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HANDBOOK OF HUMAN ENGINEERING DESIGN DATA FOR REDUCED GRAVITY CONDITIONS

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16. Abstract

The purpose of this document is to provide a Handbook of Human Engineering Design Data for Reduced Gravity Conditions for the use of engineers, designers, and human factors specialists during the developmental and detailed design phases of manned spacecraft programs. The result is a unique, 550 page document, which provides detailed and diverse quantified data on man's capabilities and tolerances for survival and productive effort in the extraterrestrial environment. It also provides quantified data and information on the space environment as well as the characteristics of the vehicular or residential environment required to support man in outer space. A detailed, topical Table of Contents has been developed to provide easy and efficient access to the data to encourage the utilization of the document among technical and professional specialists involved in the design and construction of manned spacecraft.

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PREFACE

The final report on the Astronaut Worksite Performance Program for the development of Experiment M508 is presented in three volumes. The volume designations are:

Volume	Title
I	Summary Technical Report (N70-34195 - CR-108569)
II	Detailed Technical Report
III	Handbook of Human Engineering Design Data for Reduced Gravity Conditions

The analytical, design, manufacturing and certain ground based zero gravity simulation portions of the program were performed by the Space Systems Organization of the General Electric Company Space Division.

In addition, considerable support was provided at the Manned Spacecraft Center, Marshall Space Flight Center and the Aeronautical Systems Division at Wright-Patterson Air Force Base. We would like to acknowledge those personnel who provided this support.

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FOREWORD

In the process of defining the probable usage of this text, it was determined that the basic handbook would not only be used as an authoritative reference source for individual designers in respect to establishing specifications and requirements for physical man/machine interfaces, but could also provide the basis for standardization of operational protocol development. The publication and common use of authoritative absolute descriptors of the various needs, capabilities and tolerances of crewmen might also provide the basis for the establishment of standarized levels of capabilities for describing crew selection and training criteria in respect to the designation of specific maintainability tasks to individual crewman. With this in mind, it was decided to follow the precedents set by such documents as the Handbook of Chemistry and Physics, Biology Data Book, etc., i.e., the selected format for the document should consist of a repository of detailed, quantified data in tabular or graphic form whenever possible.

A secondary purpose was also identified, namely, a need to provide a single and comprehensive document for use in manned EVA design activities by the neophyte or newcomer to the field in order that he might be made aware of those areas where the presence of a human worker could and should influence the design of orbital hardware or processes. The final document, therefore, must provide readily accessible detailed data describing all pertinent functional or survival-critical interactions between man, his working environment, his vehicle and support hardwares.

While, as previously stated, it is hoped that widespread utilization of the text material will permit standarization of design practice in respect to vehicle, equipment, and operations, the document must also be capable of providing custom-tailored specifications for unique mission/equipment/environment interactions.

Literature searches were requested from the National Aeronautics and Space Administration's Scientific and Technical Information Division as well as the Defense Documentation Center (DDC) regarding human performance in a reduced gravity environment. These searches were reviewed, and those items that appeared to contain required human performance data were ordered for review. The services of the Tufts University Human Engineering Information and Analysis Service (HEIAS) were also utilized during this effort. Volumes I and II of the HEIAS bibliographies were searched for space-related categories most relevant to the task. As a result of this search, a printout of approximately 500 references was developed. Items to be entered into the upcoming Volume III of the HEIAS Bibliography were also reviewed for relevancy. The NASA and DDC searches were arranged in ascending "AD" "STAR" accession numbers, respectively, when they were received. The basic HEIAS system carries the titles and abstracts of documents by accession number but cross-indexes the accession numbers of the documents by an alphabetical listing of primary categories relevant to human factors interests. In order to eliminate title duplication and facilitate the location of titles and abstracts, the HEIAS system was utilized as the basic collation system.

The fact that the DDC, NASA, and HEIAS information sources had different cutoff dates was considered, and an effort to complement the searches insofar as possible was made. This could not be accomplished until nearly all the major work of the search was completed and a three-way cross-reference system established between DDC, STAR and HEIAS accession numbers. An informal check from approximately a 50 percent sampling of STAR accession numbers indicated that routine acquisition of NASA reports was fairly complete and current for HEIAS. An item-by-item check against DDC search was undertaken, and items which were either missing from, or possibly not yet processed through, the HEIAS system were ordered and examined.

A basic review of currently available documentation was initiated, and basic data regarding human operator performance was collected. In this effort, the goal was to primarily gather empirical or experimental data generated in an actual or simulated reduced gravity environment.

It was felt that a document of this type should permit deliberate and detailed data to be available for four basic tasks that are currently deemed necessary when designing for maintainability in a manned orbiting system. For optimum maintainability potential, the following discrete tasks must be accomplished:

Task A. The vehicle and all its subsystem housekeeping, structural, and mission-related hardwares must be deliberately analyzed in respect to the possibility of needing in-orbit maintenance. In those instances where maintenance during orbital operations is deemed both possible and feasible, specific efforts must be expended in order to ensure ease of diagnostics, access, institution of corrective procedures, and checkout capabilities. These hardware designs shall also consider packaging and general corrective processes involved in respect to minimizing "unique" technological skills, special tooling, instrumentation, facilities, and man-hours necessary to effect the repairs while maximizing the safety and efficiency of access to the work site.

Task B. The designer shall detail all crew support facilities and equipments necessary to accomplish the transport, restraint/tethering of the crewman and his materials at the work sites, as well as to provide an environment that is conducive to both work and survival.

Task C. The responsible system designers shall develop specifications necessary to describe the physical and functional characteristics of the maintenance interface including sizing, configuration, and information flows across the man/machine interfaces at the various potential work stations.

Task D. The designers must, as part of their maintainability tradeoffs, consider the capabilities of man in light of the constraints imposed by the system and the environment in the design and assignment of maintenance roles to the "orbital man."

To reiterate, the large preponderance of material selected for this document is expressed in graphic and/or tabular form with prose commentary limited to explanations of techniques utilized in the application of specific data. Prose is also utilized in "term definition" as indicated.

In selecting the basic generic headings for Human Engineering Handbook, heavy emphasis was placed on potential usage. Section 1 contains that information related to the description of human characteristics. Provisions are made for information which will permit allowances for man's physical and functional dimensional requirements as well as descriptors of his general motor, sensory, and cognitive performance capability. Information regarding his tolerance to various forms of physical, emotional, and environmental stressors are also provided in this section.

Section 2 has provisions for absolute value data which describes the composition and the various phenomena present in the orbital extravehicular environment.

Section 3 has provisions for data which will describe the minimal and/or optimal physical and functional characteristics of hardware design where it might interface with man and modify his performance. Data in this area includes sizing, configurational, operational, and dynamic considerations for the vehicle and all its facilities including unique mission equipments, packaging and access.

Due to the "Level of Effort" nature necessitated by modified funding availability during mid-contract, it was decided to attempt to maximize the factual content of the document (in order to be truly representative of the literature available as of the cutoff date of June, 1969) rather than complete the glossary or index section. It is hoped that these shortcomings can be rectified during subsequent update efforts.

This study was accomplished as part of the Human Factors System Program under the sponsorship of Walton L. Jones, M.D., Director, Biotechnology and Human Research.

During the course of this study, a great many individuals and groups have made important and material contributions. While we cannot thank every individual involved we do wish to recognize the major support, encouragement and guidance provided by Dr. Stanley Deutsch, Chief, Man-Systems Integration Branch in the Biotechnology and Human Research Division at NASA Headquarters, Washington, D.C.

Special thanks are also due to Mr. John Jackson of the Crew Systems Division of the Manned Spacecraft Center, Houston, Texas, Mr. Stan Johns of Marshall Space Flight Center, Huntsville, Alabama and Dr. Jon Rogers, formerly of the Marshall Space Flight Center and currently with the Department of Psychology of the University of Alabama, for their support and contributions during both the early and current phases of this program.

Finally, my thanks to Donald G. Norman for extensive inputs to the organizational and final notational efforts in his capacity as General Electric Program Manager of the Astronaut Zero Gravity Performance Evaluation Program Contract, of which the Handbook effort was one part, Mr. Fred Rudek of the Life Science group for his contributions to editing the enormous mass of candidate material, and Mrs. Dolores Friz whose patient and meticulous secretarial skills were responsible for the formal final draft of the published document.

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ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

ASTRONAUT (U.S.) POPULATION

a. Overall Dimensions of the Head, Body and Limbs

Measurement	Obser-vations	Centimeters Mean	Centimeters Std. Dev.	Centimeters Range Low	Centimeters Range High	Inches Mean	Inches Std. Dev.	Inches Range Low	Inches Range High
1. Weight of Body	31	74.37	6.67	63.50	90.26	163.94	14.71	140.00	199.00
2. Height of Body, Erect	36	177.00	4.09	168.70	183.40	69.71	1.61	66.42	72.21
3. Height of Body, Normal	28	176.43	3.91	167.80	183.40	69.46	1.54	66.06	72.20
4. Height of Body, Sitting, Normal	28	92.41	2.58	87.70	97.90	36.38	1.02	34.53	38.54
5. Height of Eyes, Standing	27	164.03	5.24	151.70	178.00	64.58	2.06	59.72	70.08
6. Height of Eyes, Seated	24	80.73	2.93	74.20	85.20	31.78	1.15	29.21	33.54
7. Height to Tragion, Seated	17	79.10	2.30	74.20	82.80	31.14	0.91	29.21	32.60
8. Height to Cervical Level, Standing	28	152.98	7.15	145.50	185.40	60.23	2.82	57.28	72.99
9. Height to Cervical Level, Seated	21	65.88	2.92	58.30	70.00	25.94	1.15	22.95	27.56
10. Height to Right Mid-shoulder	38	149.82	3.94	141.10	157.70	58.99	1.55	55.55	62.09
11. Height to Left Mid-shoulder	38	150.01	3.95	142.20	158.00	59.06	1.56	55.98	62.20
12. Height to Right Shoulder	28	144.95	3.77	137.20	151.10	57.07	1.49	54.02	59.49
13. Height to Left Shoulder	28	145.24	3.78	136.80	151.30	57.18	1.49	53.86	59.57
14. Height to Acromion, Standing	28	144.25	3.74	136.60	151.20	56.79	1.47	53.78	59.53
15. Height to Acromion, Seated	24	59.96	2.26	55.30	64.00	23.61	0.89	21.77	25.20
16. Height to Nipple, Standing	28	129.11	4.20	120.80	142.20	50.83	1.65	47.56	55.98
17. Height to Armpit, Seated	10	45.23	3.54	40.60	50.20	17.81	1.39	15.98	19.77
18. Height to Elbow, Standing	3	106.60	3.92	103.50	111.00	41.97	1.54	40.75	43.70
19 Height to Elbow, Seated	18	24.06	2.83	19.20	28.00	9.47	1.11	7.56	11.02
20. Height to Wrist, Standing	3	83.30	3.83	80.00	87.50	32.80	1.50	31.50	34.45
21. Height to Knuckles, Standing	3	74.97	2.14	73.10	77.30	29.52	0.84	28.78	30.43
22. Height to Supersternal Level, Standing	28	143.68	3.46	136.70	149.70	56.57	1.36	53.82	58.94
23. Height to Substernal Level, Standing	10	124.28	3.34	118.60	128.60	48.93	1.31	46.69	50.62
24. Height to Xiphoid Level, Standing	6	118.92	2.38	115.60	122.00	46.82	0.94	45.51	48.03
25. Height to 10th Rib	8	113.06	3.23	106.80	116.10	44.51	1.27	42.05	45.71

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

ASTRONAUT (U.S.) POPULATION

a. Overall Dimensions of the Head, Body and Limbs (Cont.)

Measurement	Obser-vations	Centimeters				Inches			
		Mean	Std. Dev.	Range Low	Range High	Mean	Std. Dev.	Range Low	Range High
26. Height to Cristal Level	22	106.19	2.91	99.80	110.80	41.81	1.15	39.29	43.62
27. Height to Trunk, Standing	18	165.81	4.91	158.30	173.70	65.28	1.93	62.32	68.39
28. Height to Trunk, Seated	10	159.86	6.36	153.00	169.60	62.94	2.50	60.24	66.77
29. Height to Waist	28	107.03	2.52	101.40	110.90	42.14	0.99	39.92	43.66
30. Length from Crown to Rump	24	96.11	2.47	91.80	100.40	37.84	0.97	36.14	39.53
31. Height from Acromion to Vertex	3	37.43	1.23	36.40	38.80	14.74	0.48	14.33	15.28
32. Height from Cervical Level to Vertex	24	25.85	1.20	23.20	28.00	10.18	0.47	9.13	11.02
33. Height to Trochanteric Level	28	91.77	2.81	86.80	96.40	36.13	1.11	34.17	37.95
34. Height to Crotch	38	83.12	2.48	78.20	87.60	32.72	0.98	30.79	34.49
35. Height to Gluteal Furrow	11	80.18	2.53	76.40	84.00	31.57	1.00	30.08	33.07
36. Height to Knee	21	55.54	1.58	51.80	58.00	21.87	0.62	20.39	22.83
37. Height to Superior Kneecap Level	28	52.20	1.81	49.30	57.20	20.55	0.71	19.41	22.52
38. Height to Center Knee Floor	28	49.79	2.20	47.20	58.00	19.60	0.87	18.58	22.83
39. Height to Popliteal Position	18	43.14	2.01	38.50	47.60	16.98	0.79	15.16	18.74
40. Height to Tibia	24	46.60	1.74	42.60	48.80	18.35	0.69	16.77	19.21
41. Breadth from Forearm to Forearm	18	51.16	2.94	45.70	56.50	20.14	1.16	17.99	22.24
42. Breadth from Elbow to Elbow	20	46.13	2.75	41.80	51.30	18.16	1.08	16.46	20.20
43. Breadth from Knee to Knee	28	20.69	1.18	18.90	22.70	8.15	0.46	7.44	8.94

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

ASTRONAUT (U.S.) POPULATION

b. Dimensions of the Head

Measurement	Obser-vations	Centimeters				Inches			
		Mean	Std. Dev.	Range Low	Range High	Mean	Std. Dev.	Range Low	Range High
1. Length of Head	28	19.96	0.47	19.20	21.20	7.86	0.19	7.56	8.35
2. Breadth of Head	28	15.55	0.57	14.50	17.30	6.12	0.22	5.71	6.81
3. Circumference of Head	28	57.80	1.35	54.61	60.01	22.56	0.53	21.50	23.63
4. Height of Face, Total	25	11.94	0.64	10.80	13.30	4.70	0.25	4.25	5.24
5. Height from Pupil to Vertex	27	11.51	1.36	9.40	14.70	4.53	0.54	3.70	5.79
6. Height from Stomion to Vertex	18	18.32	1.31	16.40	21.30	7.21	0.52	6.46	8.39
7. Height from Tragion to Vertex	25	13.09	0.64	11.90	14.40	5.15	0.25	4.69	5.68
8. Length from Menton to Crinion	10	18.43	0.94	16.90	19.40	7.26	0.37	6.65	7.63
9. Length from Menton to Subnasal	10	6.64	0.61	5.80	7.80	2.61	0.24	2.28	3.07
10. Breadth from Ear to Ear	17	18.97	0.83	17.70	20.60	7.47	0.33	6.99	8.11
11. Distance Between Pupils	18	6.33	0.31	5.70	7.00	2.49	0.12	2.24	2.76
12. Depth from Nasal Root to Wall	13	19.95	0.38	19.30	20.50	7.85	0.15	7.60	8.07
13. Depth from Pronasal Position to Wall	18	22.11	0.58	21.00	23.20	8.70	0.23	8.29	9.13
14. Depth from Pupil to Wall	24	18.56	0.62	17.50	19.70	7.31	0.24	6.89	7.76
15. Depth from External Canthus to Wall	6	17.97	0.41	17.40	18.60	7.07	0.16	6.85	7.32
16. Depth from Tragion to Wall	18	9.82	0.78	8.60	11.10	3.87	0.31	3.39	4.37
17. Breadth of Ear	18	3.74	0.25	3.30	4.10	1.47	0.10	1.23	1.61
18. Length of Ear	18	6.56	0.47	5.10	7.10	2.58	0.19	2.01	2.80
19. Length of Ear above Tragion	18	3.08	0.45	2.60	4.10	1.21	0.18	1.02	1.61
20. Breadth of Nose	7	3.44	0.26	3.20	3.80	1.35	0.10	1.26	1.50
21. Breadth of Nasal Root	7	1.51	0.24	1.30	2.00	0.59	0.09	0.51	0.79
22. Length of Nose	14	5.16	0.27	4.70	5.60	2.03	0.11	1.85	2.20
23. Diameter between Tragion	9	14.39	0.46	13.40	15.00	5.67	0.18	5.28	5.91
24. Length of Bitragion-Coronal Arc	6	34.67	0.66	33.40	35.30	13.65	0.26	13.15	13.90
25. Length of Bitragion-Crinion Arc	8	32.29	1.15	30.60	34.00	12.71	0.45	12.05	13.39
26. Length of Bitragion-Inion Arc	6	28.93	1.16	27.70	30.60	11.39	0.46	10.91	12.05
27. Length of Bitragion-Menton Arc	10	31.81	0.87	30.50	33.30	12.52	0.34	12.01	13.11

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

ASTRONAUT (U.S.) POPULATION

b. Dimensions of the Head (Cont.)

Measurement	Obser-vations	Centimeters Mean	Centimeters Std. Dev.	Centimeters Range Low	Centimeters Range High	Inches Mean	Inches Std. Dev.	Inches Range Low	Inches Range High
28. Length of Bitragion-Sub-mandibular Arc	6	30.05	0.89	28.80	31.50	11.83	0.35	11.34	12.40
29. Length of Bitragion-Subnasal Arc	6	28.48	0.79	27.50	29.50	11.21	0.28	10.83	11.61
30. Breadth between Gonia	13	11.07	0.39	10.30	11.60	4.36	0.15	4.06	4.57
31. Bizygomatic Diameter between Zygomatic Bones	21	14.30	0.51	13.70	15.60	5.63	0.20	5.39	6.14
32. Length of Lips	18	5.33	0.39	4.60	6.10	2.10	0.15	1.81	2.40
33. Circumference of Neck	28	38.50	1.65	34.61	41.59	15.16	0.65	13.63	16.38
34. Length of Anterior Neck	28	10.31	1.14	7.62	12.70	4.06	0.45	3.00	5.00
35. Length of Posterior Neck	28	10.18	0.91	8.26	12.70	4.01	0.36	3.25	5.00
36. Depth from Larynx to Wall	3	16.40	1.10	15.30	17.50	6.46	0.43	6.02	6.89
37. Mid-Shoulder to Top of Head	11	27.68	1.46	25.40	30.48	10.50	0.58	10.00	12.00

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

ASTRONAUT (U.S.) POPULATION

c. Dimensions of the Trunk and Torso

Measurement	Obser-vations	Centimeters Mean	Centimeters Std. Dev.	Centimeters Range Low	Centimeters Range High	Inches Mean	Inches Std. Dev.	Inches Range Low	Inches Range High
1. Breadth of Shoulders, Acromion	28	40.24	1.70	36.20	43.30	15.84	0.67	14.25	17.05
2. Breadth of Shoulders, Across Deltoids	28	47.54	3.79	35.80	52.70	18.72	1.49	14.09	20.75
3. Circumference of Shoulders	28	117.01	4.57	109.22	128.27	46.07	1.80	43.00	50.50
4. Breadth of Chest	28	32.46	2.12	28.70	38.10	12.78	0.83	11.30	15.00
5. Breadth of Chest, Bone	8	29.93	1.72	28.00	33.20	11.78	0.68	11.02	13.07
6. Breadth of Inter Scye	28	36.13	1.95	31.90	39.80	14.23	0.77	12.58	15.67
7. Breadth of Biacromial	28	40.83	1.80	37.60	44.80	16.07	0.71	14.80	17.64
8. Circumference of Chest at Scye	38	100.87	4.22	95.25	111.76	39.71	1.66	37.50	44.00
9. Circumference of Chest at Nipple	38	96.90	4.15	89.54	104.77	38.15	1.63	35.25	41.25
10. Circumference of Right Vertical Trunk	36	168.80	6.10	158.75	181.61	66.46	2.40	62.50	71.50
11. Depth of Chest	28	24.03	1.64	21.30	27.50	9.46	0.65	8.39	10.83
12. Breadth of Waist	28	30.34	1.65	27.60	33.60	11.94	0.65	10.87	13.23
13. Diameter of Left Vertical Trunk	38	66.17	2.35	62.00	70.50	26.05	0.93	24.41	27.76
14. Diameter of Right Vertical Trunk	38	66.30	2.35	61.40	70.20	26.10	0.92	24.17	27.64
15. Width of Waist, Front	7	32.31	1.21	30.70	34.40	12.72	0.48	12.09	13.54
16. Width of Waist, Back	7	39.04	1.97	37.00	42.00	15.37	0.78	14.57	16.54
17. Depth of Waist	18	21.14	1.72	18.80	25.20	8.32	0.68	7.40	9.92
18. Front Length of Waist	28	38.07	2.17	34.29	42.55	14.99	0.86	13.50	16.75
19. Back Length of Waist	28	46.75	1.74	43.82	50.80	18.41	0.68	17.25	20.00
20. Circumference of Waist	38	82.46	4.74	72.07	92.07	32.46	1.87	28.38	36.25
21. Breadth of Hip	28	34.70	1.77	31.30	38.90	13.66	0.70	12.32	15.32
22. Breadth of Hips, Seated	27	36.46	1.54	34.00	39.90	14.35	0.61	13.39	15.71
23. Circumference of Buttocks	38	96.19	4.31	90.17	109.22	37.87	1.40	35.50	43.00
24. Breadth across Trochanters	22	33.04	1.31	31.30	35.70	13.01	0.52	12.32	14.06
25. Breadth across Iliac Crest	22	28.45	1.29	26.70	31.30	11.20	0.51	10.51	12.32
26. Length of Gluteal Arc	28	28.70	1.49	24.77	31.43	11.30	0.59	9.75	12.38
27. Length of Seat	10	47.75	1.58	46.20	51.00	18.80	0.62	18.19	20.08
28. Length of Crotch	28	70.18	3.60	63.18	76.87	27.63	1.42	24.88	30.25

