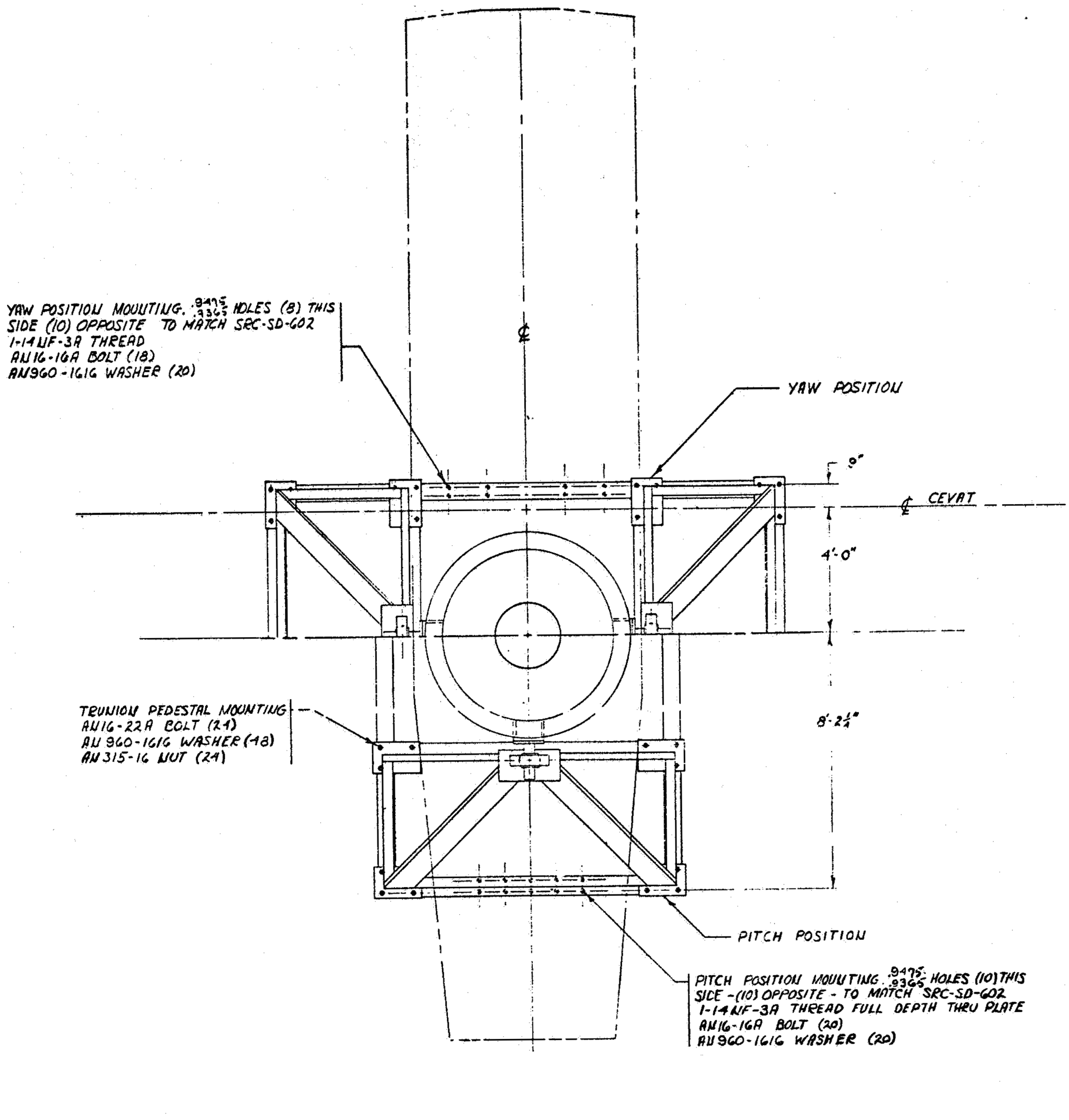


Figure A-2. Plan View of Tank Installation Locations

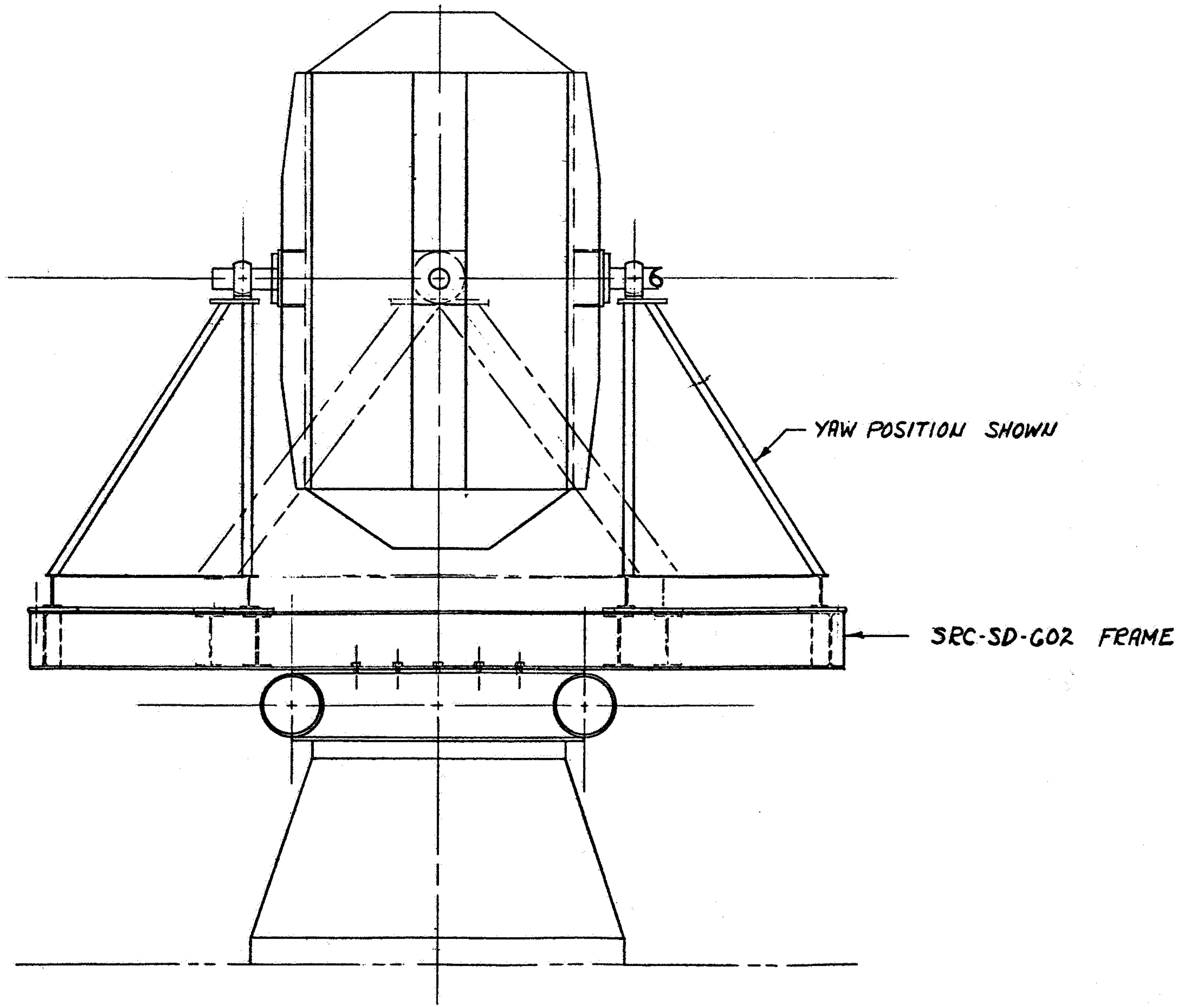


Figure A-3. Tank/CEVAT Installation, Side Elevation channels and systems onto the arm. Alternate slip rings were installed in the base of the unit. The centrifuge arm was then match-drilled to receive the tank mounting frame illustrated by figure A-4. This frame was used to tie the trunnion mounting pedestals and tank into a single assembly.

Tilt Actuation System Design - The tilt actuation system selected to handle the large mass load of the immersion tank is a simple hydraulic blowdown and snubbing system. The system is shown schematically by figure A-5. It was designed for 3000 psi maximum operating pressure using commercial quality hydraulic components. Peak flow requirements are 260 gpm, calling for an instantaneous peak power delivery of 450 horsepower. Major functional areas of the system are the power supply, the valve/actuator network and the snubbing system.

Power Supply - To satisfy the short duration, high flow requirements of maximum tilt-rate operation, an accumulator (Figure A-5, item 3) was selected as the main source of hydraulic power. The accumulator was recharged between tilt actuations by a small hydraulic pumping unit (Figure A-5, item 11) which was adjusted to an output of approximately 1.5 gpm maximum. In order to keep line losses at a minimum, the accumulator was mounted close to the solenoid control valve and discharged into the valve through a short run of 1-1/2 inch, schedule 80, pipe. The accumulator and hydraulic power unit installation locations are illustrated in figure A-6.

Valve/Actuator Network - Flow from the accumulator was directed to the actuators by a large, 3 position , 4-way spool valve (Figure A-5, item 2). The valve has a neutral spool position characteristic which blocks flow from one side of the actuators and opens the alternate side to the return line. This characteristic was utilized to provide additional snubbing for tank deceleration following high rate actuation. In this mode of operation, the spool valve was returned to neutral before full actuator travel occurred, locking fluid in the actuator and causing the fluid to be vented through a load relief valve (Figure A-5, item 4) to the opposite side of the cylinder.

Tank actuation rate was controlled by matched needle valves (Figure A-5, item 6) and restrictor check valves (Figure A-5, items 7 and 8). In the maximum rate direction of tilt, flow is regulated almost exclusively by the needle valve settings. In the tank return or cocking direction, rate is controlled to about 2.0 degrees per second by the orifices in the restrictor check valves.

The actuators (Figure A-5, item 1) were mounted in "push-pull" fashion across a common lever arm. The lever arm, shown by figure A-7, was bolted to the existing trunnion shaft mounting flange on the tank. Operating loads from the actuator were reacted through the trunnion bearing and two support bracket assemblies (figure A-8) which were welded to the legs of the trunnion bearing support pedestal.

The original bearing assemblies supplied with the tank were too light to carry the high static loads generated by the actuators and were replaced with heavy duty spherical roller bearings. Special housings shown by figure A-9 were fabricated to install these bearings.

Snubbing System - Stopping the tank after tilting was accomplished by allowing a lever attached to the tank to engage and drive an actuator piston. Oil forced out of the actuator was passed through a relief valve which absorbed the kinetic energy of the tank. The snubber lever arm, shown by figure A-10, was bolted to the trunnion shaft flange on the side opposite from that used to attach the actuators. The snubbing actuator was mounted at the end of a pipe column (figure A-11) which carried the snubbing loads into the tank mounting frame.

After each snubbing stroke, the snubbing actuator was recharged with oil from the actuation system. This was done by opening a manually operated needle valve until the snubber cylinder piston rod extended to a predetermined height. The snubber cylinder stroke was adjusted to match the energy absorption of the particular tilt rate used.

