CR 73171 #9
Available to Public

Technical Report No. 169-1

STUDY, DEFINITION AND ANALYSIS OF PILOT/SYSTEM PERFORMANCE MEASUREMENTS FOR PLANETARY ENTRY EXPERIMENTS

December 1967

GPO PRICE $ _____

CFSTI PRICE(S) $ _____

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

N68-15945
(ACCESSION NUMBER)

182
(PAGES)

NASA-CR 73171
(NASA CR OR TMX OR AD NUMBER)

1
(THRU)

(CODE)

05
(CATEGORY)

FACILITY FORM 602

SYSTEMS TECHNOLOGY, INC.
Hawthorne, California

BRANCH OFFICE

194 NASSAU STREET
PRINCETON, NEW JERSEY 08540
PHONE 924-4228

SYSTEMS TECHNOLOGY, INC.

13766 SOUTH HAWTHORNE BOULEVARD • HAWTHORNE, CALIFORNIA 90250

Technical Report No. 169-1

STUDY, DEFINITION AND ANALYSIS OF PILOT/SYSTEM PERFORMANCE MEASUREMENTS FOR PLANETARY ENTRY EXPERIMENTS

D. E. Johnston
R. F. Ringland

December 1967

Contract No. NAS2-3635

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California

PRECEDING PAGE BLANK NOT FILMED.

FOREWORD

This report was prepared under Contract NAS2-3635 between Systems Technology, Inc., Hawthorne, California, and the National Aeronautics and Space Administration, Ames Research Center. This program had two NASA project monitors. The initial project monitor was Mr. Rodney C. Wingrove, later replaced by Mr. Fred G. Edwards. The STI project engineer was Mr. Donald E. Johnston. Technical direction was provided by Irving L. Ashkenas and Duane T. McRuer of STI.

The authors gratefully acknowledge the fine work of the STI production department in the preparation of this report. Special acknowledgement is due Mr. Duane T. McRuer of STI, Mr. Rodney C. Wingrove and Mr. Fred G. Edwards of Ames Research Center, and Dr. George P. Moore, Associate Professor of Physiology, University of Southern California, for their many constructive suggestions on organization and content.

ABSTRACT

The analysis and synthesis leading to a definition of an experimental program whereby pilot performance during planetary entry can be predicted is presented. This includes an analysis of the mission to determine the piloting skills required, an examination of the literature to determine the current state of knowledge concerning skill degradation under g-forces, and the definition of an experimental program designed to provide a model predictive of human performance during planetary entry. This program relies on ground-based experimentation (human centrifuge), the results to be correlated with a limited number of in-flight entry experiments.

CONTENTS

	Page
I. INTRODUCTION	1
A. Background and Scope	1
B. Technical Approach	3
1. Mission Requirements, Vehicle Design, and System Dynamics	3
2. Piloting Tasks and Procedures	4
3. Measurements and Experiments	4
II. MISSION REQUIREMENTS, VEHICLE DESIGN, AND SYSTEM DYNAMICS	5
A. General Considerations	5
B. Mission Phases	5
1. Pre-entry	5
2. Capture	6
3. Deceleration Level Control	6
C. Vehicle Aerodynamic Configuration	8
D. Displays and Controls	8
E. Failure Modes	13
1. Failure in the Guidance and Navigation System	13
2. Rate Gyro Failure	13
3. Reaction Jet Failure	13
F. Levels of Control	14
1. Monitoring Systems Operation	14
2. Tracking Roll Commands	15
3. Tracking Roll Commands, Direct Mode	15
4. Regulating Deceleration Level	15
5. Regulating Deceleration Level, Direct Mode	15
G. System Dynamics	15
1. Monitoring Systems Operation	17
2. Tracking of Roll Commands	17
3. Tracking Roll Commands, Direct Mode	20
4. Regulating Deceleration Level	24
5. Regulating Deceleration Level, Direct Mode	31

Page

III. PILOTING TASKS AND PROCEDURES 33

A. Capture Phase 33

B. Deceleration Level Control Phase 35

C. Piloting Skills 35

1. Sensing Skills 38

2. Central Processing Skills 38

3. Actuating Skill 38

D. Environmental Effects on Piloting Skills 42

IV. MEASUREMENTS AND EXPERIMENTS 45

A. Measurements 45

1. Environmental Measurements 45

2. Performance Measurements 48

B. Experiments 51

C. Epilogue 97

V. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS 99

REFERENCES 103

APPENDIX A. PHYSIOLOGICAL CONSIDERATION IN ENTRY VEHICLE CONTROL A-1

APPENDIX B. PHYSIOLOGICAL MEASURES OF PILOT PERFORMANCE . . . B-1

EXPERIMENTS

		Page
1.	Effect of Entry Environment on Ability to Detect Display Motion in Foveal View.	56
2.	Effect of Entry Environment on Ability to Shift Point-of-Regard in Response to Status Lights	59
3.	Effect of Entry Environment on Ability to Shift Point-of-Regard in Control Task	62
4.	Effect of Entry Environment on Ability to Respond to Lights in Extrafoveal View	65
5.	Effect of Entry Environment on Tracking Ability in Control Task in Extrafoveal View.	68
6.	Effect of Entry Environment on Ability to Perform Mental Arithmetic While Tracking	72
7.	Effect of Entry Environment on Ability to Adapt to Transitions in Controlled Element Dynamics.	75
8.	Effect of Entry Environment on Ability to Generate First-Order Lead Compensation	78
9.	Effect of Entry Environment on Ability to Generate Second-Order Lead Compensation in a Control Task	81
10.	Effect of Entry Environment on Precision of Controller Manipulation.	82
11.	Effect of Reduced Blood Pressure on Sensing and Central Processing Skills	85
12.	Effect of Hypoxia on Sensing and Central Processing Skills .	87
13.	Effect of Altered Atmosphere on Sensing and Central Processing Skills at High g-Levels	89
14.	Effect of Display Characteristics on Manual Control Performance	90
15.	Effect of Manipulator Characteristics on Manual Control Performance	93
16.	Training Retention Effects on Entry Performance	95

FIGURES

		Page
1.	Typical Entry Trajectory (g-Level and Roll Attitude Versus Time).	7
2.	Trim Position of Apollo Vehicle	9
3.	Major Entry Display Elements	11
4.	Roll Channel Flight Control and Guidance System During Entry.	12
5.	Block Diagram of Roll Attitude Control Channel	17
6.	N versus p_e, Describing Function.	19
7.	System Survey for Tracking of Roll Commands	21
8.	System Survey for Tracking Roll Commands, Direct Mode. . .	23
9.	Block Diagram of Deceleration Level Control Channel . . .	29
10.	System Survey for Regulating Deceleration Level.	30
11.	Indicial Response Measures (Adopted from Ref. 15)	49
A-1.	Block Diagram of Display, Pilot Manipulator, Vehicle, and Trajectory Dynamics.	A-2
A-2.	Physiological Interrelationships Pertinent to Behavior Under g-Forces as Modified by Weightlessness Deconditioning.	A-4
A-3.	Oxygen Dissociation Curve (From Ref. A-1).	A-7
A-4.	Descriptors of Mental Functioning Correlated with Arterial Oxygen Saturation (From Ref. A-7)	A-10
A-5.	Definition of EEG Frequency Bands (From Ref. A-14). . . .	A-21
B-1.	(a) Principle of Direct Measurement of Corneoretinal Potential in Animals (From Ref. B-13)	B-6
	(b) Principle of Indirect Measurement of Corneoretinal Potential in Man (From Ref. B-13).	B-6
B-2.	Voltage Generated from a 60° Eye Movement Under Various Conditions of Light-Adaptation and Dark-Adaptation (from Ref. B-7)	B-7
B-3.	Electroretinograms (From Ref. B-11).	B-10

Page

B-4. Electromyogram (Correlated with Limb Position). B-12

B-5. EEG Tracings of Normal Young Adult During a Prolonged Vigilance Task (Ref. B-12) B-13

B-6. Visual Evoked Response from 21 Year Old Normal Subject (Ref. B-12) B-15

TABLES

		Page
I.	Typical Trajectory Parameters.	25
II.	Pilot Tasks and Procedures, Capture Phase.	36
III.	Pilot Tasks and Procedures During Deceleration Level Control Phase	37
IV.	Pilot Tasks and Procedures for Failure Indications During Both Capture and Deceleration Level Control Phases. . . .	39
V.	Environmental Effects on Piloting Skills	40-41
VI.	Interrelationships Between Experiments.	53
A-I.	Effects of "Eyeballs In" Acceleration Stress on Physiological Functioning	A-28
B-I.	Summary of Some Characteristics of Interest for Some Bioelectric Potentials	B-5

NOMENCLATURE

a_t	Total aerodynamic force (equals $\sqrt{L^2 + D^2}$)
c.g.	Denotes center of gravity (mass)
c.p.	Denotes center of pressure (aerodynamic)
D	Drag force acting along velocity vector
e	Base of natural logarithms
g	Deceleration level (perturbational)
g_o	Acceleration of gravity at entry vehicle altitude
G	Deceleration level
H	Scale height of atmosphere
j	$\sqrt{-1}$
K	Gain (generalized)
K_c	Controlled element gain
K_D	Deceleration level display gain
K_p	Pilot midband gain
$K_T\left[\frac{a_T}{\sigma_T}\right]$	Pilot indifference threshold describing function
K_v	Trajectory dynamics gain
L	Lift force acting perpendicular to velocity vector
m_c	Deceleration level command (in units of display motion)
m_e	Deceleration level error (in units of display motion)
m_f	Deceleration level feedback (in units of display motion)
N	Equivalent linear gain of nonlinear element
p	Vehicle roll rate (perturbational)
p_c	Commanded roll rate (perturbational)

p_e	Roll rate error (perturbational)
p_T	Roll rate threshold
r_o	Radius of earth
s	Laplace transform variable
T_I	Pilot lag time constant
T_K	Pilot neuromuscular low frequency lead time constant
T_K'	Pilot neuromuscular low frequency lag time constant
T_L	Pilot lead time constant
T_{N_1}	Pilot high frequency neuromuscular first-order lag time constant
V	Vehicle velocity (with respect to earth's center)
V_s	Circular velocity (equals $\sqrt{g_o r_o}$)
X_b	Longitudinal body axis of entry vehicle (axis of geometric symmetry)
Y_c	Controlled element transfer function
Y_{OL}	Open-loop transfer function (equals $Y_p Y_c$)
Y_p	Pilot quasi-linear describing function
Y_s	Stick gain
Z_b	Vertical body axis of entry vehicle
Z_{cg}	Vertical entry vehicle center of gravity offset
α	Angle of attack
δ_c	Stick deflection
ζ_N	Pilot high frequency neuromuscular second-order lag damping ratio
π	3.1416
σ	Real part of s
τ	Time constant
τ_e	Effective pilot lag at high frequencies

τ_R	Roll channel time constant (equals 1/N)
φ	Vehicle roll attitude (perturbational)
φ_c	Roll attitude command (perturbational)
φ_e	Roll attitude error (perturbational)
φ_m	Phase margin
φ_o	Trim roll attitude
ω	Imaginary part of s
ω_{c_o}	Crossover frequency
ω_N	Pilot high frequency neuromuscular second-order lag natural frequency

SECTION I

INTRODUCTION

A. BACKGROUND AND SCOPE

Man's future exploration of space beyond the moon will be in the form of extended missions, first to the nearby planets and eventually to the farthest reaches of our solar system. These missions, even those to the nearby planets, are characterized first by their long time duration — on the order of months and years instead of the days and weeks necessary for lunar exploration. This carries with it certain implications regarding the reliability of various spacecraft components as well as reliability of the crew after these long periods of time. The second characteristic is the relatively high approach velocity to the earth on return — of the same order as the velocity imparted to the spacecraft to reach the planets. This velocity must be dissipated in some controlled fashion. A central question for the designer is one of specifying the navigation, guidance, and control methods which insure successful return from a planetary mission. In particular, the designer must consider the capabilities and limitations of the pilot to serve in a backup capacity should one or more of the vehicle's automatic flight-control/guidance systems fail. The piloting skills are expected to deteriorate from baseline conditions as a result of prolonged weightlessness and the higher levels of deceleration associated with atmospheric entry at planetary velocities.

There has been considerable experimental work in the past several years which has been directed toward the definition of human performance under g-loads. A good summary of this work can be found in Ref. 9. Unfortunately, there is a relative lack of data at g-levels in excess of 6g; further, much of the data on human performance is qualitative. There are even less data regarding the effects of prolonged weightlessness. Those which do exist are inferred from bed rest and immersion experiments as well as the limited orbital and postflight data from U.S. and Russian manned space flight programs. The general lack of data on the effects of weightlessness is widely recognized and several in-flight experimental programs have been proposed which are medically oriented, for example, the series of experiments for the Orbiting Research Laboratory (ORL), see Ref. 12. However, the results of these experiments are

not entirely applicable to the entry situation under discussion here. What is sought in this investigation is a more precise definition of pilot skill and performance degradation as it pertains to the control task under high-g and as influenced by a preceding period of prolonged weightlessness.

To this end, the Ames Research Center has proposed an in-flight experimental program for the purpose of obtaining fundamental insight into the pilot's ability to navigate, guide, and control a vehicle during actual entry flight into the earth's atmosphere. The end objective of the Ames program is the development of the advanced technology necessary for the design of future manned entry vehicles as noted above. These experiments will be incorporated in the Apollo Applications Program and will be coordinated with extensive ground-based simulator experiments. The specific objectives of the Ames program (Ref. 1) are:

- To identify navigation, guidance, and control methods and flight procedures which can best make use of the pilot during the entry phase of a space mission.
- To establish design criteria for predicting man/system performance capabilities and limitations.
- To determine the actual degradations in piloting skills caused by the space environment.
- To provide data to correlate with an extensive ground-based simulation program.
- To develop indices which will allow the prediction of the limits of human tolerance to entry acceleration stresses after extended periods of weightlessness.

To support this program, Systems Technology, Inc., has conducted a study with the objective of specifying the experiments, experimental procedures, measurements, and methods of analysis necessary to provide a basis for this simulator and flight research, the goal being to place the experimental measurements on a rational and useful basis. While keeping the above program objectives in mind, the specific aims of this study were:

- To define typical astronaut's procedures and control tasks required to insure satisfactory spacecraft operation during entry.
- To specify the measurements which should be made on the astronaut and on the navigation, guidance, and control systems during the entry which will allow the determination of the pilot and pilot/system performance.

- To define a method of analysis whereby the measurements noted above may be used to determine the influence of the main flight variables on the pilot and pilot/system performance.
- To develop practical design criteria from which decisions can be made regarding the most efficient use of the pilot, the appropriate displays and controls, and the design of the navigation and guidance systems required to insure successful manual entry for use in future planetary missions.
- To determine methods of analysis which provide basic and fundamental insight into the influence of the test variables on the pilot and pilot/system performance. (These methods should result in general performance criteria, not necessarily directly interpretable in terms of a definite vehicle, control task, mission, etc.)
- To provide a general description of the displays, controls, sensors, and measuring and recording apparatus necessary to accomplish the in-flight experiments.

B. TECHNICAL APPROACH

The technical approach used in this study closely follows the organization of this report. The vehicle design and mission requirements were used as a basis for defining the required pilot tasks and procedures during entry. Using a background knowledge of human physiology and performance together with the defined tasks and procedures, the experiments and measurements necessary to define pilot skills in these tasks were laid out. The following paragraphs outline the technical approach in greater detail.

1. Mission Requirements, Vehicle Design, and System Dynamics

The major purpose of this phase of the study was to define the pilot/vehicle system dynamics pertaining to (a) the three mission phases—pre-entry, capture, and deceleration level control—and (b) the various failure modes in the entry vehicle's flight control and/or guidance and navigation systems. Five levels of pilot control and the corresponding system dynamics are defined:

Monitoring systems operation
Tracking roll commands
Tracking roll commands (direct mode)
Regulating deceleration level
Regulating deceleration level (direct mode)

These represent an increasing level of difficulty. Only the capture and deceleration level control phases were considered, as these put the greatest

physiological stress on the pilot (because of the magnitude and duration of the deceleration level).

2. Piloting Tasks and Procedures

The objective of this portion of the study was the definition of the tasks, procedures, and pilot skill requirements as functions of the mission phase and the level of control exercised. Eight generalized pilot skills or performance attributes are identified and defined:

Visual acuity
Ocular motility
Visual beam width
Audition
Coordination
Decision making
Lead generation
Actuation

At the conclusion of this study phase a literature search was conducted to determine the current state-of-knowledge concerning the variation of these skills with increasing g-level and with zero-g deconditioning. The purpose was twofold:

- To determine the functional degradations which might be expected as a result of the main flight variables, i.e., long term zero-g followed by high entry-g, which would adversely affect the pilot's ability to function as a vehicle controller.
- To determine the manner in which these physiological degradations would impair or degrade control performance.

A detailed summary of this investigation is included in Appendix A.

3. Measurements and Experiments

Out of the foregoing two phases of the study effort, coupled with certain basic criteria on the design of experiments, an experimental program was evolved, oriented to ground-based simulator (centrifuge) and in-flight experiments. The basic motivation of the program was to answer questions raised by the preceding work, i.e., to provide the advanced technology necessary for planetary entry vehicle design. The ground-based simulator results provide the baseline data necessary for the evaluation of airborne (i.e., entry vehicle in-flight) results when running the same experiment.

SECTION II

MISSION REQUIREMENTS, VEHICLE DESIGN, AND SYSTEM DYNAMICS

A. GENERAL CONSIDERATIONS

The pilot of an entry vehicle used in planetary missions will be exposed to various environmental factors, principally the weightless state, for prolonged periods of time. This implies certain decrements in his capability of controlling the vehicle during entry. At the same time, entry of the earth's atmosphere at planetary (i.e., hyperbolic) velocities is characterized (for any given vehicle configuration) by the narrowing of the entry corridor with increasing initial velocity. The lower altitude bound is formed by human tolerance of the g-stresses imposed by the greater atmospheric density; the upper bound by the necessity of avoiding skipout. The latter is a hard constraint, as skipout at hyperbolic velocities results in the vehicle never returning.

With these thoughts in mind, the primary consideration established for this study was astronaut survival. His ability to take over in the event of a failure and thereby achieve a successful entry (criterion of success — survival) was a second major consideration, subordinate to the first. Range control (control over where the vehicle lands) was given third priority, and judged far less important than the first two.

B. MISSION PHASES

1. Pre-entry

Prior to actual entry, control is exerted over the trajectory of the vehicle by means of velocity-incrementing maneuvers designed to place the vehicle at the correct attitude and flight path angle for entry. The allowable range of values for the latter is quite narrow and reflects the depth of the entry corridor. These maneuvers are based on navigational sightings, ground-tracking data, and on-board information within the guidance computer. They are not regarded as being critical in the same sense as maneuvers within the atmosphere because of the relatively long times available for determination and execution. More importantly, the vehicle is in a free-fall state (the

pilot is not subjected to g-forces) making minimal demands on the pilot's physiological integrity.

2. Capture

Subsequent to encountering the fringes of the earth's atmosphere (as defined by some arbitrary but low level of aerodynamic force acting on the vehicle), the vehicle is maneuvered on the basis of knowledge of the state variables governing its motion. Control is exercised in the general case by varying the vehicle's lift-to-drag ratio, by direct control over the lift or drag, or by rotating the lift vector in a vehicle having a fixed L/D, the means used being configuration-dependent. The latter mode of control is typical of Gemini or Apollo types of vehicles and is also felt to make minimum demands on the pilot (Ref. 2).

Figure 1 sketches a typical entry trajectory for Apollo-type vehicles in terms of g-stress felt by the pilot and typical roll maneuvers, both as functions of time. The capture phase, between 0.05g and the peak g-level encountered (arbitrary definition), is critical because of the necessity of maneuvering the vehicle so as to "hit" the approximate center of the corridor and remain there. This requires that the guidance system or the pilot solve the terminal control problem of arriving at the desired peak g-level with a near-zero flight path angle, and with the downward-directed component of the lift force exactly balancing the centrifugal force. Further, this must be accomplished despite uncertainties or deviations in initial (0.05g) flight path angle, atmospheric density, and vehicle L/D, all of which require modifications to the nominal roll attitude verus time history if the terminal conditions are to be met.

3. Deceleration Level Control

The subsequent deceleration level control phase is critical because the vehicle must tread a narrow path between the skipout boundary on one side and the pilot's deteriorating (because of time duration effects) physiological limit on the other. As the roll attitude history in Fig. 1 shows, the trim roll attitude to hold a fixed level of deceleration is continually changing. If the guidance and navigation system has failed, the pilot must continually "hunt" for the proper trim roll attitude — he has no precise knowledge of

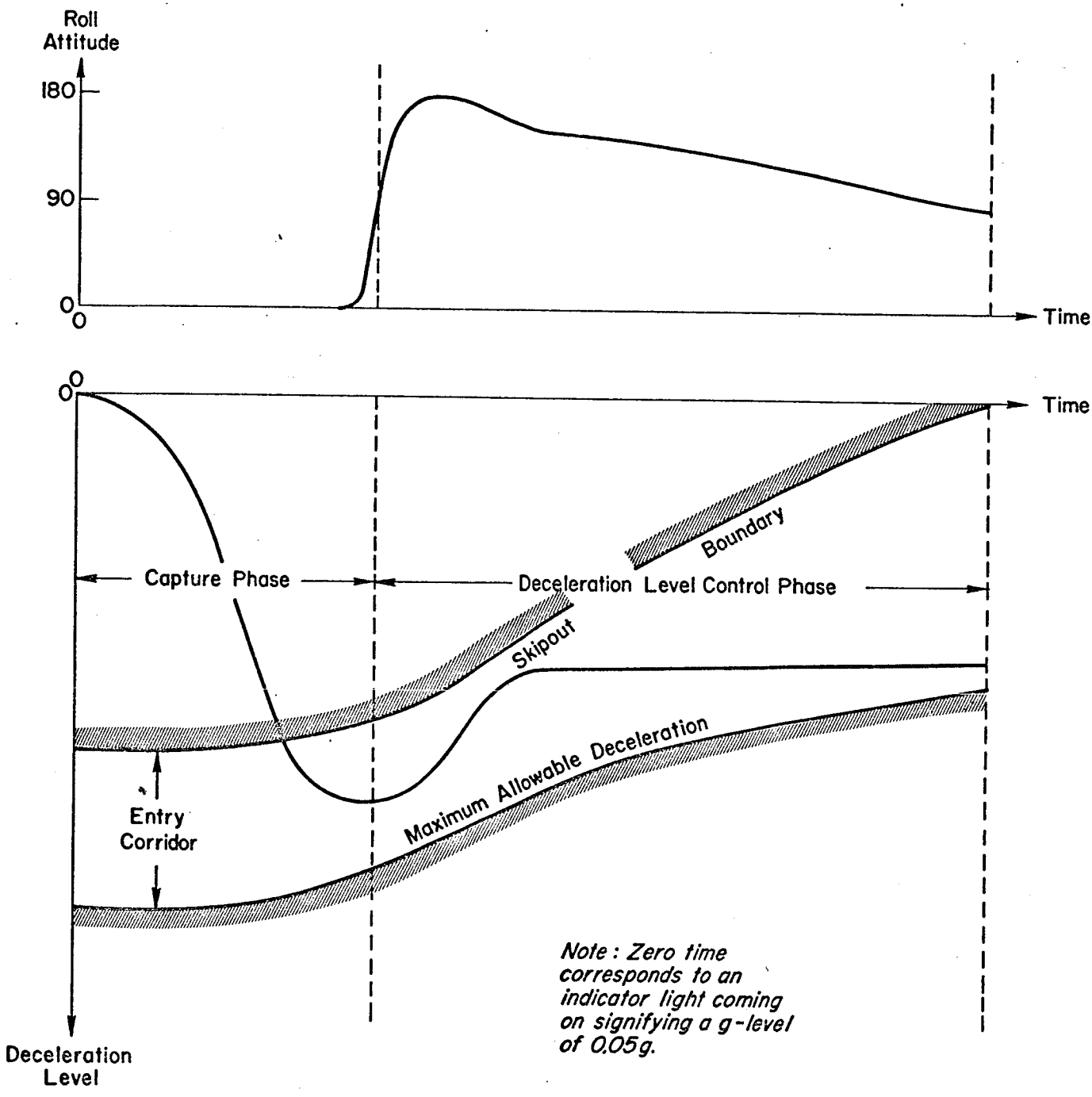


Figure 1. Typical Entry Trajectory
(g-Level and Roll Attitude Versus Time)

what it should be because of variations in initial conditions at the beginning of this phase, vehicular parameters, and so on. Cross-range control is most effective during this phase because of the high velocity. Small lateral deviations in path angle cause large cross-range shifts in the landing point.

In sum, the high g-stresses encountered, coupled with criticality of the control maneuvers required of the pilot should he be in control, make flight within the atmosphere the most crucial part of the entry mission. For these reasons, attention is directed to Apollo-type vehicles during the phases of entry between first encounter with the fringe of the earth's atmosphere and the achievement of circular velocity (the capture and deceleration control phases, respectively).

C. VEHICLE AERODYNAMIC CONFIGURATION

Figure 2 illustrates the trim position of the Apollo-type vehicle assumed for this study. It is a capsule configuration having an offset center of gravity which gives a stable trim attitude (zero net aerodynamic moment) at an L/D on the order of 0.4. Control over the orientation of the lift vector is achieved by rolling the vehicle about its stability axis. Thus the flight path may be made to deviate up (causing decreasing g-forces, increasing range) or down (causing the opposite effect), and left or right (causing cross-range changes in landing point). The relatively low valuc of L/D restricts the maneuvering capability of the vehicle (the speed with which the flight path angle can be changed) which is reflected in a narrow band of allowable initial flight path angles. But by the same token, the demands on the pilot for rapid and accurate response are lessened.

D. DISPLAYS AND CONTROLS

The guidance and control systems for this study are assumed to closely resemble the lunar Apollo configuration (Ref. 3). Briefly described, these systems are:

Reaction control system (RCS). A series of twelve reaction jets, four for rotational control about each of the body axes.

Guidance and navigation system (GNS). An inertial platform and a guidance computer. The platform is the vehicle's inertial attitude reference when commands are provided by the GNS.

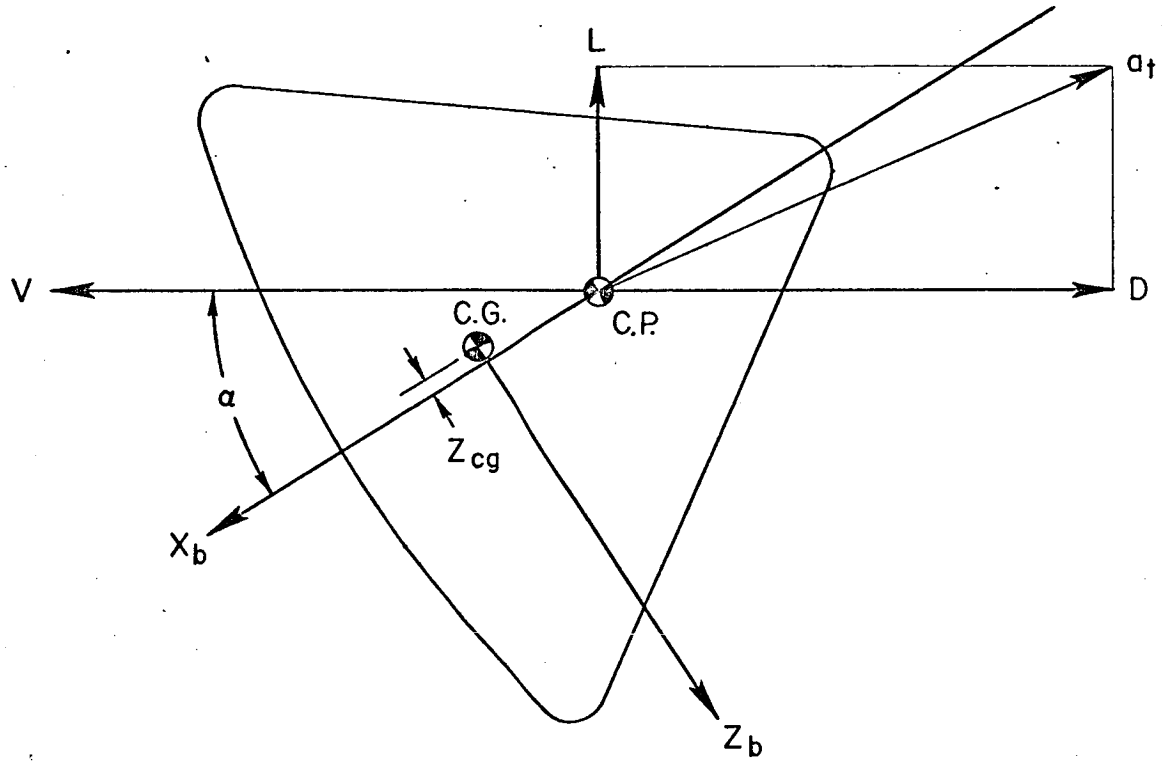


Figure 2. Trim Position of Apollo Vehicle

Stabilization and control system (SCS). Provides the interface between the GNS (and/or pilot) and the RCS. It consists of three body-mounted rate gyros, the RCS jet firing logic, the pilot's control stick, and a "strap down" inertial reference (three body-mounted attitude gyros). The latter serves as a backup inertial reference in the event of a GNS failure. During entry the rate feedbacks in roll and yaw are cross-coupled to provide the equivalent of stability axis rates to the system.

A sketch of a typical basic or backup display is shown in Fig. 3. The major components are described as follows:

Flight director attitude indicator (FDAI). This consists of the pilot's ball display, a display of the stability axis rates, and three attitude error indicators (only one of which, roll, is of major concern during entry).

Deceleration level indicator (DLI). This reads out the total deceleration in "g" as measured from body-mounted accelerometers. Two corridor warning lights which come on at 0.05g and 0.2g are also a part of this display, together with a timing indication of when they come on.

Roll attitude indicator (RAI). Roll attitude from the body-mounted roll gyro —a backup to the ball display.

Clock

Other display quantities which may be considered include the following:

- Rate-of-change of deceleration level
- Skipout monitor (as proposed in Ref. 4)
- Deceleration versus velocity profile
- Down-range and cross-range velocities
- Down-range and cross-range distances
- Indicator lights (systems status display)

The pilot's controls are presumed to consist of side-arm manipulators plus various buttons and switches for changing modes of control, disabling reaction jets, etc. The attitude manipulator is assumed to be a three-axis side-arm controller with positive centering. Deflection of the manipulator provides a rate command. Other details of the controller (centering force spring gradient, axis location, etc.) are not set for this study.

A block diagram of the system (roll channel) is shown in Fig. 4.

The pitch and yaw channels contain only rate dampers since aerodynamic forces provide a stable trim attitude in these axes. This combination of

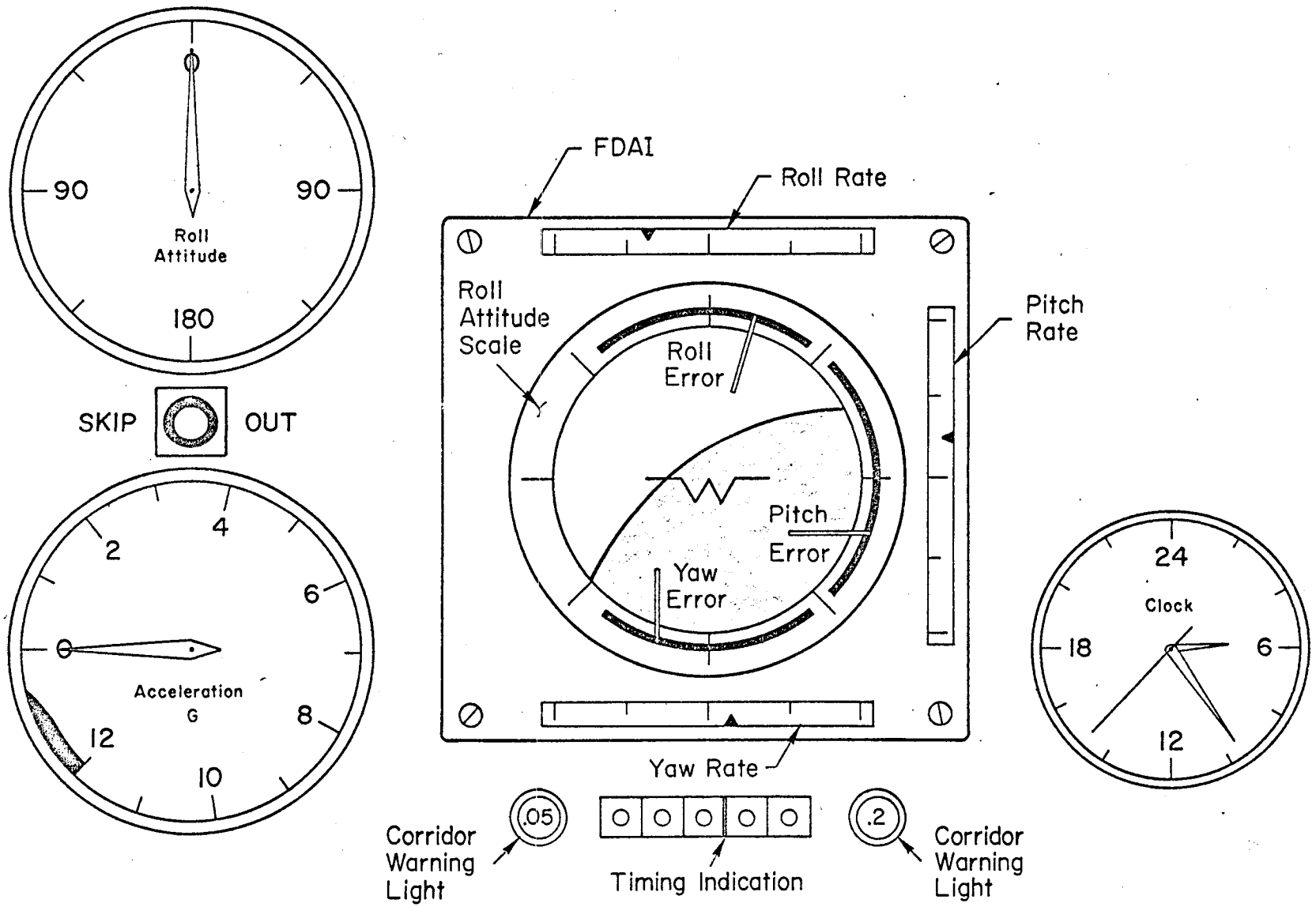


Figure 3. Major Entry Display Elements

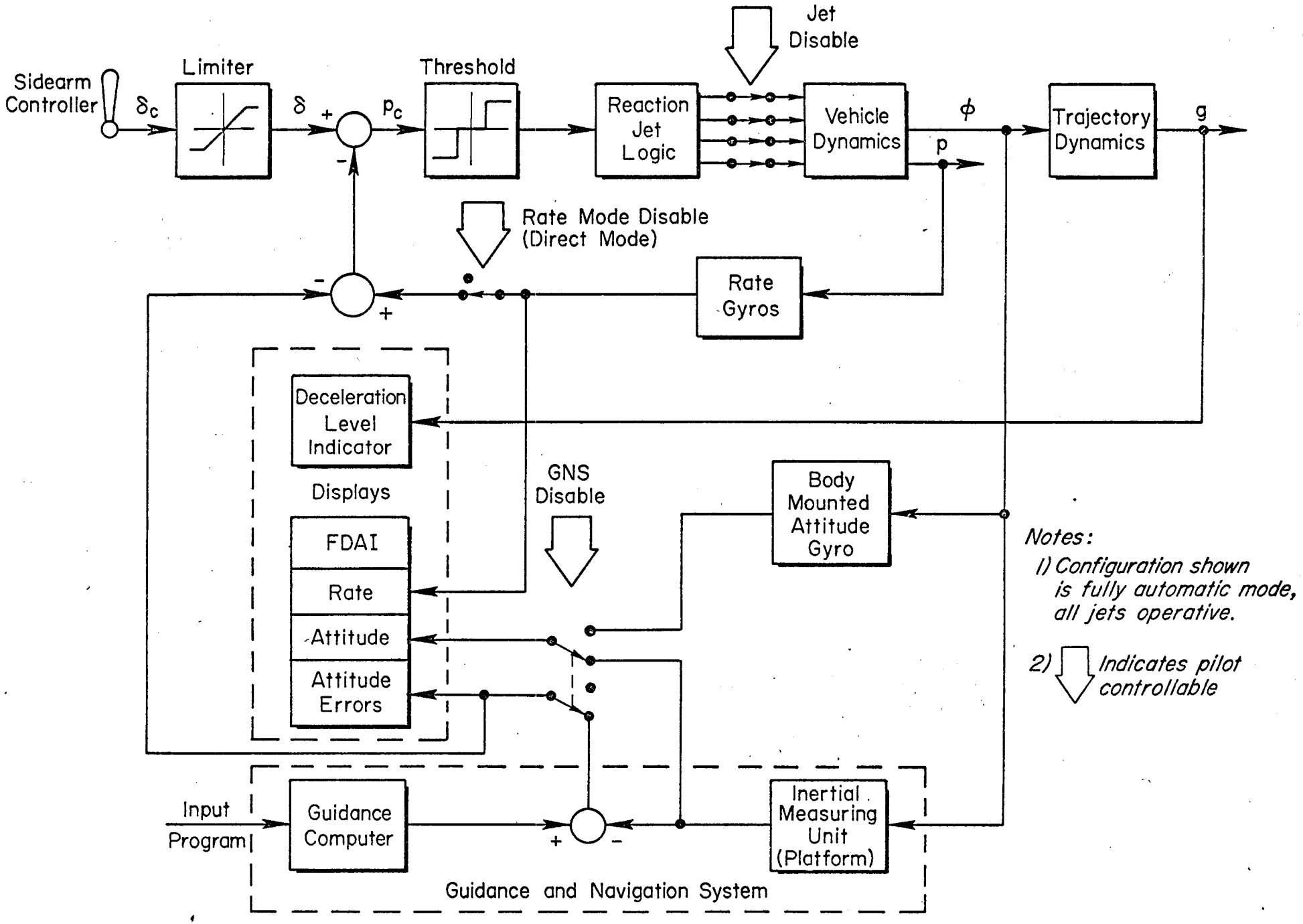


Figure 4. Roll Channel Flight Control and Guidance System During Entry

aerodynamic stability and rate damping relieves the pilot of the necessity to control in pitch and yaw unless damper failure is encountered.

E. FAILURE MODES

For this study only three categories of failures are considered:

1. Failure in the Guidance and Navigation System

If this failure has occurred prior to entry, the pilot will already be providing his own roll program and manually controlling the roll attitude to that program. Failures during entry are signified by unreasonable roll commands in relation to the instantaneous deceleration level or rate. Should this occur, the pilot disables the GNS (see Fig. 4) and guides the vehicle himself, most probably by holding a fixed level of deceleration.