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

ASTRONAUT (U.S.) POPULATION

d. Dimensions of the Arms and Hands

Measurement	Observations	Centimeters Mean	Centimeters Std. Dev.	Centimeters Range Low	Centimeters Range High	Inches Mean	Inches Std. Dev.	Inches Range Low	Inches Range High
Arms									
1. Length from Acromion to Radiale	18	33.58	1.28	31.40	36.90	13.22	0.50	12.36	14.53
2. Length from Shoulder to Elbow	28	36.82	1.19	34.70	39.90	14.50	0.44	13.66	15.71
3. Length from Shoulder to Elbow Pivot	28	33.53	1.58	30.80	36.83	13.20	0.62	12.13	14.50
4. Length of Forearm to Wrist	11	29.30	1.02	27.60	31.20	11.54	0.40	10.87	12.28
5. Length of Forearm to Grip	23	35.40	1.07	33.30	37.00	13.94	0.42	13.11	14.57
6. Length from Forearm to Hand	28	47.58	2.04	43.50	51.80	18.73	0.80	17.13	20.39
7. Scye Circumference, Right	38	46.37	2.17	42.23	50.80	18.26	0.85	16.63	20.00
8. Scye Circumference, Left	38	45.88	2.13	40.64	50.17	18.06	0.84	16.00	19.75
9. Circumference of Axillary Arm	28	31.86	1.88	27.94	35.56	12.54	0.74	11.00	14.00
10. Circumference of Upper Arm, Relaxed	17	30.49	1.82	26.50	32.60	12.00	0.72	10.43	12.83
11. Circumference of Biceps, Flexed	28	33.66	1.99	29.21	38.10	13.25	0.78	11.50	15.00
12. Breadth of Elbow	10	9.10	1.45	7.00	10.50	3.58	0.57	2.76	4.13
13. Circumference of Elbow, Relaxed	9	28.21	1.37	26.30	30.40	11.10	0.54	10.35	11.97
14. Circumference of Elbow, Flexed	28	32.21	1.87	29.21	37.15	12.68	0.74	11.50	14.63
15. Circumference of Forearm, Relaxed	23	28.11	1.00	26.50	30.00	11.07	0.39	10.43	11.81
16. Circumference of Forearm, Flexed	28	29.35	1.61	26.67	33.65	11.56	0.63	10.50	13.25
17. Breadth of Wrist	28	5.95	0.22	5.60	6.60	2.34	0.09	2.20	2.60
18. Length from Elbow Pivot to Wrist	28	27.29	1.10	25.40	29.53	10.75	0.43	10.00	11.63
19. Circumference of Wrist	28	17.54	1.42	15.88	23.50	6.91	0.56	6.25	9.25
20. Sleeve Inseam, Right	27	48.38	2.80	36.20	52.39	19.05	1.10	14.25	20.63
21. Span of Arms	37	180.37	4.55	171.13	188.60	71.01	1.79	67.38	74.25

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

ASTRONAUT (U.S.) POPULATION

d. Dimensions of the Arms and Hands (Cont.)

Measurement	Observations	Centimeters				Inches			
		Mean	Std. Dev.	Range Low	Range High	Mean	Std. Dev.	Range Low	Range High
Hands									
1. Length of Hand	25	18.98	1.28	14.30	21.60	7.47	0.50	5.63	8.50
2. Length from Wrist to Forefinger Tip	31	19.80	1.52	17.15	24.77	7.60	0.60	6.75	9.75
3. Breadth of Hand at Metacarpal	17	8.88	0.37	8.10	9.70	3.50	0.15	3.19	3.82
4. Breadth of Hand at Thumb	8	10.49	0.58	9.70	11.40	4.13	0.23	3.82	4.49
5. Circumference of Hand at Metacarpal-phalangeal Joint	33	21.18	2.99	5.90	24.79	8.37	1.18	2.13	9.75

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

ASTRONAUT (U.S.) POPULATION

e. Dimensions of the Legs and Feet

Measurement	Obser-vations	Centimeters Mean	Centimeters Std. Dev.	Centimeters Range Low	Centimeters Range High	Inches Mean	Inches Std. Dev.	Inches Range Low	Inches Range High
Legs									
1. Length from Buttock to Knee	23	60.39	1.51	57.50	63.30	23.78	0.60	22.64	24.92
2. Height of Thigh, Seated	10	15.44	0.91	14.30	17.30	6.08	0.36	5.63	6.81
3. Circumference of Upper Thigh, Standing	28	57.94	4.89	52.39	77.15	22.81	1.93	20.63	30.38
4. Circumference of Mid-Thigh, Standing	28	53.62	2.79	50.14	61.50	21.11	1.10	19.75	24.25
5. Circumference of Lower Thigh, Standing	28	39.49	1.90	36.51	43.82	15.55	0.75	14.38	17.25
6. Circumference of Knee	28	39.52	1.54	37.14	42.86	15.56	0.61	14.63	16.88
7. Circumference of Calf	28	38.52	1.96	34.61	41.91	15.17	0.77	13.63	16.50
8. Circumference of Ankle	28	22.46	1.10	20.20	25.50	8.84	0.43	7.95	10.04
Feet									
1. Length of Right Foot, Standing	28	24.99	3.19	19.05	30.48	9.84	1.26	7.50	12.00
2. Length of Left Foot, Standing	28	24.95	3.12	19.05	31.75	9.82	1.23	7.50	12.50
3. Length of Foot, No Weight	15	26.43	1.05	24.80	28.50	10.41	0.41	9.76	11.22
4. Length of Instep, Right Foot	28	27.31	3.57	20.32	34.29	10.75	1.40	8.00	13.50
5. Length of Instep, Left Foot	28	26.49	3.03	22.86	31.75	10.43	1.19	9.00	12.50
6. Breadth of Foot, Standing	27	10.29	0.54	9.40	11.50	4.05	0.21	3.70	4.53
7. Breadth of Foot, No Weight	15	9.55	0.63	8.90	11.20	3.76	0.25	3.50	4.41
8. Breadth of Heel	10	6.81	0.26	6.40	7.20	2.68	0.10	2.52	2.83
9. Breadth of Heel, No Weight	15	6.25	0.35	5.50	6.90	2.46	0.14	2.17	2.72
10. Medial Malleolus Height	16	8.84	0.62	8.10	9.70	3.48	0.24	3.19	3.82
11. Lateral Malleolus Height	15	7.06	0.32	6.40	7.60	2.78	0.13	2.52	2.99
12. Circumference of Instep, Right Foot	28	34.28	1.44	31.43	37.46	13.60	0.57	12.38	14.75
13. Circumference of Instep, Left Foot	28	34.27	1.45	31.12	37.46	13.49	0.57	12.25	14.75

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

ASTRONAUT (U.S.) POPULATION

f. Description of Nonstandard Measurements

MEASUREMENT	DESCRIPTION
1. Back Length of Waist	Distance from waist back mark to cervical prominence
2. Circumference of Buttocks	Measured at point of maximum circumference
3. Extended Arm Length	Distance from apex of armpit (equidistant) between anterior and posterior folds) along arms (extended laterally and horizontally) to the tip of forefinger
4. Front Length of Waist	Distance from waist front mark to the bottom of sternal notch
5. Instep Circumference	Circumference of foot measured with poles at apex of heel and dorsum of foot above peak of arch
6. Length of Crotch	Distance measured along the skin from the anterior wiastline through the crotch to the posterior waistline
7. Length of Gluteal Arc	Distance measured along the skin from the top of buttock fold, craniad, to posterior waist point
8. Mid-Shoulder	Point on top of shoulder at 4 inch distance from the dorsal cervical prominence
9. Mid-Shoulder to Top of Head	Vertical distance from the horizontal line at mid-shoulder point to horizontal line at top of head
10. Scye Circumference	Circumference of shoulder measured along a line extending vertically from the apex of the armpit concavity
11. Sleeve Inseam	Distance from apex of armpit to first joint of wrist
12. Vertical Trunk Diameter and Circumferences	Distance of the straight-line projection from mid-shoulder point to apex of crotch and the circumference along this line (following the skin contours)
13. Waist Level	Measured at the level of the iliac crest

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

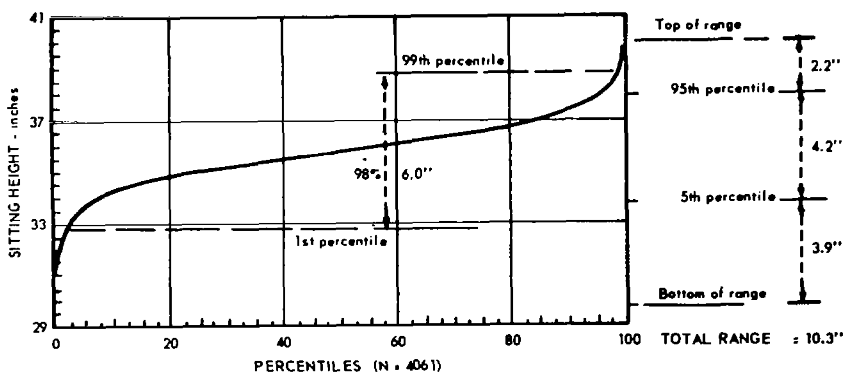
ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

HUMAN DIMENSIONS - PERCENTILES (DEFINITION)

Human dimensions are measured in a standardized manner. Such standardization is critical if data from one population are to be compared with data from a different population. One must know the position of the body, the points on the body surface from which measurements are made, and whether the body is nude or clothed. In choosing design values from tables of anthropometric or biomechanical data, the engineer should select that value which will accommodate the maximum practicable percentage of the potential user population.

a. Use of Percentile Values in Anthropometry



The meaning of percentile. Percentiles comprise the 100 equal parts into which the entire range of values is divided for any given dimension. As an illustration, sitting heights of a large sample of men were measured and the values distributed graphically into the 100 percentiles as shown in the graph above.

The designer should design according to the concept of "design limits" or "range of accommodation". This concept, exemplified in the graph, involves the evaluation of percentile ranges. Note that the variability of the extreme 10% (the largest 5% and the smallest 5% combined) exceeds the variability of the central 90%, and so does the variability of the extreme 2% (largest 1% and smallest 1% combined). By proper analysis of the data on the using population, the designer can efficiently provide precisely the adjustability needed for any desired segment of the population.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Hertzberg and Clauser (84).

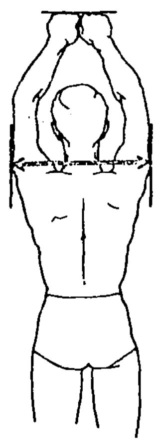
ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

CONTACT MEASUREMENTS: TOTAL BODY ENVELOPE EXPRESSED IN PERCENTILES

For the following measurements, the subject stands with his heels 12 inches apart and his toes 6 inches from the wall. His arms are extended overhead, fists touching together and against the wall, with the first phalanges parallel to the ceiling.

a. Overhead Reach Breadth



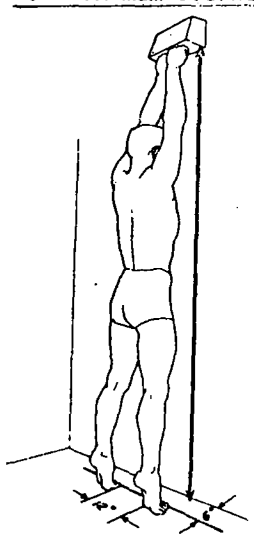
Measure the maximum horizontal distance across the arms or shoulders, whichever is the widest.

Range	Mean	Std. Dev.
13.4-16.6	14.84	0.68

Percentiles

5th	25th	50th	75th	95th
13.6	14.3	14.9	15.2	15.9

b. Maximum Overhead Reach Height



The subject raises himself maximally on his toes. Measure the maximum vertical distance from the floor to the highest point on the first phalanges as indicated by the measuring block.

Range	Mean	Std. Dev.
75.3-94.9	88.17	3.38

Percentiles

5th	25th	50th	75th	95th
83.3	85.6	88.0	90.0	93.6

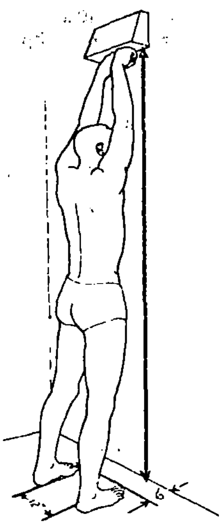
SOURCE: Alexander and Clauser (6).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

CONTACT MEASUREMENTS: TOTAL BODY ENVELOPE EXPRESSED IN PERCENTILES

c. Overhead Reach Height



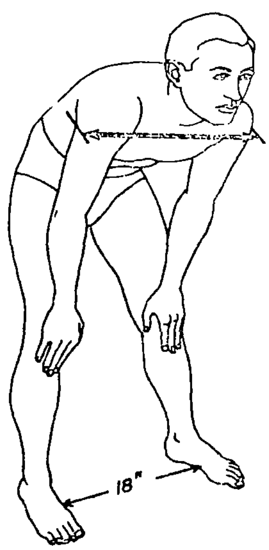
Measure the maximum vertical distance from the floor to the highest point on the first phalanges as indicated by the measuring block.

Range	Mean	Std. Dev.
72.3-91.1	84.31	3.25

Percentiles

5th	25th	50th	75th	95th
78.6	82.0	84.5	85.9	87.6

d. Bent Torso Breadth



The subject stands with his feet 18 inches apart. He bends over and places the palms of his hands on his kneecaps. The elbows and knees are locked. He looks forward, tilting his head as far back as possible. Measure the maximum horizontal distance across the shoulders.

Range	Mean	Std. Dev.
15.8-20.4	17.65	0.88

Percentiles

5th	25th	50th	75th	95th
16.3	17.1	17.5	18.1	19.1

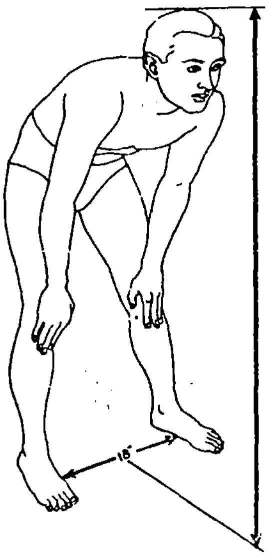
SOURCE: Alexander and Clauser (6).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

CONTACT MEASUREMENTS: TOTAL BODY ENVELOPE EXPRESSED IN PERCENTILES

e. Bent Torso Height



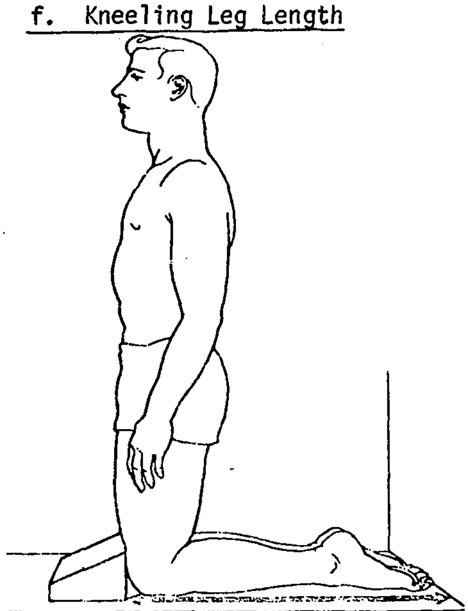
The subject stands with his feet 18 inches apart. He bends over and places the palms of his hands on his kneecaps. The elbows and knees are locked. He looks forward, tilting his head as far back as possible. Measure the vertical distance from the floor to the highest point on the head.

Range	Mean	Std. Dev.
44.1-56.8	51.52	2.76

Percentiles

5th	25th	50th	75th	95th
46.3	49.7	52.0	53.0	55.9

f. Kneeling Leg Length



The subject kneels on the measuring board with his toes extended and lightly touching the rear wall. The torso is erect with the arms hanging loosely at the sides. Measure the horizontal distance from the wall to anterior portion of both knees indicated by the measuring block.

Range	Mean	Std. Dev.
22.4-29.3	26.46	1.32

Percentiles

5th	25th	50th	75th	95th
24.3	25.5	26.5	27.2	28.7

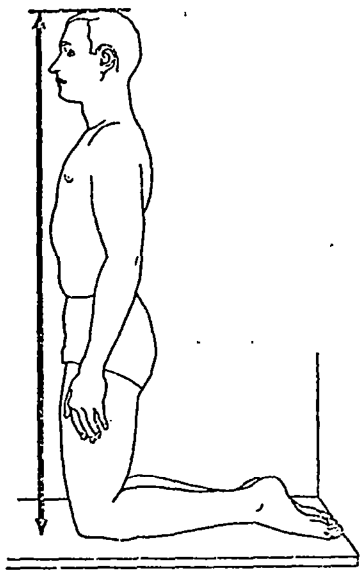
SOURCE: Alexander and Clauser (6).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

CONTACT MEASUREMENTS: TOTAL BODY ENVELOPE EXPRESSED IN PERCENTILES

g. Kneeling Height



The subject kneels on the measuring board with his toes extended and lightly touching the rear wall. The torso is erect with the arms hanging loosely at the sides. The head is in the Frankfort plane. Measure the vertical distance from the measuring board to the highest point on the head.

Range	Mean	Std. Dev.
47.2-54.8	51.33	1.77

Percentiles

5th	25th	50th	75th	95th
48.2	50.2	51.0	52.2	54.4

h. Maximum Squatting Breadth

The subject squats down in a normal fashion with the insteps of his feet 9 inches apart. The arms rest across the thighs in a comfortable position. Measure the maximum horizontal distance across the knees and lower thighs.

Range	Mean	Std. Dev.
17.6-28.2	22.21	2.13

Percentiles

5th	25th	50th	75th	95th
18.8	20.5	22.0	23.3	25.7

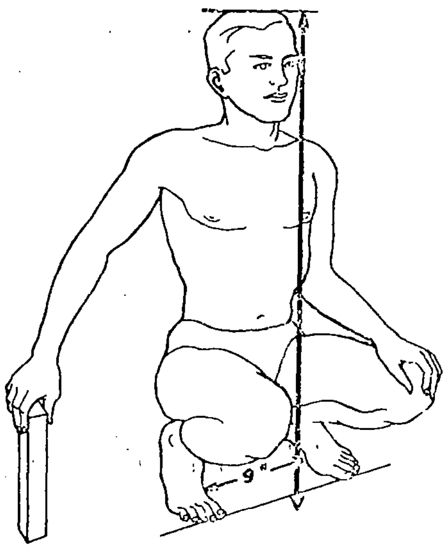
SOURCE: Alexander and Clauser (6).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

CONTACT MEASUREMENTS: TOTAL BODY ENVELOPE EXPRESSED IN PERCENTILES

i. Squatting Height



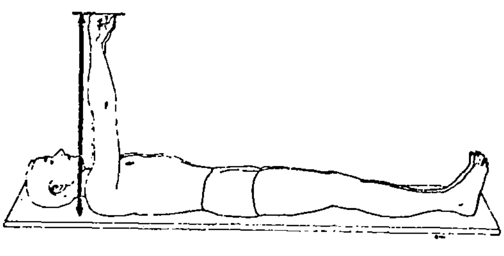
The subject squats down in a normal fashion with the insteps of his feet 9 inches apart. His torso is maintained in an erect position while he supports himself with his right hand. With the head in the Frankfort plane, measure the vertical distance from the floor to the highest point on the head.

Range	Mean	Std. Dev.
40.7-48.2	43.96	1.94

Percentiles

5th	25th	50th	75th	95th
40.8	42.5	43.6	45.4	47.0

j. Arm Reach, Supine



The subject lies supine on the measuring board. The arms are raised toward the ceiling with the shoulders remaining in contact with the measuring board. The fists are touching together with the first phalanges parallel to the ceiling. Measure the vertical distance from the measuring board to the highest point on the first phalanges.

Range	Mean	Std. Dev.
24.8-32.9	29.42	1.48

Percentiles

5th	25th	50th	75th	95th
26.4	28.4	29.2	30.1	32.2

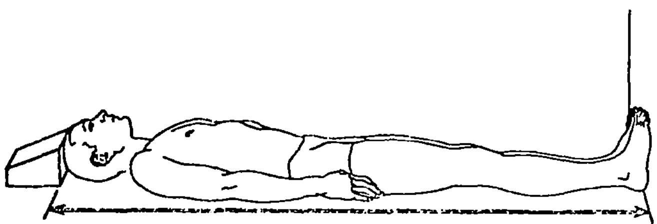
SOURCE: Alexander and Clauser (6).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

CONTACT MEASUREMENTS: TOTAL BODY ENVELOPE EXPRESSED IN PERCENTILES

k. Horizontal Length



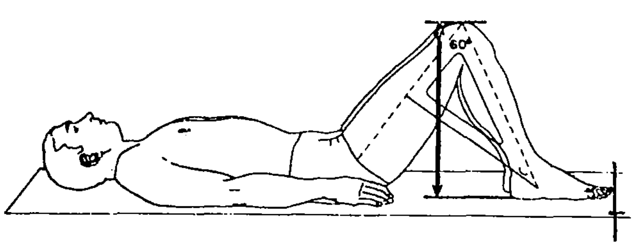
The subject lies supine on the measuring board with his feet flat against the wall. The arms are at the sides. With the head in a relative Frankfort plane, measure the maximum horizontal distance from the wall to the top of the head as indicated by the measuring block.