Connections - All interconnecting pressure lines were designed for 3000 psi operating pressure using 1-1/2 inch, schedule 80 steel pipe. Bolted flanges,(figures A-12, 13 and 14) were employed at all separation points and special manifolds fabricated wherever necessary. Heliarc welding was used exclusively for pressure line fabrication and all lines were proof tested to 4500 psi before installation. For the return lines, 2 inch pipe and conventional pipe threaded fittings were used.

Tank Actuation System Operation

The tank tilt sequence was controlled from an operating position on the centrifuge arm. The position selected was on the opposite side of the tank from the actuators so that snubber action could be observed and snubber height reset during rotation. The control position is illustrated by figure A-16. The tilt control panel consisted of a power switch and a pair of two-position, spring-centering, switches which individually controlled the tilt and return motions. Spring centering switches were necessary so that the motion of the tank would be interrupted if the operator removed his hand from the console. For experiment No. 1, powered actuation was used over the full travel of the tank so that a constant tilt velocity would result until the primary snubber was engaged. The primary snubber alone was used to decelerate the tank. For experiment No. 2, deceleration of the tank was accomplished by de-energizing the control valve before full travel, utilizing actuator lock-up plus primary snubber action. This procedure was adopted because of the higher tilt rates involved and to effect a smoother deceleration in compensation for the lack of test subject immersion.

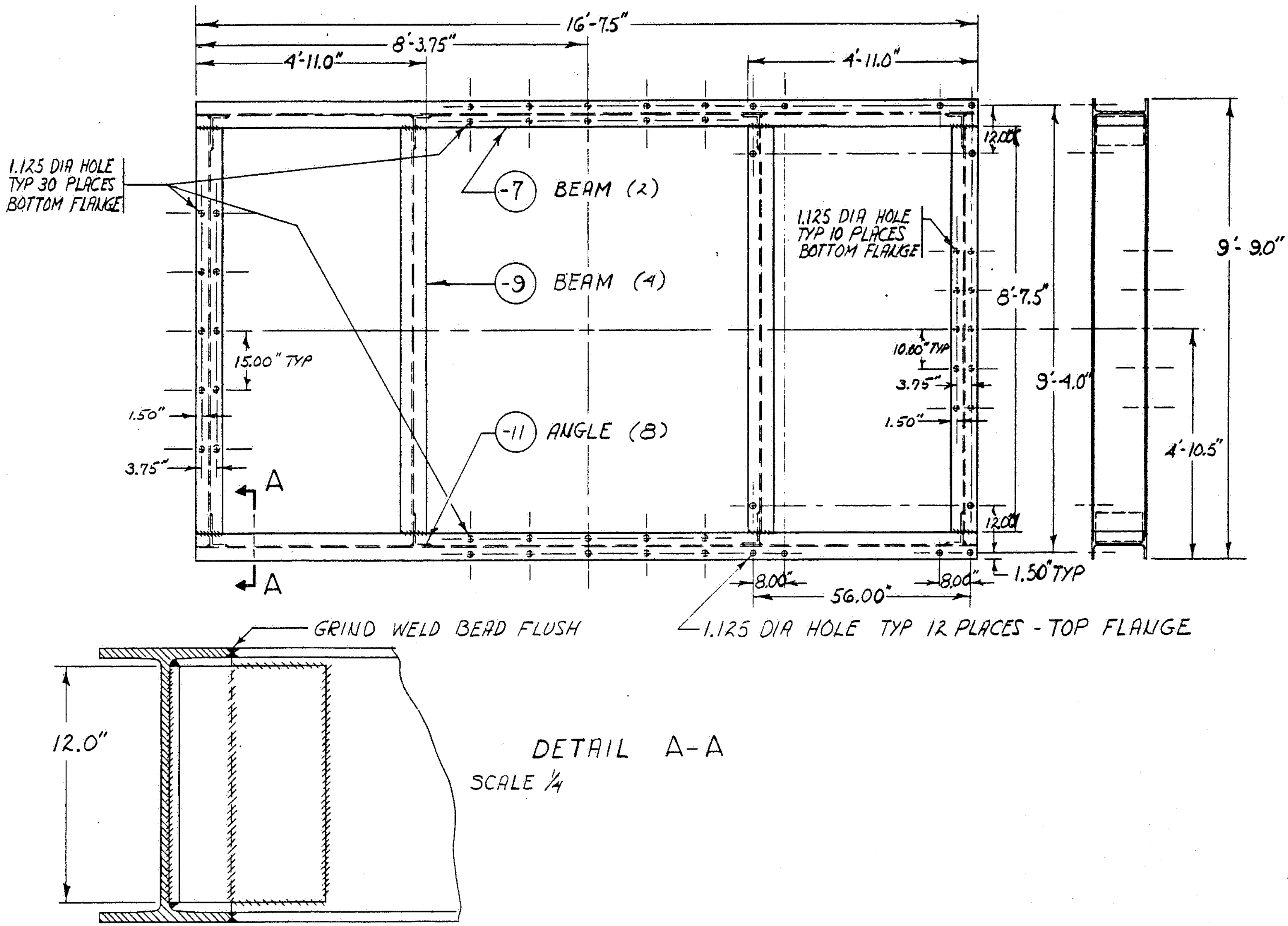
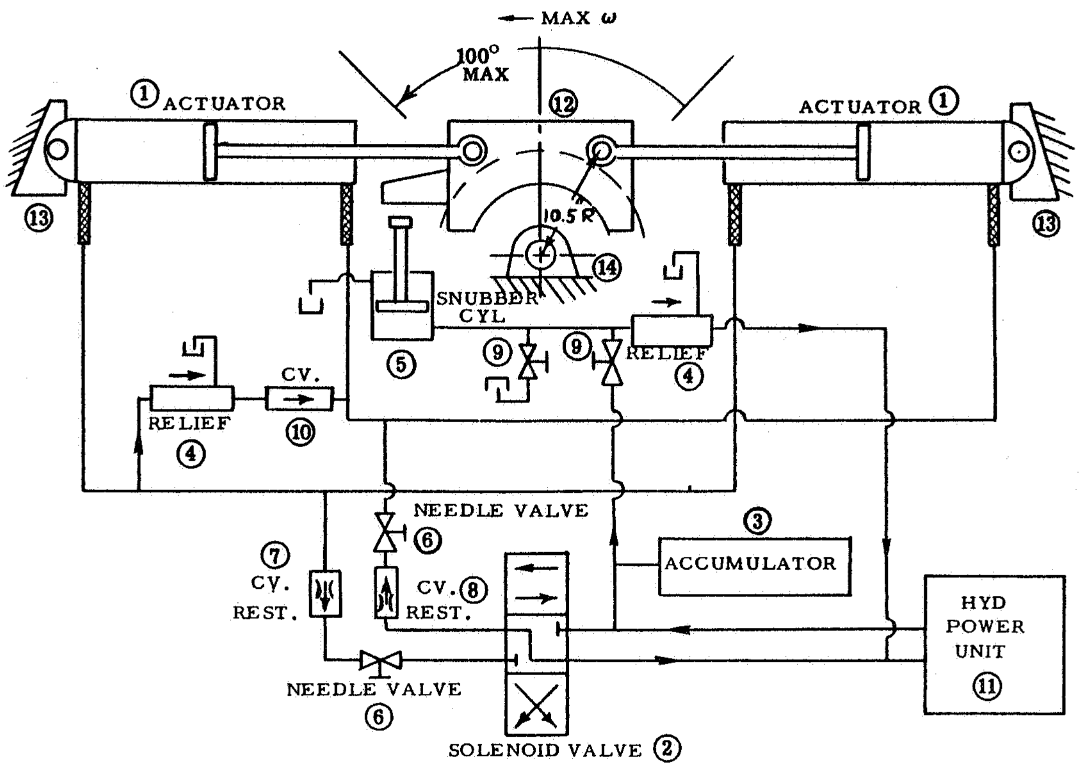


Figure A-4. Tank Mounting Frame (SRC-SD-602)



COMPONENT IDENTIFICATION

1. Linear Hydraulic Actuator Assembly - 3000 psi operating pressure, MIL-H-5606 Fluid, 18" Stroke, Rod 1.75", Bore 4.0", Clevis mounted. (Atlas Cylinder Co. HPB-2)
Rod End: 1 3/8" Eye hole, 2" Width for 1 1/4-12 Thread. (REE-96)
2. Solenoid Valve Assy. - Three position 4-way valve, spring centering, pilot operated (24 Volt D.C.). 3000 psi operating pressure. Looped port pressure drop 145 psi at 227 gpm. (Double-A Products Co. P/N AC-757-2)
3. Accumulator - Bladder Type, 3000 psi operating pressure, 750 psi precharge, 10 gpm capacity. (Greer, Hydraulics, Inc. P/N A106-200)
4. Relief Valve Assembly - Pilot operated, adjustable range 3000-4000 psi, 1.5" flanged ports. (Vickers, Inc. P/N CR-24-F-10 Modified with new spring and seals for 5606 fluid). For cover plates, see Figures A-12, 13.
5. Snubber Cylinder Assembly - Linear actuator, 3000 psi operating pressure, 5.0" Bore, 2.0" Rod idameter, 12.0" Stroke. For pedestal, See Figure A-11.
6. Needle Valve - 1.0" line size.
7. Restrictor Check Valve - 3000 psi operating pressure, 2.0" NPT connections, Reverse flow 4.5 gpm at 3000 psi (.0625" dia. orifice). (Circle Seal Co. P/N 259S-16 PP, Modified)
8. Restrictor Check Valve - 3000 psi operating pressure, 1 1/2" line size, 4.5 gpm reverse flow at 3000 psi (.0625" dia. orifice). (Southwestern Valve Corp. P/N 204053, Modified)
9. Bleed Valve - 3000 psi, 1/2" line size. (Grove 310S)
10. Check Valve - 3000 psi, 1" line size. (Republic P/N 483-1D-1)
11. Hydraulic Power Unit - Variable displacement, 0-10 gpm, adjustable pressure range 0-5000 psig. (Rucker Co. Model A-153)
12. Actuator and Snubber Lever Arm Assembly - See Figure A-7 and A-10.
13. Cylinder Support Bracket Assembly - See Figure A-8 for detail.
14. Bearing Assembly - Spherical Roller Bearing, I.D. 3.937/3.9362", O.D. 7.0856", (SKF P/N 22220C.) For housing detail see Figure A-9.