2. Rate Gyro Failure

If failure occurs prior to the 0.05g light, the pilot will be controlling through a direct mode, at least in the axis where the failure has occurred. If it occurs after the 0.05g light comes on, he disables the rate mode (see Fig. 4), thus going to the direct mode in the failed channel. He need keep only the pitch and yaw rates and attitudes within a wide tolerance. The roll attitude must be held within a few degrees of that commanded (by the GNS or the pilot). It is assumed that a "hardover" failure of the rate gyro cannot result in a hardover command (output is fused). Failure is signified by a change in the controlled element dynamics evident to the pilot in the display motion response to manipulator deflection.

3. Reaction Jet Failure

If a reaction jet has failed prior to the 0.05g warning light, the pilot will have disabled the jet (see Fig. 4). Entry is then performed at a reduced control acceleration capability in the particular channel and direction affected. If the remainder of the system is functioning correctly, entry can still be performed on full automatic.

If the failure (jet full on) occurs subsequent to the 0.05g light, it will cause the vehicle rate to diverge. At the point where the rate damper threshold is exceeded, the opposing jets will fire and will overbalance the

disturbance forces. (This assumes the system is in the normal rate command mode.) This will result in a limit cycle biased about the rate-switching threshold. The vehicle will diverge slowly in attitude, but the pilot can regain control by deflecting the stick in the opposite direction. He then can disable the jet and return to the "hands-off" condition.

If the failure should occur when in a direct mode, the divergence will not be limited (no rate damper) and full opposite stick deflection will be required to regain control. Then the jet must be disabled.

A jet failure in the closed condition results in sluggish response in one direction, but the rate damper will still be operative. If the failure is upstream of the valve solenoid, the pilot can go to "direct" to regain its use if necessary. If the failure occurs at the solenoid, the jet is lost.

If one or more of the above failures (except those which result only in a single reaction jet being inoperative) has occurred, the pilot must assume control. The controlled element dynamics and failure indications pertinent to each situation are the major determinants of the piloting skills required. If a failure occurs in either the pitch or the yaw damper, the result is a very lightly damped oscillatory mode. Since disturbances originating in the external environment are small, the major disturbances will come from cross-coupling when roll maneuvers are executed. Thus the pilot need pay only intermittent attention to control the pitch and yaw rates. In the roll channel, close attention is required to keep the roll error (GNS operative) or the deceleration level (GNS failed) within bounds.

F. LEVELS OF CONTROL

The foregoing considerations indicate five successive levels of control difficulty which depend on the failures or combinations of failures that have occurred. These are:

1. Monitoring Systems Operation

The pilot observes the operation of the flight control and guidance systems and is ready to take over at any time should a malfunction be indicated. No actual control activity is required.

2. Tracking Roll Commands

In addition to the preceding, the pilot manually controls the vehicle to the GNS-commanded attitude, either because the attitude loop has opened or otherwise malfunctioned, or because he wants to. The controlled element is essentially a K_c/s, and he need provide only gain equalization.

3. Tracking Roll Commands, Direct Mode

Same as the preceding, except the roll damper has failed. The controlled element is K_c/s^2 with a fixed roll acceleration. The pilot must provide lead compensation in addition to gain.

4. Regulating Deceleration Level

Here the GNS has failed, and the pilot uses both the roll display and the deceleration level display to regulate the g-level. The roll display is probably used as a criterion of control effort rather than an actual closure of the roll position loop in the usual sense. The roll loop is closed during the capture phase ($Y_c = K_c/s$); during the deceleration level control phase the controlled element is the very difficult K_c/s^3 with low gain. The pilot must provide very low frequency second-order lead.

5. Regulating Deceleration Level, Direct Mode

Same as preceding, except the roll damper has failed, necessitating pilot closure of the roll loop. The end-to-end dynamics are K_c/s^4 with an inner-loop closure about a K_c/s type of element. This task probably cannot be managed at the higher g-levels.

The following subsection contains a more detailed analysis of the last four control situations in terms of the open- and closed-loop (i.e., pilot/vehicle) system dynamics associated with each.

G. SYSTEM DYNAMICS

In this subsection the closed-loop analysis is based on the quasi-linear pilot model (or extensions thereof) for compensatory tracking of random-appearing inputs. This model has the widest application in the analysis of manually controlled systems in that it provides a conservative estimate of the closed-loop dynamics and pilot opinion. In those cases where the pilot

can detect coherence in the displayed error, or can take advantage of additional displayed information, he can sometimes improve performance over that predicted.

The human operator describing function in its most general form is given by (Ref. 6):

$$Y_p = K_p K_T \underbrace{\left[\frac{a_T}{\sigma_T}\right]}_{\text{Indifference threshold effects}} \underbrace{e^{-j\omega\tau}}_{\text{Nerve conduction lag}} \underbrace{\left(\frac{T_L j\omega + 1}{T_I j\omega + 1}\right)}_{\text{Equalization}} \underbrace{\left\{\left(\frac{T_K j\omega + 1}{T'_K j\omega + 1}\right)\left[\frac{1}{\left(T_{N_1} j\omega + 1\right)\left[\left(\frac{j\omega}{\omega_N}\right)^2 + \frac{2\zeta_N}{\omega_N} j\omega + 1\right]}\right]\right\}}_{\text{Closed-loop dynamics of neuromuscular system}}$$

The contribution of the indifference threshold is normally ignored (or, equivalently, lumped with the pilot gain). The remainder of the expression can be approximated in various ways, depending on the frequency range of concern.

For the frequencies associated with control of roll attitude, the low frequency neuromuscular lag/lead can be ignored and the high frequency third-order neuromuscular lag can be replaced by an equivalent pure delay. Further, it develops that lag compensation is not required in any of the four levels of control. The appropriate pilot model is then:

$$Y_p = K_p e^{-j\omega\tau_e}\left(T_L j\omega + 1\right)$$

For the frequencies associated with regulation of the deceleration level (as determined from experiment, see Ref. 4), the low frequency lag/lead is of some importance. The pilot model then becomes:

$$Y_p = K_p \left(\frac{T_K j\omega + 1}{T'_K j\omega + 1}\right) e^{-j\omega\tau_e}\left(T_L j\omega + 1\right)$$

These models are well established by experiment (Ref. 6). They are, however, insufficient to describe the pilot behavior observed on entry

simulations when the task is one of regulating the deceleration level. In this case, the following model is used, the motivation for which is discussed below:

$$Y_p = K_p \left(\frac{T_K j\omega + 1}{T'_K j\omega + 1}\right) e^{-j\omega\tau_e} \left(T_{L_1} j\omega + 1\right)\left(T_{L_2} j\omega + 1\right)$$

Here the pilot is generating a double lead — a hypothesis suggested by experimental evidence to date and confirmed in preliminary experiments and human response measurements conducted in support of this study.

1. Monitoring Systems Operation

Since the pilot is not in active control of the vehicle, closed-loop dynamics are not of concern. The pilot is using skills (primarily visual and mental) associated with monitoring.

2. Tracking of Roll Commands

A simplified block diagram showing the essentials of the roll control loop is shown in Fig. 5. The delays (on the order of a few milliseconds) associated with the reaction jet thrust buildup and decay have been ignored, as have been the rate gyro dynamics and hysteresis within the jet firing logic. The jet firing logic is represented here by a fixed output (± 10 deg/sec^2) and a ± 1 deg/sec threshold.

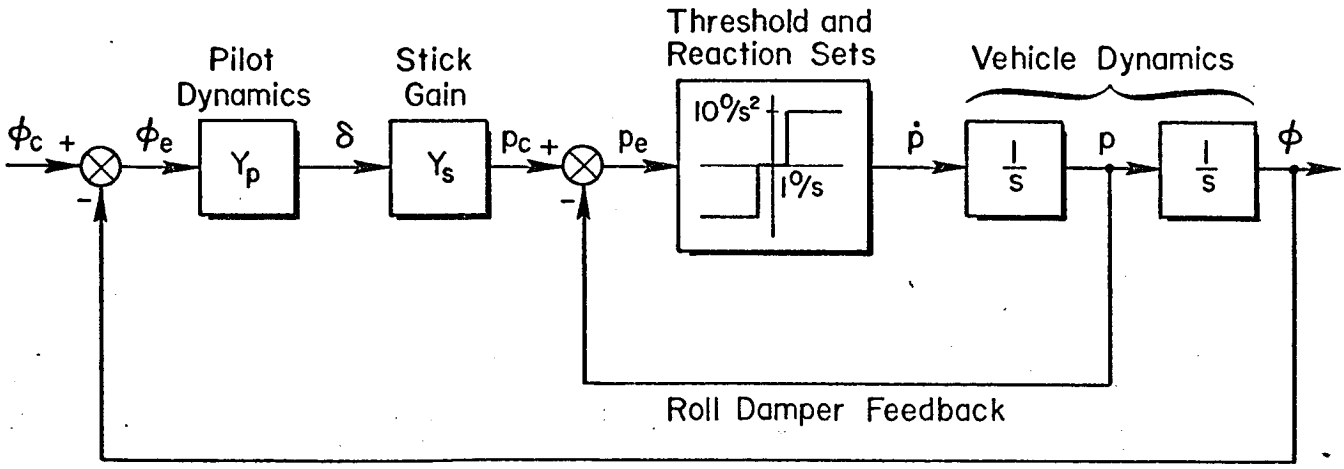


Figure 5. Block Diagram of Roll Attitude Control Channel

While recognizing the limitations of the approach, perhaps the best method for obtaining a "feel" for the effects of the nonlinear element is by means of describing functions. The describing function pertinent to this particular nonlinearity (Ref. 5) is given by:

$$N = 0 \qquad p_e \leq p_T$$

$$N = \frac{4}{\pi} \frac{\dot{p}}{p_e} \sqrt{1 - \left(\frac{p_T}{p_e}\right)^2} \quad ; \quad p_e > p_T$$

where N = Equivalent linear gain

p_T = Error threshold, 1 deg/sec

$\dot{p}$ = Controlled element acceleration, 10 deg/sec^2

p_e = Error between commanded (p_c) and actual (p) rates, deg/sec

The equivalent linear gain is plotted as a function of the input (in this case, p_e) amplitude in Fig. 6. The describing function relating vehicle response rate, p, to commanded rate, p_c, is given by:

$$\frac{p}{p_c} = \frac{N}{j\omega + N} = \frac{1}{\tau_R j\omega + 1}$$

Thus the closed-loop describing function is equivalent to a first-order lag with a time constant of $1/N$. The rate loop response is therefore amplitude- and frequency-sensitive.

The effective vehicle dynamics for the roll attitude control system of Fig. 5 may be described by the transfer function

$$Y_c = \frac{N}{s(s + N)} = \frac{1}{s\left(\frac{s}{N} + 1\right)}$$

The pilot describing function for control of this vehicle will be dependent on the effective lag break frequency and the closed-loop crossover frequency desired. Assuming the pilot will strive for a crossover in a region where the controlled element looks like a K/s, we may employ the simple model for the pilot (Ref. 6):

$$Y_p = K_p e^{-0.36s}$$

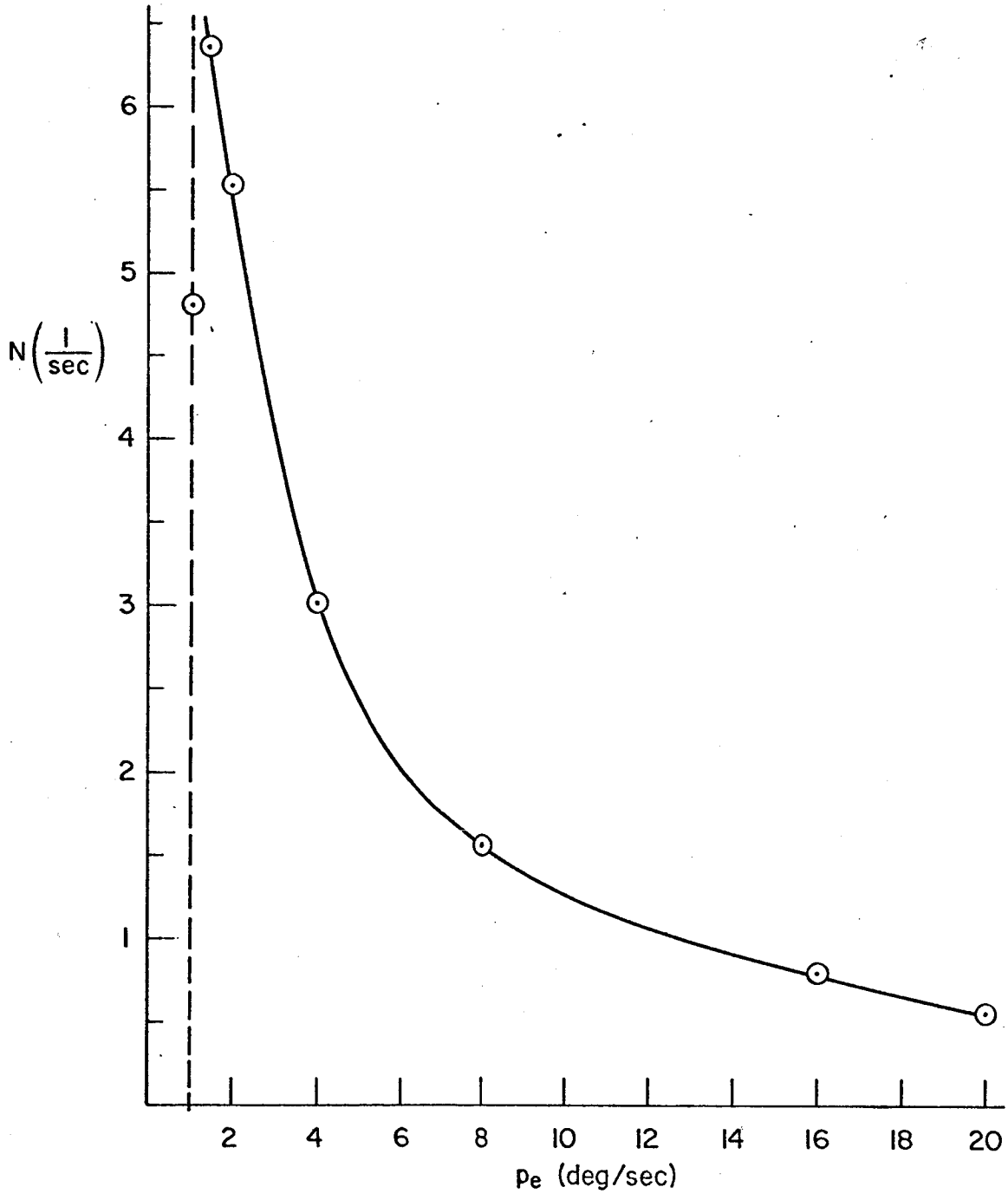


Figure 6. N versus p_e, Describing Function

The system survey plot for roll attitude control is presented in Fig. 7. In this figure, as in all succeeding system surveys, the first-order Padé approximation is used in plotting the root loci, viz:

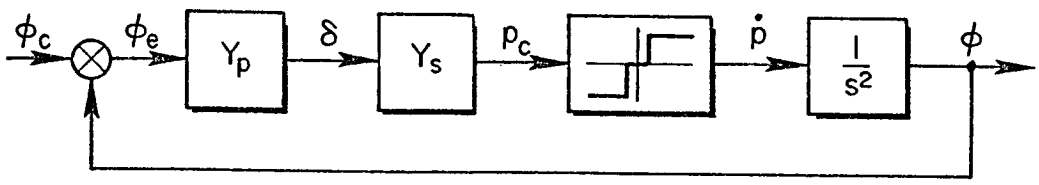
$$e^{-\tau_e s} \doteq \frac{s - \frac{2}{\tau_e}}{s + \frac{2}{\tau_e}}$$

The Bode phase of the open-loop transfer function is not approximated; however, two values of N are shown for comparison. The largest value, N = 6.36, results in a maximum roll attitude control bandwidth of approximately 3 rad/sec. However, from Fig. 6 it is noted that to achieve this value of N the difference between p_c and p must be very small. Since the vehicle has a finite inertia, the foregoing implies that p_c must remain small or the frequency of command inputs must be such that there is little phase lag between p_c and p. This then provides restrictions on the gain the pilot can employ in the roll loop if N is to remain at or near its maximum value. If the pilot tends to "overdrive" the rate command loop in order to achieve some desired roll attitude bandwidth or error level, the value of N will decrease (e.g., the N = 1 plot of Fig. 7) which in turn will reduce the maximum roll loop bandwidth available.

It would appear from Fig. 7 that the pilot should have little difficulty obtaining closed-loop roll control up to 1 or 2 rad/sec without generating lead. Thus the important pilot skills in this task will be his ability to discern attitude error and an ability to make small manipulator movements.

3. Tracking Roll Commands, Direct Mode

Without rating damping, the controlled element is a pure inertia having fixed acceleration capability. The block diagram is the same as that in Fig. 5, less the roll damper feedback, i.e.,



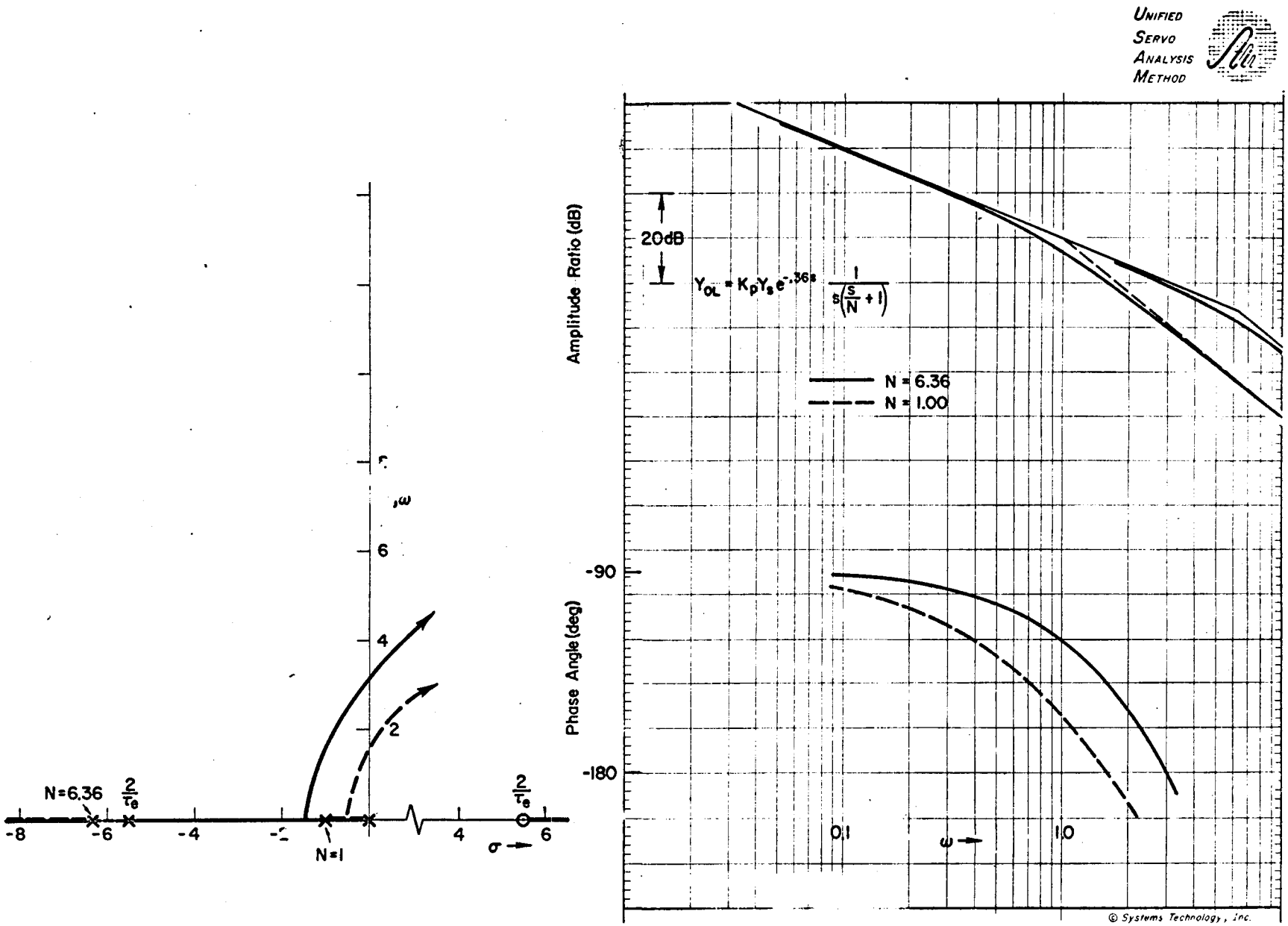


Figure 7. System Survey for Tracking of Roll Commands

The describing function for the nonlinearity is as before, but with p_e replaced by p_c:

$$N = 0 \qquad p_c \leq p_T$$

$$N = \frac{4}{\pi}\frac{\dot{p}}{p_e}\sqrt{1-\left(\frac{p_T}{p_c}\right)^2} \quad ; \qquad p_c \geq p_T$$

It has a maximum at $N = 6.36$ for $p_c = 1.414$ deg/sec (see Fig. 6).

In this instance the controlled element phase is 180 deg at all frequencies. The pilot must adopt sufficient lead to overcome the vehicle lag plus his own lag contributions in order to stabilize the system. The simplest pilot model will then be of the form

$$Y_p = K_p e^{-\tau_e s}\left(T_L s + 1\right)$$

while the controlled element is of the form

$$Y_c = \frac{Y_s N}{s^2}$$

Although past experience has shown the pilot will tend toward pulse-type manipulator motions when controlling systems of this nature, it has also shown quasi-linear analysis techniques to be valid for predicting crossover regions, system stability, etc. If we apply the pilot model characteristics and criteria of Ref. 6 we obtain the dynamic situation sketched in Fig. 8. To be conservative, the extrapolated zero frequency forcing function value has been selected for the pilot effective time delay, τ_e. This gives a value of $\tau_e = 0.51$. A lead time constant of 1 sec was selected since this represents the minimum acceptable phase margin ($\doteq$ 15 deg) in the region of 0.5 to 1 rad/sec. However, the closed-loop response would be quite oscillatory, and it is likely that the pilot would increase his lead as shown by the dashed curve in Fig. 8. Note that the additional lead does not result in appreciable increase in closed-loop bandwidth, but should reduce the oscillatory nature of the response.

Figure 8 also indicates the range of effective vehicle gains which result from various amplitude commands to the fixed roll acceleration thrusters. Maximum vehicle gain results from small manipulator (p_c) motions. Thus the vehicle will seem sensitive to small (possibly inadvertent) manipulator

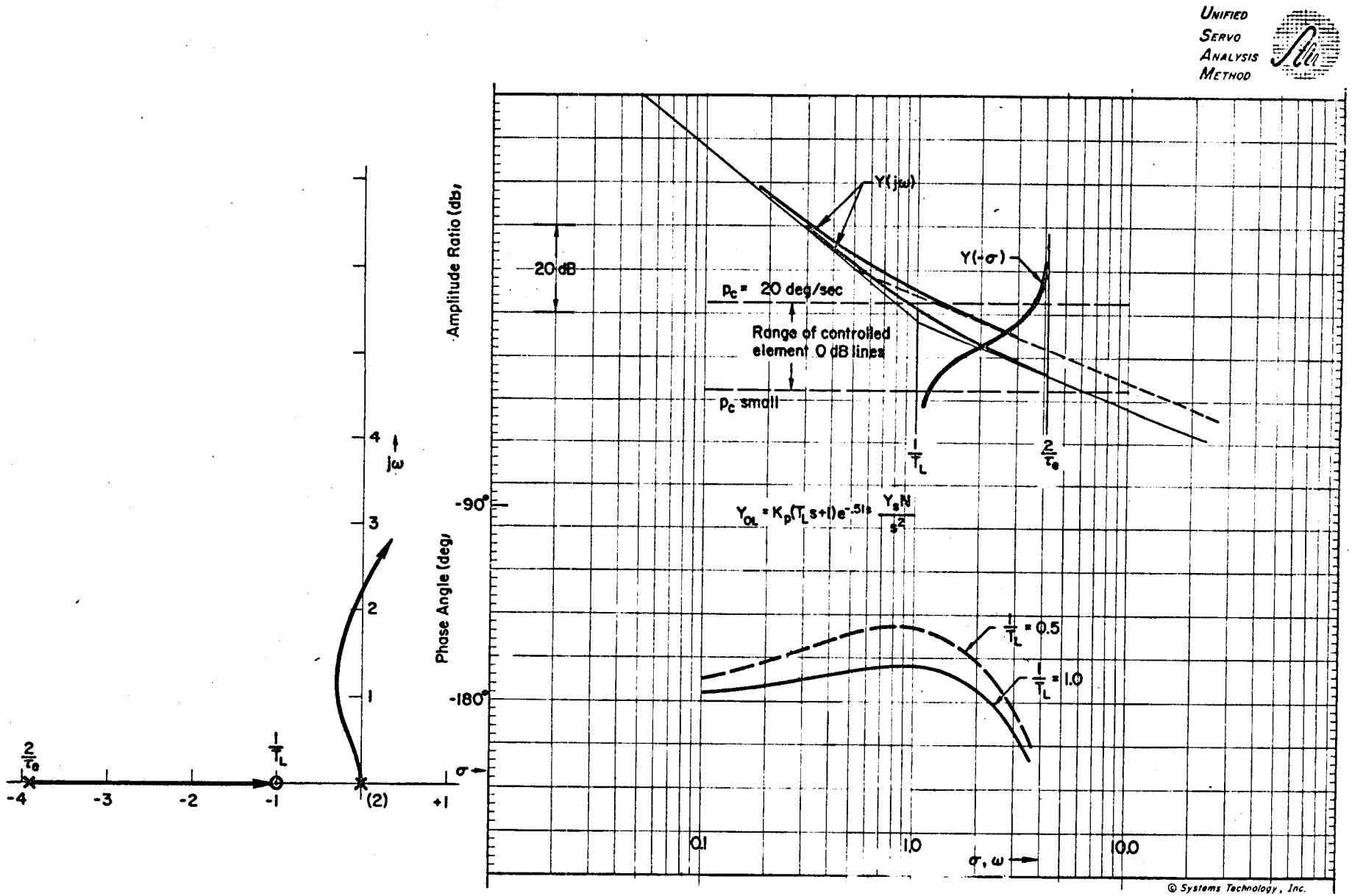


Figure 8. System Survey for Tracking Roll Commands, Direct Mode

deflections. On the other hand, the vehicle may appear sluggish if large manipulator motions are employed. Furthermore, the effective vehicle gain decreases rapidly, as indicated by Fig. 6, if the pilot attempts to tighten the roll loop by employing larger and larger manipulator motions. It would appear that the pilot's strategy under such circumstances would be to maintain his gain fixed, to operate at some nominally small manipulator deflection, and to allow the forward loop gain to decrease if larger manipulator deflections are required to combat any large errors which might develop. From Fig. 8 it is apparent that the closed-loop frequency will decrease under such circumstances. This should be acceptable to the pilot since it means that roll rates will tend to stay in "comfortable" regions, i.e., the pilot will not get the feeling that he is losing control.

For this controlled element the crucial pilot skill is the ability to generate lead because he must introduce sufficient lead to overcome his effective time lag, τ_e, and to achieve the desired system phase margin. The manipulator design could also become crucial from the standpoint of centering and breakout characteristics.

4. Regulating Deceleration Level

Pilot control of the deceleration level at supercircular velocities is quite difficult because of the unstable nature of the trajectory dynamics (Ref. 7). The transfer function relating perturbational changes in deceleration level to perturbational changes in the roll orientation of the lift vector (approximated by the vehicle's roll attitude when pitch and yaw attitudes are in the trimmed condition) is of the form

$$\frac{\delta g}{\delta \varphi} = \frac{K_V s}{s^3 + a_2 s^2 + a_1 s + a_0}$$

If the perturbations are assumed to occur from a trimmed condition (lift cancels centrifugal force) and the scale height of the atmosphere, H, is much less than the distance to the earth's center, the coefficients of the above expression are given by:

$$K_V = \frac{G^2 \sin \varphi_o}{H\sqrt{1 + (D/L)^2}}$$

$$a_2 = \frac{2G}{V\sqrt{1 + (L/D)^2}}$$

$$a_1 = \frac{g_o}{H}\left[1 - \left(\frac{V}{V_s}\right)^2\right]$$

$$a_0 = \frac{2GV}{Hr_o\sqrt{1 + (L/D)^2}}$$

The trim roll angle, φ_o, satisfies the expression

$$\frac{G \cos \varphi_o}{\sqrt{1 + (D/L)^2}} = g_o\left[1 - \left(\frac{V}{V_s}\right)^2\right]$$

Taking the values in Table I as typical, we find that $\varphi_o = \pm 120.5$ deg, and the transfer function representing the trajectory dynamics to be given by:

$$\frac{\delta g}{\delta \varphi} = \frac{0.000492s}{(s - 0.01578)\left[s^2 + 2(0.275)(0.05)s + (0.05)^2\right]}$$

where the dimensions of K_V have been converted to g/sec^2 per degree.

TABLE I. TYPICAL TRAJECTORY PARAMETERS

G	258 ft/sec^2 (8g)
H	23,500 ft
L/D	0.4
V_s	25,500 ft/sec
V	41,000 ft/sec (1.6 times circular velocity)
r_o	20.9 X 10^6 ft
g_o	31.15 ft/sec^2

The dynamics are seen to consist of a stable complex pair of poles together with an unstable pole/zero dipole near the origin of the s-plane. At frequencies far from the origin relative to the complex poles, the dynamics are equivalent to a double integration of the roll attitude perturbations with a very low gain.

A problem arises in attempting to explain how the pilot controls this system. If the roll attitude (φ) and deceleration level (g) are displayed to the pilot, there are at least two ways of closing appropriate feedback loops for control. The first, and perhaps most obvious, is a multiloop technique in which the roll attitude loop is closed as an inner loop, the deceleration level loop as an outer loop. In this instance, the roll loop would be expected to be closed tightly enough to move the roll dynamics and associated phase lags to frequencies higher than the desired closure frequency for the outer (g) loop. The effective controlled element dynamics for the outer loop then approaches a K_c/s^2; and for reasonably tight inner loop closures it appears that a stable outer loop closure in the region of 1 rad/sec should be readily attained.

Unfortunately for this hypothesis, the pilot has only a vague idea of the trim roll attitude corresponding to the desired g-level (the trim roll attitude changes with flight parameters; see page 6). He therefore has no way of converting g or $\dot{g}$ error into specific φ commands, the roll attitude error cannot be precisely established, and, consequently, a high gain closure of the φ loop is of little benefit.

An alternate control technique is a single-loop closure of deceleration level in which roll attitude is either ignored or employed as a control limiting criterion. (Too large a roll excursion implies rapid, and perhaps uncontrollable, rates of deceleration level change.) This results in controlled element dynamics of the form K_c/s^3 and a lower pilot gain than the quasi-linear model would predict. While such dynamics have been controlled by human operators under some circumstances, they generally are avoided wherever possible because the pilot must generate a second-order lead to achieve stable control. This task is sufficiently difficult and the handling rating so low that little research has been directed toward determination of pilot characteristics and/or closure criteria for the task. However,

extrapolation of the effects shown in Ref. 6 (these show decreasing crossover frequency with increasing order of the controlled element dynamics) leads one to suspect that if stable operation is to be achieved, it would have to be at quite low frequency.

Experiments performed on entry vehicle simulations (Ref. 4), as well as simplified versions (where the roll and trajectory dynamics are simplified to the forms K_c/s and K_c/s^2, respectively), show deceleration control to be characteristically oscillatory at a very low frequency ($0.07 \leq \omega_{co} \leq 0.3$, depending on the system gain, a function of trim deceleration level and display gain). Further, preliminary experimentation as a part of this study indicated that the pilot may concentrate almost entirely on the deceleration level display, although the roll attitude display is within his peripheral (i.e., extrafoveal) view. It was also shown that the pilot does not necessarily need the roll display when tracking deceleration level once he has achieved near-equilibrium conditions with respect to the trajectory dynamics. Removal of the roll attitude display resulted in little change in the closed-loop response (frequency and rms error). Thus at the present time it is felt that the pilot does not close the roll loop in the usual sense, but rather that he uses it as an indication and/or limiter of his control action in the regulation of the deceleration level.

A block diagram of the system is shown in Fig. 9, where the quantities m_c, m_e, and m_f represent g-level motion quantities in degrees of display deflection. Since experimental evidence suggests a crossover frequency on the order of 0.3 rad/sec for this situation, the vehicle dynamics approximate K_c/s^3 if the pilot uses sufficiently small manipulator deflection for τ_R to be less than 1 sec. The low crossover frequency requires that the low frequency pilot model of Ref. 6 be employed for Y_p and, in addition, a second lead must be included. Thus the pilot model proposed is of the form:

$$Y_p = K_p \underbrace{\frac{\left(\frac{s}{0.1}+1\right)}{\left(\frac{s}{0.15}+1\right)}}_{\text{Low frequency lag/lead (neuromuscular)}} \underbrace{\left(\frac{s}{0.15}+1\right)^2}_{\text{Lead compensation}} \underbrace{e^{-0.7s}}_{\text{High frequency lags (including high frequency neuromuscular elements)}}$$

It should be noted that the assumed form and magnitude of the second-order lead is quite arbitrary. The means by which the pilot generates lead is not fully understood. One means would be the detection of rate (for first-order lead) and acceleration (for second-order lead) information from the displayed quantity. However, it also has been noted in past experimental work that the pilot adopts a pulsing-type control technique when generating lead (the greater the lead requirement, the greater the pulsing tendency). It has therefore been hypothesized and shown analytically that the pilot can employ the pulse technique to generate very low frequency lead approaching that of pure differentiation. For the purpose of the present discussion, the requirement for the second-order lead, rather than the means of generating it, is the important factor.

An effective pilot lag of 0.7 sec has been assumed by way of extrapolation (Ref. 6 shows $\tau_e = 0.33, 0.36, 0.52$ for $Y_c = K_c, K_c/s, K_c/s^2$, respectively), together with a low frequency lag/lead of a smaller separation than normal. The latter is assumed in order to reduce the low frequency neuromuscular lag contribution, and implies a lower level of neuromuscular tension than has been exhibited in experiments where crossovers occur at frequencies higher than 1 rad/sec. The second-order lead is chosen arbitrarily to give the required crossover frequency at an amplitude gradient of 20 dB/decade.

The resulting system survey for the 8g tracking task is shown in Fig. 10. The closed-loop response has good low frequency characteristics (a relatively high open-loop gain at frequencies below crossover), but has phase lead in the closed-loop response below crossover together with a peaked response (greater than unity closed-loop response) in the region of crossover. These characteristics are a consequence of the compensation used and the low phase margin available. Fortunately, not much phase margin is required for the very low frequency input disturbances encountered. While the system survey reflects what is known about control of this type of element, considerably more work is necessary to validate such pilot models. In this connection, limited experimental work on other contracts at STI would suggest crossover frequencies on the order of 1 rad/sec to be possible for K_c/s^3-type elements having higher gains than those typical for low L/D entry vehicles.

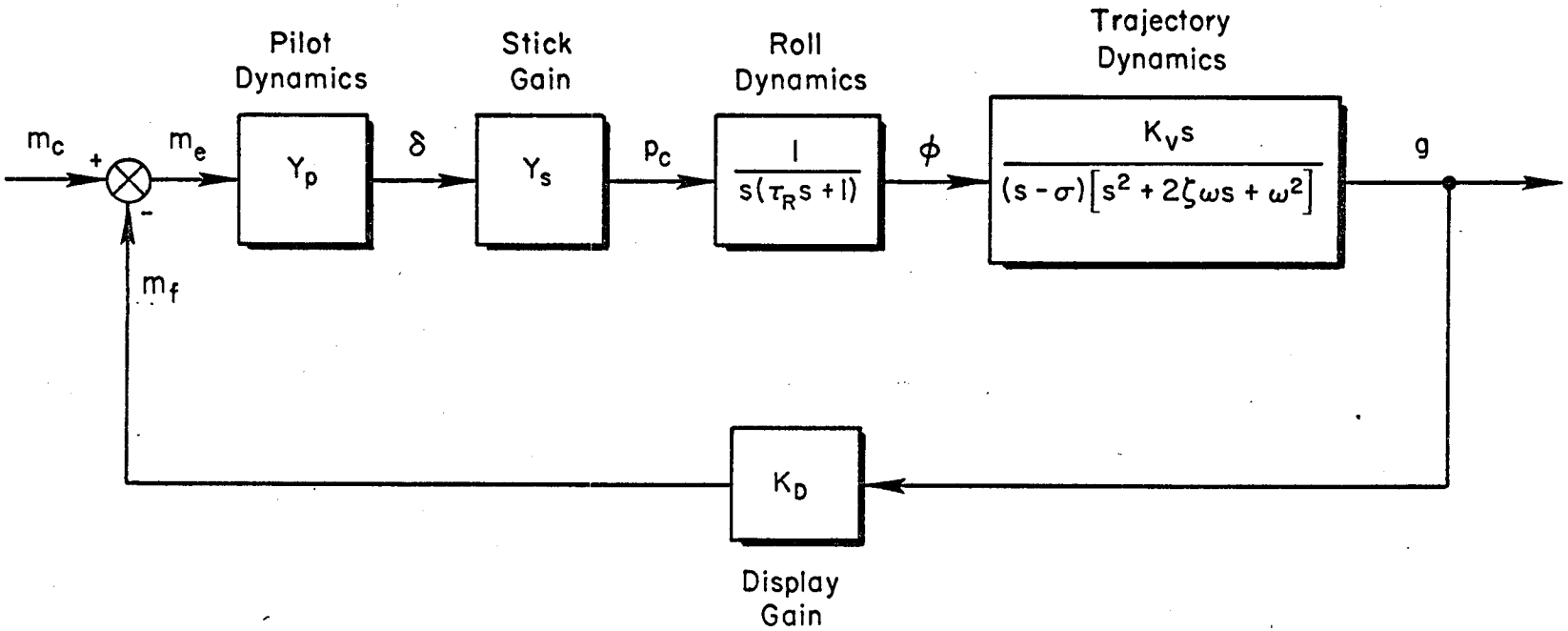


Figure 9. Block Diagram of Deceleration Level Control Channel

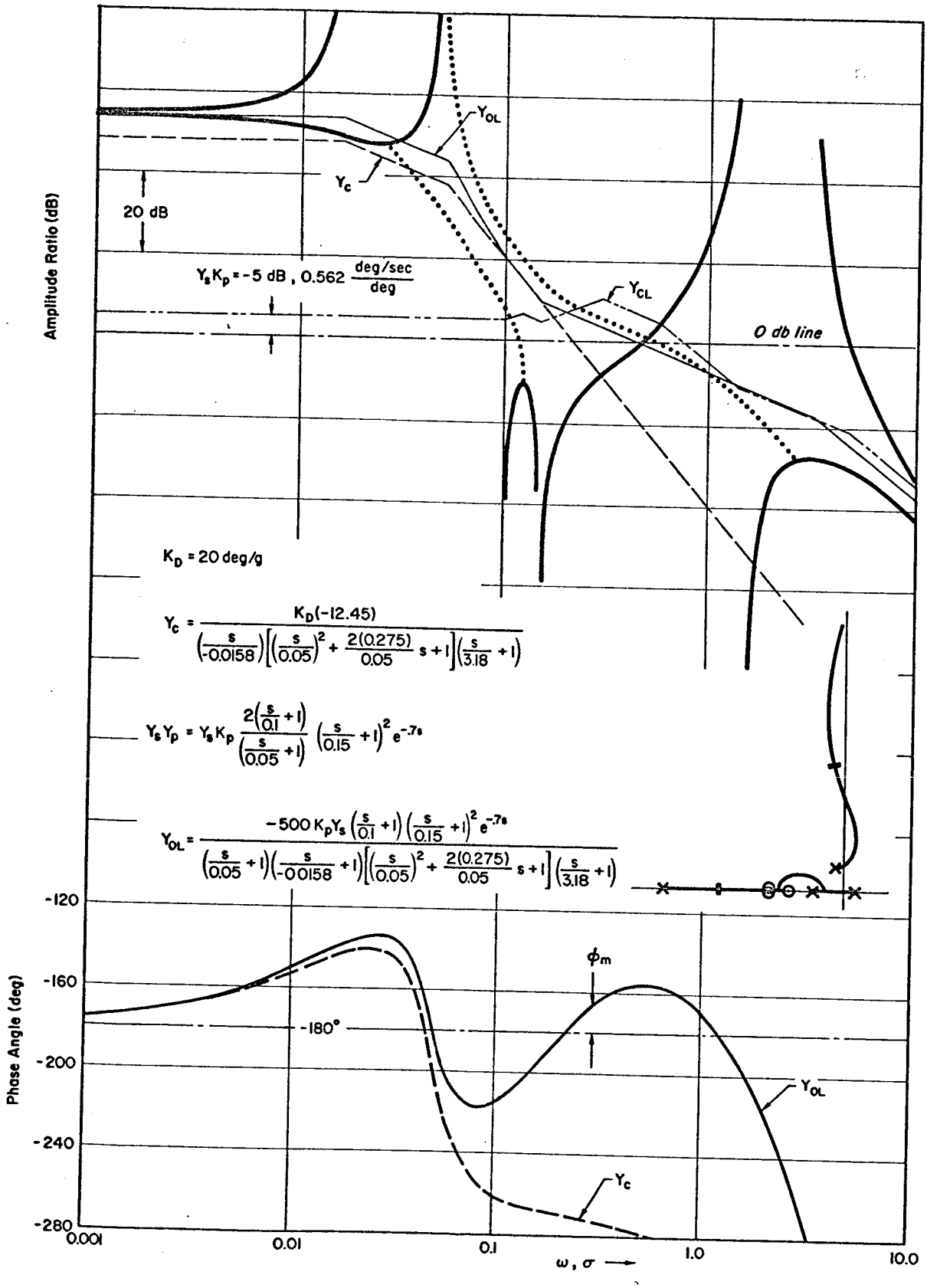


Figure 10. System Survey for Regulating Deceleration Level

To summarize this subsection, we note the following points:

- The controlled element dynamics pertinent to regulation of the deceleration level in an Apollo-type vehicle have the form (in the region of crossover) of K_c/s^3.
- The pilot generates a second-order lead at low frequencies (either from motion quantity acceleration or from critically timed control pulses) to stabilize the system.
- At the low crossover frequencies typical of such operation, the higher frequency lags of the vehicle and pilot assume a lesser degree of importance.