Range	Mean	Std. Dev.
62.3-74.6	70.01	2.35

Percentiles

5th	25th	50th	75th	95th
66.0	68.4	69.8	71.3	73.9

l. Bent Knee Height, Supine



The subject lies supine on the measuring board. The knees are raised until the angle between the upper and lower legs approximates 60 degrees. The toes are lightly touching the wall. Measure the maximum vertical distance from the measuring board to the highest point on the knees.

Range	Mean	Std. Dev.
17.0-22.0	19.76	0.90

Percentiles

5th	25th	50th	75th	95th
18.2	19.2	19.7	20.3	21.1

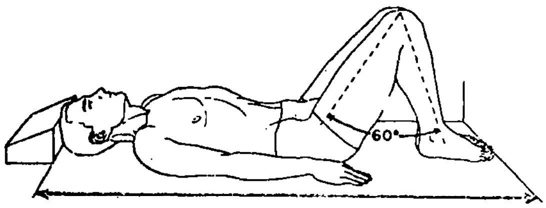
SOURCE: Alexander and Clauser (6).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

CONTACT MEASUREMENTS: TOTAL BODY ENVELOPE EXPRESSED IN PERCENTILES

m. Horizontal Length, Knees Bent



The subject lies supine on the measuring board. The knees are raised until the angle between the upper and lower legs approximates 60 degrees. The toes are lightly touching the wall. With the head in a relative Frankfort plane, measure the maximum horizontal distance from the wall to the top of the head as indicated by the measuring block.

Range	Mean	Std. Dev.
53.1-63.8	58.44	2.11

Percentiles

5th	25th	50th	75th	95th
55.1	57.0	57.7	59.8	62.0

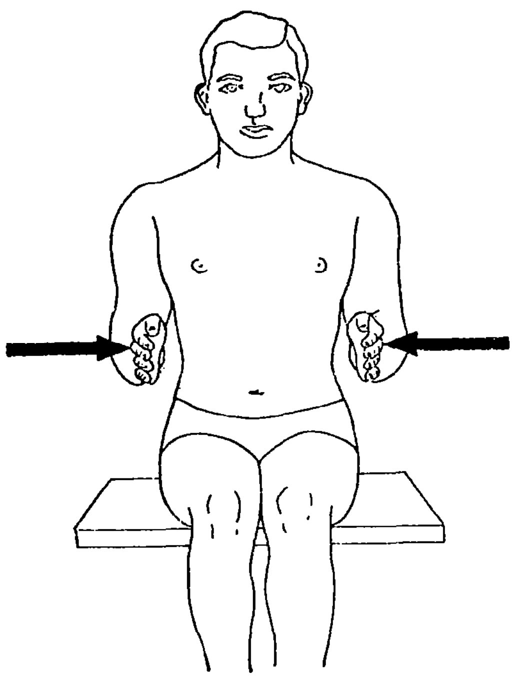
SOURCE: Alexander and Clauser (6).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

PHOTOGRAMMETRIC MEASUREMENTS: SEATED BODY ENVELOPE

a. Hand-to-Hand Breadth, Sitting



The subject sits erect, his upper arms hanging lightly against his body and his forearms extended horizontally with his fingers together and outstretched. Measure the horizontal distance between metacarpal III of the right and left hands.

Range	Mean	Std. Dev.
12.5-22.2	16.91	1.83

Percentiles

5th	25th	50th	75th	95th
13.3	15.7	16.9	18.2	19.6

SOURCE: Alexander and Clauser (6).

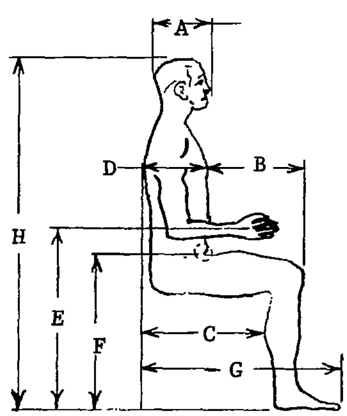
ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

PHOTOGRAMMETRIC MEASUREMENTS: SEATED BODY ENVELOPE

b. Key Body Dimensions

KEY	DIMENSIONS	RANGE	MEAN	STD. DEV.	PERCENTILE 5th	50th	95th
A	Pronasale to Wall Distance (Head in Frankfort Plane)	8.0-10.0	8.92	0.35	8.4	8.9	9.5
B	Torso to Knee Depth, Sitting	10.1-17.8	14.27	1.30	12.1	14.3	16.5
C	Posterior Torso to Posterior Calf Length, Sitting	15.5-22.2	19.06	1.26	17.0	18.9	21.5
D	Maximum Trunk Depth, Sitting	8.7-13.15	10.47	0.93	9.0	10.4	12.0
E	Floor to Upper Thigh Height, Sitting	20.3-26.3	23.41	1.15	21.4	23.4	25.2
F	Floor to Mid-Hand Height, Sitting	25.2-32.1	28.82	1.44	26.4	28.7	31.3
G	Antero-Posterior Body Envelope, Sitting	25.2-35.0	30.59	1.82	27.9	30.6	33.6
H	Floor to Vertex Height, Sitting (Head in Frankfort Plane)	47.2-59.6	53.5	2.11	49.9	53.6	56.9



The subject sits erect with knees bent at right angles.

SOURCE: Alexander and Clauser (6).

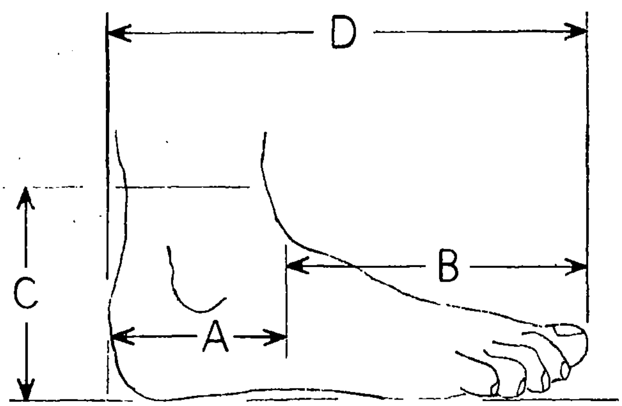
ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

PHOTOGRAMMETRIC MEASUREMENTS: SEATED BODY ENVELOPE

c. Foot Dimensions

KEY	DIMENSIONS	RANGE	MEAN	STD. DEV.	PERCENTILE 5th	50th	95th
A	Posterior Foot Length	1.92-5.28	4.39	0.40	3.84	4.40	4.92
B	Functional Foot Length	5.08-6.96	6.12	0.37	5.48	6.11	6.72
C	Functional Foot Height	2.28-3.54	3.02	0.21	2.72	2.97	3.33
D	Foot Length	7.76-11.71	10.51	0.59	9.51	10.51	11.39



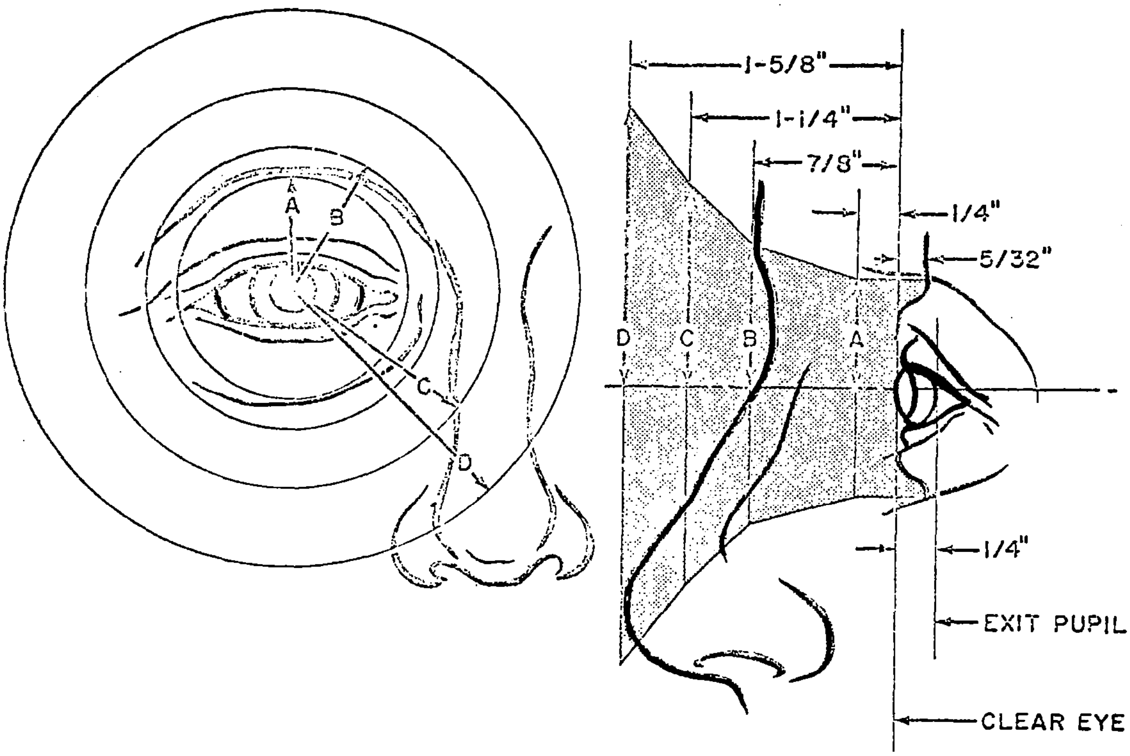
The measurements are made while the subject stands erect with his weight equally distributed on both feet.

SOURCE: Alexander and Clauser (6).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

ANATOMICAL DIMENSIONS OF THE HUMAN EYE



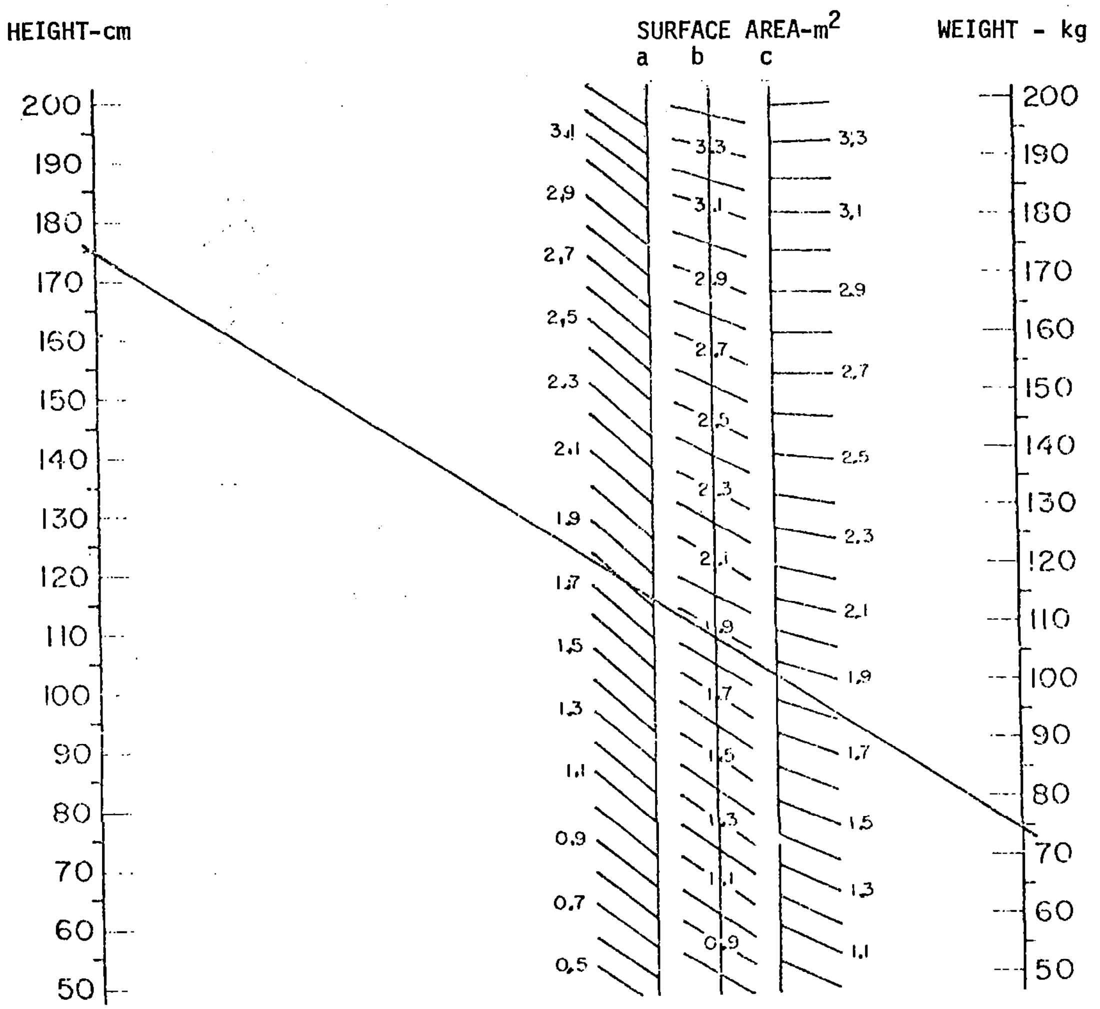
A - Superciliary Arch Requirement	11/16 inch
B - Nasal Bone Requirement	7/8 inch
C - Greater Alar Cartilage Requirement	1-1/4 inches
D - Septal Cartilage Requirement	1-3/4 inches

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and White (204).

ANTHROPOMETRY (Nude)

STATIC DIMENSIONS

NOMOGRAM FOR THE COMPUTATION OF TOTAL SURFACE AREA BASED ON HEIGHT AND WEIGHT



Example: To find the surface area of a U.S. Air Force male of mean height and weight (175.5 cm, 74.4 kg) a straight line is drawn between the two appropriate points on the height and weight scales. The slope of the line most nearly approximates the slope of the b-scale bar. The surface area of such an individual is approximately 1.9 m^2.

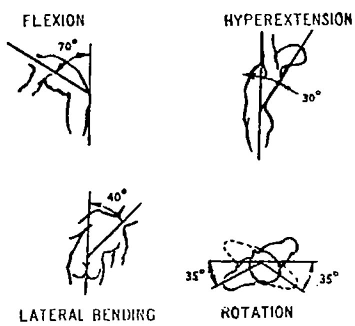
SOURCE: Webb (198).

ANTHROPOMETRY (Nude)

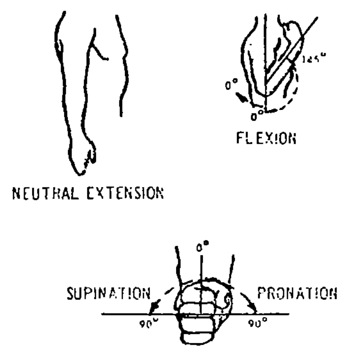
DYNAMIC DIMENSIONS

RANGE OF MOTION VALUES AND TERMINOLOGY

a. Upper Body



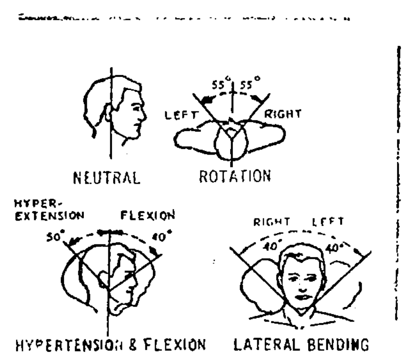
Average normal range of motion of the spine



Average normal range of motion of the elbow

MOVEMENT	AVERAGE RANGE (DEGREES)
SPINE	
Flexion	70
Hyperextension	30
Lateral Bending	40
Rotation	
Left	35
Right	35
ELBOW	
Flexion	145
Supination	90
Pronation	90
NECK	
Rotation	
Left	55
Right	55
Hyperextension	50
Flexion	40
Lateral Bending	
Left	40
Right	40

SOURCE: Batch (19).



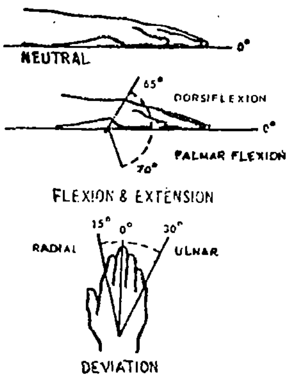
Average normal range of motion of the neck

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

RANGE OF MOTION VALUES AND TERMINOLOGY

a. Upper Body (Cont.)

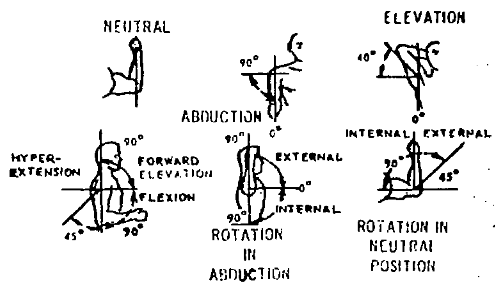


Average normal range of motion of the wrist

Average normal range of motion of the finger

MOVEMENT	AVERAGE RANGE (DEGREES)
SHOULDER	
Abduction	90
Elevation	40
Hyperextension	45
Forward Elevation	90
Flexion	90
Rotation in Abduction	
External	90
Internal	90
Rotation in Neutral Position	
External	45
Internal	90
WRIST	
Dorsiflexion	65
Palmar Flexion	70
Deviation	
Radial	15
Ulnar	30
FINGER	
Abduction	40

SOURCE: Batch (19).



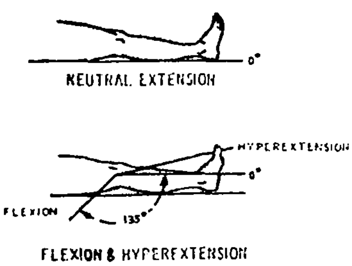
Average normal range of motion of the shoulder

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

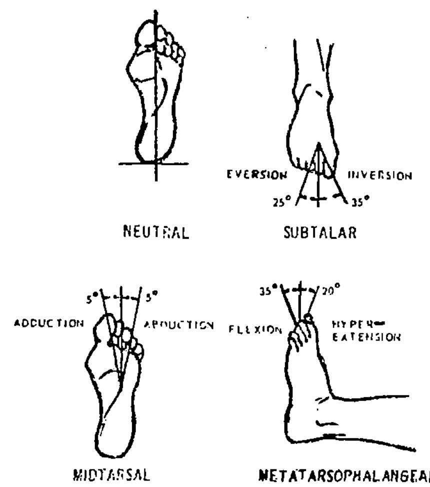
RANGE OF MOTION VALUES AND TERMINOLOGY

b. Lower Body



Average normal range of motion of the knee

Average normal range of motion of the ankle



Average normal range of motion of the foot

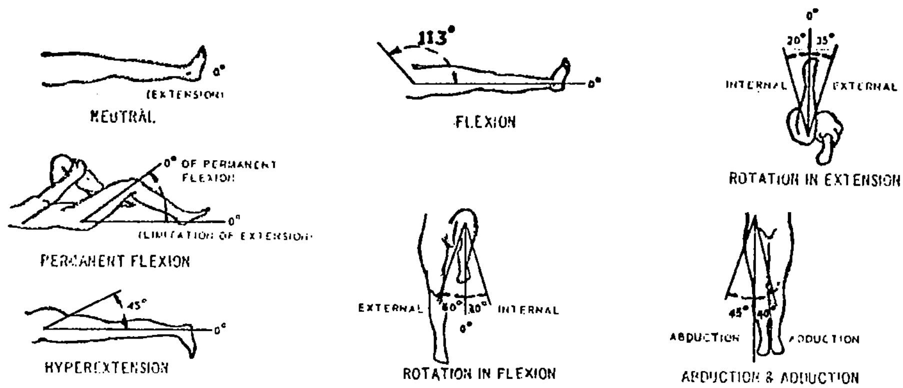
MOVEMENT	AVERAGE RANGE (DEGREES)
KNEE FLEXION	
Standing	113
Kneeling	159
Prone	135
KNEE ROTATION	
Medial	35
Lateral	43
ANKLE	
Plantar Flexion	35
Dorsiflexion	20
Extension	38
Adduction	24
Abduction	23

MOVEMENT	AVERAGE RANGE (DEGREES)
FOOT	
Subtalar	
Eversion	25
Inversion	35
Midtarsal	
Adduction	5
Abduction	5
Metatarso-phalangeal	
Flexion	35
Hyperextension	20

SOURCE: Batch (19).

RANGE OF MOTION VALUES AND TERMINOLOGY

b. Lower Body (Cont.)