Figure A-5. Tilt Actuation Hydraulic System

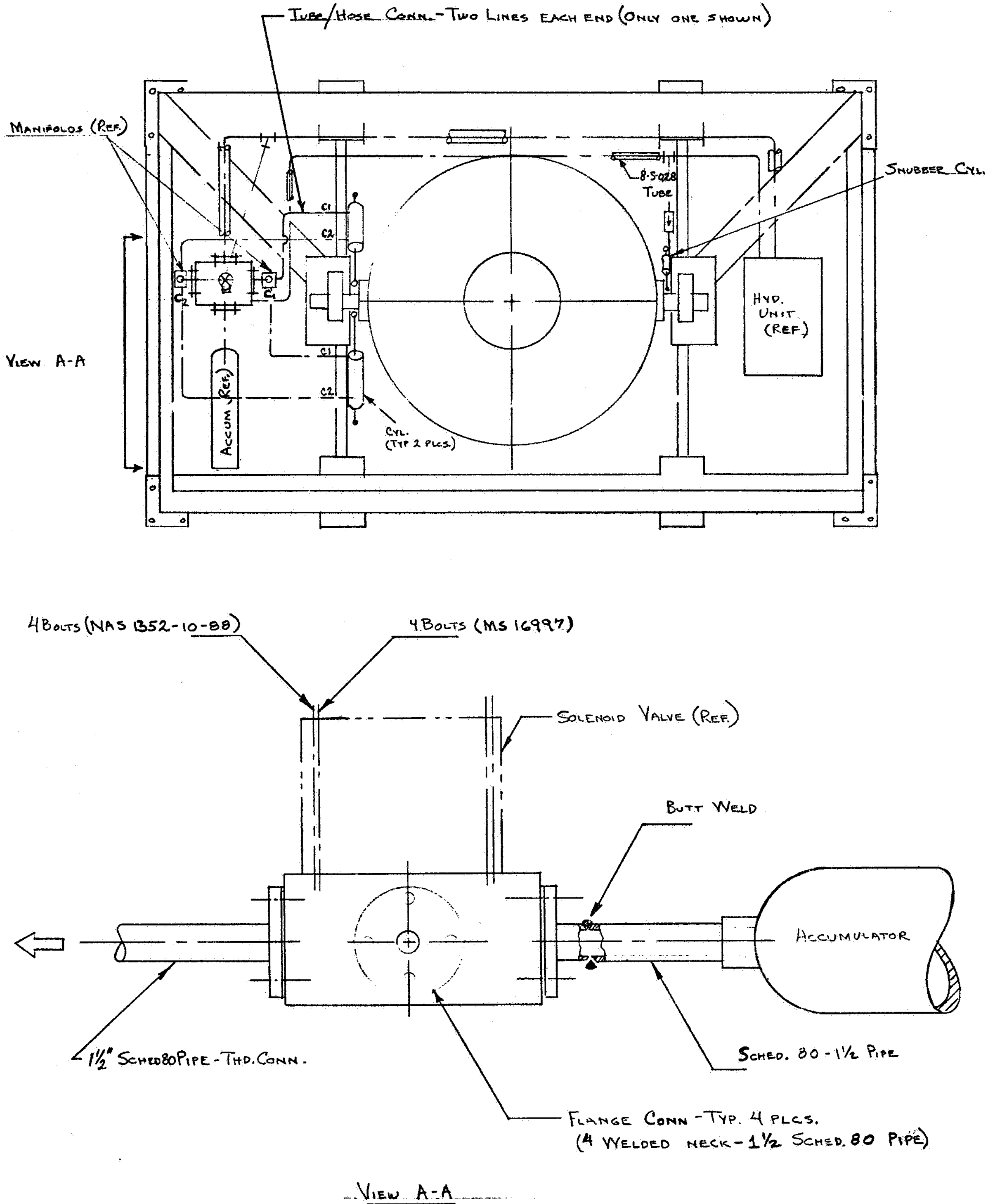


Figure A-6. Hydraulic System, General Piping Layout

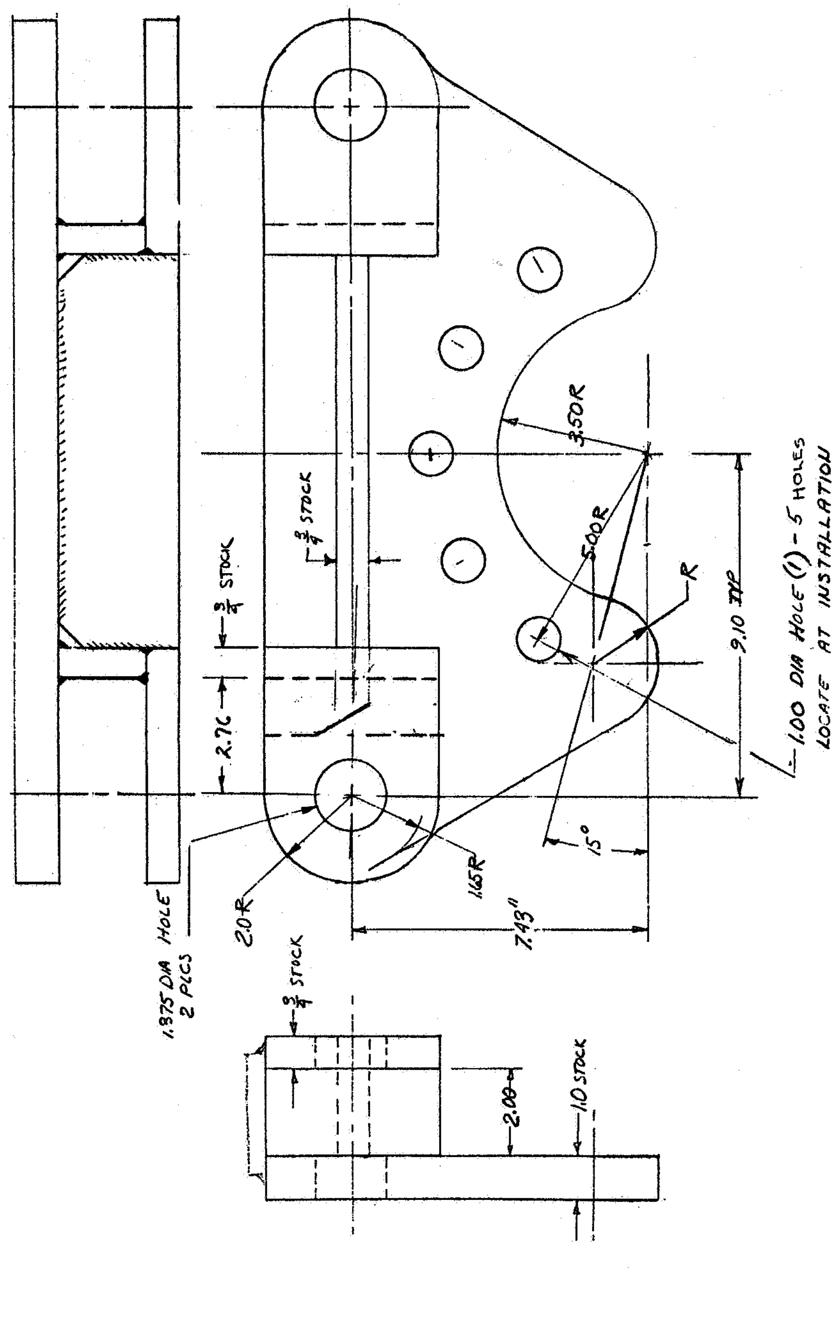


Figure A-7. Lever Arm Welded Assembly

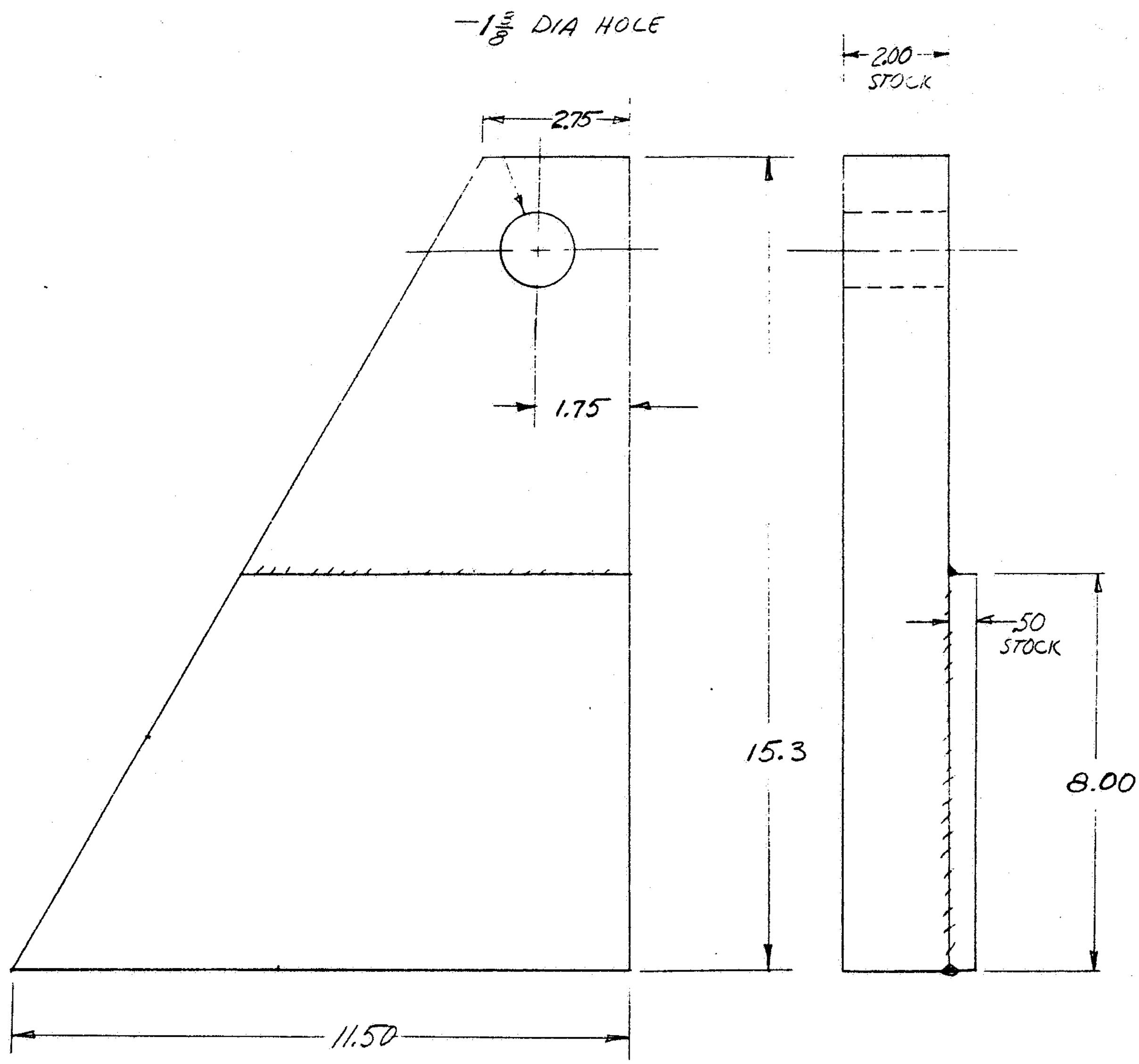