5. Regulating Deceleration Level, Direct Mode

For this mode to exist it must be assumed that both the rate damper and the guidance system have failed. The primary difference between this case and that analyzed previously is that the pilot now must perform the attitude rate damping function in addition to deceleration control. The effective vehicle dynamics for deceleration level control are approximately K_c/s^4.

Since any manipulation of the control stick results in angular acceleration, the pilot must pay attention to the roll attitude display to ascertain that any selected roll attitude is being maintained. As in the previous case, the pilot does not know the trim roll attitude and hence cannot discern φ_e directly. However we can discern rate of roll (dependent on the display gain) and therefore might be expected to employ the following control strategy:

- Select a roll attitude, φ, and stabilize to this attitude (requires generation of a first-order lead).
- Maintain zero rate of roll (no lead required)
- Observe the g-meter and estimate the timing and amplitude of the next change in roll attitude (involves the generation of a second-order lead).
- Repeat the operation.

In effect, the above strategy results in the pilot regulating and tracking in two loops simultaneously. For the inner, regulating, loop task (maintaining zero roll rate) the vehicle dynamics approximate a K_c/s. For the outer, tracking, loop the vehicle dynamics approximate a K_c/s^3. However, it must be noted that the accomplishment of the outer loop tracking also involves periodic,

momentary switching to a roll attitude change, acquisition, and stabilization task which requires first-order lead generation.

Thus, in controlling deceleration level in the direct mode the pilot must divide his attention between two displays (φ and g), must regulate vehicle motion in one loop while tracking in another, and must periodically switch his internal equalization generation from a first- to a second-order lead. This over-all task is appreciably more difficult than that of deceleration level control with the dampers operative and is considered to be unacceptable.

Rather than attempt a closed-loop synthesis of this task, let it suffice to note that one would expect the pilot's effective time delay, τ_e, to be increased. Referring back to Fig. 10 for the outer loop task, this will force the pilot to decrease his second-order lead time constants in order to maintain some phase margin. At the same time the outer loop gain must be decreased. The decrease in closed-loop bandwidth and phase margin should result in a proportional decrease in tracking performance.

SECTION III

PILOTING TASKS AND PROCEDURES

The essential control problem associated with atmospheric entry is that of maneuvering the vehicle to the approximate center of the entry corridor and maintaining the vehicle within this corridor until subcircular velocity is achieved. The tasks and procedures required to accomplish this call for a spectrum of piloting skills, and these skills can be expected to deteriorate as a result of the high-g environment aggravated by any physiological deconditioning which the pilot may have undergone because of his long sojourn in the weightless state. In this section the tasks and procedures required to accomplish successful entry are presented, followed by an identification of the skills employed. This section is concluded by a summary of what is known concerning skill decrements resulting from the pilot's environmental history (long duration weightlessness, followed by high entry g-levels).

A. CAPTURE PHASE

The double integration form of the trajectory dynamics (i.e., the deceleration level time history is approximately equal to the double integral with respect to time of roll attitude changes from trim conditions) means that the rate of change of deceleration level at the beginning of entry is quite small and deviations from nominal are difficult to detect. At the same time, any roll maneuvers required because of off-nominal conditions must be made early in the capture phase to produce the desired changes in the deceleration level history later on. The roll maneuvers required in the early stages of the capture phase therefore have a high degree of criticality associated with both the timing and amplitude of these maneuvers.

Roll maneuvers later on during the capture phase can also be quite critical. The usual technique employed in most studies of atmospheric entry is to use the maximum maneuvering capability of the vehicle, i.e., bang-bang changes in roll attitude from 0° to 180°, to maximize the range of allowable dispersions in entry conditons. The roll maneuver shown in Fig. 1 is an example — the vehicle has entered at a relatively steep flight path angle, requiring zero roll attitude (to prevent excessive peak g-load). When peak-g is reached,

the vehicle must be rolled by 180° to assure remaining captured. The timing of this maneuver is quite critical (see, for example, Ref. 8) and makes high demands on the pilot in his possible role as a substitute for the guidance computer during entry, particularly in view of the high deceleration level (see Fig. 1).

Another typical entry technique might be assumed with a view toward minimizing the criticality of vehicle roll maneuvers. For example, the vehicle may be entered at some intermediate value of roll attitude (between 0° and 180°). This attitude might be determined by predicted (from on-board and ground information) entry conditions and chosen such that, under these conditions, only small corrective roll maneuvers would be required to achieve capture. These corrections might be based on timing indications such as the time interval between corridor warning lights (see Fig. 3). A long time implies the need for a corrective roll closer to 180°; a short time implies the opposite, a roll toward 0°. Further time indications may be used in much the same fashion, e.g., the time interval between the last extra-atmospheric velocity correction and the first warning light, and the time interval between the second light and the g-level corresponding to the skipout boundary. These relieve the pilot of having to base the roll maneuvers on the low level of deceleration and its slow rate of change early in capture phase. Unfortunately, entry at such intermediate roll attitudes will generally lead to higher peak deceleration levels.

The tasks and procedures required of the pilot during capture phase are listed in Table II together with the piloting skills employed. In the event of various failure indications, additional tasks are needed. These tasks and their associated skills (which also apply to the remaining phases of entry) are given in Table IV.

Both tables show that the pilot's tasks during capture consist of visual monitoring (meters, lights, etc.), manual overrides (discrete actions), and continuous control over roll attitude, with gross maneuvering being based on discrete decisions. The most difficult tracking task involves control of roll attitude in the direct mode (no automatic damping of roll rates). The most crucial situation occurs when there is a failure in the stabilization and control system which causes a rapid divergence in attitude. This must be

overcome quickly, particularly when the corridor depth is quite narrow, otherwise the vehicle may exceed the tolerable g-level or skip out of the atmosphere.

B. DECELERATION LEVEL CONTROL PHASE

During this phase the pilot has the task of regulating the g-level to the desired point as determined by the skipout boundary, his deteriorating physiological state, and (within these two survival constraints) ranging considerations. Cross-range control is achieved by rolling the vehicle at intervals to the opposite sense, i.e., if the trim condition is $\varphi = 120^{\circ}$ he rolls to $\varphi = -120^{\circ}$. It is essential that the guidance system employ basically the same principal that the pilot would employ in entry to increase his ability to detect malfunctions. In addition, a skipout monitor such as that proposed in Ref. 4 (see Fig. 3) may be employed as a warning of impending skipout.

The tasks, procedures, and associated skills are listed in Table III and (for failure conditions) Table IV. Again, these tasks consist of monitoring functions, manual override as required, and continuous control activity in the event one or more failures have occurred in the flight control and/or guidance systems. The most difficult control task is that of regulating to a fixed g-level (GNS failed), particularly if the roll attitude is being controlled in the direct mode. As before, a rapidly diverging roll attitude is perhaps the most crucial type of failure, particularly since the pilot's responses are deteriorated at the high g-levels associated with this phase.

C. PILOTING SKILLS

The tasks and procedures outlined in the preceding subsections imply pilot exercise of various functional capabilities or skills as shown in the third column of Tables II, III, and IV. These skills are fundamental to the pilot's role in the control of the vehicle during entry, and are interrelated from both the physiological and task performance points of view. Several skills are typically employed in the performance of any particular task.

The various functional capabilities (skills) required for entry vehicle control may be divided into three categories: sensing, central processing,

TABLE II. PILOT TASKS AND PROCEDURES, CAPTURE PHASE

MAJOR TASKS	SUBTASKS	SKILLS
Verify guidance and flight control system operation. Requires monitoring of automatic systems — GNS (if operative) and SCS. Also requires that the pilot have in mind appropriate responses to failure situations.	Verify SCS in entry mode. Focus on status panel and actuate switch if SCS is not already in entry mode.	Sensing..... Visual acuity, ocular motility Central processing.. Decision-making Actuating..... Actuation (arm and hand)
	Verify operation of SCS. Focus on FDAI and take appropriate action, such as switching to direct mode, if system is behaving improperly.	Sensing..... Visual acuity, ocular motility, audition (jets) Central processing.. Decision-making Actuating..... Actuation (arm and hand)
	Verify operation of GNS. Scan panel to verify proper operation of GNS.	Sensing..... Visual acuity, ocular motility Central processing.. Decision-making
	Track commanded roll attitude (optional if GNS operative) and stabilize rates. Commands self-generated if GNS has failed. Focus on FDAI, or backup roll attitude meter, and manipulate control stick.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Coordination, lead generation* Actuating..... Actuation (hand)
Maneuver to achieve required peak deceleration level. Done automatically if all systems are functioning properly. However, the pilot can override at any time.	Determine appropriate roll attitude. (Based on the time increment between 0.05g and 0.2g lights). Focus on clock.	Sensing..... Visual acuity, ocular motility Central processing.. Decision-making
	Verify operation of GNS (if operative). Scan panel to verify proper operation of GNS.	Sensing..... Visual acuity, ocular motility Central processing.. Decision-making
	Make required roll correction (optional unless GNS has failed). Focus on FDAI, or backup roll attitude meter, and manipulate control stick.	Sensing..... Visual acuity, ocular motility Central processing.. Decision-making, coordination, lead generation* Actuating..... Actuation (hand)
	Monitor DLI for estimate of time to reach skipout boundary. Focus on DLI.	Sensing..... Visual acuity, ocular motility Central processing.. Decision-making
Roll maneuver to insure remaining captured. Required when GNS inoperative. But pilot must be able to execute it should the GNS become inoperative during this phase.	Determine proper roll trim attitude. Scan panel.	Sensing..... Visual acuity, ocular motility Central processing.. Decision-making
	Verify GNS operation (roll attitude commands proper for this point in entry). Scan panel.	Sensing..... Visual acuity, ocular motility Central processing.. Decision-making
	Make required roll maneuver (optional unless GNS has failed). Focus on FDAI, or backup roll attitude meter, and manipulate control stick.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Coordination, lead generation* Actuating..... Actuation (hand)
	Monitor status of vehicle attitudes, rates, and deceleration level. Scan FDAI, DLI, status panels, etc.	Sensing..... Visual acuity, ocular motility, visual beamwidth
	Decide on roll correction if predicted conditions at peak-g are improper.	Central processing.. Decision-making
	Make correction maneuvers. Focus on FDAI, or backup roll attitude meter, and manipulate control stick.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Coordination, lead generation* Actuating..... Actuation (hand)

*Lead generation required if controlled element is K_c/s^2

TABLE III. PILOT TASKS AND PROCEDURES DURING DECELERATION LEVEL CONTROL PHASE

MAJOR TASKS	SUBTASKS	SKILLS
Verify operation of GNS and SCS. Essentially a monitoring task in those cases where the GNS is operative.	Verify GNS for proper roll commands. Scan FDAI and DLI.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Decision-making
Roll attitude control. At pilot's option if all systems are operating; required only if roll dampers have failed.	Closed-loop control of roll attitude command provided by GNS. Focus on FDAI or roll error indication, cross-check with DLI, and manipulate control stick.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Coordination, lead generation* Actuating..... Actuation (hand)
Deceleration level control. Required only when GNS has failed.	Closed-loop control of deceleration level. Focus on DLI, cross-check roll meter, and manipulate control stick.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Coordination, lead generation* Actuating..... Actuation (hand)
Cross-range error control. Required only when GNS has failed.	Interrogate pilot/navigator for cross-range information	Sensing..... Audition
	Determine if roll maneuver is required, and when. Scan panel.	Sensing..... Visual acuity, ocular motility Central processing.. Decision-making
	Perform time-optimal roll attitude change to attitude of opposite sign. Focus on backup roll attitude meter and manipulate control stick.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Coordination, lead generation* Actuating..... Actuation (hand)
	Closed-loop control of deceleration level. Focus on DLI and manipulate control stick.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Coordination, lead generation* Actuating..... Actuation (hand)

*Lead generation required if controlled element is K_c/s^2, K_c/s^3, or K_c/s^4

and actuating. Vision and audition fall into the first category; controller manipulation into the last; all the rest are carried out (for the most part) within the central nervous system. In some cases the division is more or less arbitrary; for example, ocular motility involves subsystems which are located in the visual and central nervous systems, yet it is referred to as a sensing skill. However, for the purposes of this study we shall define the skills as follows:

1. **Sensing Skills**

Visual acuity — Involves the ability to discern detail within the foveal view, e.g., dial readings and needle motion.

Ocular motility — Involves the ability to move the eye in a controlled manner and visually fixate on different points on the display panel.

Visual beamwidth — The peripheral visual angle or cone of vision which determines the ability to assimilate information from displays outside the foveal view.

Audition — Involves the ability to detect and discriminate among sounds.

2. **Central Processing Skills**

Coordination — The ability to integrate visual, vestibular, and tactile information and to command limb movements.

Decision-making — Involves detection, assimilation, comparison, and long term memory, short term memory, etc., i.e., all mental processes leading to discrete, conscious decisions.

Lead generation — The means by which lead generation is accomplished are not clear; it may be accomplished within the eyeball (the optic nerve transmitting signals proportional to display rate), or centrally (via processing of the visual information to yield velocity and/or acceleration information), or even a combination of the two.

3. **Actuating Skill**

Actuation — This, as distinct from what has earlier been described as "coordination," refers to the pilot's physical ability to actuate buttons, switches, and his side arm controller, and also to assimilate kinesthetic information on the performance of the motor task. The capability might better be referred to as "neuromuscular skill" because the neuromuscular system is the actuating element within the pilot.

TABLE IV. PILOT TASKS AND PROCEDURES FOR FAILURE INDICATIONS DURING BOTH CAPTURE AND DECELERATION LEVEL CONTROL PHASES

EVENT	DECISION/ACTION	SKILLS
FDAI shows improper roll commands relative to DLI reading.	GNS failed; pilot to supply own commands. Scan FDAI and DLI.	Sensing..... Visual acuity, ocular motility Central processing.. Decision-making
	Disable GNS (see Fig. 4). Actuate switch.	Sensing..... Visual acuity, ocular motility Central processing.. Coordination Actuating..... Actuation (arm and hand)
	Make appropriate roll maneuvers. Focus on FDAI, backup roll attitude meter, or DLI and manipulate control stick.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Coordination, lead generation* Actuating..... Actuation (hand)
FDAI shows oscillatory roll about commanded attitude. System in rate mode.	Roll gyro failed; pilot to provide rate damping. Scan FDAI.	Sensing..... Visual acuity, ocular motility, audition (jets) Central processing.. Decision-making
	Deflect stick to oppose rates. Manipulate control stick.	Central processing.. Coordination Actuating..... Actuation (hand)
	Disable rate mode (go to direct mode, see Fig. 4). Actuate switch.	Sensing..... Visual acuity, ocular motility Central processing.. Coordination Actuating..... Actuation (arm and hand)
	Track commanded roll attitude (if GNS operative) or regulate deceleration level (if GNS inoperative). Focus on FDAI, backup roll attitude meter, and/or DLI and manipulate stick.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Coordination, lead generation* Actuating..... Actuation (hand)
FDAI shows undamped pitch or yaw oscillations. System in rate command mode.	Pitch or yaw gyro failed; pilot to provide damping. Scan FDAI.	Sensing..... Visual acuity, ocular motility, audition (jets) Central processing.. Decision-making
	Deflect stick to oppose rates. Manipulate control stick.	Central processing.. Coordination Actuating..... Actuation (hand)
	Disable rate mode in appropriate channel (go to direct mode Actuate switch.	Sensing..... Visual acuity, ocular motility Central processing.. Coordination Actuating..... Actuation (hand and arm)
	Stabilize rates. Focus on FDAI and manipulate control stick.	Sensing..... Visual acuity, ocular motility, visual beamwidth Central processing.. Coordination, lead generation* Actuating..... Actuation (hand)
FDAI shows slow divergence of pitch or yaw attitude. System in rate mode.	Reaction jet failed open. Scan status panel.	Sensing..... Visual acuity, ocular motility, audition (jets) Central processing.. Decision-making
	Pilot disables jet (see Fig. 4). Actuate switch.	Sensing..... Visual acuity, ocular motility Central processing.. Coordination Actuating..... Actuation (arm and hand)
FDAI shows roll attitude bias, and continuous jet firing heard. System in rate mode.	Reaction jet failed open. Scan status panel.	Sensing..... Visual acuity, ocular motility, audition (jets) Central processing.. Decision-making
	Pilot disables jet (see Fig. 4). Actuate switch.	Sensing..... Visual acuity, ocular motility Central processing.. Coordination Actuating..... Actuation (arm and hand)
FDAI shows rapid divergence in any channel. System in direct mode.	Reaction jet failed open. Scan status panel.	Sensing..... Visual acuity, ocular motility, audition (jets) Central processing.. Decision-making
	Pilot deflects stick to oppose divergence. Manipulate control stick.	Central processing.. Coordination Actuating..... Actuation (hand)
	Pilot disables jet (see Fig. 4). Actuate switch.	Sensing..... Visual acuity, ocular motility Central processing.. Coordination Actuating..... Actuation (arm and hand)

*Lead generation required if controlled element is K_c/s^2, K_c/s^3, or K_c/s^4

TABLE V. ENVIRONMENTAL EFFECTS ON PILOTING SKILLS

SKILLS	HIGH-G EFFECTS	LONG DURATION WEIGHTLESSNESS EFFECTS	OTHER ENVIRONMENTAL FACTORS	CRITICAL ASPECTS	EXPERIMENTAL SKILL MEASURES	INFLUENCE ON DESIGN
Sensing: Visual acuity	Deteriorates with increasing g-level and, at high enough g, with time as well. Manifestations are blurring (due to tearing and/or as a precursor of grayout), peripheral vision losses, grayout, and blackout.	All visual functions heavily dependent on blood supply to visual system. Therefore, cardiovascular deconditioning due to weightlessness will influence high-g performance.	Blood supply affected by restraint system, principally back angle. Also, long missions imply some radiation danger, leading to opacities in lens and cornea. Low illumination level will deteriorate skill.	Control tasks requiring high pilot gain (deceleration level control, for example) at high g-levels. For this example, increasing controlled element gain may outweigh acuity losses.	Laudolt ring or Snellen chart tests of visual acuity. (However, no correlation with skill as a closed-loop controller has been established.)	Illumination level, instrument design, and display gain.
Sensing: Ocular motility	Limited ocular motility (eyes fixed in central position, attempts to overcome are ataxic, uncoordinated) occurs at some point between grayout and blackout. Direct mechanical effects may contribute.	See above.	Blood supply is influenced by restraint system parameters, principally back angle.	Critical when control task requires foveal fixation on several displays in succession, i.e., latter part of capture maneuver.	Observation of eye movements in task situations requiring it, i.e., visual tracking of moving light. Also task performance measures in tasks requiring foveal fixation of time displays.	Display panel layout of instruments and indicator lights. Definition of environmental limitations versus monitoring complexity. Allowable task complexity.
Sensing: Visual beamwidth	Affected by peripheral vision losses, secondarily by peripheral perception losses due to emotional stress (tunneling of vision).	See above.	See above. Peripheral vision losses depend on stimulus, i.e., meter motion or light stimuli.	Critical in situations where response to peripheral displays (lights and meters) required, i.e., when g-level causes peripheral vision losses. Early detection of failure indications outside of foveal view.	Reaction time to peripherally located lights; task performance measures where peripheral monitoring of secondary display required.	See preceding.
Sensing: Audition	Very little direct effect. It is known, for example, that a subject can hear after vision has blacked out.	Unknown; probably minor.	Background noise in communication system and aerodynamic noise.	Most critical when response to spoken commands is required in high stress situations (e.g., latter part of capture phase) when information may not register on central processing system.	Audio acuity tests.	Extent of usability of audio cues.

(Continued on next page)

Central processing: Coordination	Tracking task measures show deterioration with increasing g-level. Probably correlated with deterioration in all central processes with increasing g and time (at sufficiently high g-level).	All central processes heavily dependent on blood supply to brain. Therefore, cardiovascular deconditioning will affect this. Also, vestibular system's adaptation to zero-g could have adverse effect.	Blood supply affected by restraint system.	Visual illusions (if they occur) or increased subjective sensitivity to g-level may cause pilot to disbelieve the instruments.	Tracking task performance measures with motion cues.	Allowable tracking task complexity.
Central processing: Lead generation	Probably deteriorates along with all other central processes to the extent that lead generation is a central process as opposed to a visual process. Visual system deterioration will also influence this skill.	Deteriorated by cardiovascular deconditioning; see preceding.	See preceding. Vibration also influences this capability, as does secondary work load.	Control of roll attitude (dampers out) or deceleration level at high-g.	Tracking task performance measures where task requires first-order and second-order lead generation.	Definition of whether certain failure conditions can be flown in emergencies; therefore, extent of flight control system and guidance system redundancy required. Environmental limitations on the above.
Central processing: Decision-making	Data are contradictory to some extent; however, most of it would indicate increasing reaction time, both simple and complex. Probably correlated with deterioration in all central processes.	See preceding.	Blood supply affected by restraint system. Emotional stress also impedes decision-making.	Most critical in failure detection at high g-levels; less so in the capture phase.	Simple and complex reaction time measures with various stimuli (perceptual distinctness heavily influences discrimination reaction time).	Definition of whether pilot can cope with various types of failure situations; therefore, extent of redundancy required.
Actuating: Actuation (hand)	Tracking task performance measures show deterioration with increasing g-levels, partially due to direct mechanical effects. Side arm controller manipulation is only movement possible above 8g or 9g.	Neuromuscular system deconditioning in weightlessness can presumably affect this. Also, there may be a training retention problem (no practice in a high-g field during mission).	Manipulator design parameters (centering force, spring gradient, shape, location, and actuating axis location) and suit restraints.	Inadvertent inputs at high-g. Degradation in timing and motion amplitude control.	Tracking task performance measures with manipulator design as the experimental variable.	Manipulator design.
Actuating: Actuation (arm and hand)	Increasing reaction time with g-level partially due to mechanical forces, particularly if test requires positive manipulation of button or switch.	See preceding.	Button and switch design parameters (location with respect to each other and with respect to actuating hand) and suit restraints.	Response to failure conditions requiring actuation of button or switch as part of the response at high-g. Degradation in timing and motion amplitude control.	Reaction time tests with button (or switch) design parameters varied.	Button and switch location and design.

It is clear from the above definitions that there are close ties between the various skills. In roll attitude control (direct mode) the pilot uses his capabilities of visual acuity, coordination, lead generation, and actuation. Add a secondary monitoring task, and the visual beamwidth, ocular motility, and decision-making abilities come into play. Finally, if he is assimilating status information from one of the other crewmen, audition becomes important. In the measurement of over-all performance in the entry role, attributing decrements therein to specific skill decrements becomes difficult, although considerable clarification results if the physiological aspects are taken into account.

D. ENVIRONMENTAL EFFECTS ON PILOTING SKILLS

In order to construct models of the human operator capable of predicting human performance in the entry environment, decrements in the piloting skills defined above must be quantitatively correlated with the major environmental variables of high entry g-levels following long duration weightlessness. An attempt was made, with very limited success, to obtain these correlations by reviewing the available literature. While there is a considerable volume of material on centrifuge experiments, the results presented do not permit definition of quantitative correlations. The literature on zero-g effects is much more limited and contains virtually no information of a quantitative nature. What can be qualitatively established from this literature review is presented in Table V.

This table gives a brief summary of the major environmental influences on the piloting skills defined above, together with an indication of the kinds of experiments used to evaluate these skills and their influences on vehicle design. The table represents a summary of the effects noted in Appendix A.

Briefly speaking, the regulation of the pilot's internal environment is disrupted. High g-levels impair respiratory efficiency which reduces the oxygen content of the blood. Blood pressure regulation mechanisms must cope with the large pressure differentials brought about by high g-levels, and these are deconditioned by long exposure to weightlessness. The end result is progressively increasing hypoxia of the tissues located at the highest levels with respect to the heart, i.e., the central nervous and visual systems. This

manifests itself in deteriorating pilot skills associated with these systems, as indicated in Table V.

In particular, the pilot's ability to react rapidly to an emergency situation, such as a sudden divergence in roll attitude, is compromised. This can be critical if the vehicle is close to the skipout boundary. The pilot's ability to control the vehicle in the more difficult control tasks, such as regulating the deceleration level (K_c/s^3-type controlled element), will also be deteriorated as the hypoxic effects become more severe. These two examples have important design implications — the panel space which can be effectively monitored by the pilot and the degree of redundancy in the guidance and flight control systems are both a strong function of the pilot's expected environment and the deconditioning which he has undergone.

Other effects due to long term weightlessness may include neuromuscular deconditioning because of lack of exercise, training retention problems (if the pilot has had no opportunity to maintain proficiency under high-g conditions), radiation effects on vision, and vestibular system adaptation to the weightless state. The end result is that some deterioration (over and above that due to high g-levels alone) is to be expected in all piloting skills except perhaps audition. This latter surmise might be used to advantage by the entry vehicle designer if he incorporates an audible backup to critical visual warnings. It may even be possible to use an audio display if the control task is relatively easy.

In this discussion there has been no reference to the quantitative decrement in these various skills. This reflects the current state of our knowledge, there being relatively little material in the current literature [e.g., Frazer (Ref. 9) for high-g effects, Lamb (Ref. 10) for weightlessness effects] which permits direct quantification of skill decrements with g-level or weightlessness duration. Past centrifuge experiments fall into two general categories: those measuring pilot performance (usually in some sort of tracking task, but also more direct measures such as reaction time, brightness discrimination, etc.), and those measuring physiological changes (respiratory and cardiovascular system performance measures). There have been very few attempts to correlate the two, even though the physiological aspects would indicate strong correspondence. Further, much of the work has been exploratory

(few runs, doubtful training to stable performance levels) and does not permit statistical inference.

The situation is even less clear with regard to weightlessness effects. Most of the past work has been oriented toward mitigating the deconditioning effects. Whether these techniques will suffice for long term missions is still an open question.

In summary, present physiological knowledge is such as to predict some deterioration in piloting skills under high-g which can be attributed to long duration weightlessness, although the extent is largely conjecture.

SECTION IV

MEASUREMENTS AND EXPERIMENTS

The preceding sections of this report have led to an identification of the gross and probable operational tasks and a definition of the piloting skills required, the latter being closely related to one or more human subsystems within the pilot. In addition, the general lack of quantitative knowledge on human performance under the environmental stresses associated with entry has been alluded to, and documented in Appendix A. The experiments described in this section are intended to fill in the gaps with quantitative measures of human system and subsystem performance such that the entry vehicle designer has sufficient data upon which to base design decisions. This section begins with a discussion on measurement techniques, continues with the experiments themselves, and concludes with a discussion of experimental priorities and organization within the context of a comprehensive program.

A. MEASUREMENTS

The various experiments outlined in the succeeding subsection may all be described as means by which human system (or subsystem) response to various stimuli under stressful environmental conditions can be determined. In effect, we seek to parameterize performance capabilities in terms of environmental conditions. To do this requires both performance and environmental measurements. The latter are discussed first as they are less complex (at least in principle).

1. Environmental Measurements

The basic purpose behind the environmental measurements described in the following paragraphs is to infer causal effects behind changes in human performance capabilities. This requires delving into the human's internal environment in some depth since his regulation of this environment (or lack thereof) is the primary reason (to judge by the available literature — see Appendix A) for performance decrements associated with his sensing, central processing, and actuating skills and their associated physiological subsystems. The environmental variables are therefore divided into two categories, external and internal.

a. External Environment. The primary variable here, at least in those experiments run on the human centrifuge, is the g-level itself. However, other factors of the subject's external environment can have an important influence, for example:

- Seat configuration and restraint system — in particular, the back angle of the seat relative to the acceleration vector. It is probably advisable to standardize this configuration early in an experimental program to permit meaningful comparison of the data obtained in a long duration series of experiments. Most pertinent, of course, would be the adoption of the system proposed for the entry vehicle.

- Suit — The suit to be used is also of prime importance, particularly since it has important functions in mitigating some of the physiological effects of high g-levels and also because it restricts freedom of movement, particularly of the manipulating arm and hand.

- Atmospheric composition and pressure — Here again, the ideal is probably the duplication of the entry vehicle.

- Temperature.

- Humidity (suit).

In all of these cases, the object is to obtain performance data for a uniform set of environmental conditions such that meaningful comparisons of performance can be obtained. When this is not the case, the differences in the environment should be carefully noted to permit the experimenter (or others) to infer the reasons behind changes which may occur in human performance.

b. Internal Environment. There is a more-or-less minimum set of biomedical instrumentation necessary before a man can be safely allowed to experience high g-levels (say, in excess of 10g) on a centrifuge. This is assumed to include his electrocardiogram, some indication of his respiration (both vital to his physical safety), and two-way communication with the experimenter and/or medical monitor, which is presumably recorded. These measurements are not sufficient to measure his internal environment for purposes of establishing cause/effect relationships between this environment and his performance in the experiment task. Two additional measurements

are needed, at a minimum. These primary environmental measurements are:

- Blood pressure — The ideal measurement would be intracranial blood pressure. Since this cannot be measured directly without "wet" preparations, blood pressure at heart level (systolic and diastolic, and by inference, pulse and mean blood pressures) will have to suffice, with the height difference between this point and the subject's head (or eyes) used to infer the blood pressure at these points.

- Arterial oxygen saturation — Here, the ideal measurement is the degree of hypoxia of the intracranial tissues, to which arterial oxygen saturation is closely related. It is most conveniently measured with an ear oximeter (see Appendix B), although at some cost in data accuracy for reasons outlined in Appendix B.

In addition to these measurements, certain others may prove useful at various times, e.g.,

- EMG of postural muscles — an indicator of the pilot's "straining," and his fatigue in doing so — less directly related to regulation of internal environment.

- EEG — to measure the state of consciousness. This has been extensively used in Russian centrifuge experiments (see Appendix A, Section 2, p. A-19) with on-line spectral analysis, and is convenient if the evoked response is used as a pilot performance measure in various experiments.

- Measures of inspired and expired gas composition.

- GSR/EDR — to permit inference of the emotional contribution to the subject's response.

If the data obtained from the experimental program establishes a clear causal relationship between blood pressure and arterial oxygen saturation on the one hand, and performance in a task on the other, it may be possible to predict additional performance decrements in the high-g environment attributable to deconditioning of the cardiovascular and respiratory systems alone. If this deconditioning can be related to duration in a space environment (see Ref. 12) it would then be possible to introduce mission duration into the prediction of entry performance.

2. Performance Measurements

The purpose of performance measurements is to find or infer particular properties of the human system or subsystem by appropriately processing the input and output signals. It is therefore necessary to supply an input stimulus (either continuous or transient) which will cause the output (response) to display the system properties. From a task performance measurement standpoint, one can classify responses as either open-loop or closed-loop. The major differences between these lie in the character of the stimulus over the time period of interest:

- Open-loop — output has no effect on the stimulus, or the stimulus triggers a preconditioned response (e.g., turn switch off or on, initial response to a step command)
- Closed-loop — output alters the stimulus

Note that the task under consideration may be closed-loop in either case, e.g., for step input tracking, the initial response may be open-loop (triggered response), and the final response closed-loop. The performance measures and measuring techniques are different for each.

a. Open-Loop Performance Measures. In the above context, open-loop responses usually result from discrete or transient stimuli. Here the occurrence of the stimulus is readily identified and the relative time-to-response or some measure of "goodness" of response is desired. The response is not, generally speaking, a discrete event in time (e.g., a "reaction time") but rather a transient, whose character may be described by indicial response measures as shown in Fig. 11. More subtle measures might be related to the:

- shape (smooth, rectangular, pulse, spike)
- number of reversals within the settling time
- amplitude

b. Closed-Loop Performance Measures. For closed-loop measurements there are at least five levels of performance measures; each level provides more information and on a somewhat different basis, e.g.,

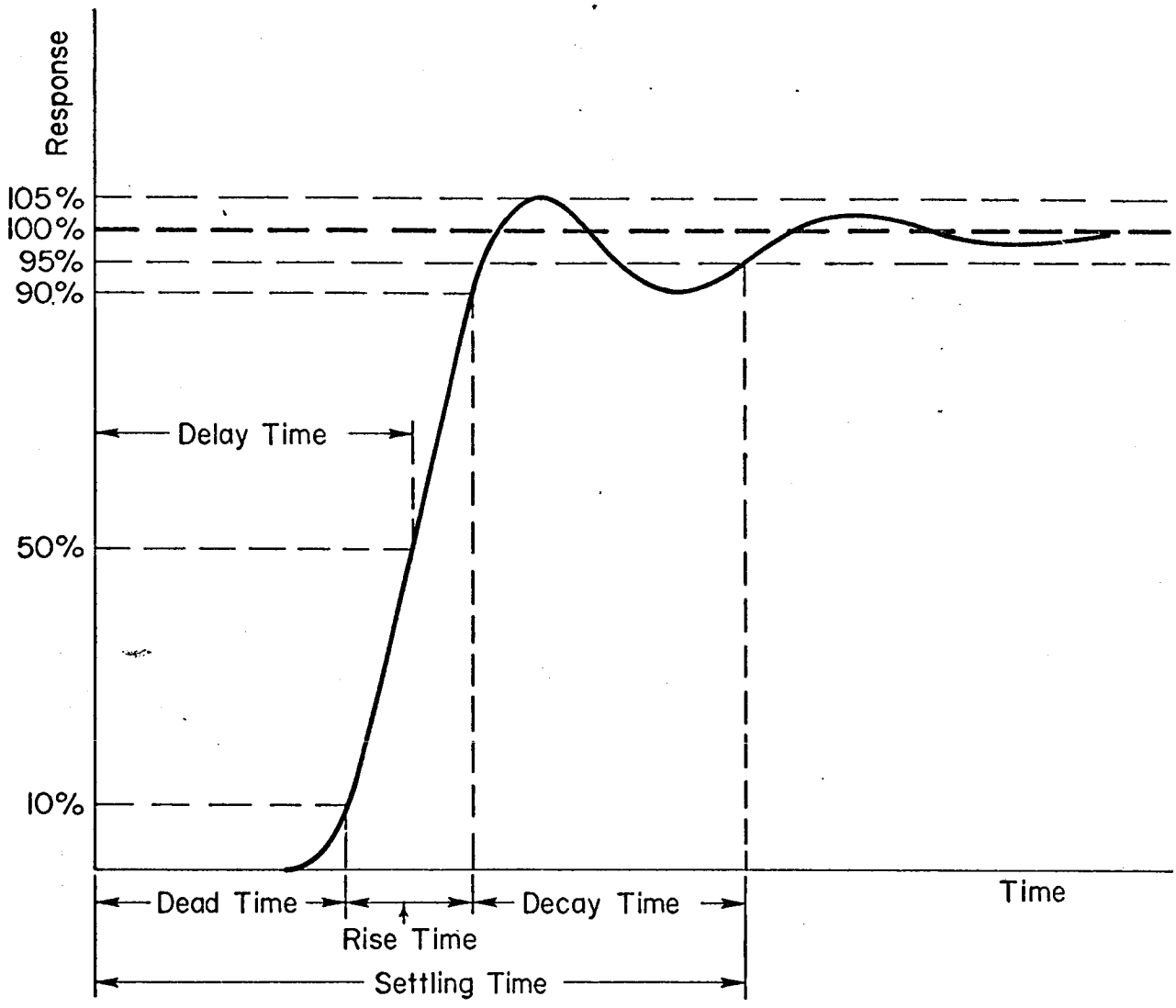


Figure 11. Indicial Response Measures (Adopted from Ref. 15)

- Strip chart trace (general waveform, number of axis crossings, etc.)
- Absolute value, $|q|$, or mean square value, $\overline{q^2}$
- Power spectral density, Φ_{qq}, and amplitude distribution, P_q
- Describing function, Y_p, and remnant, Φ_{nn}
- Nonlinear model-matching

Variations on the more sophisticated analysis techniques include quasi-linear, time-varying, on-line and off-line. A summary and comparison of the numerous techniques (e.g., Refs. 6, 14-19) is beyond the scope of this effort. However, an apparently little-used but highly effective technique worthy of special mention is the time-trace model-matching method of Ref. 20. For this method it is desirable that some level of pilot describing function model be used as a starting point, but the advantages include:

- Various nonlinearities, including pure time delays, limiting criteria, etc., can be easily incorporated and adjusted to improve the match.
- It uses a high quality data analyzer and evaluator— the human eyeball and brain— which has extreme flexibility in "homing" on a "match" which involves nonlinearities, changing criteria, etc.

c. Bioelectric Measurements. The foregoing measures have all been oriented toward determining human task performance, that is, the performance of the human element in the man/machine system. Of crucial importance in understanding the why's of human task performance limitations under environmental stress are measurements of human subsystem performance. For example, consider the degradation in tracking performance measured under high g-forces. Is the degradation primarily due to visual or central nervous system decrement? The answer to these kinds of questions lies in measuring signals within the operator, i.e., measurement of bioelectric potentials.