Average normal range of motion of the hip

MOVEMENT	AVERAGE RANGE (DEGREES)
HIP	
Rotation in Extension	
Internal	20
External	35
Flexion	113
Adduction	40
Abduction	45
Rotation in Flexion	
Internal	30
External	60
Hyperextension	45
Hip Rotation (Sitting)	
Medial	31
Lateral	30
Hip Rotation (Prone)	
Medial	39
Lateral	34

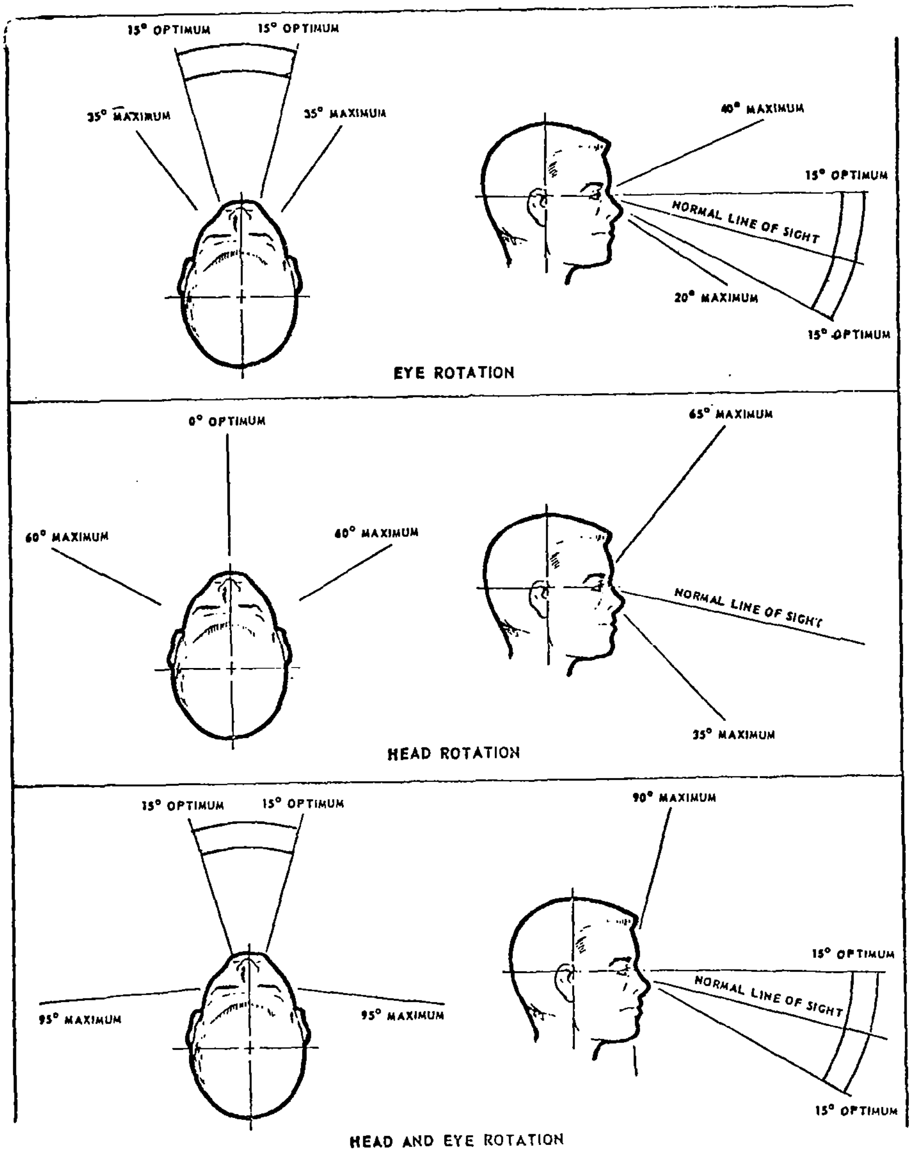
SOURCE: Batch (19).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

VERTICAL AND HORIZONTAL VISUAL FIELD

a. Eye, Head, and Head and Eye Rotation



SOURCE: Anonymous (11).

BINOCULAR VISUAL FIELDS WITH HEAD AND EYE MOVEMENT

a. Binocular Visual Fields

MOVEMENT PERMITTED	TYPE OF FIELD AND FACTORS LIMITING FIELD	HORIZONTAL LIMITS		VERTICAL LIMITS	
		Temporal Ambinocular Field (each side)	Nasal Binocular Field (each side)	Field Angle Up	Field Angle Down
Moderate movements of head and eyes, assumed as:	Range of fixation	60°		45°	
Eyes: 15° right or left; 15° up or down	Eye deviation (assumed)	15°	15°	15°	15°
	Peripheral field from point of fixation	95°	(45°)	46°	67°
Head: 45° right or left; 30° up or down	Net peripheral field from central fixation	110°	60°***	61°	82°
	Head rotation (assumed)	45°	45°	30°*	30°*
	Total peripheral field (from central body line)	155°	105°	91°	112°**
Head fixed; Eyes fixed (central position with respect to head)	Field of peripheral vision (central fixation)	95°	60°	46°	67°
Head fixed; Eyes maximum deviation	Limits of eye deviation (= range of fixation)	74°	55°	48°	66°
	Peripheral field (from point of fixation)	91°	Approx(5°)	18°	16°
	Total peripheral field (from central head line)	165°	60°***	66°	82°
Head maximum movement; Eyes fixed (central with respect to head)	Limits of head motion (= range of fixation)	72°	72°	80°*	90°*
	Peripheral field (from point of fixation)	95°	60°	46°	67°
	Total peripheral field (from central body line)	167°	132°	126°	157°**
Maximum movement of head and eyes	Limits of head motion	72°	72°	80°*	90°*
	Maximum eye deviation	74°	55°	48°	66°
	Range of fixation (from central body line)	146°	127°	128°	156°**
	Peripheral field (from point of fixation)	91°	Approx(5°)	18°	16°
	Total peripheral field (from central body line)	237°	132°	146°	172°**

*Estimated by the authors on the basis of a single subject.

**Ignoring obstruction of body (and knees if seated). This obstruction would probably impose a maximum field of 90° (or less, seated) directly downward; however, this would not apply downward to either side.

***This is the maximum possible peripheral field; rotating the eye in the nasal direction will not extend it, because it is limited by the nose and other facial structures rather than by the optical limits of the eye. The figures in parentheses on the line above are calculated values, chosen to give the maximum limit thus indicated.

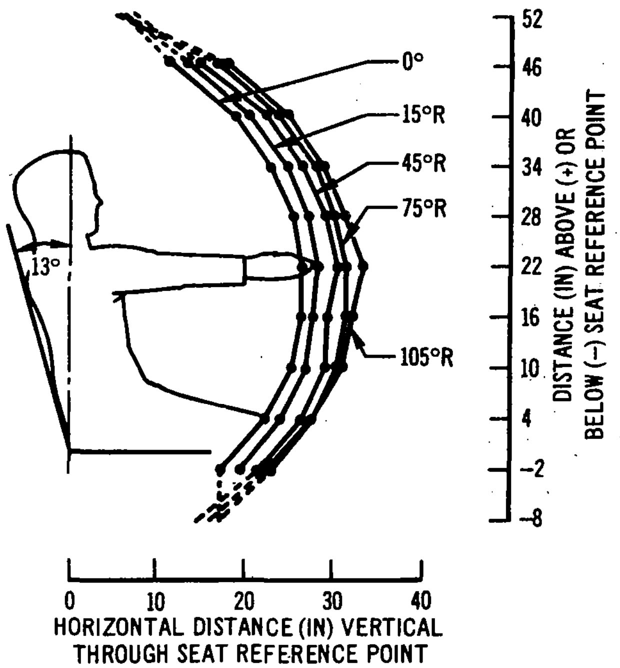
Notes: The ambinocular field is defined here as the total area that can be seen by either eye; it is not limited to the binocular field, which can be seen by both eyes at once. That is, at the sides, it includes monocular regions visible to the right eye but not to the left, and vice versa.

The term binocular is here restricted to the central region that can be seen by both eyes simultaneously (stereoscopic vision). It is bounded by the nasal field-limits of the eyes.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Wulfeck, et al (213).

REACH ENVELOPES

a. Vertical Reach



Maximum distances which can be reached by 97 percent of the population at each position. The elliptical arcs indicate the maximum boundaries of the working area for operation of manual controls (at right angles from 0 degrees to 105 degrees to the right) for this group. Seat back angle 13 degrees.

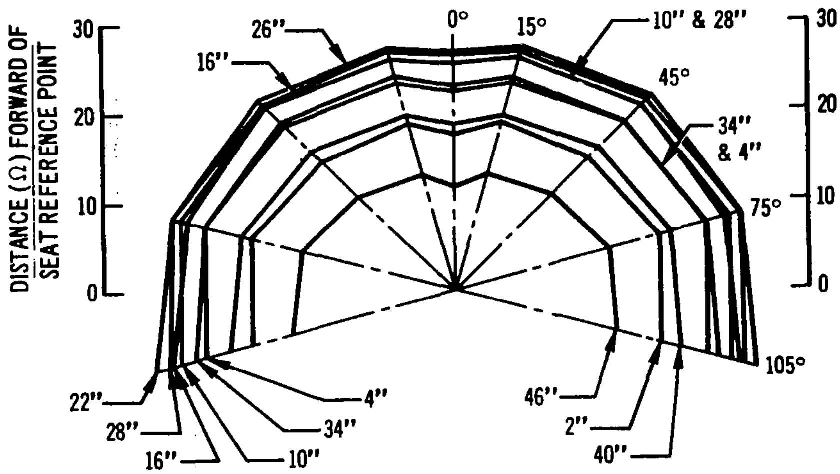
SOURCE: Human Engineering Design Criteria (88).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

REACH ENVELOPES

b. Horizontal Reach



Maximum distances which can be reached by 97 percent of the population at each position. The elliptical arcs indicate maximum boundaries for this group for operation of manual controls at various horizontal levels. Seat back 13 degrees from vertical.

SOURCE: Human Engineering Design Criteria (88).

ANTHROPOMETRY (Nude)

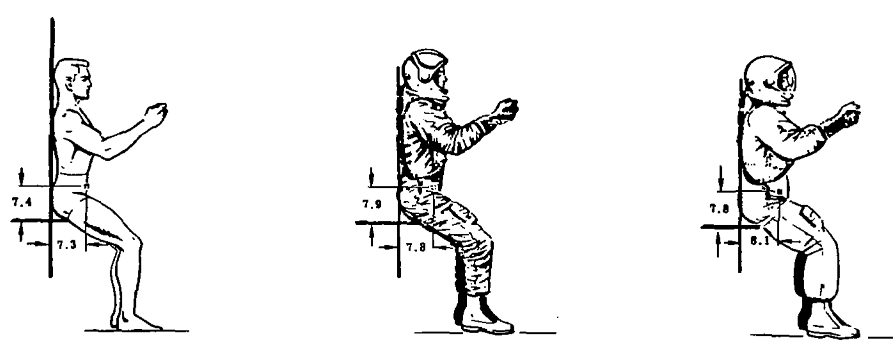
DYNAMIC DIMENSIONS

CENTERS OF GRAVITY AND MOMENTS OF INERTIA

a. Mean Centers of Gravity of Pressure-Suited Subjects

Nude | Unpressurized | Pressurized

1. Sitting



Nude | Unpressurized | Pressurized

2. Relaxed (Weightless)

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and DuBois, et al (58).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

CENTERS OF GRAVITY AND MOMENTS OF INERTIA

b. Arithmetic Means and Standard Deviations of the Sample Centers of Gravity and Moments of Inertia (N = 19)

	AXIS	CENTER OF GRAVITY (IN.)		MOMENT OF INERTIA (LB. IN SEC.^{2})	
		MEAN	S.D.	MEAN	S.D.
1. Sitting					
Nude	x	7.89	0.41	56.3	8.22
	y	4.79	0.27	66.5	9.98
	z	9.16	0.29	28.3	5.10
Unpressurized	x	8.33	0.39	67.5	9.16
	y	4.79	0.27	82.8	11.30
	z	9.76	0.30	33.6	5.72
Pressurized	x	8.62	0.38	68.8	8.70
	y	4.79	0.27	82.4	11.30
	z	9.70	0.28	34.0	5.72
2. Relaxed (Weightless)					
Nude	x	7.34	0.38	99.2	14.20
	y	4.79	0.27	89.8	15.20
	z	7.39	0.42	31.2	5.04
Unpressurized	x	7.81	0.30	118.0	15.30
	y	4.79	0.27	114.0	15.00
	z	7.86	0.45	36.2	5.03
Pressurized	x	8.08	0.29	118.0	15.20
	y	4.79	0.27	114.0	15.70
	z	7.81	0.48	36.1	4.85

Mean Age 27.4 yrs. S.D. Age 5.3 yrs.
Mean Weight 164.6 lbs. S.D. Weight 17.4 lbs.
Mean Stature 69.0 in. S.D. Stature 2.3 in.
Mean Clothing Weight 23.2 lbs. S.D. Clothing Weight 0.5 lb.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and DuBois, et al (58).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

General Considerations of a Mathematical Model for the Prediction of Dynamic Response Characteristics for Weightless Man - Weightless man will undergo transient angular and linear accelerations and decelerations as he is subjected to unbalanced external forces and moments. Internal forces and moments will be generated and reacted throughout the body when he moves his appendages. The mechanical response of the human body will depend upon the biomechanical properties of the body with respect to these special excitations. In order to develop a mathematical model which can be used to predict analytically how the human body will respond, these same biomechanical properties must be incorporated into the model.

The human body is a very complex system of elastic masses whose relative positions change as the appendages are moved. To represent this system in exact analytical terms would require an infinite number of infinitesimal, rigid masses and an infinite number of degrees of freedom. "Degrees of freedom" refers to the minimum number of independent coordinates necessary to completely specify the position of a system in space. As larger and fewer masses are chosen, the representation becomes complex but less accurate.

The problem of developing a mathematical model reduces to a determination of the optimum number and shape of the idealized masses or body segments on which the model's dynamic response characteristics are based. The optimum configuration of the model is determined on the basis of two criteria:

a. Simplicity - a minimum number of components of simple geometrical shape consistent with an accurate representation of the human body.

b. Adaptability - a model which can incorporate the biomechanical properties of any particular individual.

A simple, but reasonably accurate, model is desired to simplify analytical solutions to the related dynamics problems and make it easier to interpret physically the results.

Development of the Model - The most important biomechanical properties which will affect the dynamic response characteristics of man, and hence must be incorporated in the model, are:

a. Total mass and mass distribution

b. Location of the center of mass

c. Moments of inertia

d. Elasticity and damping of the body structure

SOURCE: Whitsett (208).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

Items a and b vary as the body position changes; hence, this variation will also affect the response characteristics. Item d becomes significant only when forces are applied very suddenly such as during an impact, and is not included in this study.

In order to develop the mathematical model, the human body structure is simplified based on the following assumptions:

a. The human body consists of a finite number of masses (or segments) and a finite number of degrees of freedom (hinge points)

b. The segments are rigid and homogeneous

c. Each segment is represented by a geometric body which closely approximates the segment's shape, mass and center of mass, length, and average density

The dynamic properties of these rigid, homogeneous, geometric bodies can be exactly determined.

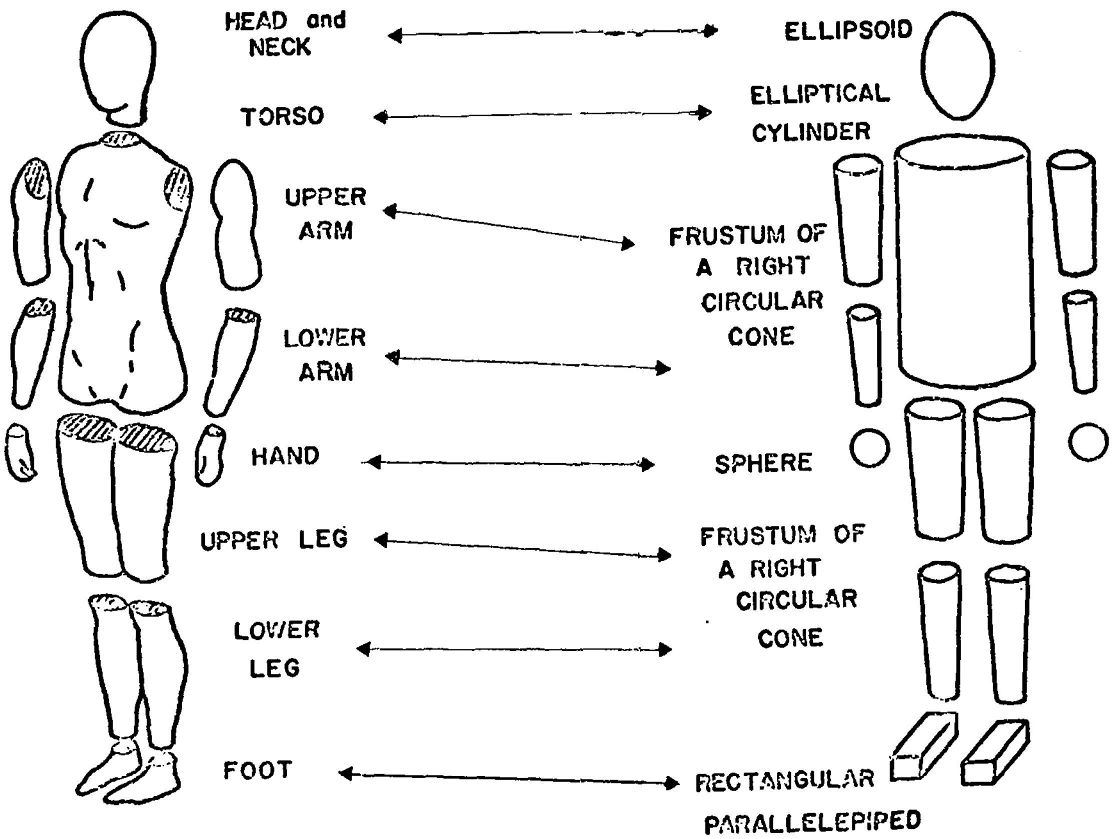
SOURCE: Whitsett (208).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

a. Body Segment Divisions and Representative Geometric Bodies



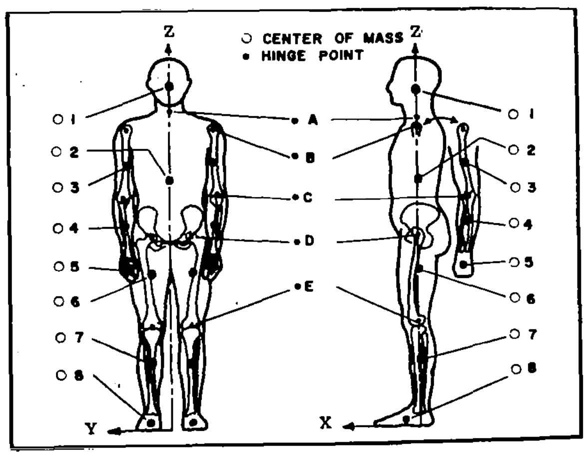
SOURCE: Whitsett (208).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

b. Location of Centers of Mass and Hinge Points of the Human Body



Body Segment Hinge Points

A. Neck - hinged only at the base of the neck (cervical)

B. Shoulder - hinged at the arm-shoulder socket

C. Elbow - hinged at the elbow joint

D. Hip - hinged at the leg-pelvis socket

E. Knee - hinged at the knee joint

The model described has 24 degrees of freedom; six rigid body degrees of freedom plus 18 local degrees of freedom. The six rigid body degrees of freedom refer to the position and orientation of the body axis system. The other 18 degrees of freedom result from the nine hinge points, each with two degrees of freedom. For instance, if a set of spherical coordinates is located at one shoulder hinge point, two angles must be specified to exactly locate the position of the upper arm.

SOURCE: Whitsett (208).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

c. Coordinates of the Segment Hinge Points and Mass Centers of USAF 50th Percentile Man

Hinge Point and Symbol*		Coordinates (Inches) X	Y	Z
Neck	• A	0	0	59.08
Shoulder	• B	0	7.88	56.50
Elbow	• C	0	7.88	43.50
Hip	• D	0	3.30	34.52
Knee	• E	0	3.30	18.72
Mass Center and Symbol*				
Head	○ 1	0	0	64.10
Torso	○ 2	0	0	46.80
Upper Arm	○ 3	0	7.88	50.83
Lower Arm	○ 4	0	7.88	39.20
Hand	○ 5	0	7.88	31.68
Upper Leg	○ 6	0	3.30	27.68
Lower Leg	○ 7	0	3.30	11.80
Foot	○ 8	2.45	3.30	1.37

d. Regression Equations for Computing the Mass (in kg) of Body Segments

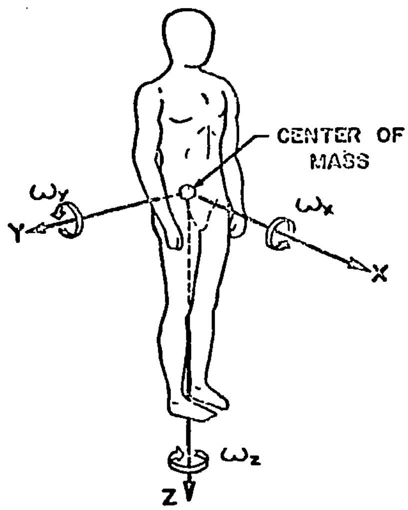
Body Segment	Regression Equation	Standard Deviation of the Residuals
Head, neck and trunk	= 0.47 x Total body wt. + 5.4	(± 2.9)
Total upper extremities	= 0.13 x Total body wt. - 1.4	(± 1.0)
Both Upper arms	= 0.08 x Total body wt. - 1.3	(± 0.5)
Forearms plus hands [a]	= 0.06 x Total body wt. - 0.6	(± 0.5)
Both forearms [a]	= 0.04 x Total body wt. - 0.2	(± 0.5)
Both hands	= 0.01 x Total body wt. + 0.3	(± 0.2)
Total lower extremities	= 0.31 x Total body wt. + 1.2	(± 2.2)
Both upper legs	= 0.18 x Total body wt. + 1.5	(± 1.6)
Both lower legs plus feet	= 0.13 x Total body wt. - 0.2	(± 0.9)
Both lower legs	= 0.11 x Total body wt. - 0.9	(± 0.7)
Both feet	= 0.02 x Total body wt. + 0.7	(± 0.3)

[a] N = 11, all others N = 12.