Figure A-8. Cylinder Support Bracket Assembly

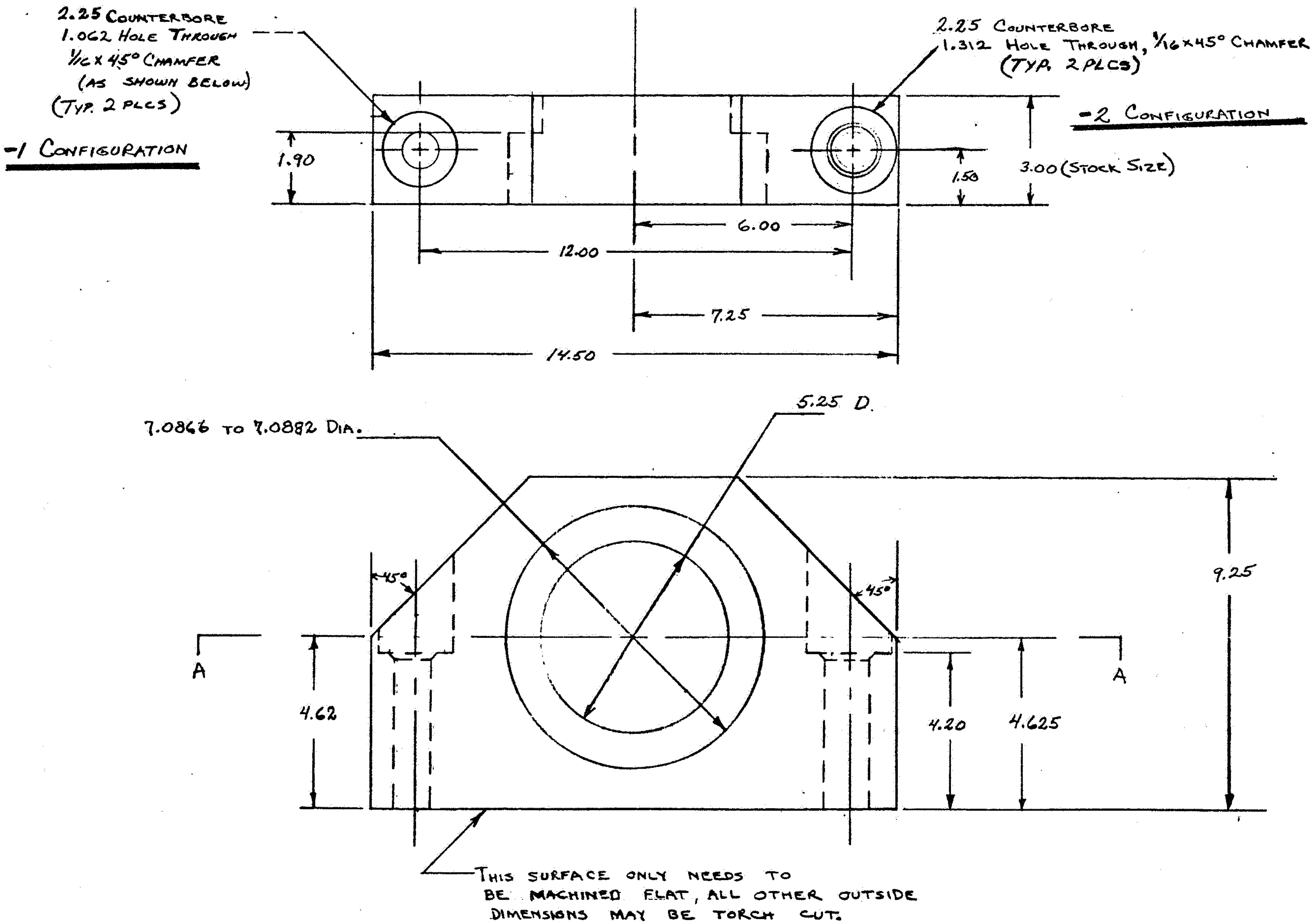


Figure A-9. Bearing Housing

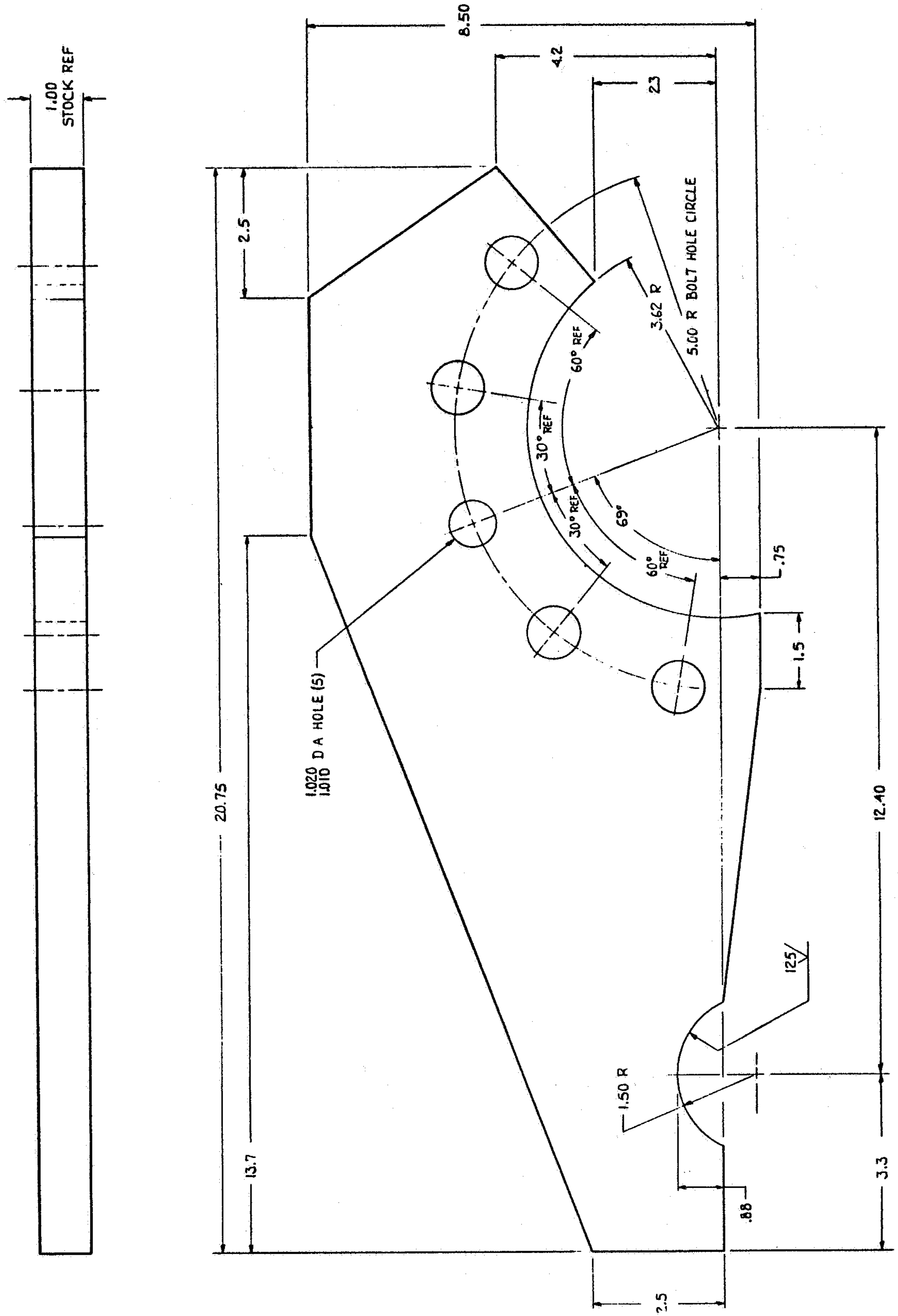


Figure A-10. Snubber Cylinder Lever

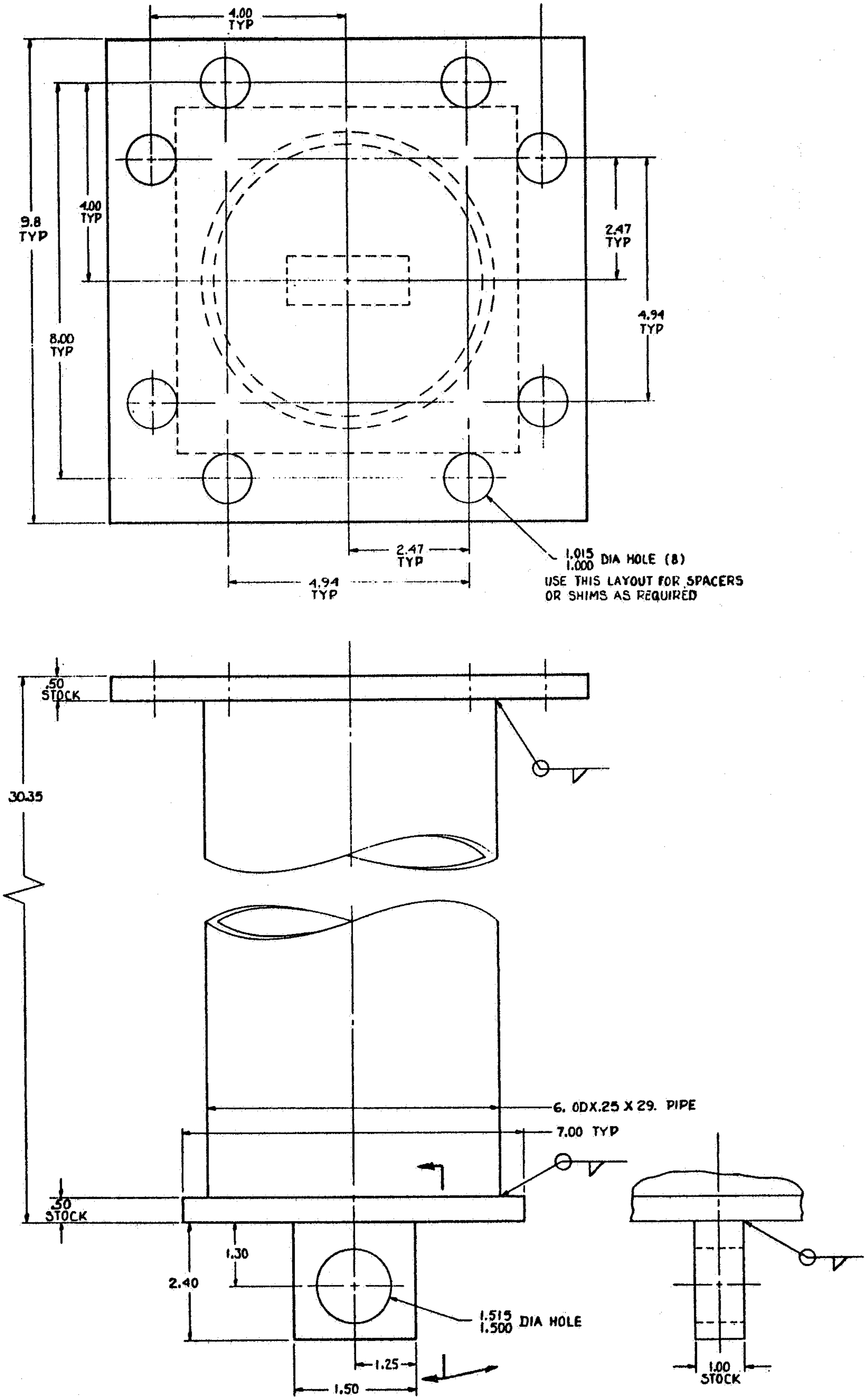