Appendix B discusses several of these measures, three of which are judged to have the most promise for determining human subsystem performance:

- EEG — electroencephalogram. For measuring the evoked response to discrete stimuli. Correlation of the evoked response in the cerebral cortex can, at least in principle, measure the sensing lag— the time between the stimulus and its appearance in the cortex. The stimulus must, generally speaking, be discrete, although there has been some work in correlating continuous stimuli with continuous cortical responses.

- EMG — electromyogram. For determining the first appearance of muscular electrical activity relative to either the sensory stimulus, or the evoked response in the cortex — the latter a measure of the central processing lag. Correlation of the EMG to manipulator motion is an indicator of the actuating lag.

- EOG — electro-oculogram. For determining visual system performance and inferring the information needs of the operator in a control task. In particular, the EOG can be used in measurements of ocular motility.

The state of the art in obtaining and recording these measurements is well developed, but interpretation is less clear. In the case of EOG, interpretation is clear provided the proper experimental protocol is followed (see Appendix B). Discrete electrical activity can be easily detected in the EMG as well, although special processing is required if these signals are to be correlated directly with the forces exerted — see Appendix B.

However, the EEG presents a problem. Detection of the evoked response against the background of the typical "alert" (very rapid, low-amplitude EEG fluctuations) pattern in the EEG is difficult. Further, this background varies with time and g-level (Appendix A, Section 2, p. A-19). Making use of this measure will generally require some development under static (1g) conditions.

B. EXPERIMENTS

The potential experiments are divided into two categories, those oriented toward measuring piloting skills, and those having more to do with the operational aspects of entry. These categories are further broken down as follows:

I. Piloting Skills

A. Sensing

1. Visual Acuity
2. Ocular Motility
3. Visual Beamwidth
4. Audition

B. Central Processing

1. Coordination
2. Decision-Making
3. Lead Generation

C. Actuating

II. Operational Aspects

A. Regulation of Internal Environment

1. Blood Pressure
2. Arterial Oxygen Saturation
3. Atmospheric Composition

B. Hardware Constraints

1. Display
2. Manipulator

C. Training Retention

There are a total of 16 experiments. The first 10 are directed toward measurement of piloting skills. The remainder are operational in nature. The latter make use of variations in the experimental setups of the former and of full entry simulations.

Table VI illustrates the relationship between the various skills being measured and the experiments themselves. In general, all of these experiments employ the human centrifuge and the protocol requires:

- Obtaining baseline data or validating the experiment (i.e., is it sensitive to the effects being measured) under static (1g) conditions.

TABLE VI

INTERRELATIONSHIPS BETWEEN EXPERIMENTS

	PILOTING SKILLS									OPERATIONAL ASPECTS					
	SENSING					CENTRAL PROCESSING				REGULATION OF INTERNAL ENVIR.			HARDWARE CONSTRAINTS		
Experiment No.	Visual Acuity	Ocular Motility	Visual Beamwidth	Audition	Coordination	Decision Making	Lead Generation	Actuation	Blood Pressure Regulation	Arterial Oxygen Saturation	Atmospheric Composition	Display	Manipulator	Training Retention
1	◉				●		●	●	●	●		○		
2	●	◉	●		○	●		○	●	●		○	○	
3	●	◉			●		●	●	●	●		○		
4			◉		●			●	●	●		○		
5			◉		●			●	●	●		○		
6				○	●	◉		●	●	●				
7	●				○	◉	●	○	●	●				
8	●				●		◉	●	●	●				
9	●				●		◉	●	●	●				
10	●				◉	○	●	◉	●	●				
11	●		●			●			◉	●		●		
12	●		●			●			●	◉		●		
13	●		●			●				●	◉	●		
14	●	●	●		●	●	●	●				◉		
15	●	●	●		●	●	●	●					◉	
16					●			●						◉

Key: ◉ Primary Purpose of Experiment

○ Secondary Aspects

● Additional Tie-ins

- Training the subjects to a stable level of performance in the high-g context (a failing of many past centrifuge experiments).

- Runs "for the money" at high g-levels for the data being sought. This data includes determination of the subject's internal environment (the cause), as well as performance measures (by which the effect is discerned).

It is recognized that there is a basic conflict between the subject's physical safety (as well as the experimental costs) and the number of high-g runs required to get stable data of high reliability. The Procrustean attitude adopted here is that if atmospheric entry is relatively safe, so is a protocol requiring many high-g (at least to the g-levels contemplated for entry) centrifuge runs. Actually, the number of centrifuge runs required to achieve a stable performance level in a particular task is relatively small provided the subject has had recent (within a few months) centrifuge experience, and has been trained in the task under static conditions. The subject unaccustomed to the centrifuge needs more runs to achieve a stable performance level (Ref. 29).

While these experiments are all intended for the human centrifuge, for measuring the effects of high g-levels on piloting skills, the zero-g effects which may influence entry performance have also been included in the experimental design. It is concluded in Appendix A that these zero-g effects appear to be associated with cardiovascular and respiratory systems deconditioning (due to long-term weightlessness) and with loss of skills (lack of training retention). The latter effect is explicitly included in Experiment 16, while the former is implicit in the remaining experiments which stress (among other things) causal factors — blood pressure and arterial oxygen saturation. The emphasis is intentional, because if a positive correlation between cardiovascular and respiratory systems degradation (as indicated by these measures) and task performance is established, it should be possible to relate such deconditioning (regardless of the cause) to additional decrements in high-g performance. Orbital flight data on deconditioning effects as a function of time should then make it possible to predict additional decrements in high-g performance.

In principle, any of these sixteen experiments could, through appropriate modification, be used during entry flight to evaluate pilot performance capabilities. However, there are certain practical considerations which would narrow the choice somewhat. Some of these considerations are:

- Mechanization in the flight context — the experiments must be compatible with flight instrumentation and space availability. This would probably eliminate Experiment 4, for example, which requires (in one of its configurations) a movable light.

- Demonstrated sensitivity to the effects being measured. This implies validation on the human centrifuge, and suggests that the final choice of which experiments are used during flight should wait on centrifuge (or similar) results.

- Cost effectiveness. Cost effectiveness considerations would suggest that the experiment be capable of yielding considerable data in the limited flight time available — these data being unobtainable on the ground and of critical importance to planetary entry vehicle design.

In view of these factors, a tentative choice among Experiments 6, 7, 8, 9, and 10 would be indicated. However, which of these best satisfies these criteria is dependent upon ground experimental results.

EXPERIMENT 1

EFFECT OF ENTRY ENVIRONMENT ON ABILITY TO DETECT DISPLAY MOTION IN FOVEAL VIEW

JUSTIFICATION

The precision of the pilot's control is dependent on his ability to detect small motions of his display. Past experiments (Ref. 22) have used Snellen charts, etc., to test visual acuity under g-forces. Unfortunately, there is no established relationship between the ability to read a Snellen chart and performance in a control task. A definition of visual acuity as related to control tasks under g-forces is therefore required.

APPLICATION OF EXPERIMENTAL RESULTS

1. Basic physiological information on human visual threshold in terms of angle or angular rate subtended at the eye
2. Criteria for display device design
   a. Configuration
   b. Size (line, numeral, indices, etc.)
   c. Illumination level
   d. Contrast
3. Possible cause/effect relationships between oxygen supply to the eye and foveal vision capabilities

EXPERIMENT DESCRIPTION

1. Typical Conduct — The display should be driven by a "canned" forcing function for repeatability. The display quantity is initially at zero displacement and rate. When the pilot first detects a rate of indicator movement, he depresses a button. The button is held depressed until the rate of indicator movement appears to stop. The button is then released. The sequence is repeated for the entire run length.
2. Display — To determine the effect of different types of display, various display configurations should be tested, e.g.,

a. Typical aircraft or spacecraft devices

- Circular meter with needle movement
- Rectangular meter with line movement

b. Expanded scale and increased boldness (width) of indicator and indices

c. Another possible variation could be to increase display light intensity with g-level via a g-sensitive rheostat

3. Forcing Function — The forcing function stimulus should be random in sign and amplitude to preclude the pilot's discerning any pattern. The forcing function can be either random ramps or the sum of sinusoids. If the latter is employed, the frequency content must be very low to test threshold effects. Note that changing the rms amplitude of the forcing function is equivalent to changing the display gain.

4. Measurements

a. Environmental

- g-level
- Time
- Blood pressure
- Arterial oxygen saturation
- EEG (as a backup to determine subject's state of consciousness)

b. Performance

- Continuous record of forcing function
- Continuous record of pilot response via button position
- EMG (to permit separation of neuromuscular contribution to pilot's reaction)
- Pilot subjective comments

5. Data Reduction — Standard statistical (cause/effect) correlation analyses

6. Factors Influencing Results

a. Display configuration

b. Display nonlinearities (i.e., needle stiction)

6. Problem Areas

   a. Many data points required to obtain statistically meaningful data

   b. Nonlinearities in the display devices

REMARKS

Here we are concerned with determining the basic visual capabilities versus g-level (e.g., visual rate threshold for line or needle movement, minimum increment separation detection, etc.). The experiment is open-loop in that the pilot reaction does not affect the stimulus. Other experiments will concern the effect on closed-loop performance.

High g-level decreases the sharpness of vision, the ability to detect small movement, rates of movement, fine lines, etc. Some methods of combating this decrease in vision capability have included increasing the display contrast; making the numerals and lines larger, etc. To be effective, the latter requires proportional increase in the numeral, marker, line, etc., separation. This then affects the display size or scale factor, which is reflected as a change in controlled element gain.

The entry tasks and procedures may require the pilot to perform attitude changes at the peak g-level when the rate of change of g-level is zero. It is therefore essential that the pilot be able to detect rate of display motion at high g. If the display is scaled so that rate of motion can be determined near peak g, the display gain may be too high for accurate control at low g-levels. Thus some tradeoff may be necessary between display gain, visual rate threshold (or even visual accuracy), and control performance. Another tradeoff may involve display size versus reduced or limited range of displayed motion quantity.

EXPERIMENT 2

EFFECT OF ENTRY ENVIRONMENT ON ABILITY TO SHIFT POINT-OF-REGARD IN RESPONSE TO STATUS LIGHTS

JUSTIFICATION

The pilot's monitoring role requires considerable shifting of gaze from point to point as he scans the display panel, particularly if he must shift his gaze to ascertain which of several possible events has occurred. Past experiments have indicated problems in moving and coordinating the eyes (Appendix A, Section 2, p. A-17) at high g-levels (double vision, ataxic movements, etc.). However, the relationships between such effects and overall task performance are unclear, indicating the need for experimentation to quantify these effects.

APPLICATION OF EXPERIMENTAL RESULTS

1. Criteria for design and assessment of crew workload (e.g., time to scan display, respond to signals, actuate push buttons, etc.) at high g's

2. Criteria for display panel design (location of status lights, actuation switches, etc.)

3. Possible cause/effect relationships between internal oxygen supply and oculomotor performance (ocular motility)

EXPERIMENT DESCRIPTION

Two possible configurations are proposed which differ somewhat in the visual identification and actuation skills required:

1. Configuration A. The experimental situation is similar to that for determining visual beamwidth (Experiment 4). A central, primary tracking task is provided to occupy the pilot's attention. A bank of status lights is located to one side of the display panel with sufficient separation from the primary task that the lights are within the pilot's peripheral vision, but sufficiently far from his foveal view that he must move his eyes to discern which light within the bank is lit. The lights within the bank are lit one at a time in random sequence and time. When a light comes on, the pilot shifts his eyes from the primary (tracking) display to the light bank. He

then determines which light is lit and punches that particular light to turn it off. He then returns his eyes and attention to the primary tracking tasks until another warning light comes on.

2. Configuration B. This is similar to the foregoing except that the switches for turning the lights off would be located on the pilot's left arm rest. The indicator lights could illuminate a symbol, numeral, or letter on the instrument panel and the pilot would turn it off via the corresponding switch at his fingertips.

   This experiment would eliminate the time and effort requirements of the pilot in reaching to the instrument panel. It would increase the requirement for fixation accuracy and visual acuity in order to decipher the symbol, letter, or numeral illuminated. This latter task could be made relatively easy or difficult by the selection of symbols (i.e., either very dissimilar or similar, respectively).

3. Measurements

   a. Environmental

      - g-level
      - Time
      - Blood pressure
      - Arterial oxygen saturation
      - EEG (as a backup to determine subject's state of consciousness)

   b. Performance

      - EEG for detection of awareness of light (evoked response)
      - EOG and movie camera for movement of eye
      - EMG for detection of command to neuromuscular system
      - Correctness or incorrectness of switch actuation
      - Level 1 or 2 tracking task performance measures
      - Continuous record of stimuli and switch positions
      - Pilot subjective comments

4. Data Reduction

   a. Open-loop responses (e.g., dead time, reaction time, etc.)

   b. Standard statistical (cause/effect) correlation analyses

5. Factors Influencing Results

   a. Difficulty of primary task

   b. Visual beamwidth

   c. Visual acuity

   d. Restraint system and/or any restrictions on pilot movement of arm (particularly for Configuration A)

6. Problem Areas

   a. Many runs required

   b. May have basic conflict between the primary task and light bank separation and the time to detect a light, i.e., the time for detection of the light will correlate with its separation from the primary task

   c. Detection of evoked response in EEG recordings may require special instrumentation

REMARKS

This experiment involves:

- Time to become aware of light in peripheral view
- Time to move eyeball and fixate
- Time to move hand to instrument panel to turn light off
- Central nervous system efficiency (pattern detection and recognition)

Thus the measurements called out are intended to separate these effects. For example, the physical effort required to reach the panel will contribute considerably more to the total response time in Configuration A; on the other hand, Configuration B will probably result in longer decision times.

EXPERIMENT 3

EFFECT OF ENTRY ENVIRONMENT ON ABILITY TO SHIFT POINT-OF-REGARD IN CONTROL TASK

JUSTIFICATION

The pilot's ability to shift his gaze from one display to another is particularly important in those instances where he has two or more control tasks requiring close attention. The dynamics of eye movement, in particular, their limitations under high g-forces become important, yet there is no quantitative data available in this context. Experimentation is needed.

APPLICATION OF EXPERIMENTAL RESULTS

1. Basic data for design and assessment of display panel layout (e.g., display separation)

2. Basic data for use in dynamic analyses of pilot/vehicle/controller in high g environment

3. Possible cause/effect relationships between internal oxygen supply and oculomotor performance (ocular motility)

EXPERIMENTAL DESCRIPTION

There are at least two possible configurations:

1. Configuration A. The general experimental situation would involve the ability to shift the eyes from one closed-loop control task to another (i.e., shift from roll attitude control to yaw rate damping) in the situation where both displays are not within the useful visual beamwidth. Two identical display devices (meters, CRT, etc.) are placed on the display panel with sufficient separation that peripheral tracking is difficult, if not impossible. Both displays are driven by the same forcing function. The displays are then blanked out alternately at 10 to 20 sec intervals (randomly in time). The pilot performs a conventional tracking task, switching attention from display to display as they are alternately covered and uncovered. This forces the pilot to move his eyes and fixate as rapidly as possible in order to keep the tracking error low.

As in the visual acuity experiments, various display configurations (e.g., dial, rectangular, etc.) may be used in pairs. However, the display configurations should not be mixed, or reflect different scaling, gain, etc., since this will introduce other variables into the task (i.e., response to step changes in the controlled element dynamics).

2. Configuration B. An alternate experimental configuration could use the first-order critical task (Ref. 23) with two separate displays as indicated in 1, above. This would provide only one measure, the operator's effective time delay; however, the incremental increase in this measure when compared with the nominal operator time delay for a single display would reflect a measure of the time required to move the eyes. The advantage of this mechanization is its simplicity and the fact that several data points can be obtained per centrifuge run. This mechanization also might be employed as an operator training device for Configuration A.

3. Measurements

   a. Environmental

      - g-level
      - Time
      - Blood pressure
      - Arterial oxygen saturation
      - EEG (as a backup to determine subject's state of consciousness)

   b. Performance

      - EOG and movie camera for movement of eye (time in motion, etc.)
      - Level 2 closed-loop performance measurements for task performance criteria
      - Level 4 (pilot describing function and remnant) performance measures for determining the incremental increase in effective reaction time (τ_e) due to eye movement and fixation dynamics at high g
      - Pilot subjective comments

4. Data Reduction

   a. Off-line nonlinear model matching techniques in which pilot model parameters are adjusted until actual pilot and model pilot system responses match

b. Off-line curve fitting of power spectra to obtain describing function factors

c. Standard statistical (cause/effect) correlation techniques

5. Factors Influencing Results

a. Difficulty of controlled element dynamics (probably should be limited to K_c/s or K_c/s^2.

b. Display separation

c. Forcing function bandwidth and amplitude

d. The entire tracking task should be consistent with those employed in Ref. 6 or similar past experiments to provide the maximum possible carryover from past data to that resulting from these experiments

REMARKS

This experiment tests:

1. The ability to move the eyeball, fixate, and resume useful control task

2. The equivalent delay or phase lag that is introduced when moving the eye at various g-levels

3. The degree to which ataxia, double vision, or other uncoordinated eye movement adversely affects pilot tracking performance

EXPERIMENT 4

EFFECT OF ENTRY ENVIRONMENT ON ABILITY TO RESPOND TO LIGHTS IN EXTRAFOVEAL VIEW

JUSTIFICATION

The available literature indicates a deterioration of the peripheral vision to result from the effects of high g-levels on visual skills (see Appendix A, p. A-16). This qualitative indication would imply a decrement in the pilot's ability to detect warning lights, status indicators, etc., which are located outside his foveal field of view. This ability is crucial to the pilot's monitoring role during entry, particularly if he already has a primary vehicle control task. Since there is presently a lack of quantitative data in this area, experimentation is needed to determine the extent of this skill as a function of the primary environmental variables.

APPLICATION OF EXPERIMENTAL RESULTS

1. Criteria for location of status, warning, failure, etc., lights on instrument panel
2. Criteria as to g-level above which light devices are of no value
3. Possible cause/effect relationship between oxygen supply to eye and field of vision

EXPERIMENTAL DESCRIPTION

1. Primary Task
   - Pilot focuses (stare mode) on primary task in center of display panel (pilot is instructed not to move his eyes from the primary task).
   - Task should be compensatory tracking of sufficient difficulty to assure continuous attention level, e.g., $Y_c = K_c/s$.
   - Forcing function may be random step or random-stationary signals.

- Performance measurement on primary task need only be sufficient to ascertain pilot is concentrating on primary task (e.g., level 1 or 2 closed-loop measurements). However, higher level measurements may be taken if desired.
- Continuous EOG and/or movie film recordings of eye movement should be made to determine if pilot is concentrating on primary task.

2. Secondary Task — There are several possible mechanizations, e.g.,

   - Light source mounted on movable, motor driven base. Light slowly moved from central portion of display panel toward periphery or vice versa, depending upon position of an actuating switch. Pilot controls actuating switch to move light out until it cannot be seen in peripheral vision. He then reverses the switch until the light can be seen. This process is repeated so that the light position is in a limit cycle at the very edge of the pilot's peripheral vision.
   - A series of lights may be mounted at close intervals across the instrument panel. The lights are programmed to flash in sequence starting from the outer edge of the display and progressing toward the center of the display. When the light first becomes apparent to the pilot, he actuates a switch which stops the sequencing device. The experimenter (or subject) then recycles the sequencer to the outermost light and the experiment is repeated.

3. Measurements

   a. Environmental

      - g-level
      - Time
      - Blood pressure
      - Arterial oxygen saturation
      - EEG (as backup to determine pilot's state of consciousness)

   b. Performance

      - Continuous record of light position
      - Continuous record of control switch position

- Level 1 and 2 tracking task performance measures
- Pilot subjective comments (e.g., see—can't see)
- EEG and EMG (see Remarks)

4. Data Reduction — Standard statistical (cause/effect) correlation analysis

5. Factors Influencing Results

   a. Difficulty of primary task
   b. Light intensity and size
   c. Which of the two secondary tasks is used

6. Problem Areas

   a. Many runs with several subjects to get statistically meaningful data
   b. Anticipate considerable scatter in data due to subject variability and influencing factors such as noted above

REMARKS

This experiment tests the optics and retina and the integrity of the neural path from the eye to the hand. If the EEG and EMG are recorded, it may be possible to discern time lags between stimulus, CNS command, and hand response. Since the stimulus is slowly changing (i.e., a moving, as opposed to a flashing light) for one of the secondary tasks, there may not be a detectable evoked response in the EEG. It should, however, be detectable with the flashing stimulus.

EXPERIMENT 5

EFFECT OF ENTRY ENVIRONMENT ON TRACKING ABILITY IN CONTROL TASK IN EXTRAFOVEAL VIEW

JUSTIFICATION

It has been shown in Ref. 21 that the operator can track one task with foveal vision and a secondary task with peripheral (extrafoveal) vision. This situation is akin to that which may be required of the entry vehicle pilot should it be necessary to control in two axes simultaneously. The literature on the effects of g-level suggests a decrement in the visual system which would deteriorate this aspect of the pilot's skill, but no quantitative data is available (Appendix A, p. A-16). Experimentation is therefore required to define the extent of this capability in a high-g environment.

APPLICATION OF EXPERIMENTAL RESULTS

1. Criteria for location of secondary task display (e.g., pitch and yaw rate)
2. Criteria for location of backup display for primary task
3. Criteria for tradeoff between display panel space and automatic control system redundancy
4. Possible cause/effect relationship between internal oxygen supply and secondary task performance

EXPERIMENTAL DESCRIPTION

1. Primary Task — The same as under Experiment 4, viz.,
   - Pilot focuses (stare mode) on primary task in center of display panel (pilot is instructed not to move his eyes from the primary task).
   - Task should be compensatory tracking of sufficient difficulty to assure continuous attention level, e.g., $Y_c = K_c/s$.
   - Forcing function may be random step or random-stationary signals.

- Performance measurement on primary task need only be sufficient to ascertain pilot is concentrating on primary task (e.g., level 1 or 2 closed-loop measurements). However, higher level measurements may be taken if desired.
- Continuous EOG and/or movie film recordings of eye movement should be made to determine if pilot is concentrating on primary task.

2. Secondary Task — There are several possible mechanizations, e.g.,

   - Three (or more) identical display devices mounted at equal angular increments (as subtended at the pilot's eye) starting from the primary task display centerline and progressing in a straight line toward the edge of the display panel. (The outermost secondary display can be as much as 50 deg from the centerline at 1g.) The secondary tracking task ($Y_C = K_C/s$) is displayed on only <u>one</u> of these devices at any one time. The pilot tracks the primary task in his foveal view and the secondary task in his peripheral view. Either a two-axis manipulator may be used or two separate single-axis manipulators. Calibration runs should be made at constant g-levels with each secondary display to determine the effect of time (minutes) at a given g-level on the performance score (pilot degradation with time).

     During actual experiment runs, the secondary task could be switched from one display device to another at time intervals which would be set by data reduction and analysis requirements. Thus, at any set g-level, the secondary tracking task would start at the display device nearest the primary display. The pilot would track the secondary task (peripheral vision) for a period sufficient to obtain meaningful data. The task would then be switched to the next device (outboard), the scoring restarted, and the run continued. This process could be repeated with the tracking task moving to successive outboard display devices without shutting down the centrifuge.

     After removing the effects of "time at a given g-level," the resulting scores would be a measure of useful peripheral tracking beamwidth versus score with g-level as a variable.

   - An alternate experimental setup might be to place the secondary display on a movable mount so that finer increments of display separation could be achieved. All other aspects would remain the same except that only one display separation could be tested per centrifuge run.

3. Measurements

   a. Environmental

      - g-level
      - Time
      - Blood pressure
      - Arterial oxygen saturation
      - EEG (to determine pilot's state of consciousness — a backup)

   b. Performance

      - Record of display separation
      - EOG (to assure at least visual concentration on primary task)
      - Performance measures of pilot tracking in primary and secondary tasks
      - If forcing function is random stationary, performance measures, as a minimum, should include $\overline{e^2}$ and ω_c in both tasks (levels 1 and 2). Higher level performance measures (e.g., levels 3, 4, 5) can be taken if desired. $\overline{e^2}$ and ω_c should be checked against the "1/3 law" (Ref. 6) to determine if only one of these measures would suffice.
      - If forcing function is random step, performance measures are the various open-loop measures and error.
      - Pilot's subjective comments.

4. Data Reduction — Standard statistical correlation tests for cause and effect relationships, validity, etc.

5. Factors Influencing Results

   a. Primary and secondary task difficulty (controlled element)

   b. Light intensity

   c. Display size, shape, and type

   d. Forcing function amplitude and bandwidth

6. Problem Areas

   a. Effect of influencing factors on interpretation of data, or,

b. Many runs with certain of the influencing factors varied intentionally

REMARKS

In this experiment, as in others, records should be kept of performance through the training period. This is necessary to permit the experimenter to determine when a stable performance level is reached.

EXPERIMENT 6

EFFECT OF ENTRY ENVIRONMENT ON ABILITY TO PERFORM MENTAL ARITHMETIC WHILE TRACKING

JUSTIFICATION

Information processing capability is one aspect of the pilot's decision-making capability. There are indications (e.g., Ref. 24) that tracking performance sometimes degrades considerably if a second information processing channel is brought into use simultaneously. This is relevant to the entry situation when (for example) oral transmission or receipt of information is required while tracking. The degree of degradation in the primary tracking task performance due to the second channel operation (distraction) is related to the pilot's total workload capacity, the percentage of this workload capacity taken up in accomplishing the primary task, and the relative importance applied to each of the two tasks by the pilot. At present, there is little or no information regarding these skills at high g-levels.

APPLICATION OF EXPERIMENTAL RESULTS

1. Criteria regarding the limitation of conversation between pilot and crew during critical maneuvers
2. Degradation factors for
   - Effect of second channel operation on tracking performance
   - Short-term memory
3. Possible indication of channel capacity and short-term memory limitations
4. Possible cause/effect relationship between the skills measured and internal oxygen supply

EXPERIMENTAL DESCRIPTION

1. General Description — The primary tracking task can be the same as that employed in the ocular motility experiments (Experiments 4 and 5) but with only one display device being

used here. Calibration runs should be made at the various g-levels with the pilot performing only the primary tracking task to obtain base level performance scores. The second channel task is then added for subsequent runs. This second task might consist of mentally adding or subtracting two 3-digit numbers where

a. Both numbers are given to the pilot orally and he answers orally, or

b. One number is displayed within his foveal view and he adds or subtracts a constant and gives the answer orally

The period or frequency of numeral presentation will have to be adjusted to the pilot's response capabilities.

2. Measurements

a. Environmental

- g-level
- Time
- Blood pressure
- Arterial oxygen saturation
- EEG (as a backup to determine subject's state of consciousness)

b. Performance

- Period or frequency of information cycle completion (number of bits per minute)
- Accuracy of mental arithmetic
- Levels 1 and 2 performance measures for tracking task
- Pilot subjective comments

3. Data Reduction — Standard statistical (cause/effect) correlation techniques

4. Factors Influencing Results

- Difficulty of primary task
- Instructions to pilot regarding relative importance of primary and secondary tasks

5. Problem Areas

- Inability to determine whether pilot received the oral transmission correctly

- Many data runs required to obtain statistically meaningful data
- Pilot's vocalizing capability under g-forces
- Development of a scoring technique for the secondary task

REMARKS

1. This experiment is also a test of the pilot's sensing skill (audition), and his ability to vocalize under high g-levels.

2. Another possible test of central processing skills is the mental addition or subtraction of two 3-digit numbers. The face validity of this test in entry is somewhat nebulous, but might reflect one of the pilot's tasks in monitoring and checking the automatic guidance and control functioning.

EXPERIMENT 7

EFFECT OF ENTRY ENVIRONMENT ON ABILITY TO ADAPT TO TRANSITIONS IN CONTROLLED ELEMENT DYNAMICS

JUSTIFICATION

The pilot's ability to recognize and adapt to a change in the controlled element dynamics is critical to his role as a backup to the various on-board automatic systems. Such changes in the spacecraft dynamics would occur if (for example) the pilot were controlling attitude error ($Y_c \doteq K_c/s$) and the roll rate damper suddenly failed ($Y_c = K_c/s^2$). The pilot's capabilities in this situation at high g-levels is unknown, although there is considerable baseline data (e.g., Ref. 25) for static (1g) condition.

APPLICATION OF EXPERIMENTAL RESULTS

1. Identification/adoption/recovery time data for application in future mission analyses
2. Criteria for application of damper system redundancy
3. Possible cause/effect relationships between skill measures (see Remarks) and internal oxygen supply

EXPERIMENTAL DESCRIPTION

1. General description — The task consists of the conventional compensatory tracking situation. The controlled element dynamics are switched from K_c/s to K_c/s^2 at random intervals. In order to catch the pilot completely unprepared for the "failure," it may be desirable to integrate this experiment with other experiments rather than conduct a separate experiment in which he knows a Y_c change will occur sometime during the run and hence is psychologically prepared.
2. Measurements
   a. Environmental
      - g-level
      - Time

- Blood pressure
- Arterial oxygen saturation
- EEG (as a backup to determine subject's state of consciousness)

b. Performance

- Levels 1 and 2 closed-loop performance measures
- Pilot subjective comment (e.g., oral identification of Y_c change at the moment he recognizes the change)

3. Data Reduction

a. Detailed analysis of level 1 (time traces) to identify transition time and to determine the change in efficiency, techniques, etc.

b. Standard statistical (cause/effect) correlation techniques

4. Influencing Factors

a. The forcing function bandwidth which will influence the closed-loop crossover frequency, the amount of neuromuscular system lag involved, and hence the degree of instability of the system with the K_c/s^2 controlled element and the time for the pilot to recognize the change

b. State of alertness of pilot, visual acuity, etc.

5. Problem Areas

a. If integrated with other experiments, this experiment will cause disruption in the other experiments

b. Many runs required to obtain statistically meaningful data

REMARKS

Reference 25 shows that under the circumstances of a change in the controlled element dynamics, the pilot transitions through three phases:

1. Recognition of change in Y_c dynamics
2. Optimal-like (bang-bang) manipulation to recover control
3. Adoption of final gain and equalization for new Y_c dynamics

In this experiment we seek to identify the changes in the time intervals corresponding to each of these phases which are associated with the causal factors (environmental measures). Provision for measurement of central processing time, i.e., the time from receipt of stimulus until command is given by command center was also incorporated in several of the visual subsystem experiments; for example, the ocular motility tests involving peripheral lights. When the peripheral light comes on, this stimulus should be reflected in the EEG trace. The time between the impulse in the EEG trace and the initial movement of the eye (EOG trace) is a measure of one processing time. The time between final positioning of the eye (EOG trace) to the light and generation of the command to the finger (EMG trace) is a measure of another processing time. However, in the latter case, the time measure will include any fixation, focus, etc., time associated with the visual subsystem.

EXPERIMENT 8

EFFECT OF ENTRY ENVIRONMENT ON ABILITY TO GENERATE FIRST-ORDER LEAD COMPENSATION

JUSTIFICATION

If the pilot is to serve as a backup controller in the presence of damper system failure, the effective controlled element dynamics may be such that the pilot must generate first-order lead. Since both vision and central processes are involved in lead generation and both are degraded by high g, the combined effect on lead generation capability must be determined.

APPLICATION OF EXPERIMENTAL RESULTS

1. Criteria regarding allowable vehicle dynamics (flight control system redundancy implications)

2. Basic data for use in analytical prediction of pilot/spacecraft/controller performance

3. Possible cause/effect relationships between internal oxygen supply and lead generating skill.

EXPERIMENTAL DESCRIPTION

There are two experimental configurations proposed, each with its various advantages and disadvantages:

1. Fixed controlled element dynamics — A general experiment which will provide the most information is similar to the compensatory tracking task experiments of Ref. 6 with the controlled element dynamics fixed and of the form K_c/s^2. The experimental setup, forcing function, etc., should match that of Ref. 6 as closely as possible in order to take advantage of the considerable body of baseline data available in Ref. 6.

   Linear and nonlinear data reduction techniques may be employed to obtain mathematical models of the pilot transfer function from which the first-order lead is identified.

2. Time-varying controlled element dynamics — This experiment is of the "critical task" type (Ref. 23). As such, it has certain advantages over that described in (1) above but also has certain disadvantages. Among the advantages, it forces the pilot to his maximum performance capabilities; requires no forcing function; provides more data points per centrifuge run; can be paced to the operator capabilities; and is quick, simple, and direct scoring. The strongest disadvantage is that it provides a single measure which, although related to the pilot's lead generating capability, is influenced by other pilot characteristics (e.g., α, τ) which are expected to vary.

   The controlled element dynamics are of the form

$$Y_c = \frac{K_c}{s^2(s+\lambda)}$$

   where λ approaches zero as a function of time. When λ is relatively large, the controlled element is of the form K_c/s^2 and the pilot adopts a single lead to obtain a region of 20 dB/decade slope for crossover. As λ moves toward zero the pilot is forced to increase his lead to maintain phase margin and the 20 dB/decade slope.

   The problem is stopped (λ frozen) when the error exceeds a preset reference value. The controlled element dynamics are recycled to the initial conditions and the problem rerun.

3. Measurements

   a. Environment

      - g-level
      - Time
      - Blood pressure
      - Arterial oxygen saturation
      - EEG (as backup to determine subject's state of consciousness)

   b. Performance

      - Levels 1 through 4 of performance measures (Configuration A), or
      - Readout of λ (Configuration B)
      - Pilot subjective comments

4. Data Reduction

   a. Standard statistical (cause/effect) correlation techniques

   b. Analog pilot model strip chart and power spectral matching techniques (Configuration A, only)

   c. Mathematical derivation of pilot describing function and remnant (Configuration A, only)

5. Influencing Factors

   a. Visual acuity and threshold (and those factors influencing them)

   b. Forcing function bandwidth (Configuration A)

   c. Rate of change of λ } (Configuration B)

   d. Selection of limit error }

6. Problem Areas

   a. Configuration A

      - Frequency content of forcing function must be accurately known
      - Pilot is expected to exhibit considerable variation with time at the higher g-levels; therefore, data analysis techniques must be consistent with such time variations (e.g., time-varying mathematical analysis or analog-model strip chart matching)
      - Few data points per run
      - Pilot may not be pushed to maximum lead generating capability

   b. Configuration B

      - As noted above, only one measurement which may be influenced by other pilot parameters
      - Pilot may switch to generation of a second-order lead if the error limit (run length) is too long

EXPERIMENT 9

EFFECT OF ENTRY ENVIRONMENT ON ABILITY TO GENERATE SECOND-ORDER LEAD COMPENSATION IN A CONTROL TASK

JUSTIFICATION

Regulation of deceleration level requires generation of a second-order lead. This has not been adequately quantified, even under static (1g) conditions, let alone the high-g condition of entry, and experimental definition is required.

APPLICATION OF EXPERIMENTAL RESULTS

1. Criteria for the degree of redundancy in the guidance and navigation systems
2. Basic data for use in analytical prediction of pilot/spacecraft/controller performance
3. Possible cause/effect relationship between internal oxygen supply and skill in generating second-order lead

EXPERIMENT DESCRIPTION

As in Experiment 8, there are two alternate configurations:

1. Fixed controlled element dynamics — The experiment, measurements, etc., are the same as in Experiment 8 except the controlled element is of the form $Y_c = K_c/s^3$.
2. Time-varying controlled element dynamics — The experiment, measurements, etc., are the same as in Experiment 8 except the controlled element is of the form $Y_c = K_c/s^3(s+\lambda)$.

REMARKS

The generation of low-frequency lead is accompanied by an increase in lags at high frequency (τ_o increases). Therefore, the frequency spectrum of interest shifts to lower frequencies as the pilot generates additional lead. Much attention must be paid to the very low frequency spectrum (e.g., 0.05 to 0.5 rad/sec) if pilot describing function factors and remnant data are to be obtained.

EXPERIMENT 10

EFFECT OF ENTRY ENVIRONMENT ON PRECISION OF CONTROLLER MANIPULATION

JUSTIFICATION

High g-levels will affect the timing, amplitude, and general precision of the pilot's controlling manipulator motions. Past experimentation (Appendix A, Section 2, p. A-24) has provided qualitative indications of those influences, but were compounded with other effects.

APPLICATION OF EXPERIMENTAL DATA

1. Basic data on reaction times, motor control (coordination), central processing of highly skilled reactions, neuromuscular loop dynamics, (ω, ζ) etc.

2. Criteria regarding ability of pilot to apply trained reactions in emergency situations or perform critical and precise manipulations

3. Possible cause/effect relationship between actuating skill and internal oxygen supply

EXPERIMENT DESCRIPTION

1. General Description — The task is a conventional single-axis compensatory tracking task. Constant amplitude step commands are introduced at random time intervals. The time between steps is sufficient to allow the subject to respond to the step and reach a steady-state, essentially zero error, condition for several seconds. The subject is instructed to follow the step as rapidly and accurately as possible. The three controlled elements noted below should be tested:

Controlled Element	Response
$Y_c = K_c/s$	one manipulator pulse
$Y_c = K_c/s^2$	two manipulator pulses (doublet)
$Y_c = K_c/s^3$	three manipulator pulses (triplet)

2. Measurements

   a. Environmental

      - g-level
      - Time
      - Blood pressure
      - Arterial oxygen saturation
      - EEG (as backup to determine subject's state of consciousness)

   b. Performance

      - Levels 1 and 2 closed-loop measures
      - EMG, EEG
      - Pilot subjective comments

3. Data Reduction

   a. The strip chart traces should be analyzed for both tracking loop (low frequency) and actuation loop (high frequency) performance measures:

      - Open-loop performance measures
      - Number of manipulator reversals
      - Pulse amplitude and width
      - Switching points and cues
      - Error

   b. EEG and EMG traces should be analyzed for indications of command processing times and delays and for event phasing with the above strip chart analysis

   c. Standard statistical (cause/effect) correlation techniques

4. Factors Influencing Results

   a. Visual acuity

   b. Manipulator characteristics (see Experiment 15)

5. Problem Areas

   a. Subject training time

   b. Subject may exhibit relearning of the task when exposed to increasing g-levels; therefore, more than one run

may have to be made at each g-level to reach leveling of learning curve — this remark applies equally to all control tasks, but is probably most noticeable in this context.