SOURCE: Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

e. Body Axis System



The body axes system, shown in Figure e, consists of a set of three orthogonal axes whose origin is always at the body center of mass and whose orientation remains fixed with respect to the axis system of the elliptical cylinder, as shown in Figure i. The Z-axis remains parallel to the cylindrical axis, the X-axis perpendicular to the major and cylindrical axes, and the Y-axis perpendicular to the minor and cylindrical axes. The positive directions and rotations are indicated in Figure e.

A local body axis system is defined as a secondary orthogonal axis system located at the center of mass of each segment. Each is oriented in the same direction as the primary body axis system in the normal position defined in c and remains fixed in position and direction with respect to that respective segment.

Biomechanical Properties. In order for the model to represent the dynamic response characteristics of man, certain biomechanical properties must be incorporated into the model. As stated earlier, these properties include mass, center of mass, average density, body dimensions, and moments of inertia. When these properties are used to define the properties of the geometric bodies which make up the model, the model will reflect the dynamic response characteristics of man. Some problems arise when the model is to represent a particular individual, since methods have not been developed for determining all these properties from living subjects. Fortunately, the most important property, body dimensions, can be readily attained. Hence for the model, only body measurement data (lengths of the segments, depths, breadths, and hinge point locations) is taken from the living subject. All other properties are estimated by the most reliable statistical methods available for various weight and body build groups.

SOURCE: Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

The mass of all segments, except the head and torso, is estimated from the regression equations and are summarized in Table f. the head and torso equations are not given in the table, therefore a method of determining the mass of these segments is developed.

a. Head, Hand, and Foot. The motion of the neck is small in comparison to that of the head. Hence, the neck is considered to be rigidly attached to the head. The head-neck combination is then represented by an ellipsoid of revolution. The major axis 2a is equal to the length dimension given in Table g. The minor axis 2b is found from

$$2b = \frac{\text{head circumference}}{\Pi}$$

since the cross-section is circular.

The mass "m" is given by

$$m = \frac{4}{3} \quad \delta \Pi a b^2$$

where δ is the average density of the head(see table h).

b. Torso. The torso takes up approximately 48.5 percent of the total body mass. Consequently, its biochemical properties will have a significant effect on the total body response.

An elliptical cylinder (shown in Figure i) is chosen to represent the torso. The dimensions of the ellipse of the cross-section are given by:

Major axis - Equal to the average of the body breadth measured at the chest, waist, and hips.

Minor axis - Equal to the average of the body depth measured at the chest, waist, and hips.

The center of mass location for the upper and lower arms and legs is given in Table h. For the other segments the center of mass is inherently at one-half the length and on the axis of symmetry.

The average density for all segments is also listed in Table h.

The lengths of the segments (defined as the vertical dimension of each segment as oriented in Figure a are based on the body measurement.

SOURCE: Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

The equations for calculating the mass moments of inertia for all the geometric bodies used in the model are summarized in Table j.

The other basic dimensions required for the moment of inertia equations (such as the diameter, major axis, and minor axis, Figure i) depend upon the particular segment. The determination of the dimensions not discussed as yet is discussed below.

a. Hand. The mass of the hand is very small in comparison to the whole body (about 0.7 percent) and even though its shape varies considerably, the effect of this variation is negligible. Hence, the hand is greatly simplified and represented by a sphere. From

$$m = \frac{4}{} \delta \Pi \left(\frac{d^3}{8}\right)$$

we have

$$\text{diameter } d = 2\left(\frac{3m}{4\,\delta\Pi}\right)^{1/3}$$

The mass of the foot is quite small in comparison to the whole body (about 1.5 percent), hence it too is greatly simplified. The foot is represented by a rectangular parallelepiped whose height and width equals the length dimension in Table h.

b. Limbs. A frustum of a right circular cone is chosen to represent the upper and lower arms and legs because its center of mass can be made to coincide with that of the segment it represents. The equations given in Table j for moments of inertia are independent of all segment dimensions except length.

c. Hinge points. The hinge points are assumed to be on the center line of the segments and are defined in Table b-c.

SOURCE: Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

f. Regression Equations for Computing Mass (in Kg) of Body Segments

BODY SEGMENT	REGRESSION EQUATION
Both Upper Arms	0.08 x Total Body Weight - 1.3
Both Lower Arms	0.04 x Total Body Weight - 0.2
Both Hands	0.01 x Total Body Weight + 0.3
Both Upper Legs	0.18 x Total Body Weight + 1.5
Both Lower Legs	0.11 x Total Body Weight - 0.9
Both Feet	0.02 x Total Body Weight + 0.7

g. Segment Lengths from Anthropometry

SEGMENT	LENGTH
Head	Stature - Cervical Height
Torso	Cervical Height - Penale Height
Upper Arm	Shoulder Height - Elbow Height
Lower Arm	Elbow Height - Wrist Height
Upper Leg	Penale Height - Kneecap Height +1.5 in.
Lower Leg	Kneecap Height - Lateral Malleolus Height -1.5 in.
Foot	Lateral Malleolus Height

Note: All heights are defined in body dimensions and body circumferences. See values below.

h. Biomechanical Properties of the Segments of the Air Force "Mean Man"

SEGMENT	WEIGHT (POUNDS)	DENSITY (POUNDS PER FOOT)	LENGTH (INCHES)	CENTROID LOCATION (% LENGTH)
Head	11.20	71.6	10.04	50.0
Torso	78.90	68.6	24.56	50.0
Upper Arm	5.10	70.0	13.00	43.6
Lower Arm	3.03	70.0	10.00	43.0
Hand	1.16	71.7	3.69	50.0
Upper Leg	16.33	68.6	15.80	43.3
Lower Leg	8.05	68.6	15.99	43.3
Foot	2.39	68.6	2.73	50.0

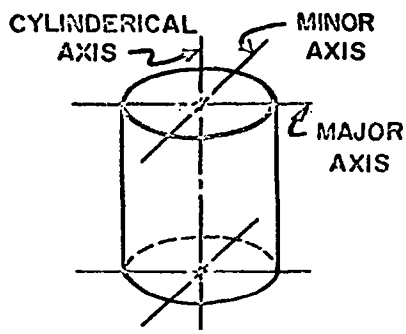
SOURCE: Appendix D (13), Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

i. Elliptical Cylinder Center of Mass Representators



j. Formulae for Calculating Local Moments of Inertia of the Segments

	Moments of Inertia		
Segment	$I_{x_{cg}}$	$I_{y_{cg}}$	$I_{z_{cg}}$
Head	$\frac{1}{5}m(a^2+b^2)$	$I_{x_{cg}}$	$\frac{2}{5}ma^2$
Torso	$\frac{1}{12}m(3a^2+\ell^2)$	$\frac{1}{12}m(3b^2+\ell^2)$	$\frac{1}{4}m(a^2+b^2)$
Upper and Lower Arms and Legs	$m\left[A\left(\frac{m}{\delta\ell}\right)+B\ell^2\right]$	$I_{x_{cg}}$	$2\frac{m^2}{\delta\ell}A$
Hand	$\frac{2}{5}m\left(\frac{d}{2}\right)^2$	$I_{x_{cg}}$	$I_{x_{cg}}$
Foot	$\frac{1}{6}m\ell^2$	$\frac{1}{12}m(c^2+\ell^2)$	$I_{y_{cg}}$

m = mass
a = semi-major axis
b = semi-minor axis
d = diameter

ℓ = length
A and B are constants for segments
c = instep length of foot
δ = average density

SOURCE: Appendix D (13), Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

Formal Computational Approach - The dynamics of a rotating body in space depends primarily upon two factors: the center of mass location of the whole body; and the moments of inertia of the whole body about axes through the body center of mass.

Center of Mass - The variation of the center of mass of the human body has been studied extensively and can be accurately predicted for a given body position without too much difficulty. The center of mass of the model is found to lie 39.09 inches from the floor of 56.6 percent of the body length.

Moments of Inertia - Predicting the moments of inertia is somewhat more involved and likely to be less accurate. Therefore an analysis is made of the mathematical model to determine:

a. Which segments have the greatest effect on the total moment of inertia

b. The effect of approximation errors due to representing the segments by geometrical bodies

c. And which segments can be further simplified without a significant loss in accuracy

The first position (position A, see Figure k) considered is the normal position, standing erect with arms at the sides. For the second position (position B, see Figure k) the arms and legs are drawn up close to the torso to give a near-minimum moment of inertia about the x- and y-axes. The moments of inertia for position B are calculated in much the same way as for position A and presented in 1. It is noted that for this new position, the center of mass moves 7.0 inches towards the head along the z-axis and 1.9 inches forward along the x-axis.

The moment of inertia of the whole body about a given axis is given by the sum of the moments of inertia of all segments about that axis. The moment of inertia of each segment as given by the following equation consists of two parts which are defined as follows:

$$I = I\ cg + md^2$$

Local Term #cg = The moment of inertia of the segment about an axis through its center of mass parallel to the given axis.

Transfer Term md^2 = A quantity given by the product of the mass of the segment times the square of the perpendicular distance between the two parallel axes.

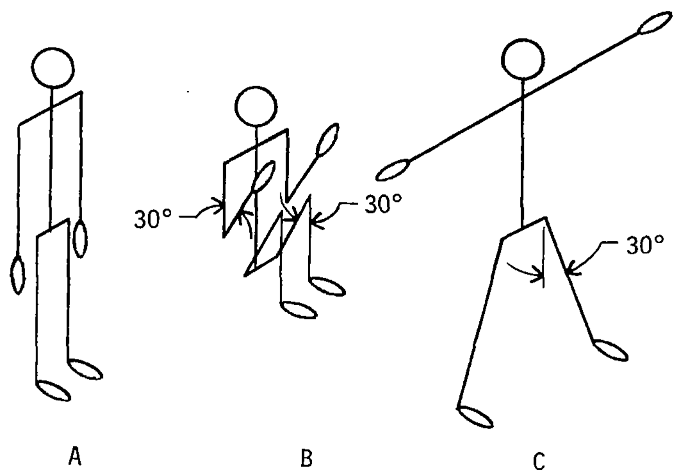
SOURCE: Appendix D (13), Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

k. Body Positions



The first position (position A, see Figure K) considered is the normal position, standing erect with arms at the sides. For the second position (position B, see Figure K) the arms and legs are drawn up close to the torso to give a near-minimum moment of inertia about the x- and y-axes. The moments of inertia for position B are calculated in much the same way as for position A and presented in 1. It is noted that for this new position, the center of mass moves 7.0 inches towards the head along the z-axis and 1.9 inches forward along the x-axis.

SOURCE: Appendix D (13), Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

ANTHROPOMETRY (Nude)

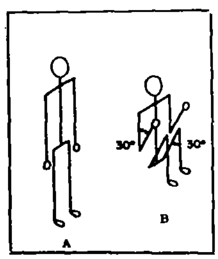
DYNAMIC DIMENSIONS

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

1. Moments of Inertia of the Segments of 50th Percentile USAF Man (Two Positions)

		Segments*								
		Head	Torso	Upper Arms	Lower Arms	Hands	Upper Legs	Lower Legs	Feet	Total
$I_{x_{cg}}$	Position A	0.0183	1.0000	0.0157	0.0056	0.0004	0.0776	0.0372	0.0006	1.2927
	Position B	0.0183	1.0000	0.0157	0.0044	0.0004	0.0620	0.0372	0.0006	1.2589
mD^2	Position A	1.5114	1.0125	0.2199	0.0405	0.0292	0.4964	1.3114	0.7388	8.1963
	Position B	0.7859	0.0092	0.0932	0.0407	0.0303	0.1496	0.0588	0.1252	1.7907
I_x	Position A	1.5297	2.0125	0.2356	0.0461	0.0296	0.5740	1.3486	0.7394	9.4890
	Position B	0.8042	1.0092	0.1089	0.0451	0.0307	0.2116	0.0960	0.1258	3.0496
$I_{y_{cg}}$	Position A	0.0183	0.9300	0.0157	0.0056	0.0004	0.0776	0.0372	0.0028	1.2269
	Position B	0.0183	0.9300	0.0157	0.0056	0.0004	0.0776	0.0372	0.0028	1.2269
mD^2	Position A	1.5114	1.0125	0.1517	0.0000	0.0137	0.4582	1.2925	0.7361	7.8284
	Position B	0.7950	0.0734	0.0292	0.0002	0.0188	0.1190	0.1015	0.1560	1.7176
I_y	Position A	1.5297	1.9425	0.1674	0.0056	0.0141	0.5358	1.3297	0.7380	9.0553
	Position B	0.8133	1.0034	0.0449	0.0058	0.0192	0.1966	0.1387	0.1588	2.9445
$I_{z_{cg}}$	Position A	0.0124	0.2300	0.0018	0.0008	0.0004	0.0154	0.0037	0.0028	0.2922
	Position B	0.0124	0.2300	0.0018	0.0020	0.0004	0.0310	0.0037	0.0028	0.3258
mD^2	Position A	0.0000	0.0001	0.0682	0.0405	0.0155	0.0382	0.0188	0.0085	0.3797
	Position B	0.0091	0.0642	0.0723	0.0405	0.0195	0.0459	0.0804	0.0420	0.6746
I_z	Position A	0.0124	0.2301	0.0700	0.0413	0.0159	0.0536	0.0226	0.0113	0.6719
	Position B	0.0215	0.2942	0.0742	0.0426	0.0199	0.0769	0.0841	0.0448	1.0004

*Positions A and B are shown in figure.
†All values are slug-ft^2.



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

Since the local terms are the most tedious to compute, it is of interest to see what contributions they make toward the total moment of inertia. In Fig. m, a comparison is made between the local and transfer terms for the two positions. Since these quantities are nearly the same about the x- and y-axes, the x-axis is not indicated.

A close look at Figures i, j, k, l and m of Inertia Response Characteristics reveals some important information. In general the local moment of inertia terms can not be neglected, particularly about the z-axis. However, it can be seen that the contribution of the local term for the several segments is zero or negligible. Hence, it can be concluded that it is unnecessary to compute the local moment of inertia for the hands, lower arms, and feet since their sum is less than the errors due to simplifying the human body. It can be further concluded that the geometric representation for the upper arms, upper and lower legs, and head need not be too accurate. For instance, a 33% variation in the moment of inertia of the upper arm would change the total moment of inertia (for position A) about the x-axis only + 0.1%. The total moment of inertia of the torso must be computed with much more care since it may contribute 10% to 35% of the total moment of inertia depending on the axis and position.

Based on the above conclusions, a simplified method is developed for computing the moments of inertia for various body positions. Starting with the moments of inertia for position a computed above as initial conditions(Ix_0, Iy_0, Iz_0) this method yields the moments of inertia for any other position (Ix, Iy, Iz) by taking into account only the changes in the transfer terms and the relative position of the body axis system. This approach greatly simplifies the mathematics, and although it neglects the changes in the local terms, there is only a slight reduction in accuracy.

The moment of inertia of the model (consisting of "p" masses or segments) about the x-axis for position A is given by

$$I_{x_0} = \sum_{i=1}^{p} I_{x_{io_{cg}}} + \sum_{i=1}^{p} m_i \left(y_{io}^2 + z_{io}^2 \right) \qquad (1)$$

When the body position changes, the moment of inertia about the same axis is given by

$$I'_{x_0} = \sum_{i=1}^{p} I_{x_{i_{cg}}} + \sum_{i=1}^{p} m_i \left(y_i^2 + z_i^2 \right) \qquad (2)$$

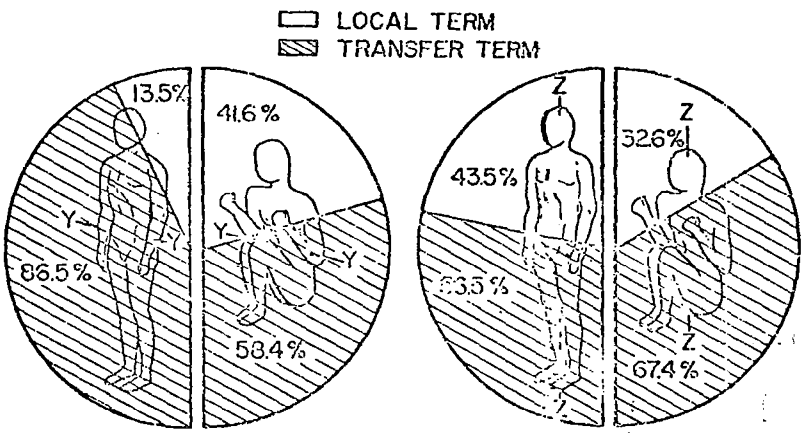
To find the moment of inertia about a parallel axis through the center of mass for this new position, the Parallel Axis Transfer Theorem is used

$$I'_{x_0} = I_x + M\left(\bar{y}^2 + \bar{z}^2\right) \qquad (3)$$

SOURCE: Appendix D (13), Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

m. Comparison of Local to Transfer Moment of Inertia Terms (Expressed as a Percent of the Total Moment of Inertia)



ABOUT THE Y-Y AXIS

ABOUT THE Z-Z AXIS

From Equations 8, 9, and 10 the moments of inertia of the model are computed for positions B and C. These results are compared with exact results taking the local terms into account in m.

n. Comparison of Moments of Inertia from Exact and Approximate Methods

	MOMENTS OF INERTIA (SLUG-FT^2)					
	I_x for Position		I_y for Position		I_z for Position	
	B	C	B	C	B	C
Exact Method	3.0496	12.225	2.9445	8.8430	1.0004	3.6210
Approximate Method	3.0845	12.225	2.9445	8.7917	0.9668	3.5356
Error	+1.14%	0.00%	0.00%	-0.58%	-3.36%	-2.36%

SOURCE: Appendix D (13), Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

now
$$I_x + M(\bar{y}^2 + \bar{z}^2) = \sum_{i=1}^{p} I_{xi_{cg}} + \sum_{i=1}^{p} m_i(y_i^2 + z_i^2) \tag{4}$$

Subtracting Equation 1 from Equation 4

$$I_x + M(\bar{y}^2 + \bar{z}^2) - I_{x_o} = \sum_{i=1}^{p} I_{xi_{cg}} + \sum_{i=1}^{p} m_i(y_i^2 + z_i^2) - \sum_{i=1}^{p} I_{xio_{cg}} - \sum_{i=1}^{p} m_i(y_{io}^2 + z_{io}^2) \tag{5}$$

Assuming the local terms do not change
$$\sum_{i=1}^{p} I_{xi_{cg}} = \sum_{i=1}^{p} I_{xio_{cg}} \tag{6}$$

and Equation 5 becomes

$$I_x = I_{x_o} - \sum_{i=1}^{p} m_i\left\{(y_{io}^2 + z_{io}^2) - (y_i^2 + z_i^2)\right\} - M(\bar{y}^2 + \bar{z}^2) \tag{7}$$

Now if only "n" masses change position, the coordinates of the "p-n" masses will remain the same and will cancel out. Then

$$I_x = I_{x_o} - \sum_{i=1}^{n} m_i\left\{(y_{io}^2 + z_{io}^2) - (y_i^2 + z_i^2)\right\} - M(\bar{y}^2 + \bar{z}^2) \tag{8}$$

In a similar manner the equations for the moments and productions of inertia about the other axes are found to be (Ref. 8).

$$I_y = I_{y_o} - \sum_{i=1}^{n} m_i\left\{(x_{io}^2 + z_{io}^2) - (x_i^2 + z_i^2)\right\} - M(\bar{x}^2 + \bar{z}^2) \tag{9}$$

$$I_z = I_{z_o} - \sum_{i=1}^{n} m_i\left\{(x_{io}^2 + y_{io}^2) - (x_i^2 + y_i^2)\right\} - M(\bar{x}^2 + \bar{y}^2) \tag{10}$$

$$I_{xy} = \sum_{i=1}^{n} m_i\left\{(x_i y_i) - (x_{io} y_{io})\right\} - M(\bar{x}\bar{y}) \tag{11}$$

$$I_{yz} = \sum_{i=1}^{n} m_i\left\{(y_i z_i) - (y_{io} z_{io})\right\} - M(\bar{y}\bar{z}) \tag{12}$$

$$I_{zx} = \sum_{i=1}^{n} m_i\left\{(z_i x_i) - (z_{io} x_{io})\right\} - M(\bar{z}\bar{x}) \tag{13}$$

SOURCE: Appendix D (13), Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

where

$$\bar{x} = \frac{1}{M}\sum_{i=1}^{n} m_i \left(x_i - x_{io}\right) \qquad (14)$$

$$\bar{y} = \frac{1}{M}\sum_{i=1}^{n} m_i \left(y_i - y_{io}\right) \qquad (15)$$

$$\bar{z} = \frac{1}{M}\sum_{i=1}^{n} m_i \left(z_i - z_{io}\right) \qquad (16)$$

$m_i \equiv$ mass of the ith segment

$x_i\, y_i\, z_i \equiv$ coordinates of the center of mass of the ith segment after some change

$x_{io}\, y_{io}\, z_{io} \equiv$ coordinates of the centers of mass of the ith segment before some change

$M \equiv$ total mass

and "n" is the number of segments which change positions from the initial conditions. For instances, if one arm is raised from position A, the center of mass of the upper and lower arm, and hand will change. Three segments are involved so n = 3 and n might refer to the mass of the upper arm, n_2 to the mass of the lower arm, and n_3 to the mass of the hand.

It is pointed out that Equations 14, 15, and 16 are exact and will always yield the coordinates of the new center of mass with respect to the center of mass location for position A.

Up to this point, nothing has been said about products of inertia (Ix_y, Iy_z, Iz_x). It should be realized that while in position A the body axis system coincides with the principal axes of inertia and there are no products of inertia, this will not be true in general. Principal axes of inertia are defined as a set of orthogonal axes about which the products of inertia are zero. In fact, in position B the principal axes are tilted forward (rotated about the 6-axis in the negative direction) approximately 8° from the body axes. Therefore, a product of inertia exists.