Figure A-11. Snubber Cylinder Extension Fitting

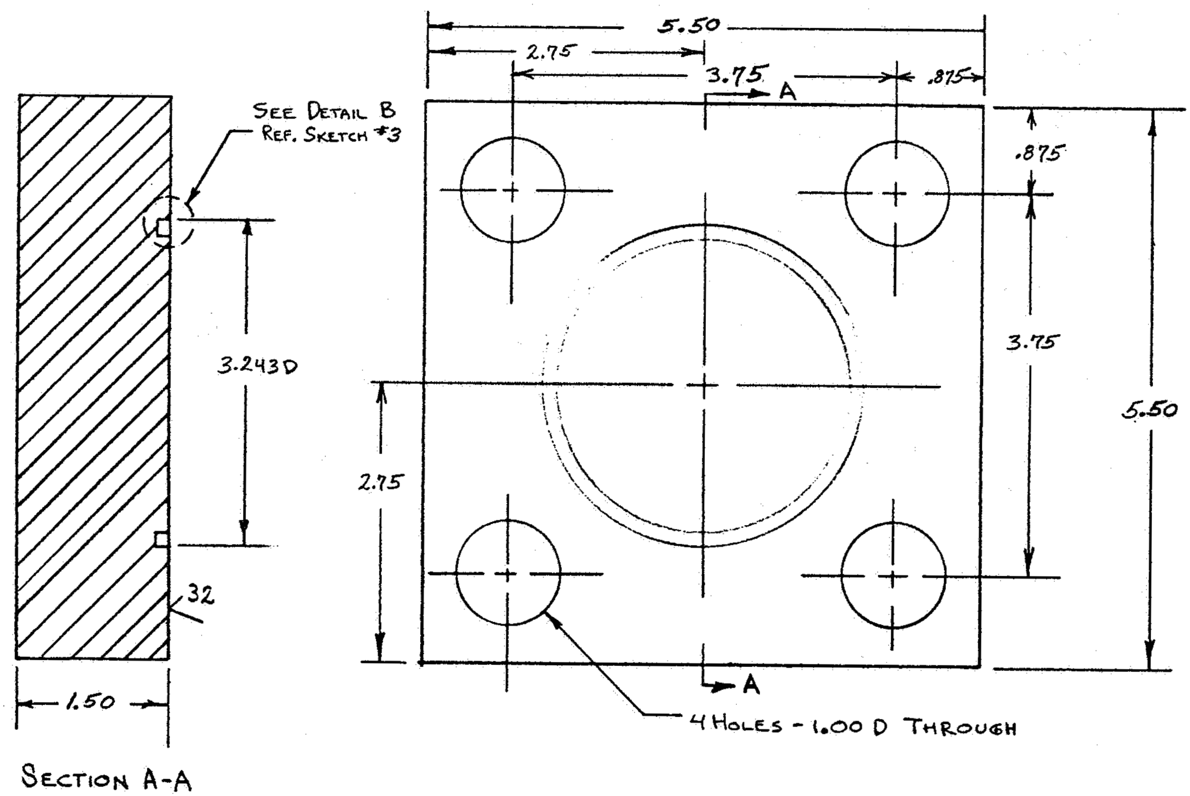


Figure A-12. Blind Flange for Vickers Relief Valve

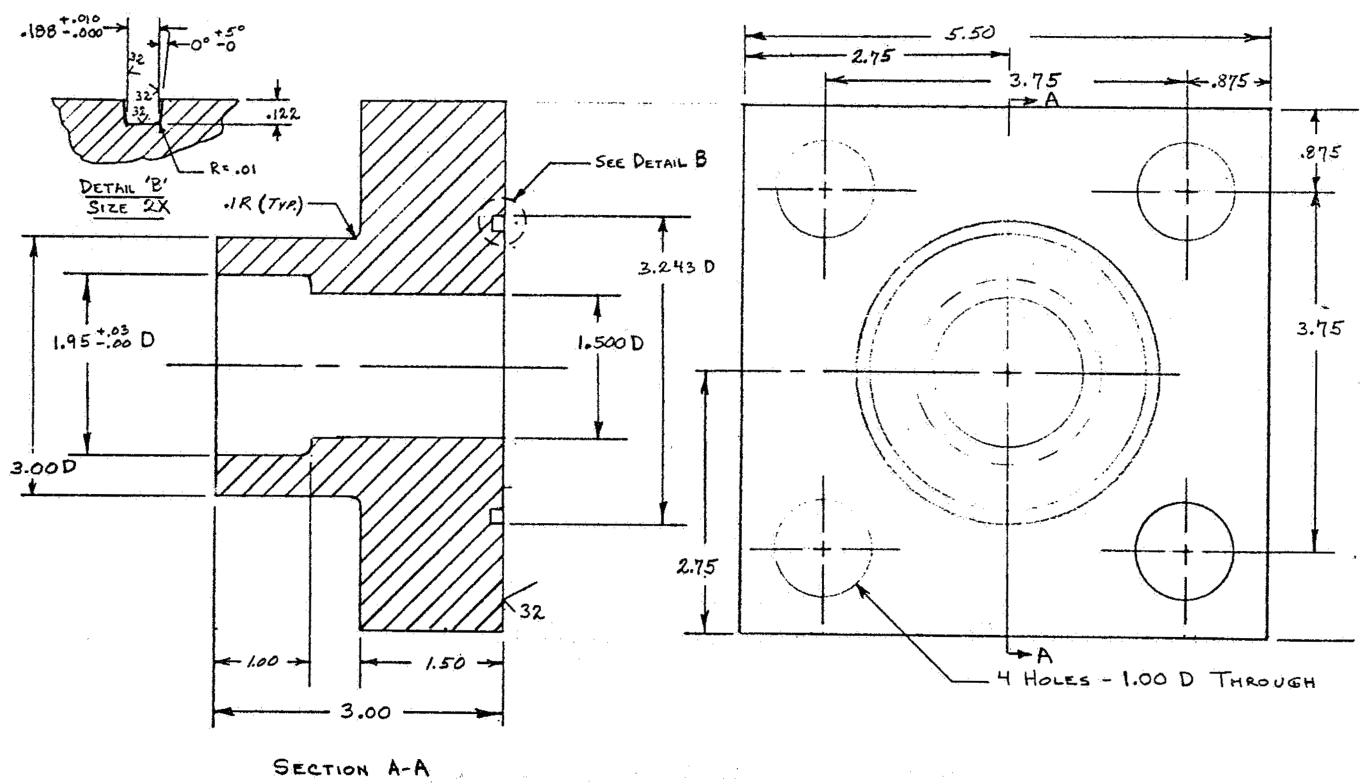
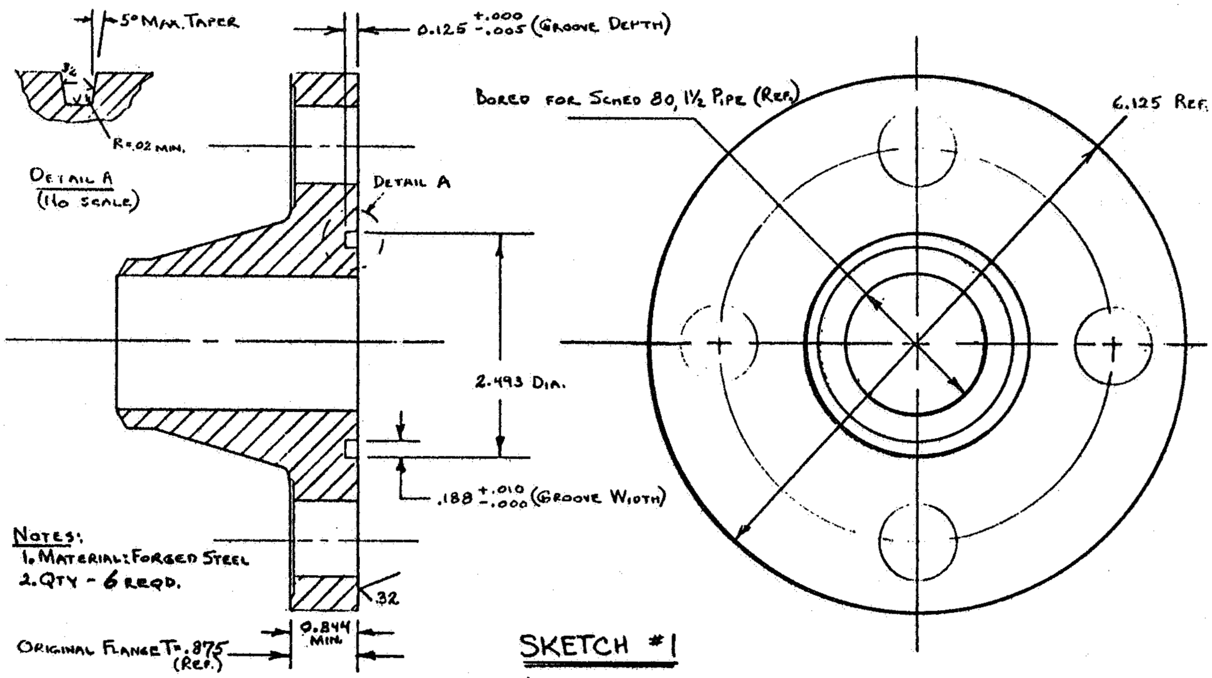
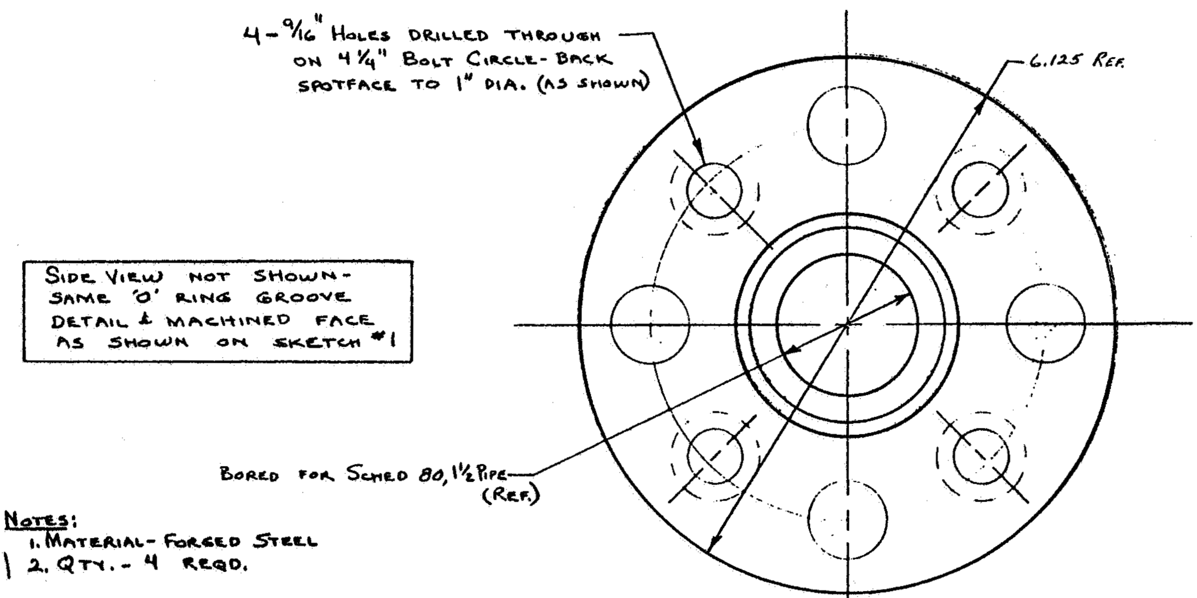