REMARKS

1. This experiment is intended to measure the (highly learned) responses to step commands to test the precision and repeatability of control via the neuromuscular subsystem as a function of the environment. Preliminary experiments at STI have shown the pilot can learn to "track" step commands via a "triggered" response. When instructed to track the step as closely and rapidly as possible, he employs the manipulator pulsing techniques noted above.

   Once he becomes skilled at the task, the results are highly repeatable. Since the response is a skilled "triggered" reaction, the signal path within the human is essentially a direct connection from the visual system to the neuromuscular system. Any deviation in the trained response with g-level should therefore be primarily attributable to the "triggering" mechanism and to change in the neuromuscular actuation loop (assuming the pilot can see the display).

2. Measurements which provide indications of the performance and functioning of the human actuation subsystem with change in environmental history are inherently contained in experiments already outlined (i.e., Experiments 1 through 9). Simple reaction times are obtainable in those experiments wherein EMG and switch actuation measurements are made (e.g., response to status lights, tracking random square waves, step change in controlled element dynamics). In addition, if the analog pilot model or mathematical describing function model techniques are employed in determining the pilot lead generating capabilities, equivalent measures of the neuromuscular actuation subsystem time constants and lags will also be obtained.

3. Another experiment which will provide a measure of the effective time delay (the higher order delays including the neuromuscular lags) is the first-order critical task, Ref. 23). This experiment has already been performed by ARC personnel at nominal and moderately increased g-levels and has shown a linear relationship between τ and increasing g-level. The basic task is the conventional compensatory tracking task where the controlled element is of the form $Y_c = K_c/(s-\lambda)$. The inverse time constant λ is increased linearly with time. The advantages, disadvantages, measurements, etc., associated with this experiment have been indicated previously.

EXPERIMENT 11

EFFECT OF REDUCED BLOOD PRESSURE ON SENSING AND CENTRAL PROCESSING SKILLS

JUSTIFICATION

In Appendix A it is indicated that the crucial aspect of human functioning as a controller at high-g is the effective oxygen supply to the visual and central nervous subsystems. The concern for the effects of weightlessness on the functioning of the cardiovascular and respiratory systems (which establish the oxygen supply) is supported by the 15 experiments proposed in Ref. 12 to be performed in an orbiting research laboratory. Two factors of importance are blood pressure regulation and blood oxygen content. It has been suggested in all of the preceding experiments that these two factors be measured and an attempt made to correlate these measures with pilot task performance. To this end, it is pertinent to separate, if possible, the effects of degraded blood pressure regulation, decreased blood oxygenation, and acceleration forces. Then, if future long-term weightlessness experiments (Ref. 12) verify a degradation in the performance of the cardiovascular or respiratory systems which would impair blood pressure regulation or oxygen content, better information will be on hand to predict the consequences of entry at various g-levels.

APPLICATION OF EXPERIMENTAL RESULTS

1. Baseline data for the effect of decreased systemic arterial blood pressure (without acceleration effects) on the performance of the pilot in control tasks

2. Baseline data for the possible reduction of the limit entry acceleration to allow for the combined effects of decreased blood pressure and increased acceleration level

3. Baseline data for comparison with orbital data

EXPERIMENT DESCRIPTION

1. General description — Equipment is described in Ref. 12 (Experiment 9, p. 96) which will decrease (safely) the heart rate and blood pressure through artificial stimulation of the Baroreceptor carotid sinus mechanism. The basic device is a neck cast made of transparent plastic lucite which is fitted about the neck of the subject.

   Vacuum lines are attached to the collar and a slight negative pressure is applied to the neck. The decrease in heart rate and systemic arterial pressure is immediate and proportional to the negative pressure applied.

   Since the visual and central nervous subsystem performance is affected to a greater degree by the blood supply than is the neuromuscular subsystem, selected experiments outlined previously should be run with the pilot's heart rate and blood pressure reduced via the device indicated above. Specifically, it is suggested that Experiments 1, 4, 5, 6, and 7 be run at nominal (1g) conditions and at moderately increased (2–6) g-levels. The negative pressure should be increased in small steps. Subambient pressures of up to 50 to 60 cm H_2O have been employed (Ref. 12). This experiment should be performed under the supervision of a physician.

2. Measurements

   a. Environmental

      - g-level
      - Time
      - Subambient neck pressure
      - Blood pressure
      - Blood oxygenation
      - EEG (to determine state of consciousness)

   b. Performance — (See Experiments 1, 4, 5, 6, and 7)

3. Data Reduction — Standard statistical (cause/effect) correlation analyses

4. Factors Influencing Results — Emotional state of subject

REMARKS

In this experiment, measurement of the EEG as an indication of consciousness is <u>not</u> a backup — its changes with blood pressure are of interest in correlating with the EEG changes seen at high g-levels.

EXPERIMENT 12

EFFECT OF HYPOXIA ON SENSING AND CENTRAL PROCESSING SKILLS

JUSTIFICATION

In Ref. 12 three experiments devoted to determination of the effects of long-term weightlessness on the respiratory system are given Priority 1 rating. The primary concern is possible degradation in performance of this system. Any degradation is likely to result in decrease of the blood oxygen saturation when the body is exposed to the high accelerations of entry. In the event that a correlation between blood oxygen saturation (blood oxygenation) and pilot performance has not been established via the previously outlined experiments (possibly due to masking effects of other variables), it is of interest to test the effect of oxygen desaturation by itself.

APPLICATION OF EXPERIMENTAL RESULTS

1. Baseline data for the effect of decreased blood oxygenation (without acceleration effects) on the performance of the pilot in control tasks

2. Baseline data for the possible reduction of the limit entry acceleration to allow for the combined effects of reduced blood oxygenation and increased acceleration level

EXPERIMENT DESCRIPTION

1. General Description— The oxygen content of the pilot's air supply should be decreased until blood oxygen saturation levels are obtained which match those measured at the various high g-levels employed in Experiments 1, 4, 5, 6, and 7. These experiments should be rerun at nominal (1g) acceleration and the results compared to isolate the effects of oxygen desaturation from the combined effects of acceleration and oxygen desaturation.

2. Measurements

   a. Environmental

      - Time
      - Blood pressure
      - Blood oxygenation
      - EEG (to determine state of consciousness)

   b. Performance (see Experiments 1, 4, 5, 6, and 7)

3. Data Reduction — Standard statistical (cause/effect) correlation analysis

4. Factors Influencing Results — Emotional state of subject

REMARKS

Experiment 11 seeks to define the effects of reduced blood pressure; this one seeks to determine the hypoxic effects. When the human is subjected to high g-levels, both effects obtain. Further, there are probably synergistic effects between the two. This suggests combining the protocols of both experiments (reduced oxygen and reduced blood pressure) to determine the extent to which these causes duplicate the effects on performance observed at high g-levels. Since certain other changes take place (e.g., hypercapnia to an undertermined degree) it may be necessary to alter the composition of the inspired air by adding CO_2 — the object, crudely speaking, is to match the pilot's internal environment (except for muscular strain) under static conditions to that observed in centrifuge runs. A comparison of the performance levels obtained under these sets of circumstances with the same subject would reveal the extent to which piloting skills are related to these internal environmental measures.

EXPERIMENT 13

EFFECT OF ALTERED ATMOSPHERE ON SENSING AND CENTRAL PROCESSING SKILLS AT HIGH g-LEVELS

JUSTIFICATION

The question of what composition of breathing air is "best" for the pilot during entry is still open. Experiments with 100 percent oxygen at reduced pressure have resulted in improved regulation of the internal environment (chiefly, a slower decay in the oxygen saturation of the arterial blood), but increased atelectasis (Ref. 9). The resulting differences in performance were not determined.

APPLICATION OF EXPERIMENTAL RESULTS

Possible criteria for the use of altered breathing atmosphere during entry.

EXPERIMENTAL DESCRIPTION

Identical to Experiment 12, above, except for pressure and composition of breathing air.

EXPERIMENT 14

EFFECT OF DISPLAY CHARACTERISTICS ON MANUAL CONTROL PERFORMANCE

JUSTIFICATION

1. GNS Operative — Theory and past experiments (e.g., Ref. 4) indicate the easiest single display quantity for the pilot to control from is roll attitude error, φ_e. The use of this display quantity eliminates the need for mental manipulations, lead generation, etc., and therefore should allow the greatest physiological degradation in the pilot before loss of his ability to control. Obviously, he still must be able to see the information displayed — which sets requirements on the display location, scaling (resolution) light intensity, etc. In addition, range of the display quantity has important implications on the precision of control. Consider, for example, an entry maneuver strategy which can call for rapid 180 deg roll attitude changes at crucial points in the trajectory (e.g., peak g) or large attitude changes for cross-range maneuvering. If such large step roll attitude commands are likely, then the φ_e display should have a range equivalent to the maximum step command so that the meter is never pegged. For example, at least one proposed Apollo display configuration was to have a ±20 deg range on φ_e. Now suppose the φ_c were to suddenly change by 180 deg. The φ_e display immediately pegs and the pilot reacts by a large step manipulator displacement. Unfortunately, he does not know the actual φ_c (only φ_e is displayed), so he holds the manipulator displaced. During this time the system is open loop. When the φ_e again gets within the meter range, the indicator suddenly moves off the peg. The pilot must catch this movement, return to closed-loop operation, and make immediate manipulator changes to arrest the roll rate. Thus he is forced into rapid response situations, both in sensing and actuation. If the next step φ_c is only 25 deg the meter also pegs. If the pilot again responds with a large manipulator deflection, the indicator will come off the peg almost immediately, and again the pilot must take fast corrective measures to avoid overshooting.

   A nonlinear φ_e display which would allow presentation of step commands up to ±180 deg but with a compressed scale toward the full-scale deflection would alleviate this situation and allow the pilot to operate closed loop at all times.

2. GNS Failed — If the GNS fails, the pilot must resort to the backup roll attitude and deceleration information. In order to help him as much as possible, it is desirable to provide this information in a manner which requires the least lead

generation on his part. Thus the minimum display should be φ, $\dot{G}$, and G. The shape, size, configuration, etc., of the various meters will affect the pilot's ability to generate lead. Furthermore, the same aspects discussed above apply here regarding pegging the $\dot{G}$ meter.

The approach suggested in this experiment is the "quickened" display where, for example, G and $\dot{G}$ are mixed and displayed as one motion quantity (Ref. 4). This approach has several advantages and disadvantages. Among the advantages are that lead is introduced into the displayed motion quantity, G, which reduces the lead generation requirements on the pilot, and that the requirement for a separate $\dot{G}$ meter is eliminated. Also, if time between G levels is used as an indication of initial capture situation, the use of "quickened" display could increase the sensitivity of this measure to variations in γ_i, ρ, and L/D. Among the disadvantages are that the display quantity does not represent the "real world" situation except when $\dot{G} = 0$. Since various combinations of G and $\dot{G}$ can give the same meter indication the pilot is never certain of his exact deceleration situation (e.g., proximity to skipout boundary). Thus another unquickened source of information should be available from which the pilot can determine his precise situation. Also the quickened display might lead to a conflict of visual and motion cues, and to conflict between φ and G visual information (since displayed G is no longer the double integral of φ). Finally, if the acceleration rate information were to be lost for any reason, the pilot would have no direct indication that the failure had occurred, and control might be lost before he could transition or adapt to the unquickened situation (this constitutes a step change in controlled element dynamics).

APPLICATION OF EXPERIMENTAL RESULTS

Criteria for display design

EXPERIMENT DESCRIPTION

A representative manual entry simulation is required which is capable of simulating a complete entry trajectory and in which the primary display consists of roll attitude error computed in and commanded from the simulated GNS. Various failures of the automatic systems (GN and control) should be programmable at crucial points in the trajectory. The backup display should consist of roll attitude and deceleration level obtained from body mounted sensors. Entry trajectories requiring large angle roll maneuvers should be flown (including representative equipment failures)

with the current Apollo φ_e and the ARC backup displays and with the displays modified as noted below.

1. φ_e Display — A ±180 deg nonlinear scaling should be provided such that the general magnitude of the roll error can be perceived by the pilot at all times and the error rate sensitivity (or gain) increases as the error nears zero, i.e., the region around zero error (e.g., ±10 deg) is expanded and the region around maximum error (±180 deg) is compressed.

2. G Display — The display shall allow mixing of G and $\dot{G}$ (quickening) in variable proportion to drive a single needle or indicator.

3. Measurements and Data Reduction — Compare overall entry performance with that obtained using current display configurations. Possible comparisons include:

   a. Time for the pilot to correctly identify failures and take appropriate corrective action

   b. Deviation from prescribed attitude or trajectory

   c. Settling time (time to stabilize at new attitude)

   d. Peak overshoot (in attitude or trajectory)

   e. Fuel expenditure

   f. Pilot subjective comments

   Regarding the quickened G display (GNS failed situation), answers to the following questions are sought:

   g. Can quickening result in conflict of visual and motion cues?

   h. Can quickening result in conflict between φ and G visual cues?

   i. How long does it take the pilot to recognize and transition to the "unquickened" situation?

   j. Do the advantages outweigh the disadvantages?

   k. If so, what is the best ratio of G and $\dot{G}$?

EXPERIMENT 15

EFFECT OF MANIPULATOR CHARACTERISTICS ON MANUAL CONTROL PERFORMANCE

JUSTIFICATION

The manipulator (sidestick) characteristics are important from several aspects. They influence pilot opinion, control precision and performance, and the apparent dynamic characteristics of the neuromuscular subsystem (they enter directly into the current mathematical model of the neuromuscular system). If the data from centrifuge simulations is to be compared with in-flight data (i.e., Gemini or Apollo), either the same manipulator characteristics must be employed in both, or information must be on hand to indicate the differences in opinion, performance, and human dynamic characteristics caused by different manipulator characteristics.

A variety of manipulator designs have been employed in centrifuge experiments. For example, in Ref. 26 five different configurations were employed in entry simulations up to 7g. These configurations differed in concept (3-axis versus 2-axis and toe pedals), axes of rotation, breakout force, and force gradient. The breakout forces varied from 0 to 3 in. lb. The pilots commented adversely on the 3 in. lb breakout, which was considered to be too high. Also, the subject pilot comment on the simulations of Ref. 4 was that he had difficulty in moving his hand at accelerations greater than 6g.

In Ref. 27 it is indicated that the Apollo 3-axis sidestick will have breakout forces of 11 in. lb in roll, 8 in. lb in yaw, and 10 in. lb in pitch. This stick has a deadzone of approximately ±3 deg and a total deflection range of ±12 deg. Reference 28 reports preliminary results of centrifuge runs to 15g with this or a similar sidestick. The pilot comments indicated that a total deflection range of ±13 deg was considered to be excessive for entry; that they were not certain whether the stick forces, gradients, and pivot points were satisfactory; and that soft stops were desired at near full throw to indicate the end of rate command and the beginning of direct control. The uncertainty about the stick forces,

gradients, and pivot points arose because of the other portions of the mission (e.g., orbit, rendezvous, etc.) in which the same manipulator would be used. The implication is that the manipulator characteristics might have to be a compromise or be variable in flight to satisfy all phases of the mission. In these simulations the pilots were generally flying to a φ_e display with GNS failures introduced at various points in the entry to determine the ability of the pilots to retain control.

On the basis of the above, it appears that additional experimentation is needed to better determine the effect of manipulator characteristics on the pilot's ability to control and to define the desirable characteristics for the high g-levels anticipated in entry at planetary velocities.

APPLICATION OF EXPERIMENTAL RESULTS

Criteria for manipulator design.

EXPERIMENT DESCRIPTION

It is suggested that Experiment 10 be repeated with various manipulator characteristics to determine the effect of such characteristics on the pilot's control precision, coordination, etc. Additional entry simulations should be run with the pilot controlling all three degrees of freedom to determine the effects of manipulator characteristics on inadvertent axis coupling, etc., and to define optimum characteristics.

Possible variables for these experiments include stick

- Inertia and balance
- Damping
- Feel (spring gradient, breakout, centering)
- Axes of rotation
- Travel
- Gain (electrical)
- Harmony between axes
- Nonlinearities

1. Measurements, Data Reduction, etc.

   Same as Experiment 10

EXPERIMENT 16

TRAINING RETENTION EFFECTS ON ENTRY PERFORMANCE

JUSTIFICATION

It is presumed that on extended duration flights (either orbital or planetary) the pilot will maintain his entry control and maneuver procedure proficiency by on-board simulation. It is also possible the spacecraft will contain an on-board centrifuge to exercise his physiological systems and maintain general body tone. It is unlikely, however, that the two will be combined (i.e., on-board centrifugation while practicing the entry maneuver).

Past centrifuge runs (Ref. 29) have indicated the pilots adopt a body straining and breathing technique in order to withstand the high forces and physiological disruptions caused by high g's. Apparently this straining technique is "learned" with experience and, in addition, the pilots must "learn" the control task in the context of changed muscular and sensory capacities under the high g's. That is, they must learn to do the physiological and performance aspects simultaneously. Since the entry maneuver is a "one shot" situation with success required on the first attempt, it is of importance to determine how long a pilot can retain this "learned" skill.

APPLICATION OF EXPERIMENTAL RESULTS

1. Criteria on training retention effects
2. Possible criteria for the need of high-g entry practice on long missions

EXPERIMENT DESCRIPTION

The experiment requires the training of several pilot subjects on a centrifuge entry simulation sufficiently complete to include pilot control of the three rotational degrees of freedom and allow for failure in the GNS. Following this centrifuge training, the subjects would

continue practicing the entry maneuver and procedures at, say, one week intervals in a nominal 1g environment. After approximately 2 to 3 months, one of the subjects would be placed in the centrifuge to test his ability to perform a successful entry on the first run. The second subject would be similarly tested after an additional 2 to 3 month period. This procedure would be repeated until a significant degradation in performance (i.e., unsuccessful entry) is obtained. When this occurs, it probably would be necessary to test another subject to determine whether the first failure was indicative of a general loss of training. If this subject performs a successful entry, the experiment would be continued at the 2 to 3 month intervals until all of the originally trained subjects had been tested. It will be imperative that the test subjects are not exposed to over 1g during the time period between their final centrifuge training run and their "test" run.

1. Measurements and Data Reduction

   a. Performance measures

      - Time for pilot to correctly identify failures and take appropriate corrective action
      - Deviations from prescribed trajectory
      - Fuel expenditure, etc.

   b. Physiological measures

      - Blood oxygen
      - Blood pressure

   c. Pilot subjective comments

C. EPILOGUE

This preliminary identification of experiments is considered to be the first step in rectifying the dearth of data to

- Quantitatively relate pilot control skill decrements identified in this study with the main flight variables
- Correlate control skill or task performance decrements with key indicators of physiological well-being

Therefore, it is recommended that these experiments be refined, expanded, and initiated at the earliest possible date. It is difficult to establish a recommended priority of experiments without knowledge of NASA research programs currently under way. However, on the bases of this study and of potential scientific importance in general, a suggested priority of experiments and/or information is as follows:

1. Quantitative correlation of cause/effect relationships between crucial (i.e., visual and central processing) pilot skill degradation and degradation in functioning of his internal life support and regulation systems
2. Separation of pilot skill degradation due to degradation of internal life support and regulation systems from that due to high g *per se*
3. Quantitative assessment of degradation in and/or limit of crucial pilot skills with total effects of increasing g level
4. Quantitative assessment of varied controlled element characteristics and of pilot long-term memory on manual control of typical entries

The possibility exists that considerable subjective information may already exist in unpublished (i.e., NASA internal working paper or memo) documentation of past astronaut training and/or spacecraft development simulations which would help guide this program. For example, astronaut comments regarding visual beamwidth and manipulator characteristics for one spacecraft development simulation at very high g are contained in Ref. 27. It is therefore recommended that effort be expended to screen NASA internal documentation of past Gemini and Apollo simulation activities for potentially applicable information.

It is equally likely that the data recorded during past Gemini flights may be of considerable benefit in preparing for future in-flight conduct of experiments such as proposed here. Although these flights were of such short duration that little, if any, degradation in pilot control skill due to weightlessness should be exhibited, analysis of specific portions of the flight tapes would be of benefit in

1. Working out techniques of analyzing the telemetry data to extract information such as pilot describing function factors, performance measures, etc.

2. Determining minimum telemetry sampling rates, time share sequences, etc., to avoid problems in analyzing future flight data for human performance measures — and hence to prepare specifications for such data recording (biomedical and skill)

Finally, the identification and quantification of the human internal life support and regulation systems degradation common to virtually all of the experiments outlined here may involve the perfection of existing (or development of new) biomedical measurement and data analysis techniques. Specifically, adequate measurement of blood oxygen content via dry techniques, e.g., the ear oxiometer, may present problems.

SECTION V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This preliminary study has been addressed to manual control of a typical fixed lift/drag vehicle entering the atmosphere at planetary velocity after an extended period of space flight (weightless conditions). The two most critical phases of such an entry have been identified as the capture phase (or maneuver), lasting from initial contact with the atmosphere until peak deceleration g is reached, and the deceleration control phase, lasting from peak deceleration until the achievement of circular orbital velocity. Typical roles, maneuvers, and tasks the astronaut/pilot may be called upon to perform in these two entry phases have been established and analyzed from the standpoint of general performance requirements and piloting skills involved.

Insofar as roles are concerned, the pilot may act as a monitor, may voluntarily take on the additional duty of controlling vehicle attitude to that commanded by and displayed from the automatic guidance system, or may perform in an emergency backup control or guidance role following malfunction of the automatic control or guidance systems. In the latter event, a rate damper failure results in the pilot's controlling a vehicle with dynamics which approximate a pure inertia (K_c/s^2) in at least one axis. This requires that he generate a first-order lead to achieve stable control. If the guidance and navigation system fails, the pilot must control vehicle attitude and deceleration level based on information from body-mounted sensors. In this event the vehicle dynamics approximate a K_c/s^3, and he must generate a second-order lead to achieve stable control. Only in the event of no failure but the pilot voluntarily in active control (second role indicated above) is there a chance that the vehicle dynamics approach the "ideal" K_c/s wherein no lead generation is required on the part of the pilot to achieve stable control.

For the typical mission envisioned here, gross attitude change maneuvers will be required during the capture phase and may be desirable during the deceleration control phase. The timing and execution of these maneuvers will be crucial to successful entry at least during

the capture phase. In the intervals between gross attitude changes, the maneuvers will be restricted to relatively small, tracking type, attitude perturbations to maintain the desired trim attitude and/or deceleration level.

The pilot skills involved in these various roles, maneuvers, and tasks were identified as:

- Sensing skills (visual acuity and beamwidth, ocular motility, and audition)
- Central processing skills (coordination, decision-making, and lead generation)
- Actuating skills (hand and arm/hand)

An attempt was made to quantitatively relate changes in these pilot skills with the flight variables of interest (long term weightlessness followed by high g at entry) based on the published results of past centrifuge experiments, simulated weightlessness experiments and short-term orbital flight. Unfortunately the literature contained insufficient data to accomplish this. There are some quantitative data, but mostly qualitative information, to indicate high g does indeed degrade both the required pilot skills and the human internal life support and regulatory subsystems (cardiovascular and respiratory). Further, the internal life support and regulatory function degradation, in particular the blood and oxygen supply to the head, is a major, if not the major, contributor to pilot visual and central process skill degradation at high g. Less information was found on zero-g effects (simulated or actual). There is some evidence, and concern, that prolonged weightlessness may deteriorate the functioning of the internal life support and regulatory subsystems. Unfortunately the published literature proved insufficient for positively establishing the latter and long term zero-g effects remain mostly conjecture.

Because of the dearth of quantitative data relating pilot skill degradation, internal life support and regulating subsystem degradation, and abnormal g environment, a series of experiments has been outlined and presented. These are not purported as original since many are patterned after experiments that have been proposed elsewhere or actually

performed under varying circumstances. For the most part they are intended to fill gaps and establish quantitative high-g baseline data that should exist but apparently does not. In context these experiments form a consistent, complementary sequence of experimentation — each is addressed to establishing performance degradation in specific, but highly interrelated, pilot skills required in and identifiable with typical entry control tasks. The conduct of these experiments does not involve measurement or data analysis techniques beyond the present state-of-art.

The results of this study have also led to the conclusion that, of the potential human system changes due to long-term adaption to weightlessness, changes which result in degradation of blood oxygen regulation and/or supply to the head will be crucial to pilot performance under the high g's of entry. Therefore most of the experiments presented are also directed toward identification and quantification of cause/effect relationships between pilot skill degradation and degradation of his internal life support and regulation systems. The latter relationship has potential long-term importance from the standpoint of extrapolating or perturbing results stemming from current experimental configurations, in planning and conducting future space experiments, and in interpreting the results therefrom. The identification and quantification of skill/internal regulation system cause/effect relationships may involve the development of new (or perfection of existing) biomedical measurement and data analysis techniques.

It is difficult to establish a recommended priority of experiments without knowledge of NASA research programs currently underway. However, on the bases of this study and of potential scientific importance in general, the suggested priority of experiments and/or information is as follows:

1. Quantitative correlation of cause/effect relationships between crucial (i.e., visual and central processing) pilot skill degradation and degradation in functioning of his internal life support and regulation systems.

2. Separation of pilot skill degradation due to degradation of internal life support and regulation systems from that due to high g per se.

3. Quantitative assessment of degradation in and/or limit of crucial pilot skills with total effects of increasing g level.

4. Quantitative assessment of varied controlled element characteristics and of pilot long-term memory on manual control of typical entries.

It is possible that some of the gross information sought in these experiments may already exist in unreduced or unpublished form from past experiments, training simulations, and actual entries (e.g., Mercury and Gemini flights). It is therefore recommended that effort be expended to screen past activities, program plans, internal NASA reports, etc., for potentially applicable data. It is also recommended that future Apollo experiment, training simulation, and actual flight plans be reviewed with an eye to obtaining some of the data sought here.

REFERENCES

1. Request for Proposal A-11903 (DD-90), A Definition and Analysis of Pilot/System Performance Measurements for Planetary Entry Experiments, April 6, 1966.

2. Miller, Albert B., Pilot Re-entry Guidance and Control, NASA CR-331, Nov. 1965.

3. Lum, B. T. F., Apollo Stabilization and Control System Analysis Manual, North American Aviation Space and Information Systems Division Rept. 211-110-63-366, 15 July 1966.

4. Wingrove, R. C., G. W. Stinnett, and R. C. Innis, A Study of the Pilot's Ability to Control an Apollo Type Vehicle During Atmospheric Entry, NASA TN D-2467, Aug. 1964.

5. Graham, D., and D. McRuer, Analysis of Nonlinear Control Systems, John Wiley and Sons, Inc., New York, 1961.

6. McRuer, D., D. Graham, E. Krendel, and W. Reisener, Human Pilot Dynamics in Compensatory Systems, AFFDL-TR-65-15, Wright-Patterson AFB, Ohio, July 1965.

7. Morth, R., and J. L. Speyer, "Divergence from Equilibrium Glide Path at Supersatellite Velocities," ARS Jour., Vol. 31, No. 3, Mar. 1961, pp. 448-450.

8. Wingrove, R. C., "Trajectory Control Problems in the Planetary Entry of Manned Vehicles," Proc. AIAA Entry Techniques Conf., Oct. 1964.

9. Fraser, T. M., Human Response to Sustained Acceleration, NASA SP-103, 1966.

10. Lamb, L. E., "Status of Knowledge of Weightlessness 1965," Appendix 5 in Space Research, Directions for the Future, Part III, Space Science Board, Nat. Academy of Sc., Nat. Research Council, Wash., D. C., Feb. 1966.

11. Chiles, W. Dean, Assessment of the Performance Effects of the Stresses of Space Flight, AMRL-TR-66-192, Wright-Patterson AFB, Ohio, Dec. 1966.

12. Vinograd, S. P., Medical Aspects of an Orbiting Research Laboratory, Space Medicine Advisory Group Study, NASA SP-86, 1966.

13. Wolkovitch, J., et al, Performance Criteria for Linear Constant-Coefficient Systems with Deterministic Inputs, ASD-TR-61-501, Wright-Patterson AFB, Ohio, Feb. 1962.

14. Taylor, L. W., Jr., A Comparison of Human Response Modeling in the Time and Frequency Domains, paper presented at the USC-NASA Working Conf. on Manual Control, Los Angeles, Calif., Mar. 1-3, 1967.

15. Kelly, R. D., et al, Techniques and Errors in Measuring Cross-Correlation and Cross-Spectral Density Functions, NASA CR-74505.

16. Lim, R. S., and W. D. Cameron, Power and Cross-Power Spectrum Analysis by Hybrid Computers, NASA TM X-1324, Dec. 1966.

17. Wierwille, W. W., and G. A. Gayne, A Theory for the Optimal Deterministic Characterization of the Time-Varying Dynamics of the Human Operator, NASA CR-170, Feb. 1965.

18. Elkind, J. I., "A Survey of the Development of Models for the Human Controller," Guidance and Control—II, ed. R. C. Langford and C. J. Mundo (Progress in Astronautics and Aeronautics, Vol. 13) Academic Press, New York, June 1964.

19. McRuer, D. T., and E. S. Krendel, Dynamic Response of Human Operators, WADC-TR-56-524, Wright-Patterson AFB, Ohio, Oct. 1957.

20. Investigation of Control "Feel" Effects on the Dynamics of a Piloted Aircraft System, Goodyear Airc. Corp. Rept. GER-6726, Apr. 1955.

21. Levison, W. H., and J. I. Elkind, Two-Dimensional Manual Control Systems with Separate Displays, paper presented at the USC-NASA Working Conf. on Manual Control, Los Angeles, Calif., Mar. 1-3, 1967.

22. Smedal, H. A., et al, The Physiological Limitations of Performance During Acceleration, paper from 33rd Meeting of Aerospace Medical Association, Aerospace Medicine, Apr. 1962.

23. McDonnell, J. D., and H. R. Jex, A Critical Tracking Task for Man-Machine Research Related to Operator's Effective Time Delay, NASA CR-674, Jan. 1967.

24. Sadoff, Melvin, Effects of High Sustained Acceleration on Pilot's Performance and Dynamic Response, NASA TN D-2067, July 1964.

25. Weir, D. H., and A. V. Phatak, Model of Human Operator Response to Step Transitions in Controlled Element Dynamics, NASA CR-671.

26. Creer, B. Y., H. A. Smedal, and R. C. Wingrove, Centrifuge Study of Pilot Tolerance to Acceleration and the Effects of Acceleration on Pilot Performance, NASA TN D-337, Nov. 1960.

27. Apollo Operations Handbook, Command and Service Module, Mission AS-204A, Spacecraft 012 (Preliminary Issue), North American Aviation Space and Information Systems Division SM2A-03-SCD12, 15 Oct. 1965.

28. Thomas, J. B., Results of Apollo I Centrifuge Program (Engineering Development and Pilot Familiarization), NASA WP-10,023, Mar. 1964.

29. Chambers, R. M., and J. G. Nelson, Pilot Performance Capabilities During Centrifuge Simulations of Boost and Reentry, ARS Preprint 1401-60, Dec. 1960.

30. McRuer, D. T., and H. R. Jex, Effects of Task Variables on Pilot Models for Manually Controlled Vehicles, paper presented to AGARD Specialists Meeting on Stability and Control, Cambridge, England, 24 Dec. 1966.

APPENDIX A

PHYSIOLOGICAL CONSIDERATIONS IN ENTRY VEHICLE CONTROL

	Page
1. REGULATION OF INTERNAL ENVIRONMENT UNDER g-FORCES	A-3
Respiratory System Performance	A-5
Cardiovascular System Performance	A-11
2. PHYSIOLOGICAL SUBSYSTEM PERFORMANCE UNDER g-FORCES	A-16
Visual System Performance	A-16
Central Nervous System Performance	A-19
Neuromuscular System Performance	A-24
Vestibular System Performance	A-26
Physiological Tolerance	A-27
3. EFFECTS OF WEIGHTLESSNESS ON HIGH-g PERFORMANCE	A-29
Cardiovascular System	A-29
Respiratory System	A-32
Visual System	A-33
Vestibular System	A-33
Central Nervous System	A-34
Neuromuscular System	A-36
4. SUMMARY	A-36
GLOSSARY OF TERMS	A-38
REFERENCES FOR APPENDIX A	A-41

APPENDIX A

PHYSIOLOGICAL CONSIDERATIONS IN ENTRY VEHICLE CONTROL

Satisfactory piloting performance of the variety of entry tasks, both continuous and discrete, depends on both training and an adequate level of fitness. This appendix is primarily concerned with the latter, that is, with an astronaut's performance from the physiological point of view. In particular, it is necessary to determine which components of the human machine are most likely to break down (give inadequate performance) under the environmental stresses of atmospheric entry as a result of long duration exposure to the space vehicle environment. The nature of these physiological failures is also important, as this factor helps establish the kinds of experiments which might be performed in order to define the extent of a pilot's role in manually controlled entry.

There are four physiological subsystems within the pilot which are essential in the performance of any control task:

- **Visual System** — the means by which information is obtained regarding the state variables of the vehicle and trajectory dynamics.
- **Vestibular System** — the pilot's acceleration sense.
- **Central Nervous System** — the means by which interpretation and integration of sensory information is effected and neuromuscular commands generated.
- **Neuromuscular System** — the means by which control activity is effected.

The closed-loop system comprised of the pilot, the vehicle and trajectory dynamics, and the displays may be represented as shown in the schematic of Fig. A-1. This figure could also be generalized to represent the pilot in a discrete task situation; the important elements within the loop in either case are shown within the dotted boxes. The various physiological elements and their interconnections are represented to the accuracy permitted by current physiological knowledge and pertinence to this discussion. The schematic is grossly oversimplified.

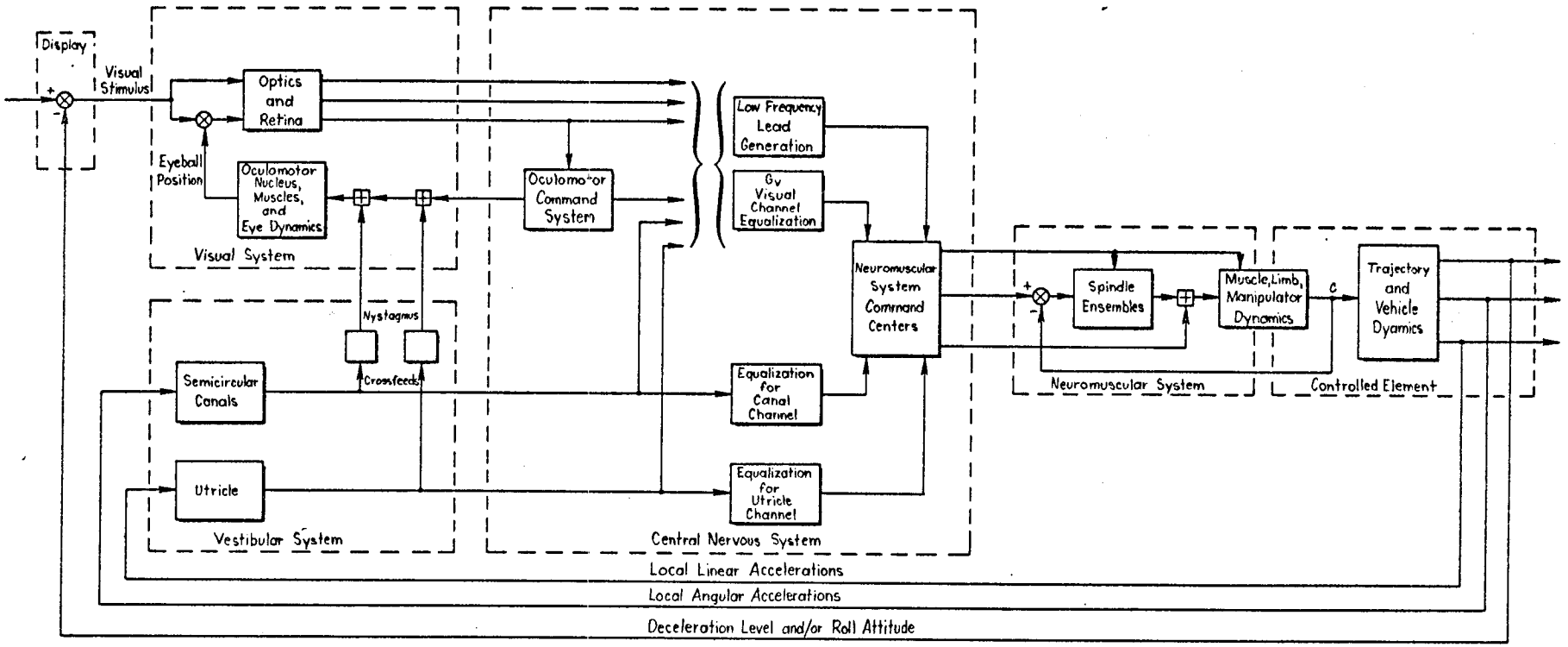


Figure A-1. Block Diagram of Display, Pilot Manipulator, Vehicle, and Trajectory Dynamics

1. REGULATION OF INTERNAL ENVIRONMENT UNDER g-FORCES

The functioning of the human under the external environment imposed by entry g-forces is crucially dependent on the functions of those physiological subsystems controlling the internal environment, the cardiovascular and respiratory systems as governed by the activity of the autonomic nervous system. In this section, the effect of g-forces on these systems is discussed. The resultant effects on the subsystems within the control loop follows in Section 2. Figure A-2 provides a summary diagram of the various interactions which are discussed in the paragraphs to follow.

The pilot's ability to withstand prolonged exposure to g-stresses is a sensitive function of his restraint system, an important parameter of which is his posture with respect to the applied g-vector. Most Russian centrifuge data are given for a 65 deg back angle (65 deg between the pilot's back and the applied acceleration). The Apollo vehicle orients the crew with an angle slightly greater than 80 deg (Ref. A-2, p. 69). In either case, the dominant acceleration is "eyeballs in" (EBI), although the "eyeballs down" (EBD) component cannot be neglected. The choice of back angle is a compromise between visual disturbances (smaller angles) and respiratory distress (angles closer to 90 deg). Reference A-2, pp. 58–59, quotes earlier work of Bondurant et al (1958) as showing an optimum position between 65 deg and 70 deg and in Ref. A-10, 80 deg is felt to be optimum. Improvements in restraint systems have presumably made the breathing distress less critical, resulting in optimum angles closer to the Apollo configuration. The question of posture and restraint system is, in any case, an important source of discrepancy in the data reported by various investigators. In the discussions which follow it should be remembered that Russian results should show an earlier (in terms of either time or g-level) onset of visual disturbance, or more pronounced cardiac disturbance, together with a somewhat reduced respiratory disturbance relative to U.S. data.