SOURCE: Appendix D (13), Barter, et al (18), Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Whitsett (207).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

It should be noted that the approximate method yields exact results for I_x, position C, and I_y, position B. This occurs because there is no change in the local moment of inertia terms $I_{x_{cg}}$ for position C and $I_{y_{cg}}$ for position B.

o. Moments of Inertia of the Different Parts of an Adult Human Body Weighing 65 kg

Part of the body	Mass, kg	Shape assumed for the calculation, and manner in which calculation is done	Moment of inertia, I, cm² kg
Bust (trunk and head), 50% of total wt.	32.5 kg / g	[a] Cylinder of height $h = 0.88$ m, radius $r = 0.13$ m (Axis of reference: axis through base of cylinder and perpendicular to axis of cylinder)	8,600
Upper arm	2.20 kg / g	Treated as truncated cone. Center of gravity, 0.145 m from shoulder; $h = 0.35$ m; $r = 0.047$ m; $r_1 = 0.040$ m	33
Forearm	2.04 kg / g	Treated as truncated cone. Center of gravity 0.54 m from shoulder, $h = 0.35$ m; $r = 0.045$ m; $r_1 = 0.027$ m	37
Fingers		Approximation	V 0.04 IV 0.12 III 0.14 II 0.12 I 0.06
Whole upper limb	4.20 kg / g	Treated as truncated cone. Center of gravity 0.32 m from shoulder; $h = 0.70$ m; $r = 0.047$ m; $r_1 = 0.027$ m	300
Lower leg	4.4 kg / g	[b] Treated as truncated cone. $h = 0.44$; $r = 0.062$; $r_1 = 0.038$	130
Whole limb	12 kg / g	$h = 0.88$; $r = 0.086$, $r_1 = 0.038$	1,460

[a] Formula for moment of inertia of cylinder referred to axis perpendicular to axis of cylinder and through base of cylinder: $I = m(3r^2 + 4h^2)/12$.

[b] The center of gravity in the whole lower limb is 0.38 m from hip joint. The radius of gyration can be found from $I = m\rho^2$, which gives $\rho = 0.34$ m.

SOURCE: Appendix D (13), Barter, et al (18), Compendium of Human Response to the Aerospace Environment, Vol. III (52) and Whitsett (207).

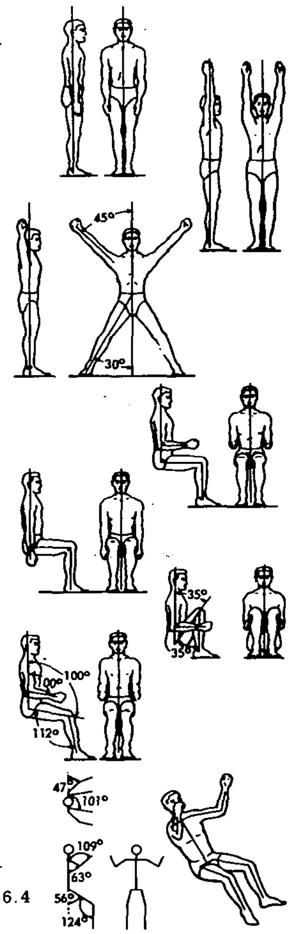
ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

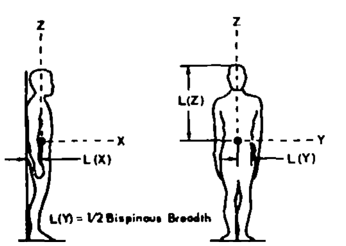
PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

p. Centers of Gravity and Moments of Inertia of USAF Males (Whole Body) in Different Positions

	Axis	Center of Gravity (in.) Mean	Center of Gravity (in.) S. D.	Moment of Inertia ($lb\text{-}in.\text{-}sec^2$) Mean	Moment of Inertia ($lb\text{-}in.\text{-}sec^2$) S. D.
1. Standing	x	3.5	0.20	115.0	19.3
	y	4.8	0.39	103.0	17.9
	z	31.0	1.45	11.3	2.2
2. Standing, arms over head	x	3.5	0.22	152.0	26.1
	y	4.8	0.39	137.0	25.3
	z	28.6	1.33	11.1	1.9
3. Spread eagle	x	3.3	0.19	151.0	27.1
	y	4.8	0.39	114.0	21.3
	z	28.5	1.90	36.6	7.9
4. Sitting	x	7.9	0.36	61.1	10.3
	y	4.8	0.39	66.6	11.6
	z	26.5	1.14	33.5	5.8
5. Sitting, forearms down	x	7.7	0.34	62.4	9.7
	y	4.8	0.39	68.1	12.0
	z	26.8	1.16	33.8	5.9
6. Sitting, thighs elevated	x	7.2	0.37	39.1	6.0
	y	4.8	0.39	38.0	5.8
	z	23.1	0.78	26.3	5.1
7. Mercury configuration	x	7.9	0.34	65.8	10.3
	y	4.8	0.39	75.2	14.0
	z	27.1	1.14	34.2	5.6
8. Relaxed (Weightless)	x	7.3	0.33	92.2	13.3
	y	4.8	0.39	88.2	13.3
	z	27.5	1.44	35.9	5.4



Sample size 66. Mean age 33.2 yrs; S. D. age 7.2 yrs. Mean weight 166.4 lbs; S. D. weight 19.8 lbs. Mean stature 69.4 in; S. D. stature 2.9 in.



The location of the centers of gravity of the body was measured along the Z-axis from the top of the head, L(Z), along the X-axis from the back plane, L(Y), and along the Y-axis from the anterior superior spine of the ilium, L(X). However, since body symmetry with respect to the sagittal plane was assumed, L(Y) is defined as equal to one-half bispinous breadth (distance between anterior-superior iliac spines).

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Hertzberg and Clauser (84).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

q. Whole-Body (Metric Units) - With Correlation Coefficients and Regression Equations Relating Stature and Weight to Moment of Inertia (N = 66)

Position	Axis	Center of Gravity [a] (Cm) Mean	S.D.	Moment of Inertia (Gm $Cm^2 x 10^6$) Mean	S.D.	$R_{1,SW}$	Moment of Inertia Regression Equations[b] (Gm Cm^2 x 10^6) S.E.			
Standing (arms at sides)	X	8.9	0.51	130.0	21.8	.98	4.73	-262.0	+1.68S	+1.28W
	Y	12.2	0.99	116.0	20.6	.96	5.96	-240.0	+1.53S	+1.15W
	Z	78.8	3.68	12.8	2.5	.93	0.95	-0.683	-0.044S	+0.279W
Standing (arms over head)	X	8.9	0.56	172.0	29.5	.98	6.36	-371.0	+2.39S	+1.63W
	Y	12.2	0.99	155.0	28.6	.96	7.79	-376.0	+2.38S	+1.47W
	Z	72.7	3.38	12.6	2.1	.86	0.98	1.6	-0.038S	+0.234W
Spread Eagle	X	8.4	0.48	171.0	30.6	.98	5.54	-399.0	+2.51S	+1.69W
	Y	12.2	0.99	129.0	24.1	.96	7.06	-305.0	+1.91S	+1.29W
	Z	72.4	4.82	41.4	8.9	.93	3.19	-114.0	+0.677S	+0.484W
Sitting (elbows at 90°)	X	20.1	0.91	69.1	10.6	.92	4.53	-104.0	+0.637S	+0.804W
	Y	12.2	0.99	75.4	13.1	.92	5.10	-153.0	+1.01S	+0.669W
	Z	67.3	2.89	37.9	6.6	.97	1.64	-59.6	+0.34S	+0.502W
Sitting (forearms down)	X	19.6	0.86	70.5	11.0	.91	4.50	-89.0	+0.574S	+0.771W
	Y	12.2	0.99	77.0	13.6	.92	5.28	-144.0	+0.913S	+0.802W
	Z	68.1	2.95	38.2	6.7	.97	1.54	-60.8	+0.341S	+0.514W
Sitting (thighs elevated)	X	18.3	0.94	44.2	6.8	.89	3.16	-38.2	+0.242S	+0.529W
	Y	12.2	0.99	43.0	6.6	.77	4.14	-25.1	+0.193S	+0.449W
	Z	58.7	1.98	29.7	5.8	.92	2.26	-34.4	+0.146S	+0.509W
Mercury Position	X	20.1	0.86	74.4	10.6	.93	4.24	-107.0	+0.699S	+0.768W
	Y	12.2	0.99	85.1	15.8	.94	5.61	-198.0	+1.27S	+0.794W
	Z	68.8	2.89	38.7	6.3	.96	1.85	-50.9	+0.297S	+0.492W
Relaxed (weightless)	X	18.5	0.84	104.0	15.0	.96	4.20	-120.0	+0.788S	+1.13W
	Y	12.2	0.99	99.8	15.0	.94	5.13	-157.0	+1.08S	+0.879W
	Z	69.9	3.66	40.6	6.1	.96	1.74	-53.4	+0.346S	+0.440W

[a] Location of CGs are with respect to the back plane, anterior superior spine of the ilium, and top of the head.
[b] S is stature in centimeters; W is weight in kilograms.

It is of interest to see what contribution each segment makes toward the total moment of inertia and what effects the local and transfer terms have on this quantity. This information is presented graphically in Figures a and b.

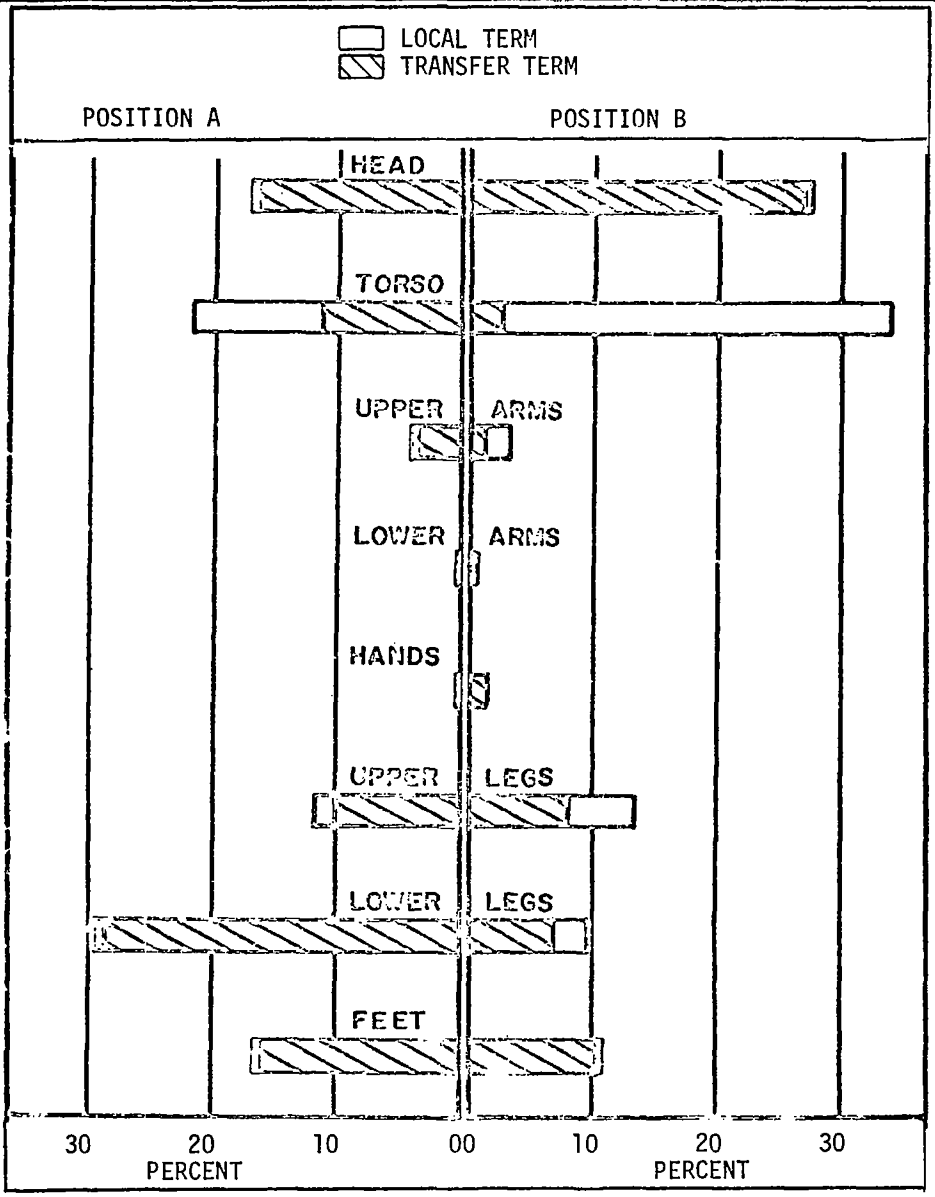
Local Term I_{cg} = The moment of inertia of the segment about an axis through its center of mass parallel to the given axis.

Transfer Term md^2 = A quantity given by the product of the mass of the segment times the square of the perpendicular distance between the two parallel axes.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52), Damon, Stoudt, et al (54A) and Whitsett (207).

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

r. Percent of Total Moment of Inertia About the Y-Y Axis for Each Segment



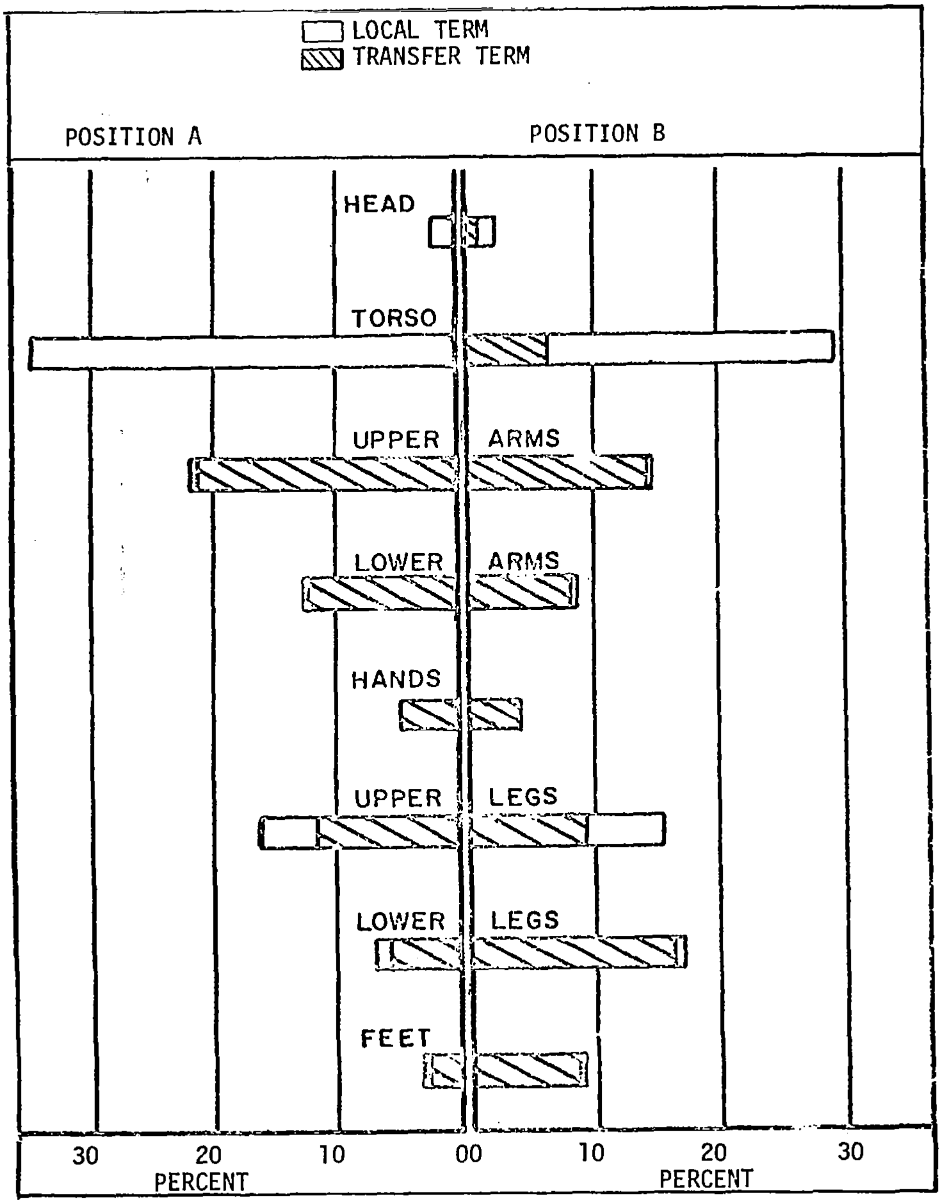
SOURCE: Whitsett (208).

ANTHROPOMETRY (Nude)

DYNAMIC DIMENSIONS

PREDICTION OF DYNAMIC RESPONSE CHARACTERISTICS OF WEIGHTLESS MAN

s. Percent of Total Moment of Inertia About the Z-Z Axis for Each Segment



SOURCE: Whitsett (208).

ANTHROPOMETRY (Pressure Suited)

STATIC DIMENSIONS

NUDE VS PRESSURE SUITED (MC-2)

a. Comparative Dimensions*

Measurement	Nude		Uninflated		Inflated	
	Median	Range	Median	Range	Median	Range
shoulder circumference	48.3	(45.1-50.5)	56.1	(54.7-61.0)	63.0	(60.0-65.0)
chest circumference	39.6	(37.7-42.2)	48.3	(48.0-52.0)	52.5	(50.5-54.2)
waist circumference	34.3	(32.0-38.8)	44.4	(42.0-47.2)	47.3	(45.2-50.0)
upper thigh circumference	25.1	(22.3-26.0)	25.7	(24.5-28.0)	27.0	(25.3-29.0)
lower thigh circumference	17.0	(15.6-18.5)	20.8	(18.2-23.6)	22.1	(21.1-24.5)
calf circumference	14.9	(14.5-17.0)	16.9	(16.2-19.4)	18.3	(16.9-19.9)
ankle circumference	9.2	(8.9-10.5)	12.1	(11.4-13.6)	12.1	(12.0-13.8)
biceps circumference	13.5	(12.7-14.5)	14.8	(14.0-16.3)	16.2	(14.9-17.0)
wrist circumference	7.0	(6.6- 7.2)	8.1	(7.9- 8.4)	9.0	(8.3- 9.2)
vertical trunk circumference	67.4	(64.4-71.5)	66.8	(64.9-70.0)		
knee circumference	15.9	(15.0-17.1)	22.1	(20.0-25.0)	21.8	(20.0-23.4)
vertical trunk circumference	64.2	(63.7-67.5)	66.5	(65.0-69.6)	67.3	(66.0-70.4)
buttock circumference	42.0	(39.1-45.5)	46.7	(45.3-51.0)	49.9	(47.3-51.0)
shoulder breadth	19.2	(18.2-19.6)	20.6	(18.6-22.0)	23.7	(13.8-25.5)
chest breadth	13.0	(10.9-12.9)	13.8	(12.7-15.1)	14.7	(14.4-15.6)
hip breadth	13.7	(12.9-14.4)	15.4	(14.1-16.3)	17.4	(16.2-18.6)
hip depth	10.3	(9.5-12.0)	11.4	(10.8-11.7)	15.0	(15.0)
chest depth	10.2	(9.8-10.7)	13.1	(12.1-13.5)	14.9	(14.2-15.2)
elbow-elbow breadth	19.9	(18.6-22.1)	23.2	(20.7-25.1)	27.7	(25.8-30.1)
knee-knee breadth	8.2	(7.8- 9.3)	12.0	(10.7-13.5)	21.3	(18.6-22.6)
sitting height	35.7	(34.7-37.7)	34.8	(33.7-36.2)	36.8	(35.6-38.5)
eye height	31.2	(29.6-33.0)	30.4	(28.4-31.7)	31.3	(29.4-32.2)
shoulder height	23.5	(22.7-24.9)	23.5	(22.1-24.5)	24.3	(23.4-25.3)
knee height	21.9	(21.3-22.8)	23.3	(22.6-23.9)	24.0	(22.9-24.6)
popliteal height	17.5	(17.2-19.8)	18.1	(17.0-18.4)	18.2	(16.8-18.9)
elbow rest height	7.8	(7.5- 9.1)	8.2	(6.3-10.1)	10.0	(9.5-11.0)
shoulder-elbow length	15.0	(14.2-15.4)	15.4	(14.5-16.1)	15.8	(15.2-16.0)
forearm-hand length	19.2	(18.5-20.0)	19.4	(18.9-20.3)	19.8	(18.6-20.7)
foot length	10.5	(10.3-11.0)	12.6	(11.8-12.7)	12.3	(11.7-12.6)
hand length	7.7	(7.5- 8.5)	7.5	(7.2- 7.7)	7.1	(6.8- 7.5)
palm length	4.5	(4.4- 4.5)	3.5	(3.9- 4.3)	4.0	(3.2- 5.9)
crotch height (standing)	33.3	(31.1-34.8)	32.4	(30.8-33.4)		
thigh clearance	6.5	(5.5- 7.1)	6.4	(6.1- 7.0)	8.1	(7.6- 8.2)

* All measurements were taken on seated subject, except crotch height. All dimensions are given in inches. These measurements were taken on six subjects wearing the MC-2 (X-15 type) full pressure suit.

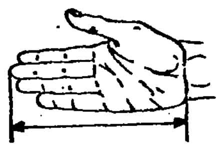
SOURCE: Anthropology Branch (12) and Webb (195).

ANTHROPOMETRY (Pressure Suited)

STATIC DIMENSIONS

GLOVE-HAND CHARACTERISTICS

a. Length - Maximally Stretched Hand



Subject's right hand is extended, palm up. With the bar of the sliding caliper lying along his palm, measure the distance from the wrist crease to the top of the longest finger.