Figure A-13. Flange, Socket Weld, for Relief Valve



SKETCH #1

600# WELDING NECK FLANGE (FORGED STEEL) MODIFIED FOR 'O' RING GROOVE SEAL



SKETCH #2

600# FLANGE - MODIFIED FOR 'O' RING GROOVE & FOUR - 9/16 HOLES ON 4¼" BOLT CIRCLE

Figure A-14. Line Flanges and Adaptors

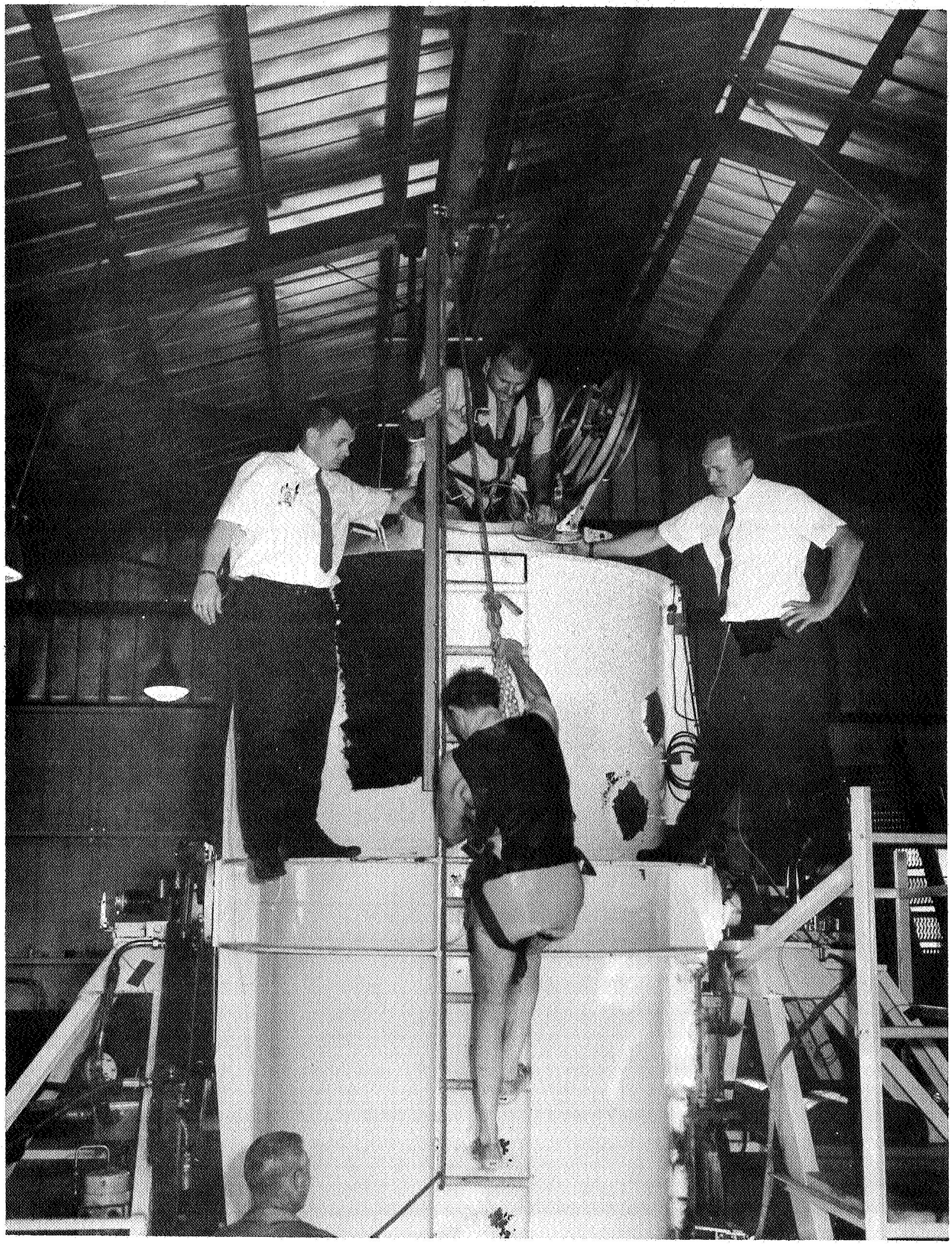


Figure A-15. Personnel Stations and Safety Tethering for Ingress and Egress from Immersion Tank

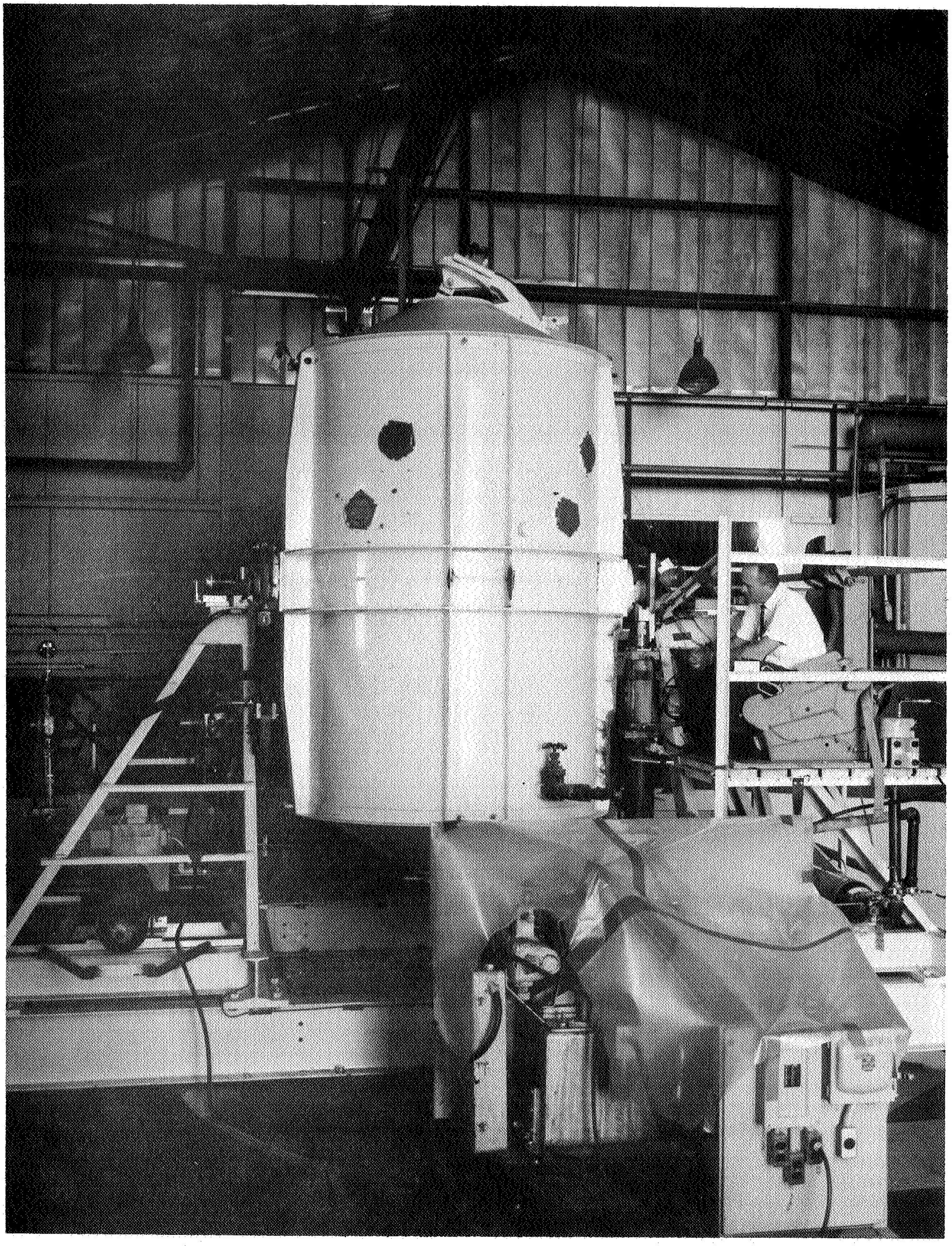


Figure A-16. Tank Facility Showing Location of Tilt Operator's Station

APPENDIX B*

DYNAMIC ANALYSIS OF CUPULAR STIMULI

An analytical determination of the linear and angular acceleration stimuli applied to the test subject's ampullae were developed. The geometric relations of the CEVAT/tank test facility shown by Figure B-1 were used to formulate a preliminary mathematical model of the test situation.