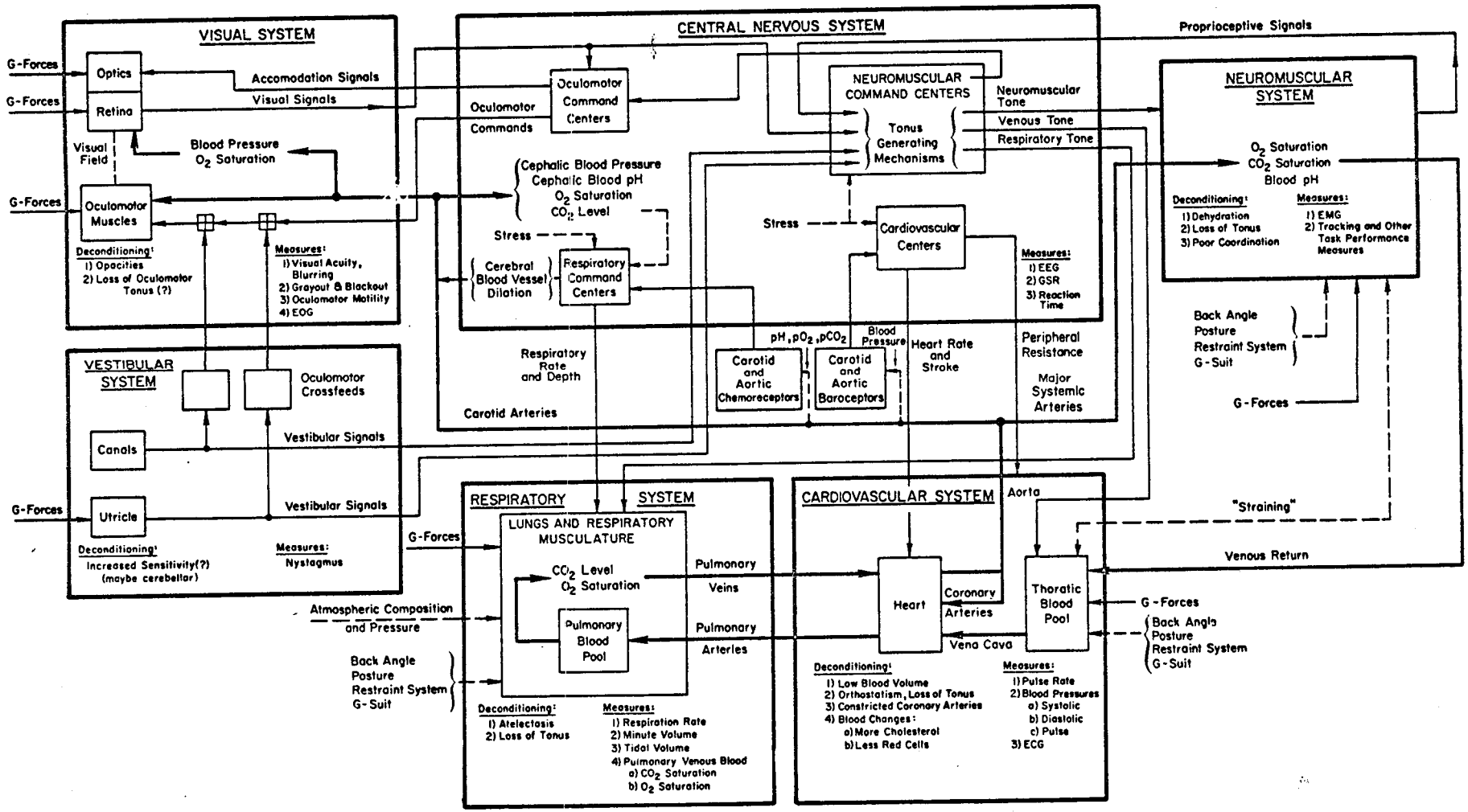


Figure A-2. Physiological Interrelationships Pertinent to Behavior Under g-Forces as Modified by Weightlessness Deconditioning

Respiratory System Performance — The respiratory system provides the means by which the body's blood supply is oxygenated and carbon dioxide is given off. Breathing effort (respiration rate and depth) is regulated by respiratory command centers within the central nervous system. This in turn responds to changes in the blood chemistry (blood pH, oxygen saturation, carbon dioxide level) sensed in the carotid and aortic bodies and (apparently) by direct sensing of the carbon dioxide content of the blood circulating within the respiratory areas of the brain stem. The same stimulus (increased CO_2) will also cause a dilation of the cerebral blood vessels in an effort to maintain sufficient oxygen and CO_2 exchange with the cerebral tissues.

Respiratory system performance is the major limiting factor in tolerating g-stress in the "eyeballs in" orientation. The nature of the changes in the functioning of the respiratory system has been confirmed by a number of investigators, although the details vary. The following qualitative description generally follows that given in Ref. A-3.

As the g-level increases, the effective vital capacity of the lungs decreases due to progressively increasing pressure on the chest, upward displacement of the diaphragm (visceral displacement), and blood pooling in the pulmonary venous bed. Thus the inspiratory reserve steadily decreases. Tidal volume tends to increase for awhile as respiration becomes deeper in compensation for increasing oxygen requirements, but eventually decreases with increasing g-level as the vital capacity goes down.

As the g-level goes up, there is an increasing disturbance of the ventilation/perfusion relationship in the lungs. The g-forces directly induce a front-to-back pressure gradient within the pulmonary circulatory system, leading to blood pooling in the posterior (dorsal) region of the lungs, and a relative lack of blood in the anterior (ventral) region. This causes at least partial collapse of the alveolar sacs (atelectasis) in the posterior region, overexpansion in the anterior region. The result is a reduction in pulmonary gas exchange, there being insufficient ventilation in the posterior portion, insufficient blood flow in the

anterior portion. Only in the intermediate regions of the lung does the gas exchange approach normal conditions. The net reduction in gas exchange implies a decreased pO_2, an increased pCO_2 in the alveoli leading to a reduction of the oxygen saturation of the blood in the pulmonary veins together with an increased carbon dioxide content (see Fig. A-3). This is equivalent to a shunting of a portion of the pulmonary blood flow. Thus the blood supply to the rest of the body has a progressively increasing degree of oxygen desaturation (hypoxemia) with a tendency to hypercapnia (increased CO_2 content). Data (Alexander et al, 1964, quoted in Ref. A-2, pp. 35–36, and Ref. A-4, p. 40; also Wood et al, 1963, quoted in Ref. A-2, p. 33) would indicate that the oxygen saturation decreases to a constant level inversely proportional to the applied g-stress unless the g-stress is relatively large. In this latter case, the saturation continues to decrease to the point where there is significant disturbance of the autonomic nervous system functioning. This results in respiration which fluctuates in rate and depth and heart rate arrhymia tending to accelerate the rate of desaturation. Endurance in the former case is presumably a function of general fatigue or general discomfort; in the latter, the end point can be a more sharply defined failure of one or more physiological subsystems.

The respiration rate increases almost linearly with g-level because of hypoxic and hypercapnic drive. The oxygen requirements have increased because the reduced pulmonary efficiency demands an increased work of breathing, as well as an increased energy expenditure involved in "straining." As the g-level increases, the pilot will employ a continuous Valsalva maneuver while exhaling through a restricted glottis. This increases the intrapulmonary pressure and promotes more rapid oxygenation of the blood. The respiration pattern becomes one of rapid inspiration followed by longer expirations during which the pilot grunts, sighs, or yells as a means of maintaining glottal restriction (Ref. A-5, p. 49).

The composition and pressure of the breathing air has an important bearing on the tolerance of g-stress. Alexander's results (Ref. A-2, pp. 35–36; Ref. A-4, p. 40) would show a small improvement in the

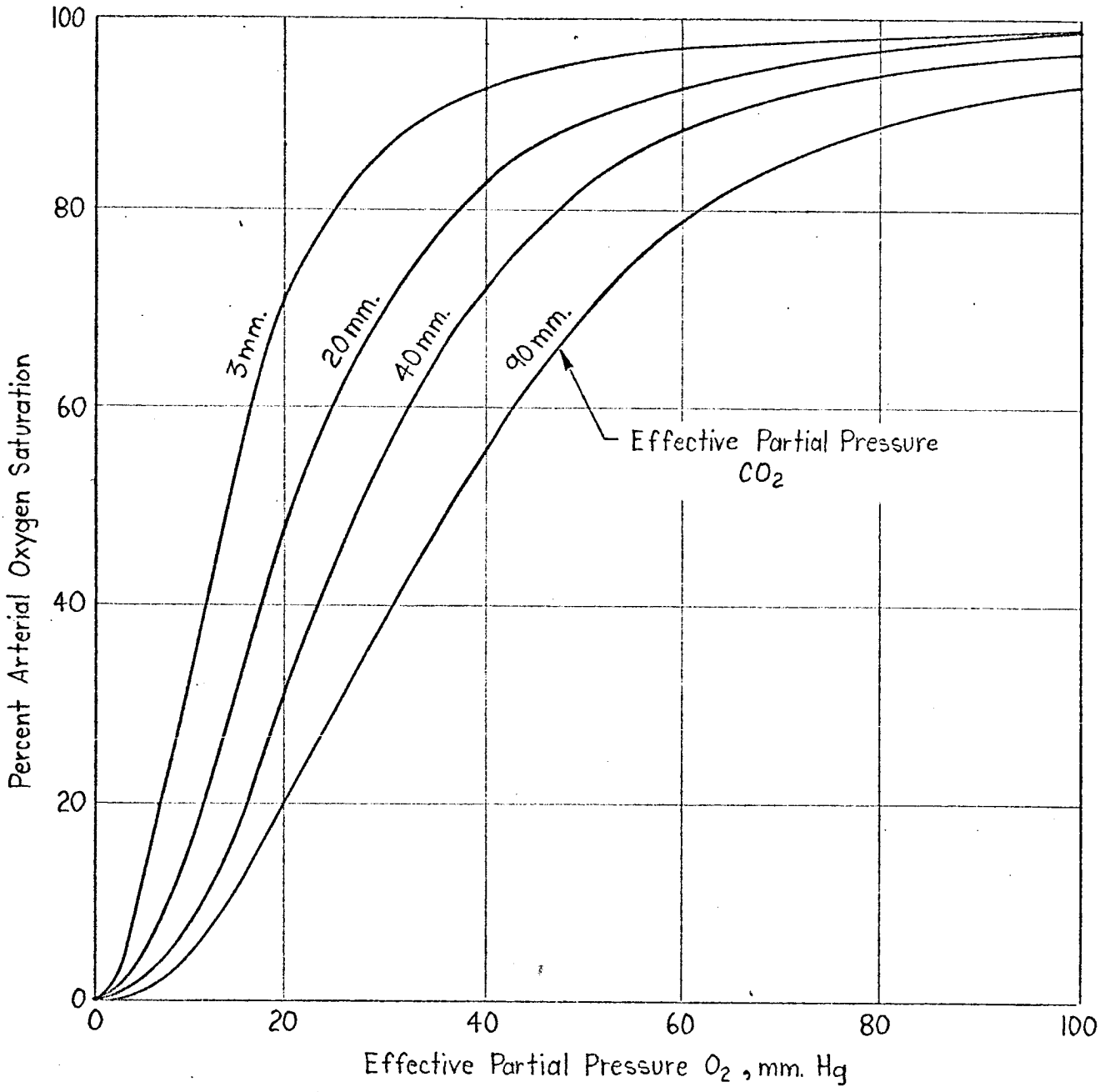


Figure A-3. Oxygen Dissociation Curve (From Ref. A-1)

oxygen saturation of the blood when breathing 5 psia oxygen instead of air at normal atmospheric pressures. There is a further improvement if positive pressure breathing is employed (Ref. A-6). However, use of pure oxygen entails a penalty — increased atelectasis (the reasons for which are not completely understood). This manifests itself in a slower recovery of oxygen saturation levels after cessation of acceleration and a marked reduction in post-run vital capacity relative to the case where air at normal atmospheric pressure is used.

It is very difficult to assign particular values of g-stress at which certain changes in respiratory system (or any other physiological system, for that matter) functioning take place. There is considerable intersubject variability, differences in experimental conditions among the various investigators, and so on, plus the fact that the changes are more or less continuous. Bearing in mind these qualifications, the following breakdown is set forth, representing a synthesis of the comments made by various workers in the field:

1g - 3.5g — Within this range the pulmonary disturbance, in terms of a pronounced degree of arterial oxygen desaturation, is minimal (Bjurstedt, Ref. A-5, p. 143), with almost all available data indicating that saturation remains in excess of 90 percent (normal is on the order of 98 percent) throughout the duration of the centrifuge run. One would infer from this that a pilot could withstand accelerations in this range for extremely long periods of time with essentially no degradation in physiological performance. General fatigue would be the limiting factor.

3.5g - 6g — The beginning of this range marks the onset of pulmonary distress — the ventilation/perfusion relationship is increasingly disturbed, with the resultant lowering of arterial oxygen saturation. About half of the available data from several investigators would indicate a leveling off of the O_2 saturation at or below 85 percent after 100-200 sec at 6g. The subjective difficulty of breathing becomes very severe. Wood (Ref. A-5, p. 137) mentions an incident where the subject, exposed to 5g while breathing 5 psia O_2, attempted hyperventilation in an effort to reduce the degree of desaturation. The result was a

severe incapacitating chest pain, terminating the centrifuge run; the subject was hospitalized with the symptoms of mediastinal emphysema. This resulted, apparently, from the very low intrapulmonary pressure in the anterior region of the lungs, resulting from the maximum inspiratory effort. Wood (Ref. A-5, p. 156) goes on to mention the distress involved in 5g, EBI — an intense feeling of breathing difficulty which increases as a function of time.

Chest X-ray studies at 6g would indicate that the major portion of visceral displacement under stress has already occurred (Ref. A-8), and that further increase in g-stress causes lesser changes in the appearance of the X-ray photographs.

It should be remarked that the 85 percent level of arterial oxygen saturation is generally considered to be the "limit allowable" for extended periods of time. In Ref. A-7, p. 108, Pappenheimer is quoted as stating that this level marks "appreciable handicap" (see Fig. A-4). Wood (Ref. A-5, p. 124) feels the pilot can perform "reasonably well" at this saturation level, but "definitely would not recommend" it if it could be avoided. He makes further qualifying remarks leading one to believe that under these conditions prompt emergency operation cannot be relied on. Various investigators have reported endurance times between 7 and 10 min at 6g, which would imply that the reduced oxygen saturation level experienced during the greater portion of the run is sufficient for those central nervous system functions governing respiration and heart rate, even though performance in the higher centers of the central nervous system may be deteriorated to some degree.

6g – 10g The 6g level, to judge by the available data, apparently marks the transition between g-stress endurance times determined by general fatigue and subjective tolerance (at the lower g-levels) and those determined by more or less pronounced physiological failure, i.e., disturbances in autonomic functions. Above 6g, subjects have severe dyspnea (breathing difficulty), severe substernal chest pain (not entirely understood, but probably related to displacement of the heart), and a tendency to cough, particularly on attempted deep inspiration. The respiration rate continues to increase, the tidal volume to

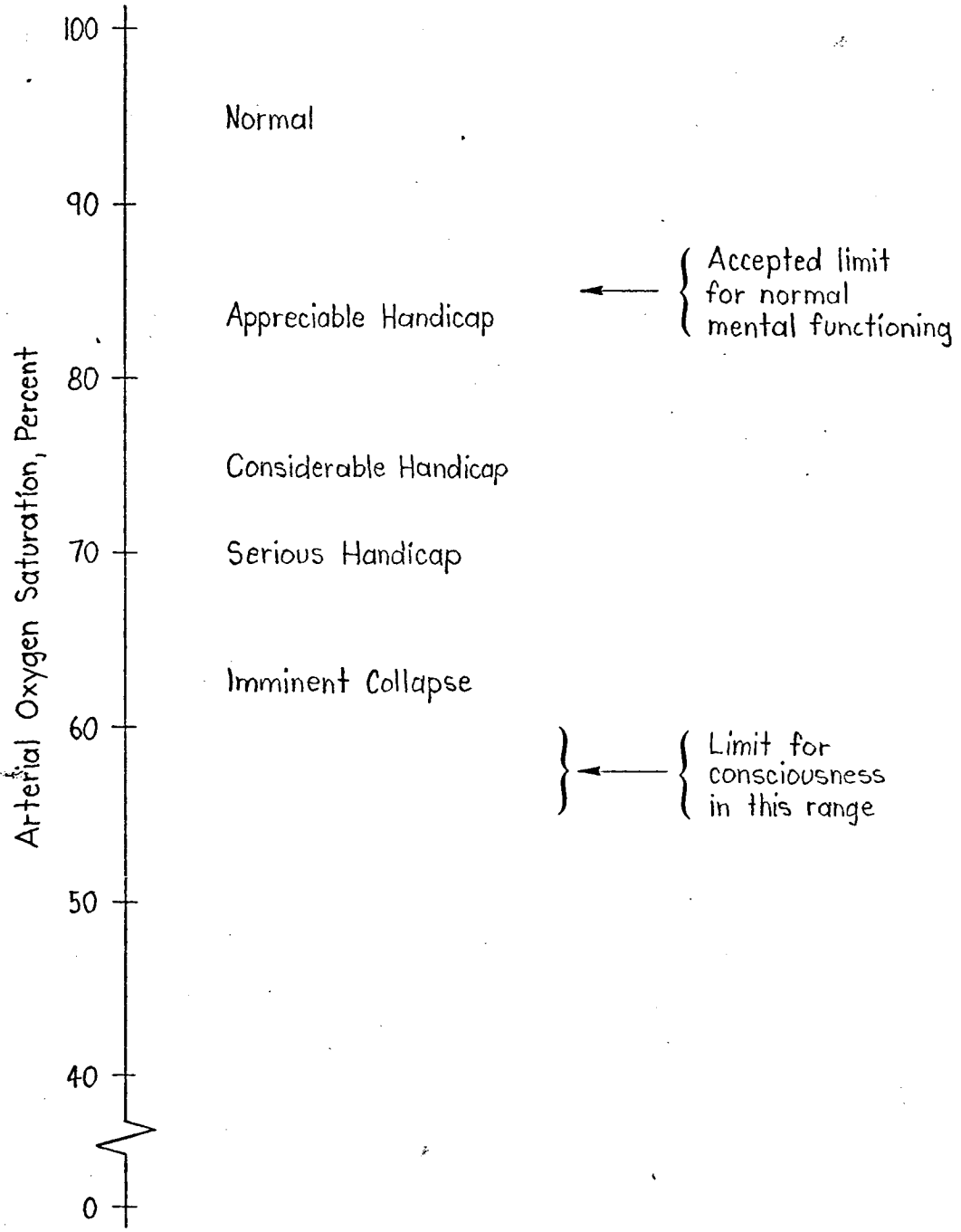


Figure A-4. Descriptors of Mental Functioning Correlated with Arterial Oxygen Saturation (From Ref. A-7)

decrease. In the 8g – 10g range there is a tendency for the respiratory rhythm to become irregular and more rapid toward the end of a particular centrifuge run (Ref. A-9), indicating some compromise of central nervous system regulatory function. The arterial oxygen saturation falls below the 85 percent point for g-levels in excess of 6, but (apparently) still tends toward a steady state. This steady state is on the order of 70 percent at 10g, and may never be reached before the subject terminates the run.

10g – 15g There are very limited data for levels in excess of 10g. However, the trends noted above would indicate a very rapid arterial oxygen desaturation. In addition, tidal volume approaches the maximum attainable, but becomes small enough with increasing "g" to be comparable to the pulmonary dead space. Each respiratory cycle does little more than ventilate the latter. Some Russian data (Ref. A-9) would indicate cessation of respiration in some subjects above 10g, in virtually all subjects at 15g, presumably due to the inability to inhale against the external pressures imposed. One concludes from this and other data available that the subject's respiratory response never has a chance to achieve a "steady-state" operation at stress levels at and above 12g. His endurance is largely dependent on the oxygenation of his tissues prior to the onset of acceleration.

In connection with these levels of stress, it has been noted that stress profiles typical of entry vehicles (that is, a buildup to a peak of, say, 10g, followed by a drop to a level of 5g or 6g, which is sustained to the end of the run) are among the most disliked by subjects. The "surge" to 10g or more leads to the pain, coughing, and general distress typical of that level which tends to persist throughout the remainder of the profile (Schmidt, Ref. A-5, pp. 141 – 142).

Cardiovascular System Performance — The cardiovascular system, comprising the heart and circulatory system, acts to maintain blood flow and blood pressure in all parts of the body. The blood flow and pressure at any particular point in the circulatory system is dependent on the caliber of the blood vessel involved, the hydrostatic pressure

differential between its location and the heart's, the heart rate and stroke volume, and, finally, the venous return to the heart. Regulation of the blood pressure at any point is accomplished chiefly by changes in the heart's rate and stroke volume (per cardiac cycle) and by changes in the caliber of the blood vessels in various parts of the system.

Control over these changes is exercised chiefly by the certain command centers in the brain. These are responsive to sensed pressure changes in the aortic and carotid sinuses. In addition, hormonal (adrenalin) stimulation directly affects heart rate. The latter is one means by which emotional stress is manifested.

The blood flow returning to the heart is also a function of the venous tone and neuromuscular activity. The body's venous bed contains a large portion of its blood supply, and dilated veins imply poor return to the heart. Activity of the muscles provides a "pumping" action which will increase venous return. (Activity also has some influence on arteriolar diameter as evidenced by the greater blood flow to active muscles.) An additional factor is, of course, the overall blood volume, a reduction of which will result in poorer blood pressure regulation.

In centrifuge runs and during atmospheric entry, the pulse rate will rise in anticipation of the imposed acceleration stress, with (in the case of the former) less experienced subjects having a more pronounced cardiac response. This emotional factor makes it difficult to determine what degree of cardiac response is due to the physical stresses imposed, at least for the lower g-levels. The blood pressure regulating reflex will also affect the heart rate as indicated above; a drop in the blood pressure sensed in the carotid sinus results in an increased heart rate. This reflex has a response time between 6 and 10 sec (Ref. A-2, p. 11), meaning that the rate of onset of g-stress is an important factor in blood pressure regulation.

For very rapid onsets, the cerebrospinal fluid tends to shift downward, increasing the cerebral vascular volume. This mechanical action is more immediate, and tends to maintain blood flow to the brain. In any case, increasing g-levels result in an increased pressure

differential between the heart and head which results in an increase in heart rate (emotional factors aside) which is directly related to g-level and back angle.

The heart stroke volume, i.e., volume of blood delivered for each beat, tends to increase directly with heart rate up to the point where shortening of the period of diastole begins to affect atrial filling. Given an adequate venous return, the heart stroke will increase with heart rate up to some point, then begin to fall. There is also evidence to indicate that the right ventricle of the heart will increase its stroke, presumably in response to a hypercapnic drive, in an effort to increase pulmonary blood flow (Ref. A-11).

The heart stroke is also (as indicated above) a function of venous return to the heart. This tends to decrease with increasing g-stress because of blood pooling within the venous system of the abdominal and pulmonary cavities. Here again, back angle and posture with respect to the direction of acceleration together with "straining" effort have important bearing on the amount of blood pooled. Venous tone is also important, as a low tonus results in a greater capacity of the venous system, hence less return.

The degree of vascoconstriction in the cerebral blood vessels will also affect blood flow. The two factors tending to increase flow are the hypercapnic drive (increased carbon dioxide within the arterial blood will cause dilation of the cerebral blood vessels) and the general stress reaction.

A second indicator of cardiovascular system performance is the appearance of the electrocardiogram (ECG). The reports of several investigators would indicate regular and progressive changes in the appearance of the ECG and shifts in the electrical axis of the heart with changes in the heart rate. In addition, certain irregularities (extra systoles, for example) tend to be associated with emotional stress and thus correlate with the experience level of the subjects. Other changes in measurable components of the ECG occurring over a period of time in high g's are indicative of incipient visual or cerebral disturbance within 10–20 sec (Fraser quoting Marnkhanyan,

Ref. A-2, p. 19). Generally speaking, it appears that the heart rate tends to falter, with increasing incidence of irregularities, toward the end of a run at moderate to high stress levels. This is presumably indicative of disturbances in the central nervous system regulatory function and/or a progressive failure of the cardiac oxygen supply (insufficient oxygenation of the coronary blood supply or reduced coronary blood flow).

A review of the literature on the effects of "eyeballs in" acceleration on cardiac performance leaves one with a strong impression of a high degree of correlation between respiratory and cardiovascular system performance. As a function of the applied g-level, the changes may be described as follows:

1g – 3g In this range some authors report no change or only a slight change, presumably because of the dominant influence of emotional stress on cardiac response. In Ref. A-11 this is attributed to the adequate functioning of the pulmonary system, including its venous tone, in this range. The blood pressure regulating reflex will have some effect, even at these low g-levels, depending on back angle. However, the stress reaction would appear to be dominant.

3g – 6g In this range the pulmonary system efficiency is dropping. Pulmonary blood flow increases with increased stroke of the right heart. The hydrostatic pressure gradient within the lung causes pulmonary blood pooling; and, in addition, there is pooling in the venous bed of the abdominal cavity. The pilot mitigates this by straining, and a continuous Valsalva maneuver, both of which tend to increase the venous return. The heart rate and the systolic, diastolic, and pulse pressures have all increased; the emotional stress contribution, at least in the steady-state condition, is somewhat less important. For a bench mark, the pulse rate is on the order of 110 beats/minute at 6g.

6g – 10g Reference A-9 gives an example of the pulse rate history of a subject exposed to 6g or 8g. There is an anticipatory rise in pulse rate prior to centrifugation which

continues to rise as the g-level builds up. There is generally an overshoot; the pulse rate tends to decrease slightly after steady-state g's are reached. This steady state is maintained until the limit of endurance is approached, then the pulse rate shows a tendency to gradually decrease. Toward the latter portion of this phase, irregularities begin to appear in the ECG, followed by the subject's terminating the run. Reference A-9 also notes for this particular experimental setup that the 8g point may represent some sort of limit; the pulse rate does not overshoot for this case as it does for the lower g-levels. Reference A-3 gives typical pulse rates (120 beats/minute) and blood pressures (150/115) at the 8g level, remarking that for inexperienced subjects these numbers tend to be even higher. Reference A-9 quotes pulse rates as high as 180 beats/minute at 8g, to give an idea of the possible range of cardiac response. Toward the upper end of this range there is a (subject-dependent) tendency for occasional premature systoles — probably a stress effect, but perhaps indicative of "limit allowable." Reference A-9 mentions a greater tendency toward sinus arrhythmia and premature contractions at 10g than at 8g. In any case it is apparent that the cardiovascular system is approaching its stress limit at 10g. One further remark: The 6g level marks the beginning of a tendency toward petechia of the skin in dependent regions where local blood pressures are highest. These increase with increasing g-level, then decrease because of the shorter endurance times at the higher levels.

10g – 15g

The 10g level is, for back angles between 65 deg and 80 deg, particularly the former, the point above which adequate cerebral blood pressure cannot be maintained. Visual disturbances indicative of inadequate blood flow begin to appear at some point during a 6g run; however at 10g they appear immediately. One concludes that the cardiovascular system is incapable of maintaining sufficient cerebral blood flow; endurance is a function of the oxygenation of the cerebral tissues at the beginning of the run.

2. PHYSIOLOGICAL SUBSYSTEM PERFORMANCE UNDER g-FORCES

Visual System Performance—The pilot, in fulfilling his manual entry role, is in the same situation regarding his dependence on visual cues as the pilot of an aircraft flying on instruments. The important parameters of visual system performance are essentially the same in both instances. Perception of an event presupposes some level of illumination, degree of contrast, size, and so on. Thus, the threshold of vision (minimum light intensity perceivable), brightness discrimination, and visual acuity are of paramount importance. The accommodation capability of his eyes, the breadth of his visual field, and his ability to perceive, recognize, and react to visual stimuli are of general importance in the more secondary monitoring tasks. Visual system performance is measured in terms of these several parameters, most of which involve central nervous system functions as well.

Like the central nervous system, the visual system is most sensitive to hypoxic conditions. The most sensitive element appears to be the junction between the ganglion and bipolar cells of the retina (Lewis and Duane quoted in Ref. A-2, pp. 14–15). Partial failure of the retinal blood supply (blood flow during only part of the cardiac cycle) results in peripheral vision loss or grayout (subjective visual decrements); complete failure results in blackout (Duane quoted in Ref. A-2, pp. 14–15). Reducing the oxygen content of the retinal blood supply also results in visual decrement. Reference A-7 quotes earlier work as showing detectable visual decrement under mild hypoxic conditions equivalent to 7000 ft in altitude (equivalent to approximately 92 percent oxygen saturation of the arterial blood). The combination of both effects, reduced retinal blood flow and reduced oxygen content of the retinal blood supply, can presumably account for much of the subjective and observed visual decrement under "eyeballs in" accelerations. Further, the visual system will be more sensitive to reduced blood pressure as a result of g-forces than will the central nervous system because intraocular pressure is greater than intracephalic, with the result that a higher blood pressure is required to maintain flow.

In addition to those effects due to retinal eschemia, there are additional difficulties apparently due to changes in the eye's optical properties. Subjective reports of blurred vision (loss in visual acuity) can be attributed to tearing if tearing occurs. When it does not, one is left with a tentative explanation of lens displacement. In Ref. A-3 it is shown that corneal distortion is not a problem up to 8g, while decrements in visual acuity have been shown to occur independently of the direction of the g-vector (White and Jorve quoted in Ref. A-2, pp. 70-71).

The eye also has difficulty in moving within its orbit. Reference A-16 correlates difficulty in moving the eye with the progression from the initial stages of grayout to blackout. Voluntary effort could overcome this, but resulted in ataxic movements. Reference A-3 notes an inability to fuse two images under g-forces, but does not correlate this with the magnitude and duration of the g-stress. Possible explanations include a disruption of the oculomotor loop used in visual tracking of moving objects due to hypoxia, increased mechanical forces required to move the eye, and/or fatigue (due to some degree of hypoxia) of the extraocular muscles.

The available literature has relatively little quantitative data on visual decrement for the "eyeballs in" direction. Reference A-17 gives some results on mean contrast requirements as a function of background illumination and g-level up to 7g, EBI. These data show a greater variation with the illumination level than with "g", although sensitivity to the latter becomes more pronounced between 5g and 7g, EBI. Several authors have quoted some unpublished data due to Alexander which show grayout threshold in terms of g-level (presumably a subjective judgment) as a function of "effective physiological angle" measured between the perpendicular to the applied g-force and a line between the subject's eye and heart (Ref. A-4, p. 39; Ref. A-2, pp. 69-70). These data predict a grayout threshold in the Apollo capsule of 7.5g, and for the typical posture used in the Russian literature (65 deg back angle), approximately 4.3g. However the published Russian results do not reflect a tolerance this low. In the following paragraphs, the visual decrements which occur are related

to the g-level of their occurrence. It will be noted that the decrements are almost entirely qualitative in nature.

1g – 6g Within this range of g-levels, the literature would indicate minor visual decrements, although Ref. A-3 mentions a minor blurring of vision which does not impair a subject's ability to read a Snellen chart, provided tearing does not occur. The Ref. A-18 data on brightness discrimination changes within this range have already been mentioned; the decrements to 5g are minor over a range of illumination of 10^3. To summarize, the most likely source of pronounced visual decrement is tearing, which may or may not occur.

6g – 8g Reference A-17 mentions the range of g-levels between 6g and 12g as being subject to possible tearing, apparent loss of peripheral vision, and with some difficulty in keeping the eyes open. Reference A-17 also quotes White and Jorve as demonstrating a decrement in visual acuity at 7g such that targets are required to be twice the detectable size at 1g to be perceived. Reference A-3 mentions blurring of vision (without tearing) within the range 6g–8g. It is apparent that this range of g-stresses marks the beginning of visual difficulty for all subjects, although the decrements are still not too serious.

8g – 12g Both U. S. and Russian investigators mentioned the 8g level as being the point where grayout is likely to occur, particularly toward the end of a centrifuge run (Refs. A-3 and A-9). Reference A-9 correlates grayout with a shift to the low frequencies on the EEG at 8g, 10g, and 12g, visual difficulties (grayout) occurring almost immediately at the 12g level. Reference A-10 confirms this. Reference A-10 also mentions a feeling of pressure on the eyes accompanied by tearing at 10g.

12g – 15g Above the 12g level, data are quite sparse. Reference A-17 states that there are 5 sec of essentially undisturbed vision at 14g, while Ref. A-9 states that a "rapidly occurring visual disorder" (previously described in Ref. A-9 as grayout) characterizes this g-level. In another paper, Ref. A-18, it is

stated that recurrent blackout occurs at 15g. Informal NASA communications (Thomas, 1964) indicate the visual field to be roughly 3 to 4 inches in diameter on a panel some 25 inches from the pilot's eyes in a simulated Apollo entry at 15g. It is fairly clear that the pilot's visual performance at 12g and above is very seriously deteriorated and functions for only a short while.

Central Nervous System Performance—The functioning of the central nervous system, inclusive of autonomic functions, is critically dependent on the oxygen tension within the brain tissue. Performance under acceleration is thus a function of the oxygen tension prior to centrifugation as well as the arterial oxygen saturation and cephalic blood flow during the course of a centrifuge run. An additional complicating factor is the emotional stress state of the subject.

The functions performed by the central nervous system are so many and varied as to make the choice of pertinent performance measures (pertinent, that is, to the evaluation of performance potential during entry) quite difficult. Further, there is the additional problem of predicting performance in the actual entry tasks from the performance measured in more simplified test situations. Finally, most performance measures (i.e., reaction time tests) involve sensory and motor elements, thus making isolation of the purely cerebral contribution to measured performance deterioration under acceleration stress ambiguous. This is because the sensory and motor elements are also undergoing a deterioration in functional capability.

To get around these difficulties, the approach widely used, particularly in the Russian investigations, is to measure the electrical activity of the brain, the electroencephalogram (EEG), and to draw conclusions concerning the functional state of the central nervous system from changes in the appearance or frequency content of the biopotentials measured. Unfortunately, interpretation of EEGs is not unequivocal. Certain general changes are indicative of certain things, but these are not easily quantified. The state of the art as reflected in the literature would indicate its use as a general indicator of central nervous system integrity to be valid; however it will not reflect the subtle deterioration of those

higher functions which are the first to be affected by decreasing oxygen tension. A description of the changes observed follows, and is taken from several sources in the recent Russian literature (Refs. A-9, A-10, A-12–A-14) and, by way of comparison with the changes occurring under purely hypoxic conditions, Ref. A-15.

The changes which are observed are dependent on location of electrodes on the skull and on intersubject variation. However three more or less distinct phases are seen, depending on deceleration level and the time duration at a particular deceleration level. In addition, the amplitudes through the first two phases tend to be proportional to both g-level and time duration. The EEG frequency definitions used are shown in Fig. A-5. These phases are described as follows:

Phase I This might be described as desynchronization of the EEG. The α-rhythm becomes relatively less important, with the β- and γ-rhythms becoming more prominent. The very slow δ- and θ-rhythms tend to decrease. The overall amplitudes increase. The appearance is that seen during increased levels of attention. This might be attributed to an increase in the overall sensory input impinging on the brain from various receptors (Russian interpretation), or to the response of brain stem areas which regulate overall cortical electrical activity.

Phase II This phase is characterized by an increase in the relative magnitude of the α-rhythm (in some subjects quite apparent even when the eyes are open) against a somewhat increased background of fast asynchronous waves (β- and γ-rhythms). The slow waves remain more or less unchanged; the overall amplitude increases still further. This appearance is attributed by Russian authors to an inhibition of the afferent impulses, but more generally may reflect the beginning of central nervous system disorders due to an insufficient blood supply.

Phase III This phase appears at the higher g-levels toward the end of the centrifuge runs, appearing sooner as the g-level is increased. It is characterized by a more or less rapid shift ("scissors")* to the very low frequency δ- and θ-waves together with a decreasing amplitude of the overall EEG. The α- and β-rhythms both

*Russian terminology.

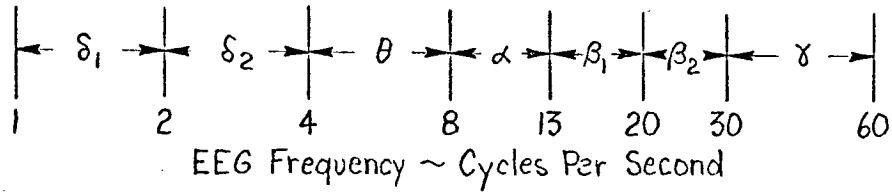


Figure A-5. Definition of EEG Frequency Bands
(From Ref. A-14)

decrease markedly relative to the remaining frequencies. This character is associated with incipient grayout or blackout, cardiac and respiratory disturbances. The subject terminates the run shortly after this phase occurs. Its cause is attributed to further disruption of the blood supply and/or further increase in inhibition of afferent impulses. The subject will eventually become unconscious if centrifugation is prolonged past the appearance of this phase. It would appear that the occurrence of the shift to low frequencies is a reasonable criterion for the limit of endurance. However, considerable disruption of central nervous system functioning has already occurred by this point.

With respect to central nervous system disturbance, Ref. A-15 notes that in exposing subjects to altitude conditions of 16,000 ft (arterial oxygen saturation would be on the order of 75 percent, i.e., considerable handicap) no change in the EEG could be detected, although various tests of the central nervous system showed disruption. Exposure to 20,000 to 23,000 ft (O_2 saturation 65 percent or less) showed somewhat increased activation of β- and (50 percent of the time) α-rhythms, with eventual preponderance of slow waves.

From this one can surmise that the Phase I condition under acceleration is caused primarily by the alerting effect of acceleration on the nervous system; but the remaining phases show the increasing effects of oxygen starvation as well. Electroencephalogram changes apparently correlate with a reduction of the arterial oxygen saturation below the 70 to 80 percent level. Thus the EEG is an indicator of stress and arousal during acceleration, but shows deterioration of central nervous system functioning "late in the game," i.e., after considerable central nervous system disruption has already occurred.

The changes in the EEG character with increasing g-level may be outlined as follows:

1g – 6g The available references do not provide any data for "eyeballs in" accelerations below 6g. However, the foregoing considerations relating arterial oxygen saturation to changes in EEG activity would indicate Phase I activity only up to about the 3g level, with the appearance of Phase II between 3g and 6g, the appearance

occurring earlier and earlier as the g-level is increased. Reaction time measures show a small increase with increasing "g" in this range (for example, Ref. A-4, p. 47). None of the available references give any information on changes in reaction time with time duration at a particular g-level, although in the 3g to 6g range the trend of arterial oxygen saturation with time would indicate progressively increasing disruption of central nervous system functions. This reaction time variation, if it exists, should be more pronounced at the higher g-levels (more rapid change in saturation level) and early in the run (before the saturation reaches steady state).

Reference A-9 mentioned disruption of cardiovascular and respiratory functions toward the end of the run at 6g, implying an EEG shift to the low frequencies at this time, although it was not specifically mentioned.

6g – 10g Reference A-14 (probably the same series of experiments as in Ref. A-9) indicates the shift to Phase III occurs toward the end of the run at 8g; at the approximate mid-point of the run at 10g. The changes from Phase I to Phase II and from Phase II to Phase III are more distinct at the higher g-levels in this range, the latter change being correlated with visual, cardiac, and respiratory disturbances, although the phasing of the disturbances is not indicated. Note that these Russian experiments are for back angles of 65 deg. Larger angles will shift the changes in EEG to higher g-levels and/or to later times during the course of a run.

There are further increases in reaction time measures. The data of Ref. A-4, p. 47, shows a more rapid increase in reaction time with increasing g-level above 6g. Reference A-5, p. 147, mentions "mental confusion," with oxygen saturation on the order of 70 percent upon termination of centrifuge runs at 10g after 2 minutes. It is clear that exposure to 10g for longer than about a minute involves considerable deterioration of central nervous system functions.