Human Engineering Applications

1. Access of the entire hand into a receptacle.
2. Location of fingertip controls in depth of receptacle.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILES (N=27)

	$\bar{X}$	S.D.	PERCENTILE* 5th	50th	95th
Condition 1	19.38 cm; 7.63 in.	1.16 cm; 0.45 in.	17.73 cm; 6.98 in.	19.26 cm; 7.58 in.	21.27 cm; 8.37 in.
Condition 2	19.84 cm; 7.81 in.	1.22 cm; 0.48 in.	18.29 cm; 7.20 in.	19.84 cm; 7.81 in.	21.72 cm; 8.55 in.
Condition 3	19.70 cm; 7.76 in.	1.39 cm; 0.55 in.	17.42 cm; 6.86 in.	19.54 cm; 7.69 in.	22.03 cm; 8.67 in.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

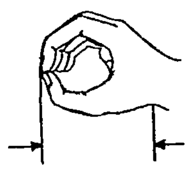
SOURCE: Garrett (70) and Hertzberg, et al (84).

ANTHROPOMETRY (Pressure Suited)

STATIC DIMENSIONS

GLOVE-HAND CHARACTERISTICS

b. Length - Thumb and Forefinger Touching



Subject's right hand is extended, the tips of the thumb and forefinger lightly touching. Holding the bar of the sliding caliper parallel to the long axis of the thumb, measure from the wrist crease to the farthest point of digit 2.

Human Engineering Applications

1. Effective length of the hand for grasping operations.
2. Determination of length of hand support for those controls which require precise positioning.
3. Location of controls within an aperture.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILES (N=27)

	$\bar{X}$	S.D.	PERCENTILE* 5th	50th	95th
Condition 1	11.88 cm; 4.68 in.	1.02 cm; 0.40 in.	10.09 cm; 3.97 in.	11.74 cm; 4.62 in.	13.70 cm; 5.39 in.
Condition 2	13.27 cm; 5.22 in.	1.19 cm; 0.47 in.	11.27 cm; 4.44 in.	13.02 cm; 5.13 in.	15.56 cm; 6.12 in.
Condition 3	13.50 cm; 5.31 in.	1.18 cm; 0.46 in.	11.38 cm; 4.48 in.	13.49 cm; 5.31 in.	15.64 cm; 6.16 in.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

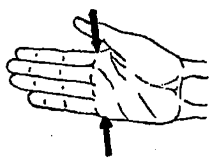
SOURCE: Garrett (70) and Hertzberg, et al (84).

ANTHROPOMETRY (Pressure Suited)

STATIC DIMENSIONS

GLOVE-HAND CHARACTERISTICS

c. Breadth - Metacarpal



Subject's right hand is extended, palm up. With the bar of the sliding caliper lying across the back of his hand, measure the maximum breadth across the distal ends of the metacarpals (knuckles).

Human Engineering Applications

1. Access of the flattened hand through an aperture.

2. Minimum length of handgrips and/or handles.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILE (N=27)

	$\bar{X}$	S.D.	PERCENTILE*			
			V%	5th	50th	95th
Condition 1	8.84 cm; 3.48 in.	0.55 cm; 0.22 in.	6.21	7.97 cm; 3.14 in.	8.81 cm; 3.47 in.	9.69 cm; 3.82 in.
Condition 2	9.59 cm; 3.77 in.	0.60 cm; 0.23 in.	6.21	8.50 cm; 3.35 in.	9.54 cm; 3.76 in.	10.58 cm; 4.16 in.
Condition 3	9.52 cm; 3.75 in.	0.66 cm; 0.26 in.	6.96	8.50 cm; 3.35 in.	9.53 cm; 3.75 in.	10.55 cm; 4.16 in.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

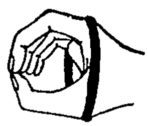
Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

SOURCE: Garrett (70) and Hertzberg, et al (84).

GLOVE-HAND CHARACTERISTICS

d. Circumference - Thumb and Forefinger Touching



Subject's right hand is extended with the tips of the thumb and forefinger lightly touching. With the tape passing over the distal ends of the metacarpals (knuckles) of all five digits, measure the circumference of the hand.

Human Engineering Applications

1. Determination of the dimensions of apertures and workspace areas designed for occupation by a man's hand in the tip position.

2. Location of certain types of controls (toggles, rotary switches, etc.) in depth of receptacle.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILE (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE* 5th	50th	95th
Condition 1	27.36 cm; 10.77 in.	1.77 cm, 0.70 in.	6.48	24.17 cm; 9.51 in.	27.17 cm; 10.70 in.	30.97 cm; 12.19 in.
Condition 2	28.87 cm; 11.37 in.	1.65 cm 0.65 in.	5.71	26.41 cm; 10.40 i .	28.84 cm; 11.35 in.	31.15 cm; 12.26 in.
Condition 3	31.27 cm; 12.31 in.	1.53 cm; 0.60 in.	4.91	28.30 cm; 11.14 in.	31.65 cm; 12.46 in.	33.25 cm; 13.09 in.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

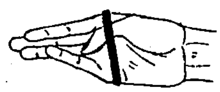
SOURCE: Garrett (70) and Hertzberg, et al (84).

ANTHROPOMETRY (Pressure Suited)

STATIC DIMENSIONS

GLOVE-HAND CHARACTERISTICS

e. Circumference - Metacarpal, Minimum



Subject extends and narrows his right hand as small as possible. With the tape, measure the circumference around the distal ends of the metacarpals (knuckles) of digits 2 and 5.

Human Engineering Applications

1. Determination of minimum dimensions for ingress and egress of the hand into an aperture.

2. The smallest spatial envelope for placement of the hand anywhere.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILE (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE* 5th	50th	95th
Condition 1	23.77 cm; 9.36 in.	2.30 cm; 0.91 in.	9.69	20.06 cm; 7.90 in.	23.82 cm; 9.38 in.	26.87 cm; 10.58 in.
Condition 2	26.19 cm; 10.31 in.	2.62 cm; 1.03 in.	10.00	21.92 cm; 8.63 in.	26.38 cm; 10.38 in.	29.69 cm; 11.69 in.
Condition 3	28.03 cm; 11.04 in.	2.79 cm; 1.10 in.	9.96	23.55 cm; 9.27 in.	28.27 cm; 11.13 in.	31.94 cm; 12.57 in.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

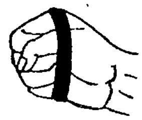
SOURCE: Garrett (70) and Hertzberg, et al (84).

ANTHROPOMETRY (Pressure Suited)

STATIC DIMENSIONS

GLOVE-HAND CHARACTERISTICS

f. Fist Circumference



Subject makes a tight fist with his right hand. With the tape passing over the distal ends of the metacarpals (knuckles) of all five digits, measure the circumference of the fist.

Human Engineering Applications

1. Determination of the minimum dimensions of apertures and workspaces designed to accept a man's hand.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILES (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE*		
				5th	50th	95th
Condition 1	29.02 cm; 11.42 in.	1.99 cm; 0.79 in.	6.87	26.02 cm; 10.25 in.	29.00 cm; 11.42 in.	32.11 cm; 12.64 in.
Condition 2	30.77 cm; 12.11 in.	1.42 cm; 0.56 in.	4.61	28.39 cm; 11.18 in.	30.87 cm; 12.15 in.	32.87 cm; 12.94 in.
Condition 3	31.91 cm; 12.56 in.	1.60 cm; 0.63 in.	5.01	29.44 cm; 11.59 in.	32.06 cm; 12.62 in.	34.09 cm; 13.42 in.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

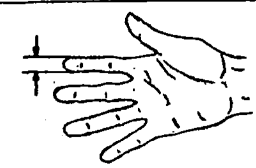
SOURCE: Garrett (70) and Hertzberg, et al (84).

ANTHROPOMETRY (Pressure Suited)

STATIC DIMENSIONS

GLOVE-HAND CHARACTERISTICS

g. Finger Breadth - Digit 2



Subject's right index finger is inserted into a series of graduated holes. Record the diameter of the hole which most closely approximates the maximum breadth of the finger.

Human Engineering Applications

1. Sizing of apertures to permit entry of the index finger.
2. Determination of minimum distance between control buttons.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILES (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE* 5th	50th	95th
Condition 1	2.04 cm; 0.80 in.	0.12 cm; 0.12 in.	5.87	1.91 cm; 0.75 in.	2.07 cm; 0.81 in.	2.25 cm; 0.88 in.
Condition 2	2.37 cm; 0.93 in.	0.11 cm; 0.05 in.	4.84	2.19 cm; 0.86 in.	2.38 cm; 0.94 in.	2.55 cm; 1.00 in.
Condition 3	2.57 cm; 1.01 in.	0.17 cm; 0.07 in.	6.46	2.36 cm; 0.93 in.	2.58 cm; 1.01 in.	2.82 cm; 1.11 in.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

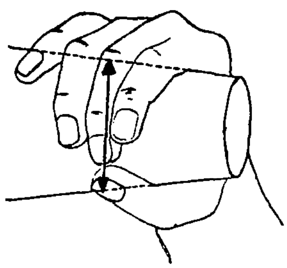
SOURCE: Garrett (70) and Hertzberg, et al (84).

ANTHROPOMETRY (Pressure Suited)

STATIC DIMENSIONS

GLOVE-HAND CHARACTERISTICS

h. Grip Breadth - Inside



Subject holds a cone at the largest circumference that he can grasp with his thumb and middle fingers just touching. Record the diameter of the cone corresponding to this maximum circumference.

Human Engineering Applications

1. Determination of the maximum diameter of rod shaped or cylindrical objects which a man can completely enclose with the fingers of one hand (handles, struts, etc.).

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILES (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE* 5th	50th	95th
Condition 1	4.87 cm; 1.92 in.	0.41 cm; 0.16 in.	8.33	4.32 cm; 1.70 in.	4.86 cm; 1.91 in.	5.55 cm; 2.19 in.
Condition 2	4.37 cm; 1.72 in.	0.40 cm; 0.16 in.	9.12	3.75 cm; 1.48 in.	4.32 cm; 1.70 in.	5.16 cm; 2.03 in.
Condition 3	4.03 cm; 1.59 in.	0.47 cm; 0.19 in.	11.70	3.23 cm; 1.27 in.	4.03 cm; 1.59 in.	4.83 cm; 1.90 in.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

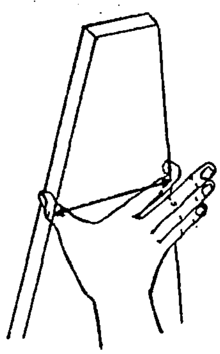
Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

SOURCE: Garrett (70) and Hertzberg, et al (84).

GLOVE-HAND CHARACTERISTICS

i. Hand Spread Across Wedge



Subject places his right hand on the measuring wedge so that the distal joint of his thumb is on the right edge of the wedge and the distal joint of digit 2 is on the left edge of the wedge. Subject slides his hand down the sides of the wedge to the maximal spread while maintaining joint contact on the edges. Reading is taken at the last 1/4 inch line completely cleared.

Human Engineering Applications

1. Determination of the maximum size of wheels to be grasped and/or turned by these two segments of the hand.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILES (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE* 5th	50th	95th
Condition 1	12.42 cm; 4.89 in.	1.41 cm; 0.55 in.	11.34	9.83 cm; 3.87 in.	12.22 cm; 4.81 in.	14.65 cm; 5.77 in.
Condition 2	10.37 cm; 4.08 in.	1.27 cm; 0.50 in.	12.24	8.57 cm; 3.37 in.	10.24 cm; 4.03 in.	12.40 cm; 4.88 in.
Condition 3	8.89 cm; 3.50 in.	1.27 cm; 0.50 in.	14.29	7.01 cm; 2.76 in.	9.00 cm; 3.54 in.	11.28 cm; 4.44 in.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

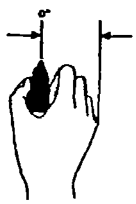
SOURCE: Garrett (70) and Hertzberg, et al (84).

ANTHROPOMETRY (Pressure Suited)

STATIC DIMENSIONS

GLOVE-HAND CHARACTERISTICS

j. Hand Clearance Around Knob



Subject extends his right hand and grasps the knob on the measuring instrument between his thumb and forefinger. The knob indicator points up to zero. Using a vertical wooden block, measure from the knob center to the most protrusive point on the hypothenar surface of the hand.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILES (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE* 5th	50th	95th
Condition 1	6.73 cm; 2.65 in.	1.03 cm; 0.41 in.	15.38	4.36 cm; 1.72 in.	6.76 cm; 2.66 in.	8.62 cm; 3.39 in.
Condition 2	8.26 cm; 3.25 in.	0.83 cm; 0.33 in.	10.03	7.01 cm; 2.76 in.	8.34 cm; 3.28 in.	9.48 cm; 3.73 in.
Condition 3	9.47 cm; 3.73 in.	1.01 cm; 0.40 in.	10.69	7.62 cm; 3.00 in.	9.65 cm; 3.80 in.	10.98 cm; 4.32 in.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

SOURCE: Garrett (70) and Hertzberg, et al (84).

ANTHROPOMETRY (Pressure Suited)

DYNAMIC DIMENSIONS

GLOVE-HAND CHARACTERISTICS

a. Maximum Rotation - Supination

Subject extends his right hand and grasps the knob on the measuring instrument between his thumb and forefinger. Subject then rotates the knob to his right, using only his hand, wrist, and arm, until he achieves maximum supination of his right hand.

Human Engineering Applications

1. Determination of the maximum number of degrees a rotary switch may be turned clockwise with one movement.

2. Determination of the number of discreet motions by the operator to complete a task involving rotary motion, i.e, tightening a bolt or screw.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILES (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE*		
				5th	50th	95th
Condition 1	221.67°	33.03°	14.90	170.82°	223.89°	280.64°
Condition 2	188.52°	35.03°	18.58	137.87°	185.34°	239.07°
Condition 3	120.19°	27.30°	22.63	67.68°	122.53°	151.27°

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

SOURCE: Garrett (70) and Hertzberg, et al (84).

ANTHROPOMETRY (Pressure Suited)

DYNAMIC DIMENSIONS

GLOVE-HAND CHARACTERISTICS

b. Maximum Rotation - Pronation

Subject extends his right hand and grasps the knob on the measuring instrument between his thumb and forefinger. Subject then rotates the knob to his left, using his hand, wrist, and arm, until he achieves maximum pronation of his right hand.

Human Engineering Applications

1. Determination of the maximum number of degrees a rotary switch may be turned counter-clockwise with one movement.

2. Determination of the number of discreet motions by the operator to complete a task involving rotary motion, i.e., tightening a bolt or screw.

ANTHROPOMETRIC DATA EXPRESSED AS PERCENTILES (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE* 5th	50th	95th
Condition 1	157.78°	28.75°	18.22	120.52°	157.10°	195.98°
Condition 2	128.52°	28.18°	21.93	87.38°	127.76°	173.50°
Condition 3	78.33°	20.37°	26.00	52.69°	73.71°	110.43°

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

* The percentile values for a particular set of data are treated as though plotted on normal-probability graph paper, and a smooth curve fitted to the points by conventional curve-fitting procedures.

SOURCE: Garrett (70) and Hertzberg, et al (84).

PSYCHOMOTOR

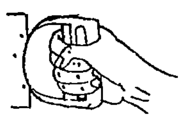
FORCE EMISSION

PSYCHOMOTOR

FORCE EMISSION

UPPER EXTREMITY

a. Grip Strength



Subject grasps the Smedley Hand Dynomometer, fully extends his right arm, and squeezes the instrument. Recording is taken from the instrument

Human Engineering Application

1. Determination of the amount of force loading on double-handled squeeze controls.

2. Limits of a man's hand to hold onto something against a force.

3. Can be used with the coefficient of friction at the grasped surface.

NOTE: The impedance of the pressurized gloves in fitting the hand into the handle of the dynomometer affected performance.

FORCE DATA EXPRESSED AS PERCENTILE (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE 5th	50th	95th
Condition 1	48.11 kg; 105.84 lb.	8.60 kg; 18.91 lb.	17.87	30.50 kg. 67.10 lb.	47.58 kg; 104.68 lb.	58.31 kg; 128.28 lb.
Condition 2	35.89 kg; 78.96 lb.	6.40 kg; 14.08 lb.	17.84	27.85 kg; 61.27 lb.	35.52 kg; 78.14 lb.	48.32 kg; 106.30 lb.
Condition 3	30.22 kg; 66.49 lb.	4.77 kg; 10.50 lb.	15.79	19.05 kg; 41.90 lb.	30.96 kg; 68.10 lb.	36.74 kg; 80.82 lb.

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

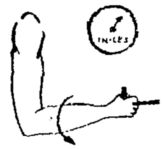
SOURCE: Garrett (70).

PSYCHOMOTOR

FORCE EMISSION

UPPER EXTREMITY

b. Maximum Torque - Supination



Subject grasps the metal handle with the shank between digits 2 and 3. His thumb touches the finger tips. On signal, the subject exerts his maximum effort in turning the handle to his right. Reading is taken from memory device on the torque wrench.

Human Engineering Application

1. Determination of the maximum resistance allowable on a rotary switch.

2. Determination of the maximum torque for bolts, fasteners, etc.

3. Limitation of man's capacity for torque around an axis in or near his forearm.

TORQUE DATA EXPRESSED AS PERCENTILE (N=27)

	$\bar{X}$	S.D.	V%	PERCENTILE (In.-Lb.) 5th	50th	95th
Condition 1	121.48 in.-lb.	30.12 in.-lb.	24.79	83.30	79.85	58.08
Condition 2	119.44 in.-lb.	25.14 in.-lb.	21.05	117.76	121.23	88.75
Condition 3	95.93 in.-lb.	28.96 in.-lb.	30.19	178.95	151.38	142.06

Condition 1: Subject wearing unpressurized suit but barehanded.

Condition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

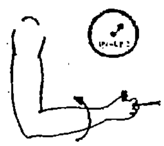
SOURCE: Garrett (70).

PSYCHOMOTOR

FORCE EMISSION

UPPER EXTREMITY

c. Maximum Torque - Pronation



Subject grasps the metal handle with the shank between digits 2 and 3. His thumb touches the finger tips. On signal, subject exerts his maximum effort in turning the handle to his left. Reading is taken from memory device on torque wrench.

Human Engineering Applications

1. Determination of the maximum resistance allowable on a rotary switch.

2. Determination of the maximum torque for hand tightened bolts, fasteners, etc.

3. Limitation of man's capacity for torque around an axis in or near his forearm.

TORQUE DATA EXPRESSED AS PERCENTILE (N=27)

				PERCENTILE (In.-Lb.)		
	$\bar{X}$	S.D.	V%	5th	50th	95th
Condition 1	153.89 in.-lb.	45.02 in.-lb.	29.25	100.44	92.49	79.32
Condition 2	161.48 in.-lb.	47.59 in.-lb.	29.47	151.99	158.75	145.89
Condition 3	151.30 in.-lb.	49.94 in.-lb.	33.01	222.90	252.60	244.88

Condition 1: Subject wearing unpressurized suit but barehanded.

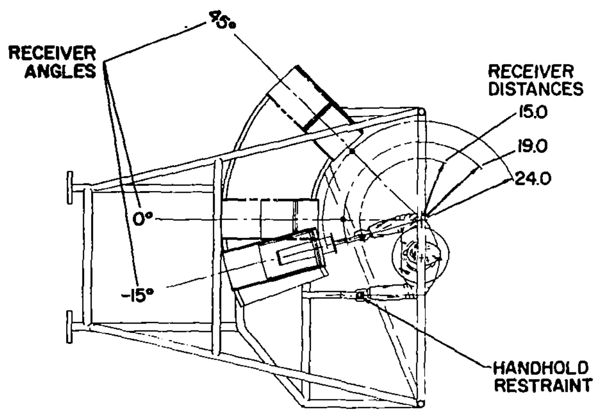
Uondition 2: Subject wearing unpressurized suit and gloves.

Condition 3: Subject wearing suit and gloves pressurized to 3.5 psig.

SOURCE: Garrett (70).

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

Data for the succeeding force emission tables were generated under the following conditions. Restraints wer varied in the number and location of the energy sinks provided to the subject. Accessibility conditions were evaluated by changing the location and orientation of the force receiver apparatus with respect to the subject. The subjects performed all tasks wearing an Apollo state-of-the-art suit pressurized to 3.5 psig.