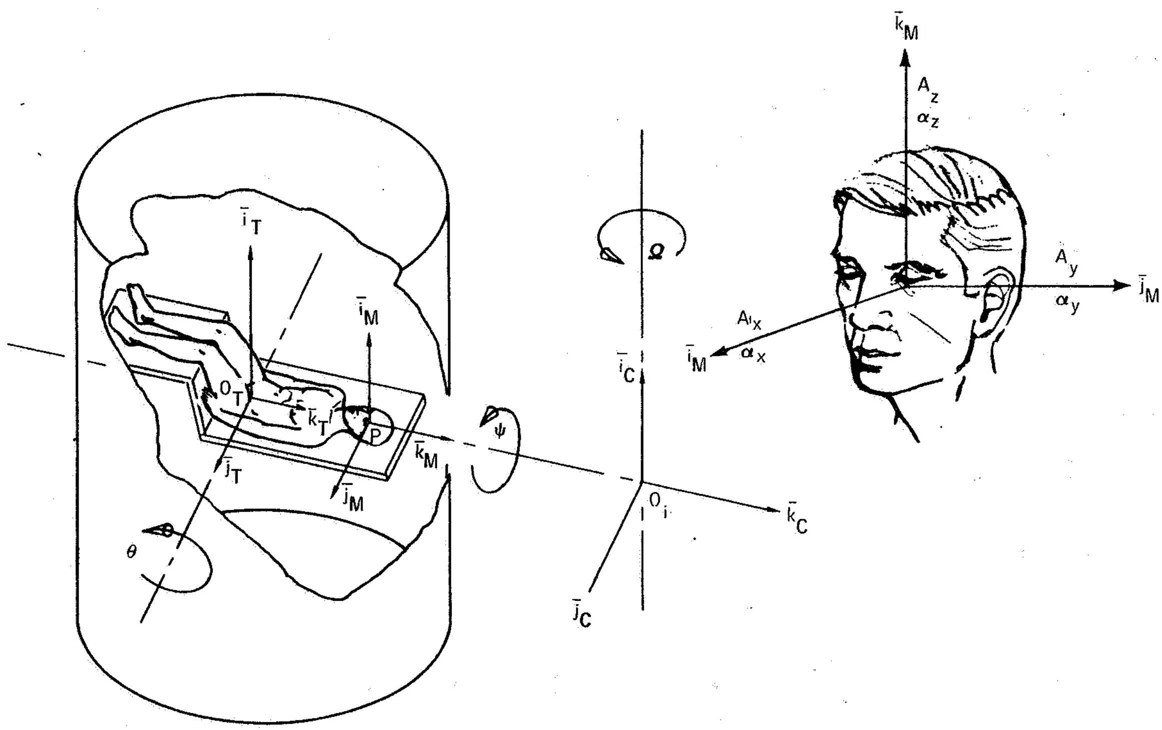


Figure B-1. CEVAT/Tank/Test Subject Relationships

*Derived by Mr. Art Greensite

Let P represent a point fixed with respect to the T frame, and let $\bar{r}_P$ denote the radius vector from O_I to P. Then

$$\bar{r}_P = \bar{r}_T + \bar{r}_o \tag{1}$$

where

$\bar{r}_T$ = radius vector from O_T to P

$\bar{r}_o$ = radius vector from O_I to O_T

Now

$$\dot{\bar{r}}_P = (\bar{\omega}_T + \bar{\omega}_c) \times \bar{r}_T + \bar{\omega}_c \times \bar{r}_o \tag{2}$$

where

$\bar{\omega}_T$ = angular velocity of T frame with respect to C frame.

$\bar{\omega}_c$ = angular velocity of C frame with respect to I frame.

A further differentiation yields

$$\ddot{\bar{r}}_P = \dot{\bar{\omega}} \times \bar{r}_T + \dot{\bar{\omega}}_c \times \bar{r}_o + \bar{\omega} \times (\bar{\omega} \times \bar{r}_T) + \bar{\omega}_c \times (\bar{\omega}_c \times \bar{r}_o) \tag{3}$$

where

$$\bar{\omega} = \bar{\omega}_T + \bar{\omega}_c \tag{4}$$

This reduces to

$$\ddot{\bar{r}}_P = \left(\frac{d\bar{\omega}_T}{dt}\right)_T \times \bar{r}_T + \dot{\bar{\omega}}_c \times (\bar{r}_o + \bar{r}_T) + \bar{\omega}_c \times (\bar{\omega}_c \times \bar{r}_o)$$

$$+ \bar{\omega}_T \times (\bar{\omega}_T \times \bar{r}_T) + \bar{\omega}_c \times (\bar{\omega}_c \times \bar{r}_T)$$

$$+ 2 (\bar{r}_T \bullet \bar{\omega}_c) \bar{\omega}_T - 2 (\bar{\omega}_c \bullet \bar{\omega}_T) \bar{r}_T \tag{5}$$

The above expression gives the <u>linear</u> acceleration sensed by the subject with the sensory organ having a radius vector, $\bar{r}_T$, with respect to the T frame.

The components of $\ddot{\bar{r}}_P$ in the T frame are (assuming that $\bar{r}_T = Z_T \bar{K}_T$) :

$$\ddot{\bar{r}}_P = \Big[Z_T \ddot{\theta} - r_o \; \Omega^2 \sin\theta - Z_T (\dot{\psi}^2 - \Omega^2 \cos^2\psi) \sin\theta\cos\theta$$

$$- Z_T \Omega \; \dot{\psi} \sin^2\theta \cos\psi \Big] \bar{i}_T$$

$$+ Z_T \Big[\ddot{\psi} \sin\theta + 2\dot{\psi}\dot{\theta} \cos\theta + 2\Omega \dot{\theta} \sin\theta\cos\psi \Big] \bar{j}_T$$

$$+ \Big[r_o \; \Omega^2 \cos\theta - Z_T (\dot{\theta}^2 + \dot{\psi}^2 \sin^2\theta + \Omega^2 \cos^2\theta$$

$$- 2\Omega \dot{\psi} \sin\theta\cos\theta\cos\psi - 2\Omega\dot{\theta} \sin\psi) \Big] \bar{k}_T \tag{6}$$

Assuming that he does not move with respect to the couch, the <u>angular</u> acceleration sensed by the subject will be (assuming constant centrifuge speed) :

$$\dot{\bar{\omega}}_T = \left(\frac{d\bar{\omega}_T}{dt} \right)_T + \bar{\omega}_c \times \bar{\omega}_T \tag{7}$$

The components of this in the T frame are :

$$\dot{\bar{\omega}}_T = - \Big[\ddot{\psi} \sin\theta + \dot{\psi}\dot{\theta} \cos\theta + \Omega (\dot{\psi} \sin\psi\cos\theta + \dot{\theta}\sin\theta\cos\psi) \Big] \bar{i}_T$$

$$+ \Big[\ddot{\theta} - \Omega \dot{\psi} \cos\psi \Big] \bar{j}_T$$

$$+ \Big[\ddot{\psi} \cos\theta - \dot{\psi}\dot{\theta} \sin\theta + \Omega (\dot{\theta}\cos\theta\cos\psi$$

$$- \dot{\psi}\sin\theta\sin\psi \Big] \bar{k}_T \tag{8}$$

$$\bar{\omega}_T = p\,\bar{i}_T + q\,\bar{j}_T + r\,\bar{k}_T$$

$$p = -\dot{\psi}\sin\theta$$

$$q = \dot{\theta}$$

$$r = \dot{\psi}\cos\theta$$

$$\left(\frac{d\bar{\omega}_T}{dt}\right)_T = \dot{p}\,\bar{i}_T + \dot{q}\,\bar{j}_T + \dot{r}\,\bar{k}_T$$

$$\dot{p} = -\ddot{\psi}\sin\theta - \dot{\psi}\,\dot{\theta}\cos\theta$$

$$\dot{q} = \ddot{\theta}$$

$$\dot{r} = \ddot{\psi}\cos\theta - \dot{\psi}\,\dot{\theta}\sin\theta$$

$$\bar{\omega}_c = \Omega\,\bar{i}_c$$

$$= \Omega\cos\theta\cos\psi\;\bar{i}_T - \Omega\sin\psi\,\bar{j}_T + \Omega\sin\theta\cos\psi\,\bar{k}_T$$

$$\bar{r}_T = x_T\,\bar{i}_T + y_T\,\bar{j}_T + z_T\,\bar{k}_T$$

$$\bar{r}_o = -r_o\,\bar{k}_c$$

$$= r_o\sin\theta\,\bar{i}_T - r_o\cos\theta\,\bar{k}_T$$

Write Eqs. 6 and 8 as

$$\ddot{\bar{r}}_P = G_x\,\bar{i}_T + Z_T\,G_y\,\bar{j}_T + G_z\,\bar{k}_T \tag{9}$$

$$\dot{\bar{\omega}}_T = H_x \bar{i}_T + H_y \bar{j}_T + H_z \bar{k}_T \tag{10}$$

where

$$G_x = Z_T \ddot{\theta} - r_o \Omega^2 \sin \theta - Z_T (\dot{\psi}^2 - \Omega^2 \cos^2 \psi) \sin \theta \cos \theta$$
$$- Z_T \Omega \dot{\psi} \sin^2 \theta \cos \psi$$

$$G_y = \ddot{\psi} \sin \theta + 2 \dot{\psi} \dot{\theta} \cos \theta + 2 \Omega \dot{\theta} \sin \theta \cos \psi$$

$$G_z = r_o \Omega^2 \cos \theta - Z_T (\dot{\theta}^2 + \dot{\psi}^2 \sin^2 \theta + \Omega^2 \cos^2 \theta$$
$$-2 \Omega \dot{\psi} \sin \theta \cos \theta \cos \psi - 2 \Omega \dot{\theta} \sin \psi)$$

$$H_x = - \ddot{\psi} \sin \theta - \dot{\psi} \dot{\theta} \cos \theta - \Omega (\dot{\psi} \sin \psi \cos \theta$$
$$- \dot{\theta} \sin \theta \cos \psi)$$

$$H_y = \ddot{\theta} - \Omega \dot{\psi} \cos \psi$$

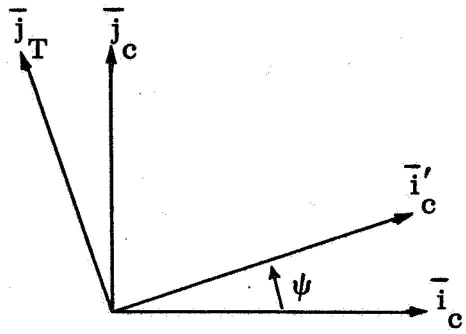
$$H_z = \ddot{\psi} \cos \theta - \dot{\psi} \dot{\theta} \sin \theta + \Omega (\dot{\theta} \cos \theta \cos \psi$$
$$- \dot{\psi} \sin \theta \sin \psi)$$

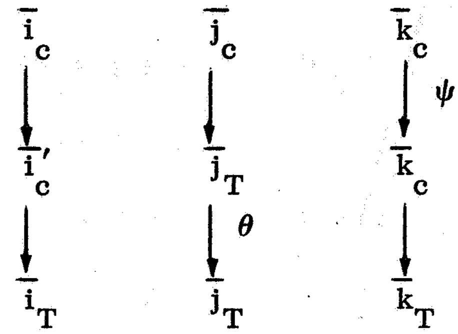
We then have

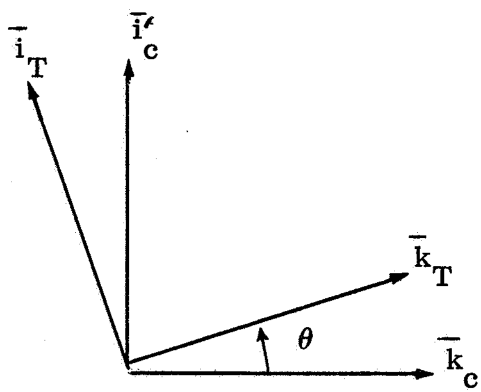
$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = C_M^T \begin{bmatrix} G_x \\ Z_T G_y \\ G_z \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix} = C_M^T \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} \tag{12}$$