10g – 15g The shift to the low frequency θ- and δ-waves occurs almost immediately at 12g and higher accelerations according to Ref. A-14, although an increase in back angle to 78 deg

postponed the shift to the mid-point of the run (this would be more typical of U. S. results). Reaction time measures show slightly more than a twofold increase at 12g over 1g conditions (Ref. A-10), with the greater part of the change occurring above 7g. The Russian results also show immediate disruption of respiratory and cardiac functions, with respiratory standstill in most cases above 12g (Ref. A-9).

The overall picture is one of progressively greater and more rapid central nervous system disruption with time as the g-level is increased, due primarily to oxygen starvation, which is in turn related to the changes in respiratory and cardiovascular functioning with increasing "g".

Neuromuscular System Performance — It is difficult to measure neuromuscular system performance by itself; one must include the effects of other physiological subsystems, particularly the integrating and coordinating activities of the cerebellum, in any such evaluation. However, some qualitative statements can be made concerning the gross capability and activity of the neuromuscular system as inferred from the data available on pilot performance under g-loads.

Electromyographic (EMG) measurements of the electrical activity of the muscles show increasing tonus with increasing g-level. Reference A-22 reports increases in the EMG amplitude up to 5g, then a leveling off (skeletal muscles — the paper is not specific); Ref. A-23 reports more or less linear increases in the amplitude of the EMG to 8g, as measured from the subject's controlling forearm in a tracking task. Reference A-9 reports increasing EMG amplitude (quadriceps femoris muscle of leg) while the g-level is increasing, reaching a peak when the "plateau" is reached. At the 8g level, the biopotentials begin a gradual decrease about half way through the run, which is probably associated with the increasing degree of hypoxemia and subjective fatigue feelings. The inference is clear. The EMG amplitudes reflect the pilot's "straining" efforts to resist the g-forces, and also show the effects of muscular fatigue.

The gross muscular capabilities of the pilot are severely limited under acceleration stress. Reference A-2, p. 72, quotes earlier work as indicating limb or body motion only to 8g; lifting the head to 9g;

and manipulating a side arm controller to well beyond 15g. This means that high-g entry trajectories will make it extremely difficult to react to emergency situations requiring the pilot to reach forward to the instrument panel for switch activation and the like. On the other hand, control tasks are possible with properly designed manipulators to g-levels at which elements other than neuromuscular elements fail, i.e., vision and respiration.

Some work has been done on the design of manipulator configurations which minimize the decrement in tracking scores expected with increasing g-level. Coordinating movement of the stick in three axes simultaneously is difficult under high-g conditions, with pilots expressing a preference for a two-axis stick-plus-pedals arrangement (Ref. A-24). The Ref. A-17 results with a Mercury-type side arm controller show a tendency toward inadvertent inputs in the form of a steady-state bias in stick position in one or more axes. It seems reasonable to attribute this result to a "dulling" of the pilot's sensation of where his hand is or the force he is exerting on the stick. The cause could be the space suit and gloves he is wearing, the force/deflection and/or centering characteristics of the stick, the general magnitude of sensation to which he is exposed ("swamping" his awareness), and possibly even a degree of numbness brought about by inadequate blood supply to his forearm and hand. By eliminating or distorting some of the neuromuscular feedbacks, these effects, if present, would make the control task under high-g loads more difficult.

Many investigators have examined the operator's performance in a tracking task under acceleration loads. The specific results obtained in each case are highly dependent on the task variables; difficult tasks result in deteriorated performance at relatively low g-levels (e.g., Ref. A-24 shows deterioration above 4g for lightly damped aircraft dynamics), while easy tasks can be controlled with slight deterioration at high g-levels (e.g., Ref. A-19 shows slight — 20 percent error increase — deterioration at 14g). In either case, the results are difficult to generalize. The major factor appears to be pilot work load. The Ref. A-18 results with Mercury simulations suggest that realistic simulation of entry tasks, while difficult to generalize, give a better feel for

what is likely to happen because of the more realistic work load. These results show difficulty in concentration on all aspects of the task, large and variable increases in reaction time to discrete panel indications, disruption of the timing and precision of controller inputs, and so on (Ref. A-17). The same report shows relatively little deterioration in various reaction time or immediate memory tests. Reference A-24 reports that pilots had difficulty in manipulating the side arm controller above 6g, the pilots reporting a feeling of greater stick inertia. The conclusion to be reached from these (and other) results is that performance in the realistic entry situation may be inferred from test data provided there is some way of correlating the relative work loads between the test and actual situations.

Vestibular System Performance — The influence of a pilot's vestibular senses on his performance under acceleration stress is determined more or less indirectly. Tracking scores, for example, are usually improved if motion cues are provided; that is, if the motion of the centrifuge cab is tied to the dynamics of the simulated vehicle. Even here, there still exists some question. As the centrifuge is spun up, the pilot is subjected to a rotating environment — the g-forces continually change direction. This can lead to vertigo in the initial phases of a run on a moving-base simulator that would not be present in the entry vehicle, with the result that tracking scores in a simulator run are deteriorated by some amount (Ref. A-19), relative to the actual case.

Contributing additional uncertainty in the performance of the vestibular system is evidence which indicates that the utrical and semicircular canal signals are not independent; a pilot's sense of rotation is influenced by the acceleration level. Considerable work has been done in this area, particularly in connection with the weightless state (Refs. A-20 and A-21). The results would indicate that the effective sensitivity of the canals to rotational accelerations is a function of the acceleration level, being relatively less sensitive in zero-g and more so under high-g. This would imply a greater nystagmus reaction to angular accelerations during entry; however this has not been verified in centrifuge entry simulations and may not be very important.

The continuous influence of the vestibular system input on muscle tone has been demonstrated by Yuganov (Ref. A-21), who showed a greater decrease in EMG activity in the weightless state among animals having normal vestibular responses than among delabyrinthized animals. The same sort of response applies to venous tone as well (Ref. A-21). In human subjects the overall EMG activity increases with increasing acceleration up to approximately 5g due to action of both vestibular and proprioceptive senses (Ref. A-22). The inference here is that the pilot's "straining" is largely automatic, at least at the lower g-levels, and due (to some extent) to utricular stimulation. However, the relative importance of vestibular, as opposed to proprioceptive, senses in maintaining neuromuscular tonus is uncertain.

Physiological Tolerance — The gross effects of acceleration stress as described in the preceding paragraphs are summarized in Table A-I. The last column of this table indicates the major factors affecting endurance, with a rough idea of the time durations expected as determined by various investigators (Refs. A-9, A-17, and A-24).

The time durations reflect subjective endurance, for the most part; the subjects terminate the runs. However, this does not mean that a complex piloting task could be accomplished effectively throughout this time, even though most of these data are taken for the subject performing some sort of tracking task. The impression gained from the literature is that the occurrence of the shift to low frequencies in the EEG, the faltering of respiration and heart rates, and visual disturbances in the form of grayout are more or less closely correlated with the oxygen tension of the cerebral tissue and/or the oxygen saturation of the arterial blood — to estimate a number for the latter, 80 percent. This degree of hypoxia or hypoxemia amounts to an appreciable handicap on the pilot's abilities, particularly for the higher mental functions which may be required for emergency situations. What is required is an established correlation of these measures such that a more objective end point can be chosen for tolerance. Estimates based on current information show that at levels of 8g or less, the subject usually terminates the run before the shift in the EEG to low frequencies occurs. This may

TABLE A-I. EFFECTS OF "EYEBALLS IN" ACCELERATION STRESS ON PHYSIOLOGICAL FUNCTIONING

"Eyeballs In" Acceleration Level — g

RESPIRATORY SYSTEM	CARDIOVASCULAR SYSTEM	CENTRAL NERVOUS SYSTEM	VISUAL SYSTEM	ENDURANCE
Disturbance of respiratory function minimal up to 3.5g. Tidal volume and respiration rate increase to increase oxygen intake.	Heart rate largely a function of emotional state of subject in this range. No disturbance of cardiovascular function. Blood pressure regulating reflex will have some effect in this range.	The available literature does not give an indication of EEG variations in the range of 1g–6g. However, respiratory and cardiac functioning in this range would lead one to expect Phase I behavior throughout a run at levels up to approximately 3g; then Phase II behavior occurring earlier and earlier in the run as the g-level increases. Other data available (reaction time measures, etc.) indicate only minor central nervous system effects in this range. Increasing concentration is required in complex tasks.	Visual decrements in this range are minor, although tearing can occur above approximately 4g, leading to blurring of vision. Brightness discrimination undergoes slight decrement.	Subject's tolerance in this range primarily a function of fatigue. Respiratory, cardiac, central nervous system, and vision suffer only minor decrements in this range. At 6g, tolerance is on the order of 8–12 minutes, being limited by chest pain, subjective feeling of breating difficulty.
Ventilation/perfusion relationship increasingly disturbed in this range as g-level increases. At 6g, the oxygen saturation of the blood is down to approximately 85 percent at end of 2 minutes. Intense subjective feeling of breathing difficulty, which increases with time. Considerable visceral displacement at 6g. Respiratory rate continues to increase.	Heart rate and stroke increase to increase blood flow through lungs. Pulmonary and thoracic blood pooling increase; straining required to improve endurance (Valsalva maneuver). At 6g, pulse is on the order of 110 beats/minute.			
In this range, respiratory disorder becomes progressively worse. Arterial oxygen saturation drops below 85 percent. Respiratory function tends to become irregular toward the end of a run above 8g, indicating regulatory disorder. At 10g, arterial oxygen saturation approximately 70 percent after 2 minutes, assuming subject does not terminate run sooner. Tendency to cough on inspiration, increasing chest pain, increasing respiratory rate; but decreasing tidal volume as g-level increases.	Pulse rate continues to increase with increasing g-level, with a tendency toward irregularities (extra systoles, arrythmia, etc.) toward the end of a centrifuge run. Skin shows small petechia at end of run.	The occurrence of Phase III EEG behavior toward the end of a run at 8g and mid-point of a run at 10g reflects increasing central nervous system disruption. Available data suggest more rapidly increasing reaction time with g-level, "mental confusion" as a possible cause of run termination, and general erratic regulation of respiratory and cardiac functions.	Some loss of peripheral vision, difficulty in keeping eyes open, loss in visual acuity. Some investigators mention blurred vision without tearing in this range.	Subject's endurance still limited by fatigue feelings, but mental functioning toward end of run is deteriorated as a result of lowered oxygen tension. Tolerance is on the order of 2.5–5 minutes at 8g.
			At 8g, grayout and/or loss of peripheral vision occurs toward end of a run, occurring sooner and sooner as the g-level increases. At 12g, it occurs almost immediately. Subject has sensation of eyeball pressure and pain. Loss of eye motility correlated with onset of grayout.	Endurance begins to be limited by visual disorders, although ability to withstand respiratory difficulty is major factor in long endurance. Mental functioning seriously deteriorated at 10g, with endurance time on the order of 1–2 minutes.
Tidal volume approaches pulmonary dead space as g-level increases above 10g. Rapid oxygen desaturation. Some Russian data indicate complete cessation of respiration in increasing number of subjects as g-level goes up — a few at 10g, practically all at 15g.	Adequate cephalic blood pressure cannot be maintained above 10g; visual disturbances occur sooner or later in the course of a run.	The "scissors shift" to the low frequency Phase III EEG behavior occurs almost immediately at 12g and above, with reductions in the EBD component of acceleration effecting an improvement. Cardiac and respiratory functions both irregular, indicating further central nervous system disruption due to impeded blood flow and low oxygen saturation.		Above 10g, pulmonary functioning cannot compensate — endurance is a function primarily of the oxygenation of tissues and blood at start of run; very little gas exchange takes place above 10g. At 12g, endurance time is on the order of 0.5–1 minute.
			Visual disturbance almost immediate above 12g, with tendency to black out evident at 15g.	In this range, endurance is a function of how long subject can "hold his breath" while straining maximally — blackout becomes a leading cause of run termination. At 15g, endurance is on the order of 10–20 seconds.

be indicative of the possibility that adequate cerebral functioning continues throughout these runs, and hence that cerebral function is not the limiting factor. But at 10g the endurance time is halved (to 30 sec) and 12g probably represents the upper limit on allowable peak "g". This is based on the EEG shift to low frequencies. Less demanding (mentally) tasks would enable these limits to be extended. In sum, it is felt that reliable mental functioning, an index of which is oxygen tension of the brain or an EEG indication, is a major limiting factor on a pilot's ability to perform in the entry role above 8g.

3. EFFECTS OF WEIGHTLESSNESS ON HIGH-g PERFORMANCE

The physiological deconditioning which can be expected on long duration space missions (on the order of a year) results primarily from the weightless state, although other details of the space environment (confinement, inactivity, radiation, altered atmosphere) have contributing or moderating (exercise, diet, clothing) effects. Reference A-25 probably contains the best account of the deconditioning effects and metabolic changes resulting from the weightless state. In the following paragraphs this reference and others in the available literature are briefly reviewed for those physiological changes having a bearing on a pilot's performance potential in the entry role.

Cardiovascular System—With the exception of the effects of physical exertion during boost and the general level of emotional stress, the initial changes in the cardiovascular function upon transition to the weightless state are closely comparable to those which take place in bedrest experiments. Weightlessness implies the lack of a hydrostatic head within the circulatory system, which results in less blood pooling in the lower extremities and more within the thoracic and pulmonary cavities. Stretch receptors within the great veins of the body and atria of the heart trigger the so-called Gauer-Henry reflex. The antidiuretic hormone (ADH) secreted by the pituitary gland is inhibited, resulting in increased blood flow to the kidneys with the consequent increase in urine production. The resulting diuresis acts to reduce blood plasma volume. The lack of a hydrostatic head also alters the

osmotic pressure balance of the lower body, resulting in a transfer of fluids from the muscular tissue to the capillaries. This tends to maintain plasma volume, and diuresis continues, with the result being a progressive dehydration of the body and loss of weight. These changes are usually evident within 24 hours in both bedrest and orbital flight experience.

The resultant loss of body fluids will tend to increase the concentration of red blood cells. A compensatory mechanism reduces the production of red cells by the bone marrow, leading to a restoration of the normal red cell count. This tendency is intensified if less than normal (for the individual subject) demands are made on the cardiovascular system or if the radiation dosage (results in destruction of bone marrow) is significant. Over the long term, the blood volume (plasma volume, red cell mass) is reduced.

A second major contribution to the deconditioning of the cardiovascular system results from the reduced level of activity. This results in part from the reduced energy requirements in maintaining blood flow and is aggravated if the overall activity level is reduced. Prolonged inactivity is correlated with a general dilation of the peripheral arterioles. The heart size tends to decrease and the coronary arteries will decrease in size, both effects reducing the overload capability of the heart. There is a higher concentration of blood lipids (e.g., cholesterol). The resting heart rate and blood pressures tend to decrease in the early phases, but increase later on as cardiovascular deconditioning continues. Relative inactivity will also tend to decrease muscle tone (see below) and promote decalcification of the skeleton.

The overall picture is clinically similar to that resulting from a bedrest regimen. The loss of circulatory system and cardiac muscle tone and decrease in blood volume lead to orthostatic intolerance upon return to the 1g environment — the cardiovascular system loses its capability of maintaining sufficient blood flow to the brain. The exercise tolerance is reduced and the overall work efficiency goes down.

There appear to be several means by which these deconditioning effects can be countered. Perhaps the most obvious is that of insuring an adequate level of muscular and cardiovascular system activity through exercise. In this connection, the Gemini VII flight results would indicate a shirt sleeve environment to be helpful, in that it permits greater freedom of movement, more vigorous exercise, and generally more comfortable conditions.

The deconditioning of the blood itself can be alleviated by a mildly hypoxic atmosphere (Ref. A-25). This has an effect similar to that seen in people acclimated to high altitudes. The red cell count remains high, red cell production likewise, and the coronary blood vessels and heart size show less signs of deterioration. Hypoxic conditions also tend to inhibit skeleton decalcification.

An adequate water intake can help minimize dehydration. Even better is to add the use of lower body negative pressure. This has been demonstrated to sharply increase the hydration of the body, and suggests that it could be used 24 hours prior to entry to restore the normal fluid balance. On the other hand, this could result in a considerable lowering of pulse rate because of the higher blood pressures. It is necessary to validate this procedure to evaluate other side effects.

Maintenance of circulatory system tone is a more difficult question. Inflatable thigh cuffs were used on Gemini V and VII with inconclusive results. The idea was to minimize orthostatic intolerance, and the flight results would indicate some improvement in venous tone of the legs (there was a smaller increase in leg volume). However, tilt table response still showed considerable orthostatism (i.e., greatly elevated pulse, lowered blood pressures). Exercise will also mitigate the loss of tone to some extent. However, bedrest experiments where the subject was permitted to exercise still show poor cardiovascular system response to standing. Since proprioceptive and vestibular senses influence the maintenance of circulatory system tone, and those senses are stimulated by a gravitational field, some sort of artificial gravity, or periodic conditioning in an on-board centrifuge, may be indicated if the degree of orthostatism which would otherwise result is intolerable for entry.

The implications of these deconditioning effects on the pilot's performance in the entry role are felt to be the most serious of all. If they cannot be mitigated by one means or another, the result will be an earlier (in terms of time and g-level) failure of the blood supply to the head, with the attendant earlier deterioration of central nervous and visual system functions. Bedrest experiments (Ref. A-32) have shown the nature of these effects — an exaggerated cardiac response (pulse rate) and an earlier failure of vision. Loss of venous, arterial, and cardiac tone contribute, as well as the decreased blood volume if no countermeasures (rehydration before entry) are taken. Radiation exposure also has a debilitating effect on the circulatory system, particularly in red blood cell production.

A second factor which may be of importance is the development of aneurysms and/or hemorrhages under g-loads as a result of the low tonic state in the circulatory system. The greater tendency toward superficial hemorrhages of the skin (petechia) as a result of bedrest followed by g-exposure has been demonstrated in Ref. A-32. If the prolonged weightless state leads to serious weakening of the major blood vessels, serious internal hemorrhages could occur, with disastrous results. The extent of this danger is completely unknown; bedrest or water immersion experiments to date are of short duration compared to the space missions under consideration.

Respiratory System — The major effects of the weightless state would appear to be losses in respiratory muscle tone and pulmonary circulatory system tone. The former leads (based on bedrest experiments) to a loss of pulmonary efficiency manifesting itself in an increase respiratory rate and reduced vital capacity and tidal volume. The latter implies increased pulmonary blood pooling. Both reduce the pilot's tolerance of high g-forces — the respiratory rate will rise somewhat more rapidly with g-forces and blood oxygenation will show a more rapid drop with time and g-level. The respiratory function will falter at an earlier point in time due to the more rapid deterioration of cerebral blood flow (cardiovascular deconditioning).

The composition of the spacecraft's atmosphere can also lead to deteriorating effects if high oxygen partial pressures are used (leads to atelectasis as indicated earlier).

Exercise and a mildly hypoxic atmosphere will both make increased respiratory system demands, leading to a lessened degree of deconditioning. During entry an oxygen-rich atmosphere can be used with positive pressure-breathing to maintain oxygen saturation at higher levels — although this carries subsequent penalties (atelectasis).

Visual System—Weightlessness has no apparent direct effect on the functioning of the visual system. However, it, like the bone marrow, is quite sensitive to radiation. The occurrence of a large solar flare results in a shower of high energy atomic particles, principally protons, which could result in some loss of transparency in the lens and/or cornea of the eye. In effect, there is a danger of cataracts as a result of solar flares, leading to a loss in visual acuity. This danger is a sensitive function of the type and extent of radiation protection employed on long duration missions.

A second possible effect is loss of accommodating power because of long confinement in the spacecraft environment where the visual field is restricted. This is of relatively minor importance during entry (instrument flight). During entry, therefore, the major visual decrements expected are due to an earlier dysfunction of the cardiovascular system leading to an earlier onset of visual disturbances. This has major implications on the pilot's performance in the entry role.

Vestibular System—Russian experience with "space sickness" (Titov, Tereshkova, Feoktistov, Yegorov) has prompted considerable interest in the Russian literature on the functioning of the vestibular apparatus. In contrast, U. S. astronauts have experienced no particular difficulty. There doesn't appear to be a satisfactory explanation for these differences unless one correlates long test pilot experience with high resistance to motion sickness. This contrasts with the brief training periods of some of the Russian astronauts who had difficulty.

In any case, the functioning of the vestibular apparatus and the part that vestibular signals play in forming the pilot's perception of

the external world are imperfectly understood. The participation of utricular signals in the maintenance of skeletal muscle and venous tone seems fairly clear. The reduced stimulation of the utricle in the weightless state results in lowered EMG of the skeletal muscles and dilation of the venous bed, even in nonskeletal muscles (Refs. A-20, A-21, and A-30). This implies reduced tone for the venous system as well as the neuromuscular system as a result of long duration exposure to weightlessness. In subjects with defective otoliths, the reduction in muscle biopotentials is less pronounced.

In this connection, the reduced utricular stimulation apparently results in an increase in the sensitivity to g-forces. Both U. S. and Russian astronauts report a greater subjective sensitivity to the initial forces of atmospheric entry, although peak forces feel similar to centrifuge experience (Refs. A-26 and A-31). This would imply a more rapid buildup of skeletal muscle biopotentials with g-loads, of venous circulatory tone, and of sensitivity to semicircular canal stimulation. The first of these effects could deteriorate time tolerance to g-loads through more rapid fatiguing; the remaining two are felt to be of lesser significance. However, the astronauts' comments to the effect that peak entry g-forces felt no different than centrifuge experience led them to expect would imply that there is a limit to the increase in biopotentials — the incremental increase in fatigue is probably minor. It could well be that the major effect of the increased sensitivity during the early stages of entry g-force buildup will be to increase any tendency to disbelieve instruments (deceleration level and vehicle body axis rates). It could also lead to increased nystagmus during these stages. In any case, the subjective report of increased g-force sensitivity and its effect on the buildup of biopotentials is unsupported by quantitative evidence and must remain conjectural for the present. A similar remark applies to possible disturbances in the astronaut's perception (illusions, etc.) during entry.

Central Nervous System — With respect to the direct effects of weightlessness on the central nervous system, the available Russian literature stresses the new coordination and adaptation of afferent

signals from proprioceptive, vestibular, and visual senses in the regulatory activity of the autonomic functions as well as in motor activity (Refs. A-21, A-26, and A-27). The high variability of such things as respiratory and pulse rates, not to mention EEGs, is attributed to the central nervous system's efforts to "come to terms" with the new environmental situation, as well as the general level of excitement. The initial adaptations are felt to be incomplete and/or unstable as evidenced by persistence of illusions (not confirmed by U. S. experience), "space sickness," erratic pulse, sweating in response to moderate work loads, and so on. This is in contrast to investigators in this country who feel the reactions of the astronauts to be quite normal under the circumstances of the situation, i.e., relatively rapid adaptation to the weightless state with the variations in such things as pulse rate well within the normal range of behavior under the work loads imposed.

The Russian literature also reports the central nervous system to be affected in terms of motor activity. Astronaut performance as a function of time in zero-g (vehicle orientations, handwriting, medical checks, etc.) would indicate that the major portion of the zero-g adaptation takes place within 24 hours; indeed, within two or three hours to judge by some of the data (Refs. A-28 and A-29). However, these conclusions are qualified by noting that the novelty of the situation at the beginning of flight may exaggerate performance decrements, i.e., the initial deterioration in motor performance may not be as bad as the data would indicate. Some data on tracking task performance would also show deterioration from baseline (ground) conditions, but these data are not correlated with the time during orbital flight (after some zero-g practice or the first trial) when they were taken. The tentative conclusion from these indications is that a more or less complete adaptation of motor functions to the zero-g environment should take place on a long duration mission such that performance of a tracking task, for example, will approach baseline performance.

The impression one is left with after reviewing these varying opinions is that Russian writers are quite concerned over the reactions of their

astronauts, while U. S. writers express a high degree of confidence in the ability of an astronaut to adapt to the new situation.

The implications for entry are two: First, and probably most important, is the deteriorated functioning of the central nervous system due to cardiovascular and (to a lesser extent) respiratory deconditioning. Thus the shift in EEG to low frequencies can be expected to occur sooner in time and/or g-level relative to the case where there is no deconditioning. Various other central nervous system performance measures can similarly be expected to show earlier deterioration because of the deteriorated blood supply to the head (both pressure and oxygenation). Second are any direct effects (indicated above) of adaptation to weightlessness on the coordination of autonomic and motor functions under high g-forces. This might broadly be described as a training retention problem — maintenance of high-g skills.

Neuromuscular System — The biopotentials of the skeletal musculature decrease during weightlessness as a result of changed or reduced proprioceptive and vestibular stimulation (Refs. A-21 and A-30). This loss of tone leads (in the absence of such mitigating factors as exercise) to a loss of muscle strength and size. This was manifested on the long duration Gemini flights by quite perceptible muscular stiffness and soreness after landing, particularly in the legs (Ref. A-21). During entry this occurrence would clearly imply loss of strength, increased fatigue, and (because the muscular tension level which can be maintained is presumably lower) increased lag in motor responses in a closed-loop control task.

4. SUMMARY

The preceding discussion has shown that an astronaut's performance during atmospheric entry is heavily dependent on certain physiological functions affected by his environmental history before and during entry. To be specific, the following conclusions have been drawn from this examination of physiological considerations:

1. Very little quantitative data exist in the literature at the present time which would enable a designer to configure a vehicle to

obtain a near-optimum distribution of control functions between the man and the machine. This is particularly true of long term weightlessness effects.

2. The existing data on high-g effects show the major causes of performance decrement ("eyeballs in" accelerations) to originate in:

    a. The respiratory system

    b. The cardiovascular system

3. The performance decrements observed as a result of high "g" occur primarily in:

    a. The visual system

    b. The central nervous system

4. The existing data on weightlessness would indicate:

    a. That the primary deconditioning effect lies in the cardiovascular system, i.e., regulation of blood pressure.

    b. That retention of high-g skills (to the degree that physiological functioning permits) during long duration exposure to zero-g may prove to be a problem.

5. The vestibular system's function and importance in this situation (long duration weightlessness followed by the high "g" of entry) is largely a matter of conjecture at the present time.

The end result is a reduction in the astronaut's performance potential under any fixed set of environmental and task variables relative to baseline (centrifuge) conditions. However, even the baseline is not as well defined as it could be.

GLOSSARY OF TERMS

alveoli — The small air sacs within the lungs where gas exchange (O_2 and CO_2) with the blood takes place.

aneurysm — Arterial or venous blood vessel dilation due to the pressure of the blood on weakened vessel walls.

aortic baroceptors — Stretch receptors similar to Golgi tendon organs located in the arch of the aorta which respond to changes in the aortic capacity, and thus to the blood pressure within the aorta.

aortic chemoreceptors — Two small bodies located in the arch of the aorta where it leaves the heart. The afferent nerves leaving this body are (apparently) excited by changes in the pO_2, pCO_2, and pH of the blood supply to these bodies.

atelectasis — Refers to a collapsing of the alveoli with consequent reduction in gas exchange.

autonomic nervous system — That portion of the central nervous system which is self-controlling. Visceral, glandular, cardiovascular, and (to a large extent) respiratory functions are governed by the autonomic nervous system.

blood pH — The level of activity of effective hydrogen ion (H^+) concentration in the blood, i.e., $pH = -\log a_H$, where a_H is the effective H^+ concentration — a measure of the acid-base balance.

carbon dioxide level — Refers to the amount of carbon dioxide (CO_2) in the blood, mostly in chemical combination (carbonic acid, bicarbonic ions, and with hemoglobin). It is usually measured in terms of partial pressure (pCO_2) in mm of Hg, i.e., that partial pressure of CO_2 in an atmosphere to which the blood is exposed at which no net exchange of carbon dioxide takes place.

carotid baroceptors — Stretch receptors responding to blood pressure changes within the carotid sinus. The latter is a local dilation of the carotid artery near the point where it splits into the internal and external carotid arteries, i.e., in the neck behind the lower jaw.

carotid chemoreceptor — A small body having the same function as the aortic chemoreceptor, located in close proximity to the carotid sinus.

continuous Valsalva maneuver — The straining technique used by a pilot to resist g-forces. It consists of rapid inhalation followed by slower exhalation during which outflow is restricted. The abdominal muscles are tensed. This has the effect of increasing intrapulmonary pressure which a) promotes gas exchange, b) reduces the tendency to atelectasis, and c) promotes venous return to the heart.

diastole — The dilation, or period of dilation, of the heart, particularly the ventricles.

diastolic blood pressure — The minimum blood pressure measured at some point. It corresponds to the heart's diastole.

ECG — Electrocardiogram; a recording of the electrical activity of the heart as measured by electrical potentials at various points on the body.

EEG — Electroencephalogram; a recording of the electrical potentials measured between various points on the head — a measure of the brain's electrical activity.

EMG — Electromyogram; a recording of the electrical activity of certain muscles or muscle groups, depending upon the location of the electrodes.

EOG — Electro-oculogram; a recording of electrical potential changes at various points surrounding the eye; used as a measure of eyeball position.

expiratory reserve — The volume of additional air which can be exhaled after normal (for the circumstances) expiration.

GSR — Galvanic skin response; a measure of the electrical resistance of the skin. This changes with emotional arousal.

hypercapnia — A condition of carbon dioxide surplus.

hypoxia — A condition of relative oxygen starvation.

inspiratory reserve — The volume of additional air which can be inhaled after normal (for the circumstances) inspiration.

ischemia — A condition of blood starvation.

minute volume — The volume of air breathed in one minute, i.e., the tidal volume times the respiration rate.

orthostatism, orthostatic intolerance, orthostatic hypotension — This refers to a complex of symptoms relating to the regulation of blood pressure. The subject is placed on a tilt table in the horizontal position, the pulse is allowed to reach a stable level, and the table is then tilted to the vertical and his cardiovascular response is measured. The normal response is a slight increase in pulse rate with blood pressures (systolic, diastolic, and pulse) remaining essentially unchanged. Orthostatism is manifested by a greater increase in pulse rate, a drop in systolic and pulse pressures, and in severe cases, syncope (rapid drop in blood pressure, heart rate, accompanied by fainting). Thus orthostatic intolerance implies an inability of the cardiovascular system to properly regulate blood pressure under changing g-forces applied in an "eyeballs down" direction.

oxygen level — The amount of oxygen (O_2) in the blood, mostly in combination with hemoglobin, and measured in terms of the partial pressure (pO) in mm of Hg at which no net O_2 exchange takes place.

oxygen saturation — Refers to the relative (to 100 percent, or full saturation) oxygen content of the blood, a function primarily of the degree to which the blood's hemoglobin has combined with oxygen.

petechia — A small, pinpoint, purplish-red spot caused by a small hemorrhage within the skin.

pulmonary dead space — That portion of the lung's volume not participating in gas exchange with the blood, i.e., excluding the alveolar sacs (alveoli).

pulse pressure — The difference between systolic and diastolic blood pressures.

stress reaction — As used in this appendix, this refers to the changes in autonomic functions (i.e., those regulated by the autonomic nervous system) caused by the emotional stress of the entry situation. As an example, the pilot's anticipation of the danger and discomfort involved will cause an anticipatory rise in pulse rate, secretion of adrenalin, and a general "tensing up" before actual entry begins.

systole — The contraction, or period of contraction, of the heart, particularly the ventricles.

systolic blood pressure — The peak blood pressure measured at some point corresponding to the heart's systole.

tidal volume — The volume of air inhaled (or exhaled) each respiratory cycle.

tone, tonus — The degree of vigor and tension. In the muscles or the veins, this refers to the passive resistance to stretch.

venous bed — Refers to the system of veins in a particular region, containing most of the blood in that region.

vital capacity — The maximum volume of air which can be inhaled starting from full expiratory position (no additional air can be exhaled) and inhaling to full inspiratory position (no additional air can be inhaled). The vital capacity is made up of the inspiratory reserve, the tidal volume, and the expiratory reserve.

REFERENCES FOR APPENDIX A

A-1. Ruch, T. C., and J. F. Fulton, Medical Physiology and Biophysics, W. B. Saunders Co., Philadelphia, 1960.

A-2. Fraser, T. M., Human Response to Sustained Acceleration, NASA SP-103, 1966.

This report is a literature review.

A-3. Smedal, H. A., T. A. Rogers, T. D. Duane, G. R. Holden, and J. R. Smith, The Physiological Limitations of Performance During Acceleration, paper presented to the annual meeting of the Aerospace Medical Association, Atlantic City, N. J., Apr. 1962.

This report represents a summarizing account of a program conducted on the Johnsville centrifuge through early 1962.

A-4. Webb, P., ed., Bioastronautics Data Book, NASA SP-3006, 1964.

This volume is a data compilation on a variety of environmental influences on the human organism.

A-5. Calloway, D. H., ed., Human Ecology in Space Flight, New York Academy of Science, New York, 1966.

This book is an edited transcript of the proceedings of the First Conference on Human Ecology in Space Flight held in Princeton, N. J., Oct. 1963.

A-6. Kovalenko, Ye. A., V. L. Popov, and I. N. Chernyakov, Effect on Brain Oxygenation of Breathing Oxygen During Acceleration, NASA TT F-228, Dec. 1964, pp. 220–223.

This is a brief report on Russian centrifuge experiments using dogs.

A-7. Pugh, L. G. C. E., "The Effect of Acute and Chronic Exposure to Low Oxygen Supply on Consciousness," in K. E. Schaefer, ed., Environmental Effects on Consciousness, Macmillan Co., New York, 1962, pp. 106–116.

This book is a compilation of papers presented at the First International Symposium on Submarine and Space Medicine, New London, Conn., Sept. 1958.

A-8. Hershgold, E. J., "Roentgenographic Study of Human Subjects During Transverse Accelerations," Aerospace Medicine, Vol. 31, No. 3, Mar. 1960, pp. 213–219.

X-rays show posterior half of diaphragm elevated 6 cm; anterior depressed slightly with decreased vascularity in anterior region at 6g. At 12g, X-rays show further changes in same direction, but not as pronounced.

A-9. Barer, A. S., "Limit of Human Tolerance to Transverse Accelerations and the Physiological Reaction of the Body," in N. M. Sisakyan and V. I. Yazdovskiy, ed., Problems of Space Biology, Vol. II, Joint Publications Research Service, U.S. Dept. of Commerce, Rept. 18,395, 27 Mar. 1963, pp. 266-282.

Major Russian reference on the effects of EBI accelerations.

A-10. Kotovskaya, A. R., S. I. Lobashkov, S. F. Simpura, P. M. Suvorov, and G. F. Khlebnikov, "The Effect of Long-Lasting Transverse Accelerations on the Human Body," in N. M. Sisakyan and V. I. Yazdovskiy, ed., Problems of Space Biology, Vol. II, Joint Publications Research Service, U.S. Dept. of Commerce, Rept. 18,395, 27 Mar. 1963, pp. 251-258.

A-11. Kiselev, A. A., "Some Characteristics of the Hemodynamics and Gas Exchange in the Lesser Circulation During Transverse Chest-Back Accelerations," in N. M. Sisakyan and V. I. Yazdovskiy, ed., Problems of Space Biology, Vol. II, Joint Publications Research Service, U.S. Dept. of Commerce, Rept. 18,395, 27 Mar. 1963, pp. 244-250.

This paper presents the results of some experiments on unanesthetized dogs, and would indicate a critical g-level of 3g above which the cardiovascular system begins to compensate for decreasing pulmonary efficiency.

A-12. Izosimov, G. V., and A. N. Razumevev, "The Effects of Different Degrees of Long-Lasting Transverse Accelerations on the Electrical Reactions of the Human Cerebral Cortex," in N. M. Sisakyan and V. I. Yazdovskiy, ed., Problems of Space Biology, Vol. II Joint Publications Research Service, U.S. Dept. of Commerce, Rept. 18,395, 27 Mar. 1963, pp. 259-265.

Despite the title, this paper contains a more or less qualitative description of the EEGs measured on rabbits together with interpretation. Provides a correlation between duration and "scissors shift" to low frequencies in the EEG.

A-13. Gazenko, O. G., B. B. Yegorov, G. V. Izosimov, Yu. P. Limanskiy, A. N. Rasumeyev, and P. M. Suvorov, "Changes in the Bioelectric Activity of Different Parts of the Brain During Exposure to Prolonged Accelerations," in V. V. Parin, ed., Aviation and Space Medicine, NASA TT F-228, Dec. 1964, pp. 102-105.

Qualitative description of EEGs measured during centrifugation of people, rabbits, and cats.

A-14. Barer, A. S., and V. B. Zubavrin, "Character of EEG and Work Capacity in Man During Exposure to Back-Chest Accelerations," in N. M. Sisakyan, ed., Problems of Space Biology, Vol. 4, NASA TT F-368, Mar. 1966, pp. 330-340.

Relates EEG changes to acceleration levels.

A-15. Malkin, V. B., "An Electroencephalogram of an Acute Hypoxic Hypoxia," in V. V. Parin, ed., Aviation and Space Medicine, NASA TT F-228, Dec. 1964, pp. 297–301.

Describes certain visible changes occurring during hypoxic conditions and correlates them with EEG changes. For example, states that an equivalent altitude of 5000 meters shows no changes on EEG, but obvious impairment of central nervous system functioning (speech, spelling errors).

A-16. Beckman, E. L., T. D. Duane, and K. R. Coburn, Limitations of Ocular Motility and Pupillary Dilation in Humans Due to Positive Acceleration, Naval Air Development Center Rept. NADC-MA-6-140, 1961.

"Eyeballs down" experiments.

A-17. Chambers, R. M., and L. Hitchcock, Effects of Acceleration on Pilot Performance, Naval Air Development Center Rept. NADC-MA-6219, 26 Mar. 1963.

Gives a summary of Johnsville centrifuge experience as regards various performance measure decrements, including vision, reaction time, tracking task performance, etc.

A-18. Chambers, R. M., Long-Term Acceleration and Centrifuge Simulation Studies, paper presented to the Joint Aerospace Medical Div./ Aeronautical Systems Div. Conference on Crew Escape Techniques for Aerospace Vehicles, W-PAFB, Ohio, Feb. 1963.

Gives some further Johnsville data.

A-19. Creer, B. Y., J. D. Steward, and J. G. Douvillier, Influence of Sustained Accelerations on Certain Pilot-Performance Capabilities, paper presented to the Annual Meeting of the Aerospace Medical Association, Atlantic City, N. J., Apr. 1962.

Johnsville centrifuge experiments with pilots performing a tracking task. Mentions gondola motion as a contributor to disorientation of pilot on spin-up, with resultant deterioration in tracking scores.

A-20. Yuganov, Ye. M., "The Problem of Functional Characteristics and Interaction of the Otolithic and Cupular Portions of the Vestibular Apparatus Under Conditions of Altered Gravity," in N. M. Sisakyan, ed., Problems of Space Biology, Vol. 4, NASA TT F-368, Mar. 1966, pp. 48–63.

Gives a summary of some experiments performed between 1961 and 1963 to determine the influence of gravity on vestibular sensation.