ROTATION MATRIX



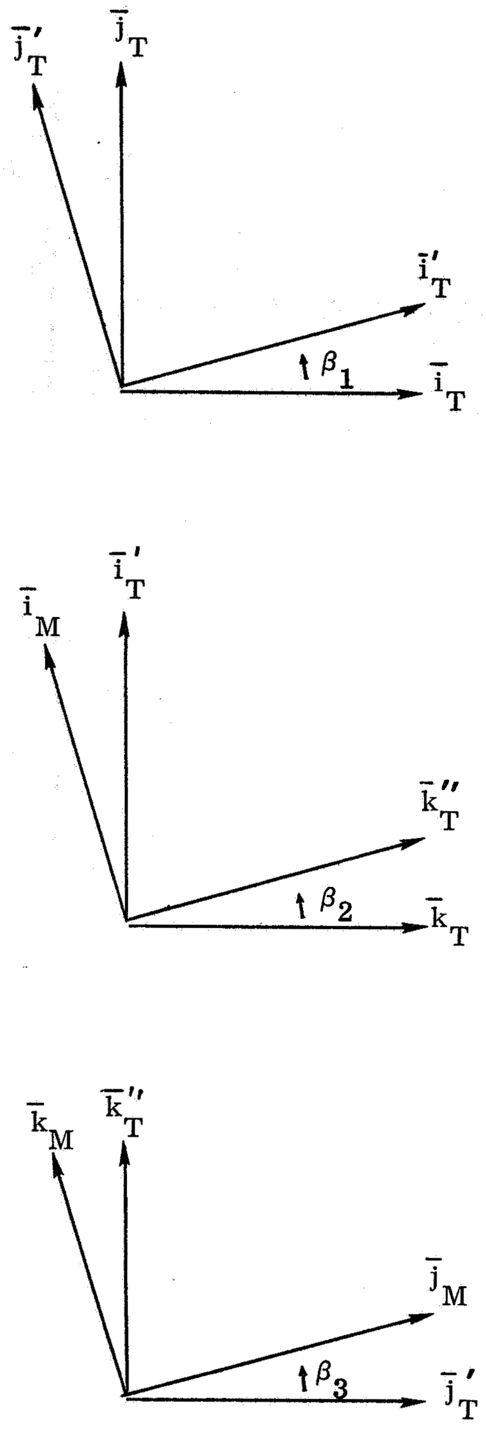


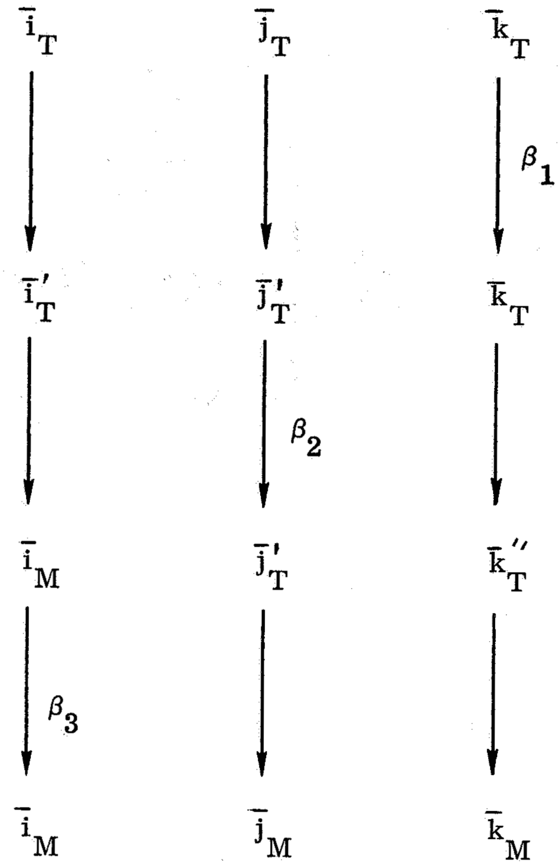


$$\begin{bmatrix} \bar{i}_T \\ \bar{j}_T \\ \bar{k}_T \end{bmatrix} = C_T^c \begin{bmatrix} \bar{i}_c \\ \bar{j}_c \\ \bar{k}_c \end{bmatrix}$$

$$C_T^c = \begin{bmatrix} c\,\theta\, c\,\psi & c\,\theta\, s\,\psi & -s\,\theta \\ -s\,\psi & c\,\psi & 0 \\ s\,\theta\, c\,\psi & s\,\theta\, s\,\psi & c\,\theta \end{bmatrix}$$

Note: Within the bracket, "c" signifies cosine and "s" signifies sine.





$$\begin{bmatrix} \bar{i}_M \\ \bar{j}_M \\ \bar{k}_M \end{bmatrix} = C_M^T \begin{bmatrix} \bar{i}_T \\ \bar{j}_T \\ \bar{k}_T \end{bmatrix}$$

Where:

$$C_M^T = \begin{bmatrix} c\beta_2\, c\beta_1 & c\beta_2\, s\beta_1 & -s\beta_2 \\ s\beta_3\, s\beta_2 c\beta_1 - c\beta_3\, s\beta_1 & s\beta_3\, s\beta_2\, s\beta 1 + c\beta_3\, c\beta_1 & s\beta_3\, c\beta_2 \\ c\beta_3\, s\beta_2\, c\beta_1 + s\beta_3\, s\beta_1 & c\beta_3\, s\beta_2\, s\beta_1 - s\beta_3\, c\beta_1 & c\beta_3\, c\beta_2 \end{bmatrix}$$

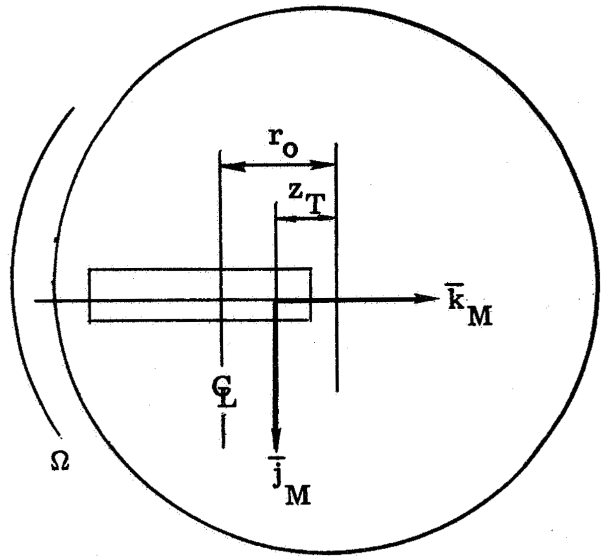


Figure B-2. Subject Orientation No. 1

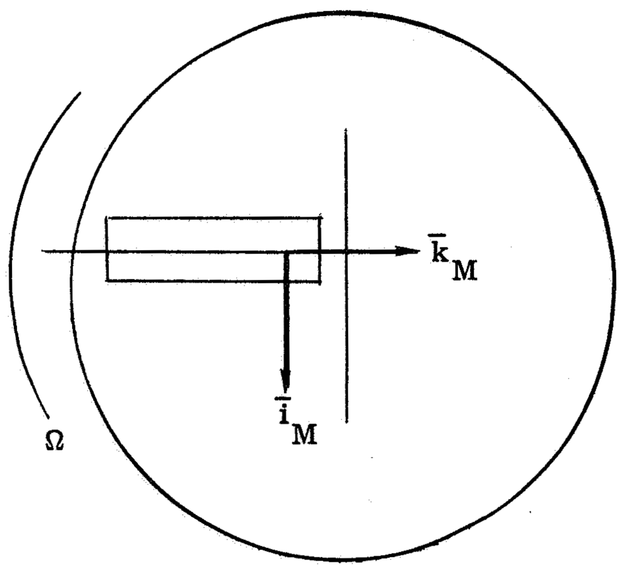


Figure B-3. Subject Orientation No. 2

CASE I

Subject orientation: Figure B-2

Excitation: pitch

$$\beta_1 = \beta_2 = \beta_3 = 0$$

$A_x = Z_T \ddot{\theta} - (r_o - Z_T \cos\theta)\, \Omega^2 \sin\theta$

$A_y = 2Z_T \Omega \dot{\theta} \sin\theta$

$A_z = r_o \Omega^2 \cos\theta = Z_T (\dot{\theta}^2 + \Omega^2 \cos^2\theta)$

$\alpha_x = \Omega \dot{\theta} \sin\theta$

$\alpha_y = \ddot{\theta}$

$\alpha_z = \Omega \dot{\theta} \cos\theta$

CASE II

Subject Orientation: Figure B-2

Excitation: yaw

$$\beta_1 = \beta_2 = \beta_3 = 0$$

$A_x = 0$

$A_y = 0$

$A_z = (r_o - Z_T)\, \Omega^2$

$\alpha_x = -\Omega \dot{\psi} \sin\psi$

$\alpha_y = -\Omega \dot{\psi} \cos\psi$

$\alpha_z = \ddot{\psi}$

CASE III

Subject orientation: Figure B-3

Excitation: pitch

$$\beta_1 = 90°$$

$$\beta_2 = \beta_3 = 0$$

$A_x = 2Z_T \Omega \dot{\theta} \sin \theta$

$A_y = -Z_T \ddot{\theta} + (r_o - Z_T \cos \theta) \Omega^2 \sin \theta$

$A_z = r_o \Omega^2 \cos \theta - Z_T (\dot{\theta}^2 + \Omega^2 \cos^2 \theta)$

$\alpha_x = \ddot{\theta}$

$\alpha_y = -\Omega \dot{\theta} \sin \theta$

$\alpha_z = \Omega \dot{\theta} \cos \theta$

CASE IV

Subject orientation: Figure B-3

Excitation: yaw

$$\beta_1 = 90°$$

$$\beta_2 = \beta_3 = 0$$

$A_x = 0$

$A_y = 0$

$A_z = (r_o - Z_T) \Omega^2$

$\alpha_x = \Omega \dot{\psi} \cos \psi$

$\alpha_y = \Omega \dot{\psi} \sin \psi$

$\alpha_z = \ddot{\psi}$

ABSTRACT

This document is a portion of the final report prepared under Contract NAS 1-7309, Feasibility Study of a Centrifuge Experiment for the Apollo Applications Program. The contract was performed for the Langley Research Center, National Aeronautics and Space Administration, Hampton, Virginia. The complete final report consists of the following documents:

NASA CR-66649 GDC-DCL-68-001 (SRC-AN-703)	Volume I	Space Research Centrifuge Configuration, Installation and Feasibility Studies
NASA CR-66650 GDC-DCL-68-002 (SRC-SD-604)	Volume II	Specification and Test Requirements-Space Research Centrifuge Engineering Development Prototype
NASA CR-66651 GDC-DCL-68-003 (SRC-MS-112)	Volume III	Experimental Requirements for the Space Research Centrifuge
NASA CR- GDC-DCL-68-004 (SRC-MS-302)	Volume IV	Manned Centrifuge Test Report

This study examines the application of an on-board centrifuge as a versatile research tool for the measurement of human physiological responses in the space environment. A realistic orbital centrifuge is configured based on a specified series of experiments dealing primarily with vestibular and cardiovascular physiology. Experiment feasibility is established in terms of spacecraft stability, reliability, safety, economics, weight, power and other influential factors. A ground based prototype of the orbital machine is defined and the required test program outlined. The effect of cross-coupled angular accelerations induced by the interaction of the astronaut/machine/vehicle motions is examined by a series of ground centrifuge tests with human subjects.