A-21. Yuganov, Ye. M., "Physiological Reactions in Weightlessness," in V. V. Parin, ed., Aviation and Space Medicine, NASA TT F-228, Dec. 1964, pp. 431 – 434.

A descriptive paper; little data.

A-22. Isakov, P. K., Ye. M. Yuganov, and I. I. Kas'yan, Effects of Gravity on Body Functions and Problems of Space Flight, NASA TT F-275, Nov. 1964.

Another descriptive paper. Some data on perception of force in 1g and Og conditions.

A-23. Volkov, A. A., V. G. Denisov, Yw. I. Kirilenko, V. I. Mankevich, S. G. Mel'nik, G. P. M. Khaylovskiy, and V. F. Onishchenko, "On the Structure of a Command Signal and the Operator's Psychophysiological Capabilities for Control Under Conditions of Overloads," Cybernetics and Automation, Joint Publications Research Service, U.S. Dept. of Commerce, Rept. 37,072, 17 Aug. 1966, pp. 215 – 231.

This paper starts out with a discussion of man/machine dynamics and how they are influenced by choice of feedback quantities, then goes into some experimental results under g-loads. These include physiological measures; no performance data are given except qualitatively.

A-24. Creer, B. Y., H. A. Smedal, and R. C. Wingrove, Centrifuge Study of Pilot Tolerance to Acceleration and the Effects of Acceleration on Pilot Performance, NASA TN D-337, Nov. 1960.

Johnsville centrifuge experiments for acceleration tolerance evaluation while performing a tracking task; also side arm controller evaluation.

A-25. Lamb, L. E., "Status of Knowledge of Weightlessness, 1965," Space Research, Directions for the Future, Part III, Appendix 5, Space Science Board, National Academy of Sciences, National Research Council, Wash., D. C., Feb. 1966, pp. 191 – 208.

This account describes in a qualitative fashion the changes in an astronaut's metabolism resulting from weightlessness, together with the relation between the weightless state, a bedrest regime, and hypodynamia as deconditioning agents.

A-26. Gazenko, O. G., and A. A. Gurjian, Physiological Effects of Gravitation, FTD-MT-65-223, 7 Oct. 1965.

This reference summarizes Russian thinking on the subject of weightlessness, taking into account the results of Vokshkod I and II (both 24 hour missions)

A-27. Kas'yan, I. I., V. I. Kopanev, and V. I. Yazdovskiy, "Reaction of Cosmonauts to Weightlessness," in N. M. Sisakyan, ed., Problems of Space Biology, Vol. 4, NASA TT F-368, Mar. 1966, pp. 260-277.

Airplane parabolas and Vostok flights.

A-28. Parin, V. V., Yu. M. Volynkin, and P. V. Vassilyev, Manned Space Flight, Some Scientific Results, paper presented to the COSPAR Symposium, Florence, Italy, May 1964.

A random dispensing of Russian space flight data with very little interpretation or correlation. Contains cardiac, respiratory, EEG, weight change, and blood composition data together with results of handwriting tests.

A-29. Isakov, P. I., V. A. Popov, and L. S. Khachatur'yants, Problems in Evaluating the Physical Fitness of Cosmonauts, NASA TT F-9593, Oct. 1965.

Gives performance measures (time to finish) for procedural tasks (medical checks, vehicle maneuvers); also limited tracking task performance changes (but not as a function of time during flight!) and visual performance changes between ground and flight.

A-30. Kitayev-Smyk, L. A., "The Body Position (Postural Reactions) of Animals in Weightlessness," in V. V. Parin, ed., Aviation and Space Medicine, NASA TT F-228, Dec. 1964, pp. 211-212.

Influence of vestibular senses on postural muscle tone in weightlessness demonstrated.

A-31. Berry, C. A., D. O. Coons, A. D. Catterson, and G. F. Kelly, "Man's Response to Long-Duration Flight in the Gemini Spacecraft," Gemini Midprogram Conference, NASA SP-121, Feb. 1966, pp. 235-261.

Discussion of physiological measurements in Gemini IV, V, and VII.

A-32. Kotovskaya, A. R., L. I. Kakurin, N. I. Konnova, S. F. Simpura, and I. S. Grishina, "Effect of Prolonged Hypokinesis on Human Resistance to Accelerations," in N. M. Sisakyan, ed., Problems of Space Biology, Vol. 4, NASA TT F-368, Mar. 1966, pp. 317-324.

Bedrest experiment with two subjects for three days, three subjects for twenty days. Results showed detectable deterioration for the first two subjects, dramatic results for the latter three — two failed to achieve 7g before visual failure. Bedrest regimen incorporated no exercise.

APPENDIX B

PHYSIOLOGICAL MEASURES OF PILOT PERFORMANCE

	Page
CARDIOVASCULAR PERFORMANCE MEASURES	B-1
ECG (Electrocardiogram)	B-1
Blood Pressure	B-2
Retinal Photography	B-2
RESPIRATORY SYSTEM PERFORMANCE MEASURES	B-2
Ear Oximeter	B-3
Respiration Analyzer	B-3
BIOELECTRIC PERFORMANCE MEASURES	B-4
EOG — Electro-Oculogram	B-4
ERG — Electroretinogram	B-9
EMG — Electromyogram	B-11
EEG — Electroencephalogram	B-13
GSR — Galvanic Skin Response	B-15
REFERENCES FOR APPENDIX B	B-17

APPENDIX B

PHYSIOLOGICAL MEASURES OF PILOT PERFORMANCE*

J. A. Anderson and R. F. Ringland

The monitoring of physiological performance in centrifuge and related experiments pertinent to entry vehicle control is of prime importance in inferring the physiological origin of performance decrements. This Appendix is intended to provide a brief introduction to the types of measurements which can be made and their use to the experimenter. It is far from complete. For example, entire texts have been written on the subject of electrocardiograms. In other cases (e.g., electroencephalograms) the state-of-the-art is still undergoing development. In all cases, attention has been confined to those important measurements of more or less general application.

CARDIOVASCULAR PERFORMANCE MEASURES

Perhaps the most important measure of the functioning of the cardiovascular system is afforded by the electrocardiogram, at least in centrifuge experiments, as it provides information vital to the subject's physical safety and can be monitored on-line. Blood pressure measures are likewise an important indicator.

ECG (Electrocardiogram). The ECG (or EKG) has been in use for a considerable number of years. It consists of the recording of the electrical potentials measured between electrodes located on various parts of the body (there are several more or less standardized configurations of electrode placement). The waveform of the electrical signal derived from one set of electrodes and its phasing (or change in appearance) with respect to the waveform obtained from another set of electrodes can be correlated with various events (e.g., heart sounds,

*A portion of the work represented by this Appendix was carried out under Contract NAS2-3746, "Experiments for a Theory of Manual Control Displays."

atrial filling, ventrical contraction, etc.) in the cardiac cycle (Ref. B-1). Thus this measure provides a prime indicator of the heart's functioning.

The on-line monitoring of the ECG requires expert interpretation by the medical monitor. In addition, the ECG, in common with other bioelectric measurements to be discussed later, requires amplification and recording of relatively low level voltages with the attendant problems of noise and interference.

Blood Pressure. The most convenient means of determining blood pressure during centrifuge runs is similar to that used in the doctor's office — systolic, diastolic, and pulse pressures measured periodically with an inflatable cuff on the subject's arm (noncontrolling) at heart level. These measures show characteristic changes with both emotional and physical stress (see Appendix A).

Retinal Photography. The blood pressure of importance to the subject's performance in any particular task is that effective at eye level. It must be high enough to assure continued flow through the eye against the intraocular pressure of approximately 25 mm Hg. When blood flow to the retina ceases through part of the cardiac cycle, the subject experiences grayout — when it ceases entirely, blackout occurs (Appendix A).

In principle, retinal photography provides an indication of the retinal blood flow by noting the dilation and contraction of retinal blood vessels and their correlation with events in the cardiac cycle. Blood pressure within the cranial cavity can thus be inferred for pressure in the vicinity of 25 mm Hg (intraocular pressure).

Unfortunately, the state-of-the-art in retinal photography has not yet progressed to the point where it can be used in the centrifuge environment (problems with vibration, varying focal lengths, etc.).

RESPIRATORY SYSTEM PERFORMANCE MEASURES

The evidence available to date suggests a strong degree of correspondence between a subject's blood oxygen saturation (and thus his degree of hypoxia) and his performance under high g-loads (see

Appendix A). Thus measurement of this parameter is most important. Measures of respiratory mechanics (tidal volume, vital capacity, respiration rate, etc.) are only means to this end. The composition and amount of inspired and expired air can also be measured with varying degrees of accuracy. Clearly, the closer the measure is to the ideal (that is, the oxygen content of the body's tissues, particularly in the central nervous system or visual system) the more accurate it is likely to be (within the constraints of the measurement technique).

Ear Oximeter. The most convenient method of inferring the blood's oxygen content is by measuring the amount of light transmitted from a controlled source through the subject's ear. This is the principle of the ear oximeter. The light transmitted is affected by the oxygen content of the blood flow to the ear, the consumption of the oxygen by the ear's tissue, the blood flow to the ear (affected by the autonomous nervous system), and so on. With all these other factors, the oximetric technique still provides reasonable results, although with a considerable degree of variability, to judge by Refs. B-2 and B-3. In these references, the results obtained using this technique were compared against those made with an arterial cuvette (a "wet" technique — a probe is passed through an artery to the aortic arch over the heart), and the resultant calibration used to infer blood oxygen content with the oximeter measurement alone.

Respiration Analyzer. Another means of inferring the hypoxic state of a subject is by analysis of his respiration. The volume, flow rate, and composition of inspired and expired gasses is measured. Several means for doing this exist, for example, the analyzer discussed in Ref. B-4. Unfortunately, while such devices permit calculation of oxygen uptake, carbon dioxide excretion, mass flow rate, and the like; they do not give a measure of the blood's oxygen concentration, which is the parameter of interest in determining the subject's degree of hypoxia. The degree of hypoxia depends not only on the oxygen uptake, but also the rate at which it is consumed in the body — a function of the stresses imposed. Nevertheless, respiration analysis does permit inference of the subject's pulmonary efficiency.

BIOELECTRIC PERFORMANCE MEASURES

In addition to the preceding measures of a subject's physiological functioning in the regulation of his internal environment, there are several additional bioelectric measurements (one has already been mentioned, the ECG) which permit the experimenter to infer the performance of certain physiological subsystems within the subject's control loop (see Fig. A-1, Appendix A). They are of particular interest to the experimenter interested in performance measurements. Table B-1 summarizes the characteristics of these signals, each one of which is discussed in greater detail below.

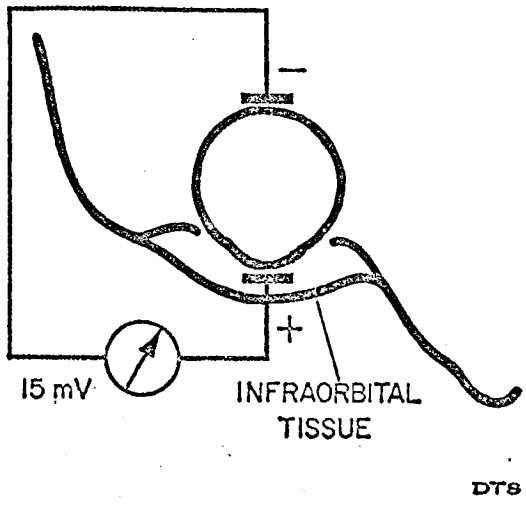
EOG — Electro-Oculogram. Of the greatest importance in determining the pilot's performance in a complex control task is determining his point of regard — which instrument he is looking at. This permits one to infer the information being used by the pilot in his task. Several means have been devised for determining the subject's eye motion — systems which photograph the corneal reflections, make use of contact lens-type devices, and so on. However the most frequently used is electro-oculography (EOG).

This technique makes use of the fact that the cornea is about 15 mV positive with respect to the opposite pole of the eye. Thus, if two electrodes are placed near the inner and outer canthii of the eye, motions of the eye in the horizontal plane will put the positive cornea nearer or farther from one of the electrodes, and thus a voltage will be developed across the electrodes (Fig. B-1). The origin of the "cornea-retinal" or "corneal-fundal" potential is disputed. This voltage can be amplified and gives an indication of the position of the eye. The voltage is proportional to the sine of the deflection of the eye, but for small (15 deg) excursions is approximately linear. Similarly, if electrodes are placed above and below the eyes, vertical movements can be measured. Although the voltage across the eyeball may range from 10 to 30 mV, voltages measured with EOG electrodes for large eye movements usually are considerably less than a millivolt — records typically show values of 10 to 40 microvolts per degree of rotation (Refs. B-5 and B-6). Because of the "physical" genesis of the EOG, time of response of the

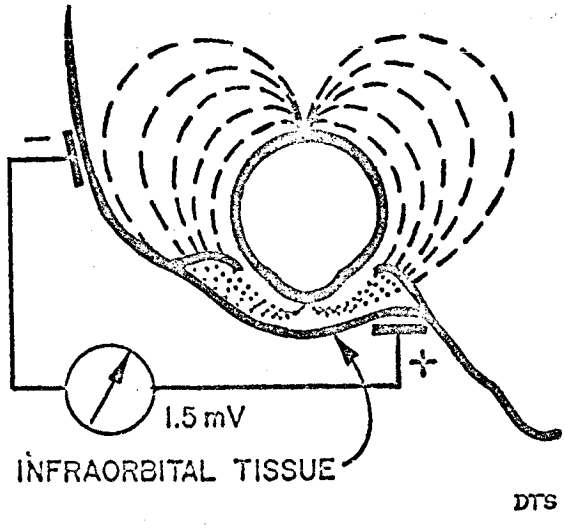
TABLE B-I

SUMMARY OF SOME CHARACTERISTICS OF INTEREST FOR SOME BIOELECTRIC POTENTIALS

ELECTROPHYSIOLOGICAL RESPONSE	PHYSIOLOGICAL ORIGIN	SIGNAL LEVEL	FREQUENCY RANGE OF SIGNAL	ELECTRODE TYPE, NUMBER, PLACEMENT
EOG (Electro-oculogram)	Electrically charged dipole (eyeball) rotating in socket	5 – 1000 μV	DC – 100 cps	Ag-AgCl electrodes, 2 for each direction (2 horizontal, 2 vertical) placed near eyeball
ERG (Electroretinogram)	Bioelectric events in layers of the retina	5 – 3000 μV	0.5 – 80 cps	Fluid filled contact lens and an indifferent electrode
EMG (Electromyogram)	Summated action potentials from contracting muscle fibers	5 – 2000 μV	2 – 10000 cps (hi-fi) 30 – 3000 cps (adequate)	Either 2 skin electrodes placed on skin above muscle or penetrating needle electrodes into muscle (for single fiber recordings)
EEG (Electroencephalogram)	Summated synaptic potentials from nerve cells in underlying brain	5 – 200 μV	0.1 – 100 cps	Skin electrodes placed on scalp over area of brain of interest
GSR (Galvanic Skin Response) or: EDR (Electrodermal Response)	Activity of sweat glands	5 – 3000 μV	0.01 – 3 cps	Measure either voltage or impedance change between skin electrodes



(a) Principle of Direct Measurement of Corneoretinal Potential in Animals (From Ref. B-13)



(b) Principle of Indirect Measurement of Corneoretinal Potential in Man (From Ref. B-13)

Figure B-1

EOG to a movement is very rapid, and limitation of response due to biological time constants is not a problem.

Unfortunately, this elegantly simple method is also prone to a large number of artifacts and errors.

As was noted, the EOG amplitude is directly proportional to the value of the corneo-retinal potential. Unfortunately, this potential is not constant but depends on many variables. There are fluctuations from day to day due to the state of the subject's health, nutrition, and inheritance, and many other physiological variables. However, these long-term fluctuations are usually not of significance since they do not greatly affect short experiments, and merely require that the system be recalibrated before each experiment. More serious is the observation that the corneo-retinal potential is strongly dependent on the immediate past history of exposure to light of the eye (Refs. B-7 and B-8). Kolder and North (Ref. B-7) have shown that a dark adapted animal, when exposed to light, shows a large transient increase in corneo-retinal potential. This peak value increase can be as much as 2 or 3 times the dark adapted value, and it can take over an hour to attain a new steady-state value. The new steady-state value is not equal to the old, dark adapted value. Similar changes, though not as large, occur when light is turned off. (See Fig B-2.) These dramatic changes in corneo-rctinal potential, and

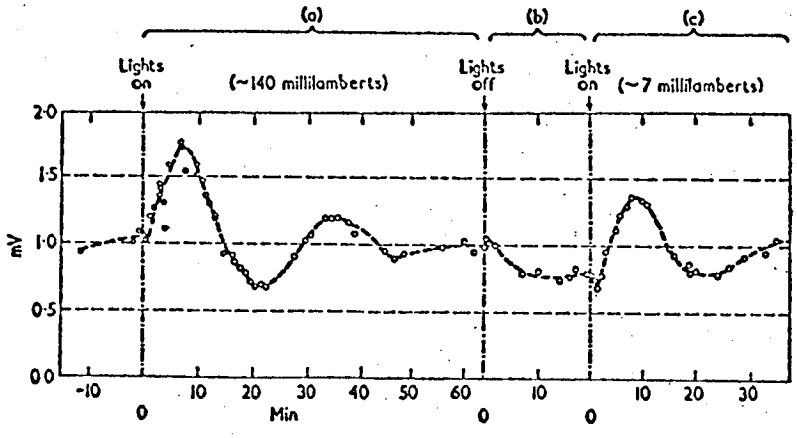


Figure B-2. Voltage Generated from a 60° Eye Movement Under Various Conditions of Light-Adaptation and Dark-Adaptation (from Ref. B-7)

thus, indirectly, in EOG raise some points for which no data is available. The experiments demonstrating these effects used overall illumination. It is conceivable that an experimental system involving visual scanning of areas of different brightness could generate very complex and unpredictable changes in corneo-retinal potential reflecting the immediate past history of the eye.

In any system involving recording small dc signals of biological origin, many technical problems arise. There is the perpetual problem of electrode polarization and, more serious, drift of electrode polarization, and the problem of drift in the amplifiers. There are also problems due to potentials due to other electrical activity in the body. However, these problems can be handled with reasonably careful technique and with the excellent commercial equipment available at present.

A subtle problem, affecting calibration, is also present. If recording electrodes are accurately placed so as to have the axes of each pair of electrodes at right angles to each other, a motion of the eye along one of the axes produces, as expected, a large potential between the electrodes in the axis of motion but also a small potential between the other set of electrodes. This artifactual potential has not been studied carefully but appears to be due to several causes. First, as noted, the eye does not perform a simple rotation about a point when it rotates but performs complex maneuvers. Second, the simple analysis of the EOG system assumes that the rotating eyeball is embedded in a homogeneous medium of constant resistance, an assumption at variance with the facts.

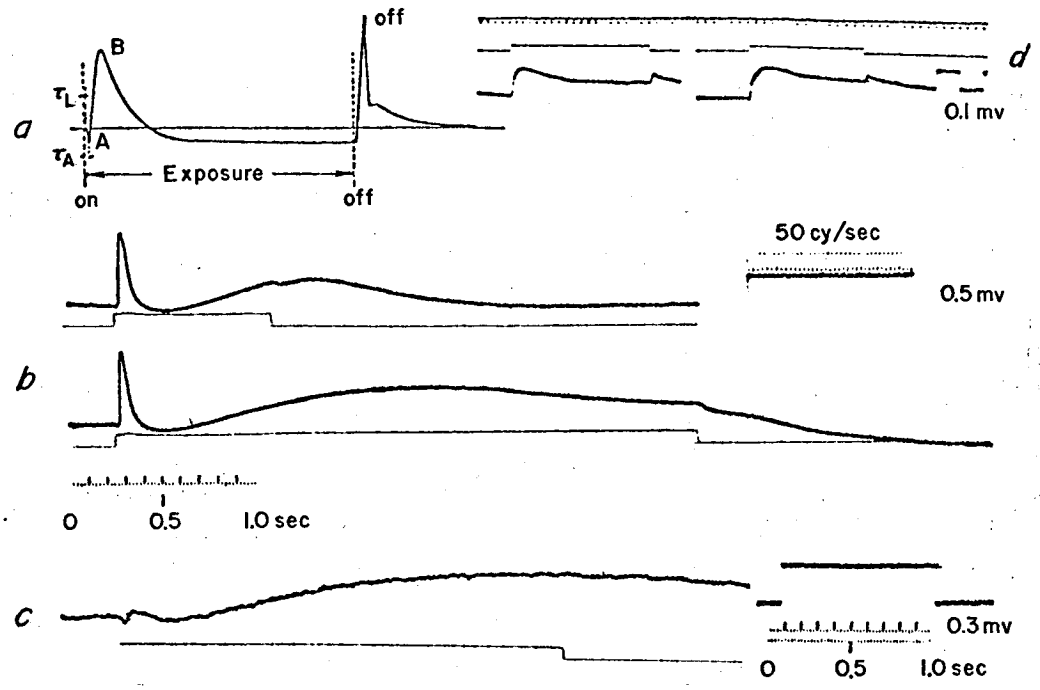
Ford (Refs. B-9 and B-10) has mentioned the presence in his records of a group of artifacts. They appear when the eye makes a move from one fixation point to another and are sharp spike-like transients on the trace when the eye moves and when it is about to move back to its original position. Ford claimed that the majority of his subjects showed this artifact, and felt that it might be caused by reflex motions of the eyelid musculature. Other observers have not considered this artifact to be of significance.

Artifacts caused by pickup of electrical activity (EMG) of the muscles moving the eyeball do not appear to be a problem in EOG recordings. The EOG recording electrodes are separated from the eye muscles by the bony orbit, and the bodies of the muscles are at right angles to and fairly distant from the EOG electrodes. Also the frequency spectrum of EOG and EMG are sufficiently different so that simple filtering is enough to remove the interfering signal. Quite complex techniques, involving fine needle electrodes, are necessary to demonstrate eye muscle EMG.

All artifacts, drifts, and inherent noises allow an accuracy that most observers claim to be in the neighborhood of 1/2 to 1 deg over short (i.e., minutes) periods of time. Frequency recalibrations are necessary and, for accurate work, should be perhaps a minute apart.

ERG — Electroretinogram. One of the first bioelectric phenomena discovered was the electrical response of the eye to light, noted in the middle of the 19th century. In a dark adapted eye, the electrical response to a flash of light, measured between an electrode on the cornea and an indifferent electrode, is approximately that shown in Fig. B-3. There is a rapid initial corneal negative deflection, called the "a" wave, a fast positive deflection called the "b" wave, and a long slow positive response called the "c" wave. The ERG is very much a mass effect, and the genesis of the different waves is open to some dispute. However, it is generally agreed that the ERG is a composite of at least three distinct processes. Process "PI" (the terminology is Granit's and is now standard) is responsible for the "c" wave and apparently originates in the cells of the pigment epithelium (the pigmented cell layer next to the retina). The "c" wave is present only in the dark adapted eye, is of long latency, and requires relatively high light intensity to be produced.

Process "PII" is primarily responsible for the "b" wave. It is largest in the dark and diminishes in the light. It is apparently derived from activitiy in the inner ganglion cell layer (one of the nerve cell layers between the receptor cells and the light). It can be produced by a relatively small amount of light, and is reduced in the light adapted eye.



a. Cone retina of horned toad, Phyronosoma. (Charfee and Sutcliffe, Amer. J. Physiol., 95, 1930, p. 250)

b. Cat; dark adapted. Two flash durations. Intensity about 700 m.c. Note a-wave just visible, b-wave with fast oscillation, drop below baseline before c-wave begins, and d-wave or off-effect as a retardation of fall of response at cessation of illumination.

c. Guinea pig, dark adapted. Intensity about 900 lux. Definite a-wave, indication of double b-wave. In this eye the c-wave or secondary rise tends to be the most prominent phase of the response. Light signal below retinogram in this and in b.

d. Gecko. Intensity 1250 m.c. First record is 3.8 sec illumination after 1 min in the dark, second record 2.8 sec illumination after 2 min in the dark. Time marks 0.2 apart. (Dodt and Heck, Pflüg. Arch. ges. Physiol., 259, 1954, p. 226. By courtesy of E. Dodt, Physiological Institute, Freiburg in Bresgau)

Figure B-3. Electroretinograms (From Ref. B-11)

Process "PIII" is primarily responsible for the "a" wave. This process is apparently primarily a response from the cones although the rods play some part. It requires a high light intensity to be provoked. It is abolished in the light adapted eye. Further discussion of these processes is contained in Ref. B-1.

The processes can be dissociated by their responses to various agents. Some chemicals or physiological states selectively suppress one or another process.

The main frequency components of the ERG lie between 0.5 and 80 cps. The electrode now almost universally used is a large contact lens containing a chlorided silver wire. The space between the contact lens and the eye is filled with a conducting transparent solution, either saline or a methyl-cellulose-saline mixture. One experimenter reports that such electrodes can be worn for up to four hours with little or no discomfort. Special contact lenses containing wires suitable for use as electrodes are available commercially.

Even though the exact mechanisms of production of the ERG are not fully understood, it serves as a useful indicator of retinal function. Interference with function produces characteristic changes in ERG and these changes can be used diagnostically in some cases. If it is desired to know if a signal was actually getting to the first stage of the visual receptor organs, this would prove to be a useful technique. However, simpler techniques, such as the evoked response, are available that tell much the same thing at a higher level in the nervous system.

EMG — Electromyogram. The electromyogram is a recording of a summation of action potentials from contracting muscle fibers. In centrifuge experiments, EMG recordings serve as an indicator of the pilot's "straining" in particular muscles, and (if the muscles are involved in actuation) the neuromuscular effort involved in control activity. They can also serve as an indicator of the neuromuscular contribution to the pilot's lag — increased muscle tonus implies reduced lag, and results from a higher level of bioelectrical activity (greater EMG readings).

EMG signals can be recorded several ways. The simplest is to place standard skin electrodes, such as the Beckman series of electrodes, on the surface of the muscle. This gives an integrated response from many fibers. If it is desired to record from single muscle fibers, it is necessary to use needle electrodes. For accurate reproduction of all frequency components in the EMG signal, an amplifier with 3 dB points at 2 and 10,000 cps is recommended. For clinical use, amplifiers with less demanding characteristics (3 dB points at 30 and 3,000 cps) are acceptable.

The EMG recordings thus obtained look like those of Fig. B-4, taken from recent STI experiments. The muscular effort involved in deflecting the stick in one direction (contracting fibers) is indicated by the increased EMG voltages. The baseline level is a measure of the muscle's tone.

It has been suggested that simultaneous recording from both agonist and antagonist muscles, if properly processed, might yield a signal proportional to the forces required to move the limb. The EMG might be processed by rectifying the two signals, passing them through a low pass filter, and summing with opposite sign.

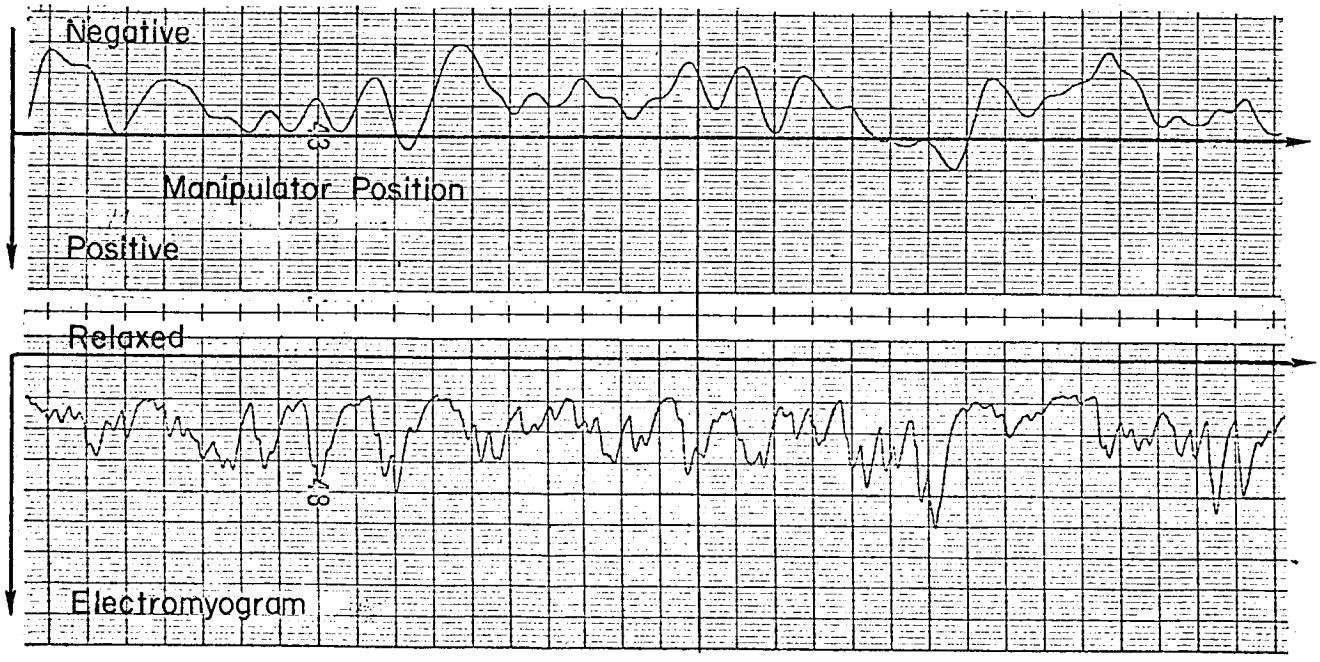


Figure B-4. Electromyogram (Correlated with Limb Position)

In this trace, the recorded signal is a rectified and filtered [filter: $1/(s/50+1)(s/20+1)$] EMG taken from two electrodes on the triceps (elbow extensor). Thus an increase in the voltage level (downward deflection of the trace) reflects a neuromuscular command to deflect the manipulator away from the body (positive deflection).

EEG — Electroencephalogram. Ever since they were discovered by Berger in the 1920s, "brain waves" have been the subject of intensive study. They have proved remarkably intractable to meaningful analysis but an experienced student of the EEG can determine from an EEG record the approximate state of arousal of a normal subject (i.e., whether the subject is asleep or awake). The EEG has proved exceedingly valuable in medicine where it can be used to diagnose many forms of illness (Fig. B-5).

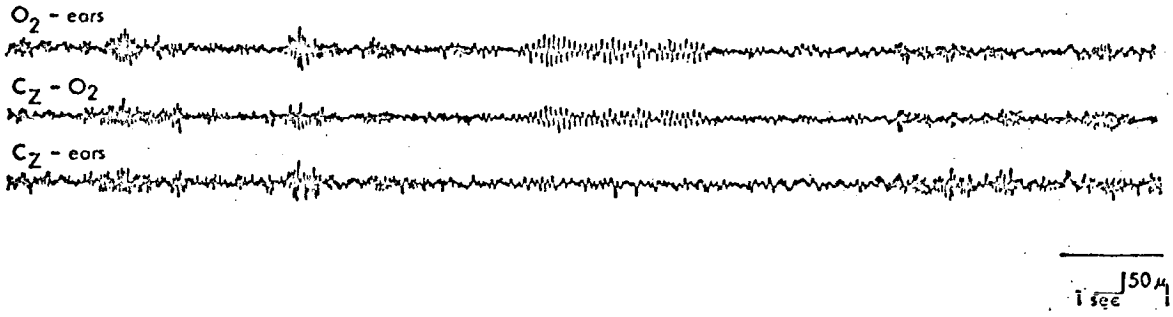


Figure B-5. EEG Tracings of Normal Young Adult During a Prolonged Vigilance Task (Ref. B-12)

EEG can be recorded quite easily, either by monopolar electrode techniques, measuring the voltage between an electrode on the skull and an indifferent electrode, or by bipolar electrode techniques, measuring the voltage between two electrodes placed over homologous portions of the brain.

The frequencies of interest in the EEG run from about 1 cps to about 40 cps. The famous "alpha rhythm," a very prominent large amplitude wave seen when the subject is relaxed with closed eyes, has a frequency of about 12 cps. Amplitudes of the recorded signal are low, generally less than 100 μV.

In centrifuge experiments, the EEG has been used (see Refs. A-10, A-14, and A-15 of Appendix A, for example) as an indicator of the functional state of the central nervous system, with the waxing and waning of various frequency components being correlated with the subject's stress level and degree of CNS hypoxia (i.e., with g-load and time duration at a particular g-level). Used in this fashion, the EEG signals are spectrum analyzed in "slices." Every ten seconds or so, the EEG recordings from a particular set of electrodes are analyzed, the results being displayed as a sort of power spectrum. The changes in this power spectrum are used to infer the subject's state of consciousness.

A closely related bioelectric potential usually recorded with the same electrode placements and techniques should be of even greater value to the experimenter interested in pilot performance under high g-levels. When a sudden flash of light, or a click, is presented to a subject, a sudden burst of nervous activity occurs in the part of the brain receiving visual or auditory stimuli. If EEG electrodes are placed over these areas, characteristic voltages, called "evoked potentials," are observed (Fig. B-6). Generally these voltages are on the order of the EEG voltages, and are thus interfered with, but various simple computer techniques that are presently available are capable of extracting the evoked potential by averaging potentials from many presentations of the stimulus. Small special purpose computers are commercially available for this application.

Evoked potentials are of interest since their shape and amplitude bears a direct relationship to the functioning of the sensory pathway up to the level of the cortex. Also, it is possible in some sensory modalities to insert a coded signal into the sensory system, a certain pattern of flashes, say, and then determine its presence or absence at the cortical level by appropriate analysis of the EEG. Since average response techniques are used, a certain stability of response is assumed, and thus such a technique is applicable only under certain conditions. Such an evoked response system would be ideally suited to study of visual function under high-g conditions or other stressful situations.

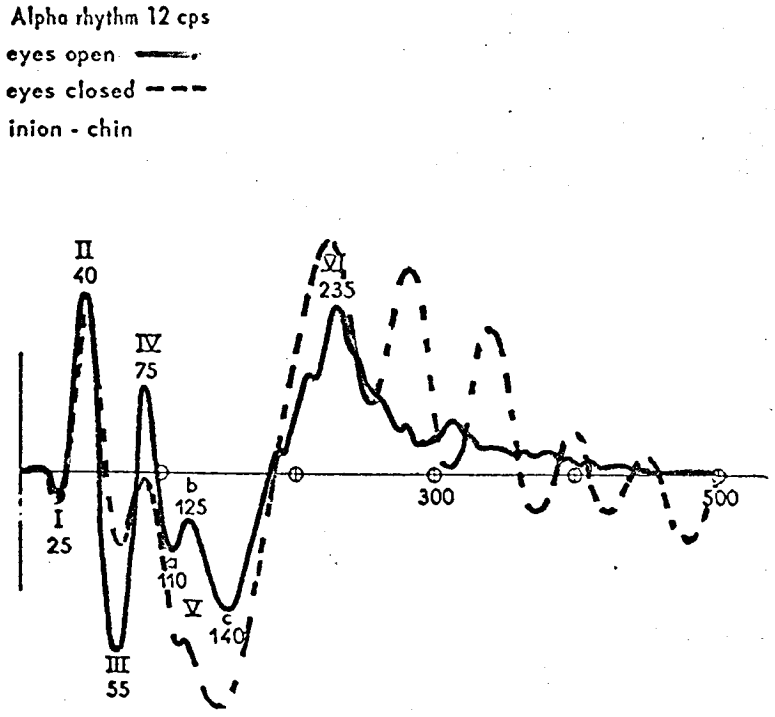


Figure B-6. Visual Evoked Response from 21 Year Old Normal Subject (Ref. B-12)

GSR — Galvanic Skin Response. There are two generally accepted ways of recording the "galvanic skin response," or, as is now preferred, the "electrodermal" response (EDR): change in voltage and change in impedance. In a man, two electrodes are attached to the hand, one on the palm and one on the back of the hand. Then these electrodes can be attached directly to an amplifier and a potential recorded, or the impedance between the two electrodes can be measured with an ohmmeter of some kind. As far as can be determined, the responses recorded by the two methods are identical. The impedance measuring system is slightly more complicated, and direct measurement of voltage is preferred. These responses are very slow and the amplitude of spontaneous electrodermal activity is on the order of 1 mV. There are components down to a few microvolts. In a normal cat, spontaneous electrodermal activity in the foot pads produces about 12 large responses per minute. The highest frequency component present seems to be only a few cps, perhaps 2 or 3 cps.

At one time, there was considerable interest in the elctrodermal response in man as an indicator of general state of anxiety. At present, evidence for this is not very strong, although there is definitely some connection with the emotional state of the subject.

REFERENCES FOR APPENDIX B

B-1. Ruch, T. C., and J. F. Fulton, Medical Physiology and Biophysics, 18th ed., W. B. Saunders Co., Philadelphia, 1960.

B-2. Wood, E. H., A. C. Nolan, D. E. Donald, and L. Cronin, "Influence of Acceleration on Pulmonary Physiology," Federation Proc., Vol. 22, No. 1024, 1964.

B-3. Alexander, W. C., R. J. Sever, W. E. Fedderson, and F. G. Hoppin, "Acceleration ($+G_X$) Induced Hypoxemia and Crew Performance," Aerospace Medicine, Vol. 35, No. 257, 1964.

B-4. Breeze, R. K., and G. W. Campbell, The Design, Fabrication, and Feasibility Testing of a Prototype Airborne Respiration Analyzer, NASA CR-741, Mar. 1967.

B-5. Kris, Christine, "Vision: Electro-Oculography," Medical Physics, Vol. III, Otto Glasser (ed.), The Year Book Publishers, Inc., Chicago, Illinois, 1960, p. 692.

B-6. Jayle, G. E., R. L. Boyer, and J. B. Sarraco, L'électro-retinographie: Bases physiologiques et Données Cliniques, T.II., Masson et. Cie, Editeurs, 1965; Dixième Partie. Notions complémentaires d'électro-physiologie oculaire chez l'homme.

B-7. Kolder, H., and A. W. North, "Oscillations of the Corneo-Retinal Potential in Animals," Opthalmologica, Vol. 152, 1966, pp. 149-160.

B-8. Arden, G. B., "The Sensory Effects of Drugs: Electrophysiological Investigations of the Mechanism of the Action of Drugs in the Eye," Recent Developments in Vision Research, Milton A. Whitcomb (ed.), Publication 1272, National Academy of Sciences-National Research Council, Washington, D. C., 1966.

B-9. Ford, A., "Significance of Terminal Transients in Electro-Oculographic Recordings," A.M.A. Arch. of Opthalmology, Vol. 61, 1959, p. 899.

B-10. Ford, A., C. T. White, and M. Lichtenstein, "Analysis of Eye Movements During Free Search," J. Opt. Soc. Amer., Vol. 49, 1959, p. 287.

B-11. Granit, R., Receptors and Sensory Perception, Yale Univ. Press, New Haven, 1955.

B-12. Symposium on the Analysis of Central Nervous System and Cardio-Vascular Data Using Computer Methods, NASA SP-72, 1965.

B-13. Kolder, H., "Automatic Recording and Evaluating Oscillations of Indirectly Measured Corneoretinal Potential in Man," Medical Research Engineering, Vol. 6, No. 1, 1967.