FORCE TYPE

SUSTAINED = FORCE MAINTAINED FOR 4 SECONDS
IMPULSE = PEAK FORCE OBTAINED IN 1 SECOND

RECEIVER DISTANCES

15" ≃ 90° ELBOW ANGLE
19" ≃ 135° ELBOW ANGLE
24" ≃ 180° ELBOW ANGLE

HANDLE ORIENTATION

LOCAL VERTICAL
LOCAL HORIZONTAL

RANGE – MAX = LARGEST FORCE
MEAN = AVERAGE OF ALL FORCES
RANGE – MIN = SMALLEST FORCE

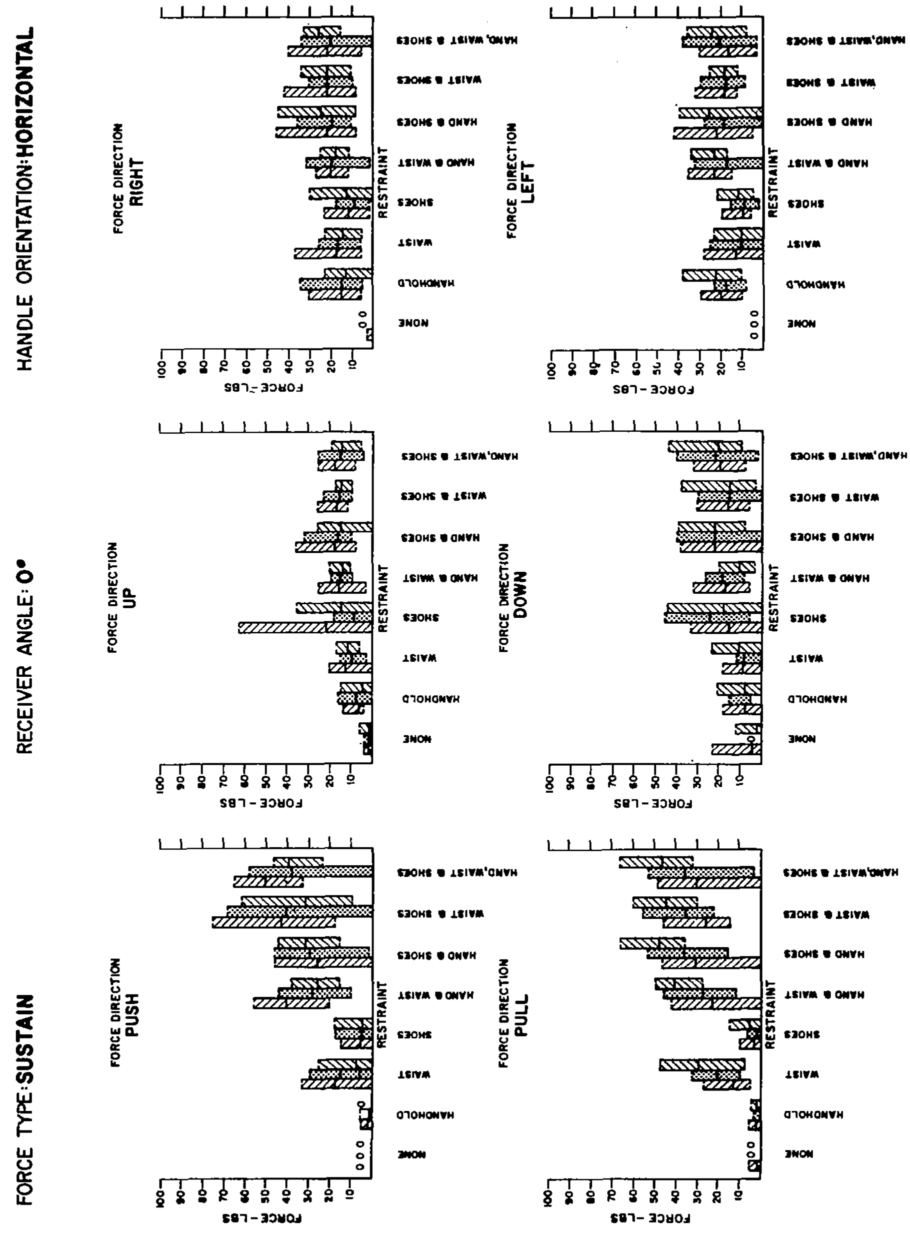
SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

a. Force Type: Sustain, Receiver Angle: 0°, Handle Orientation: Horizontal



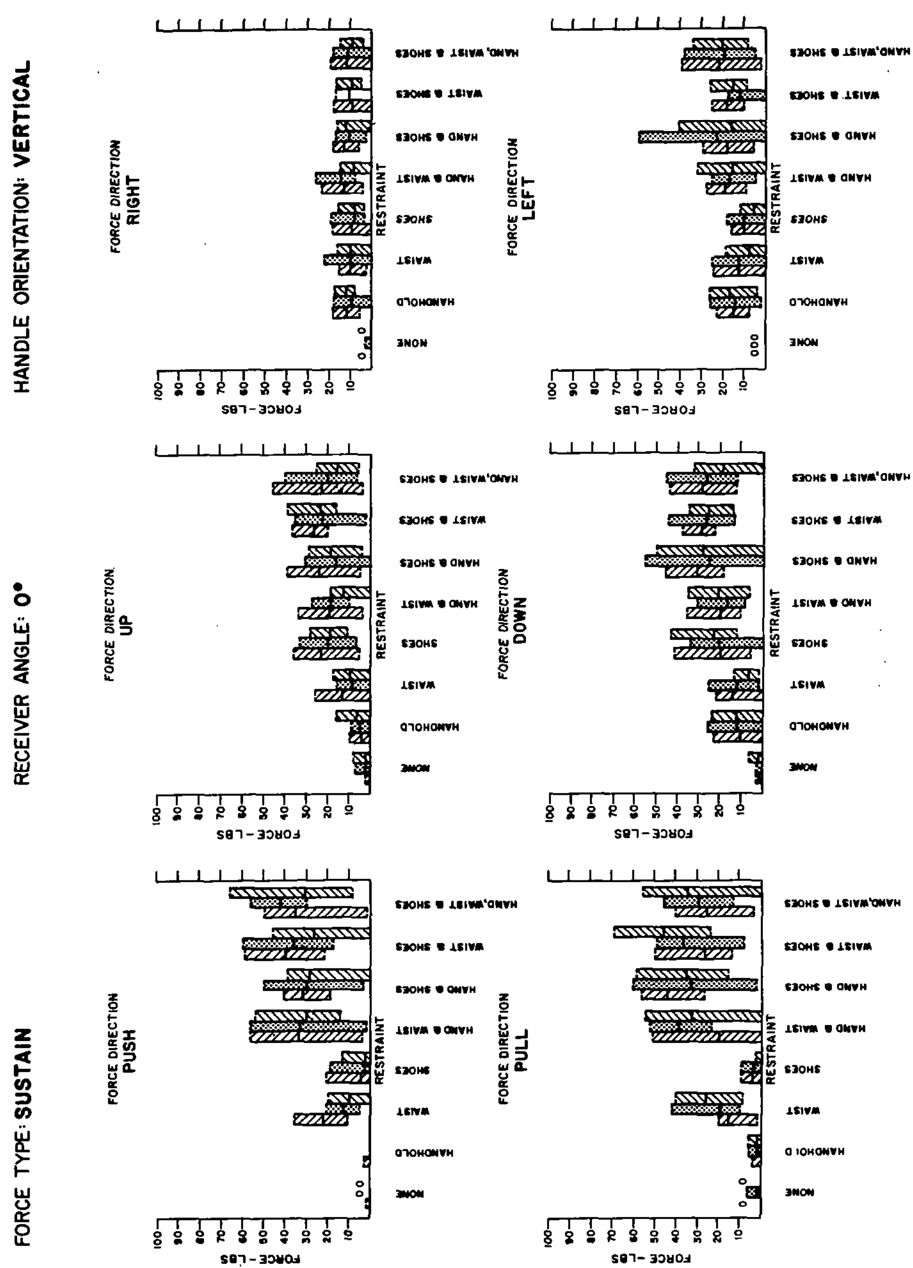
SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

b. Force Type: Sustain, Receiver Angle: 0°, Handle Orientation: Vertical



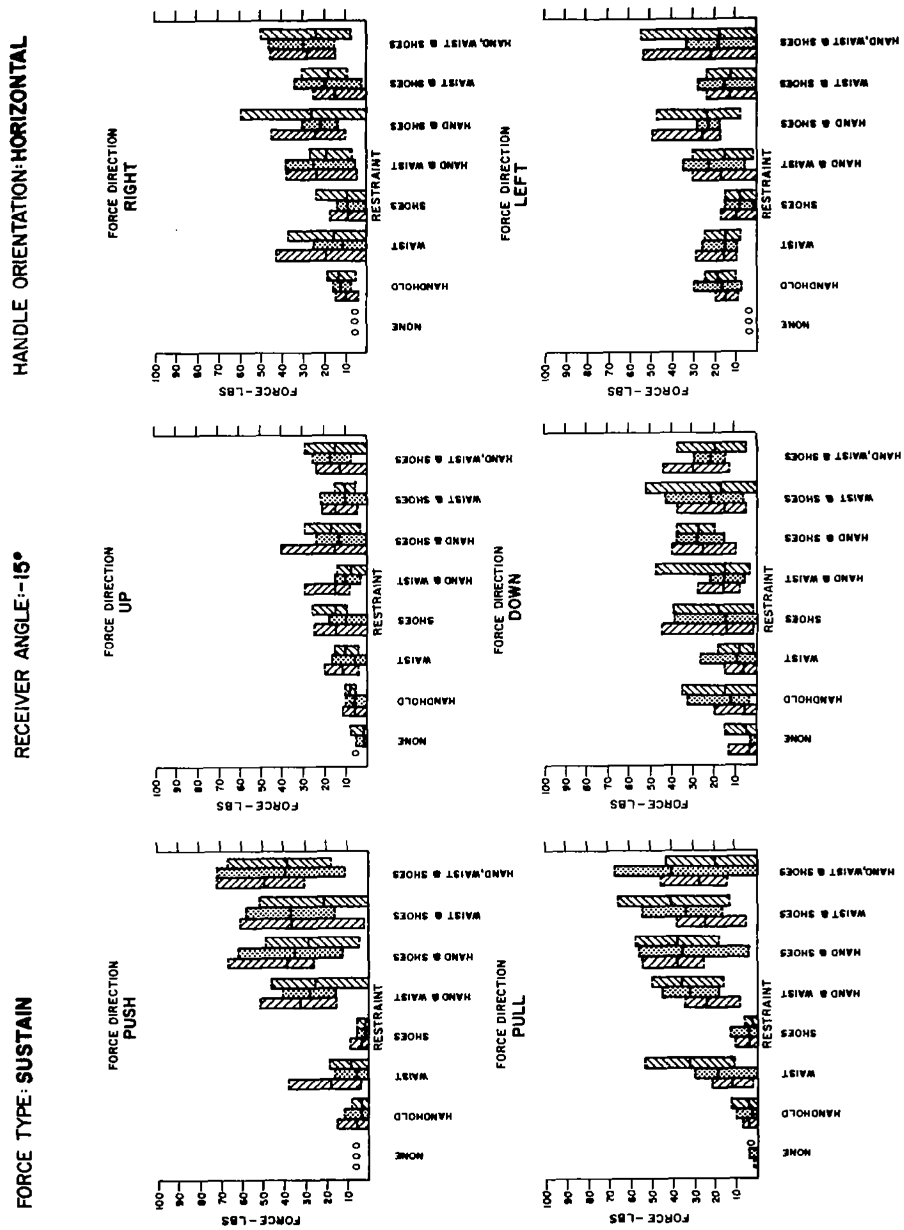
SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

c. Force Type: Sustain, Receiver Angle: -15°, Handle Orientation: Horizontal



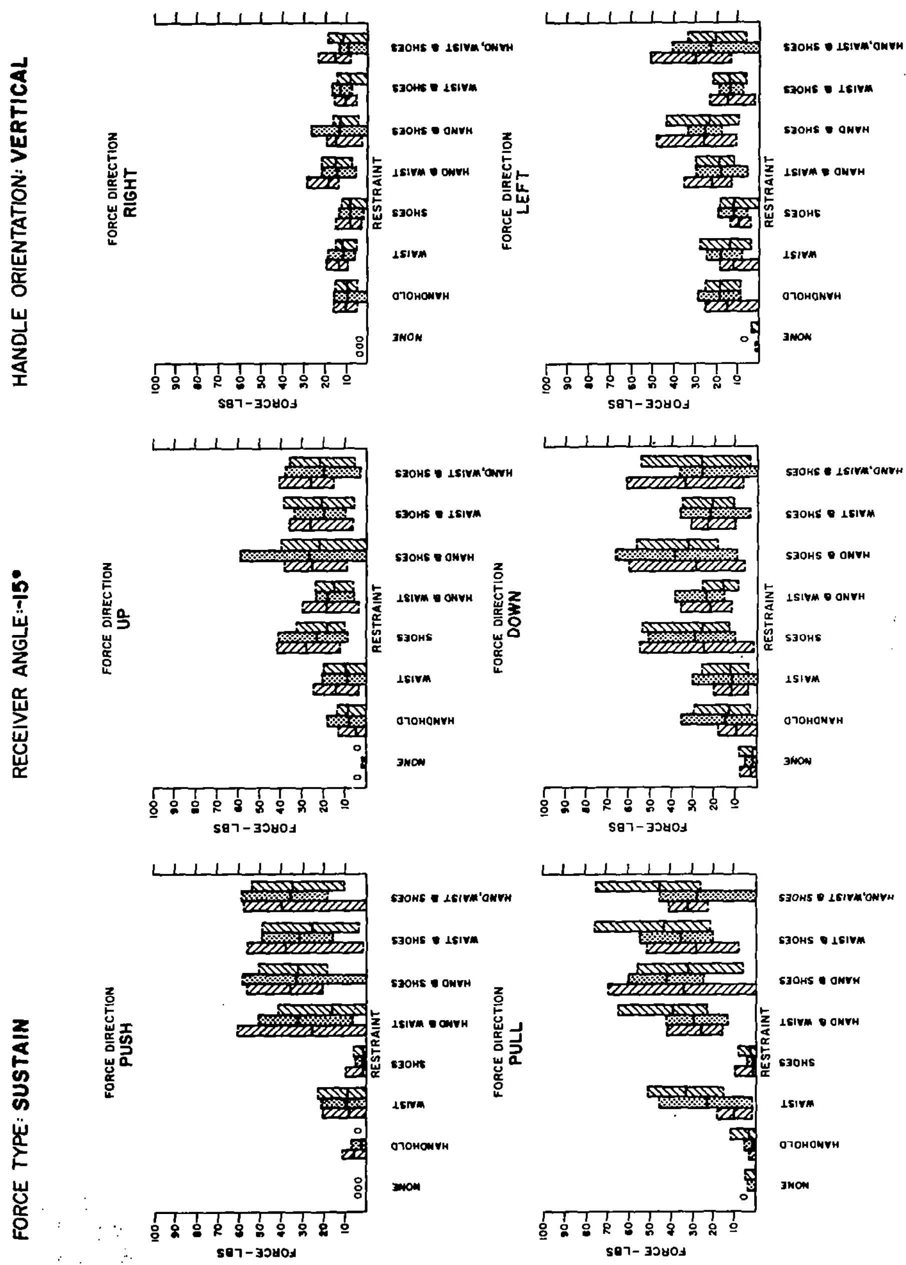
SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

d. Force Type: Sustain, Receiver Angle: -15°, Handle Orientation: Vertical



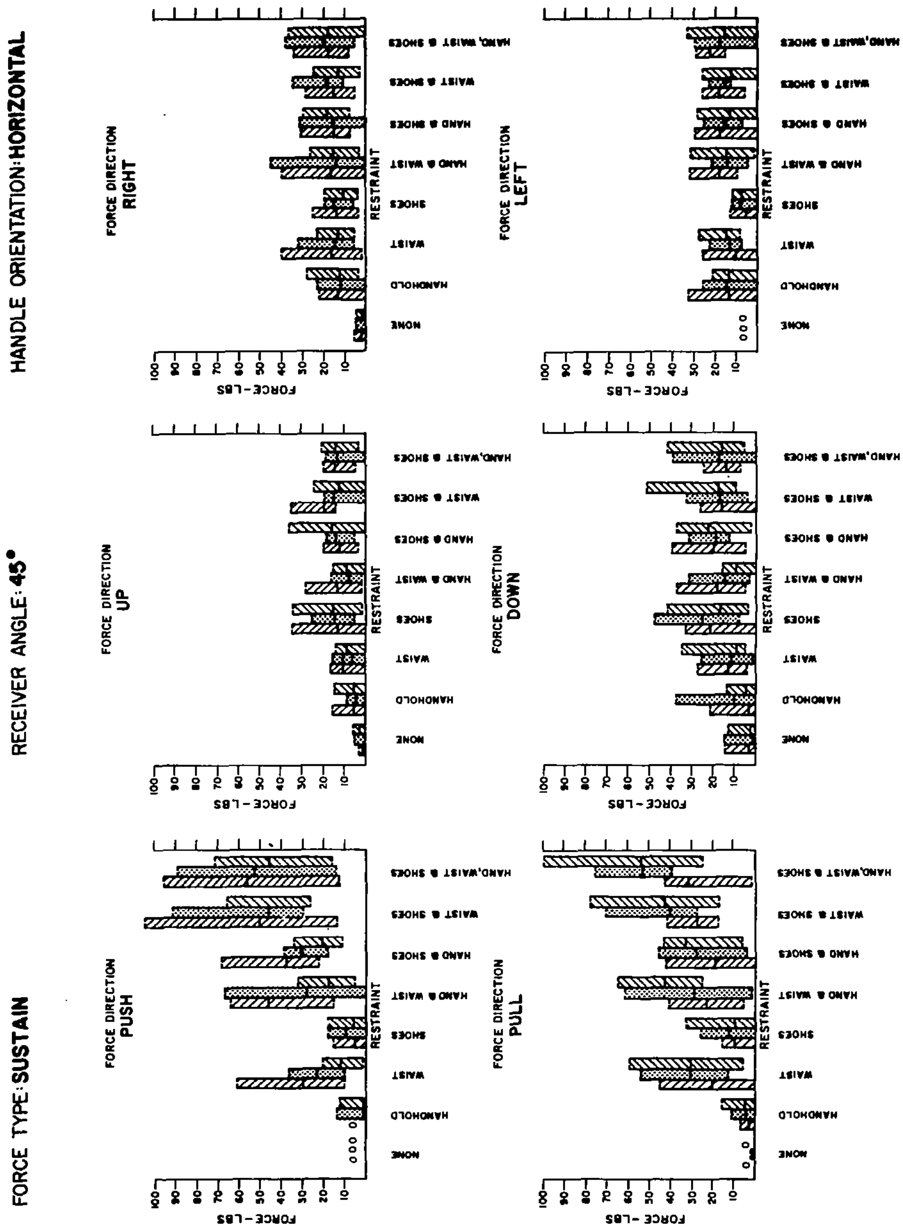
SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

e. Force Type: Sustain, Receiver Angle: 45°, Handle Orientation: Horizontal



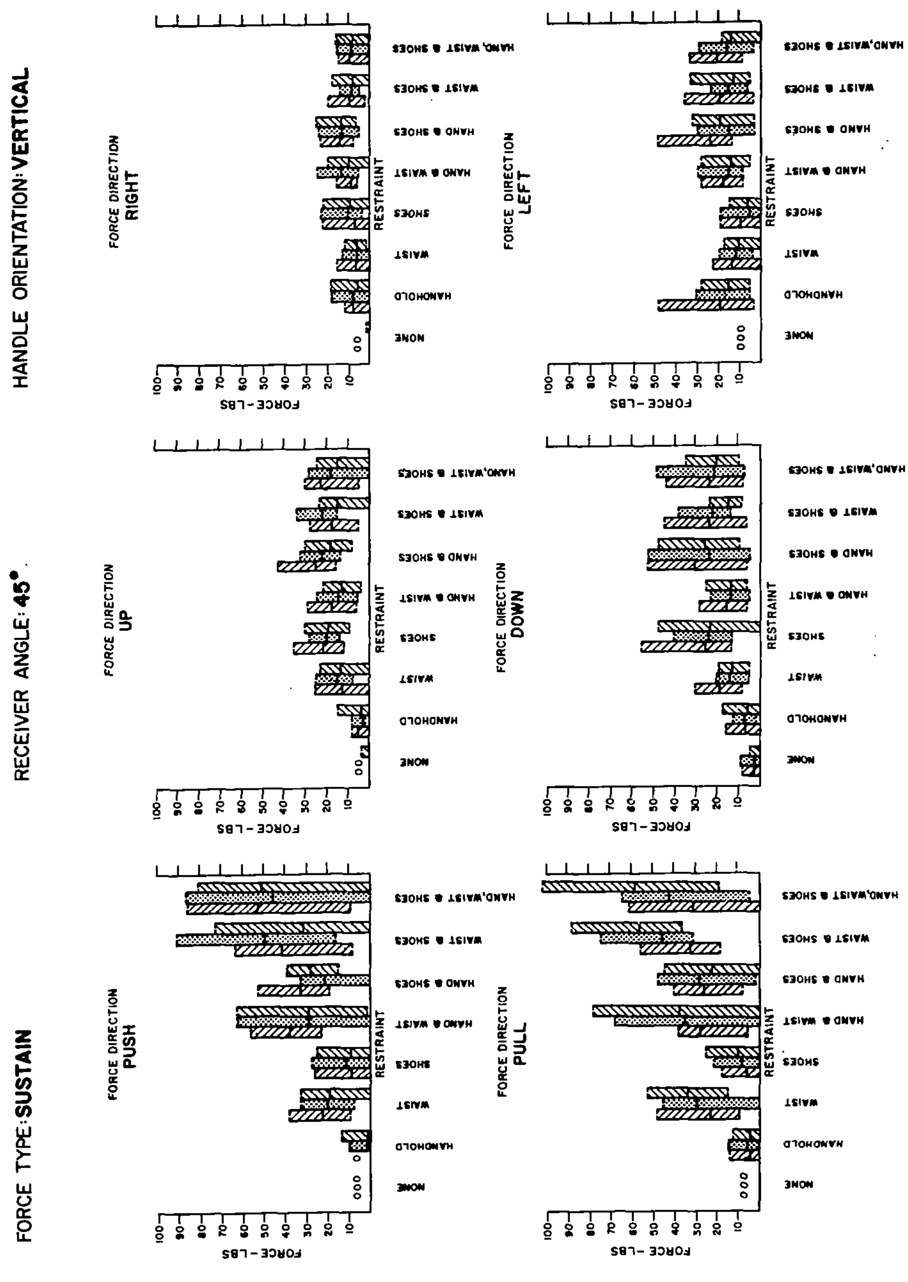
SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

f. Force Type: Sustain, Receiver Angle: 45°, Handle Orientation: Vertical



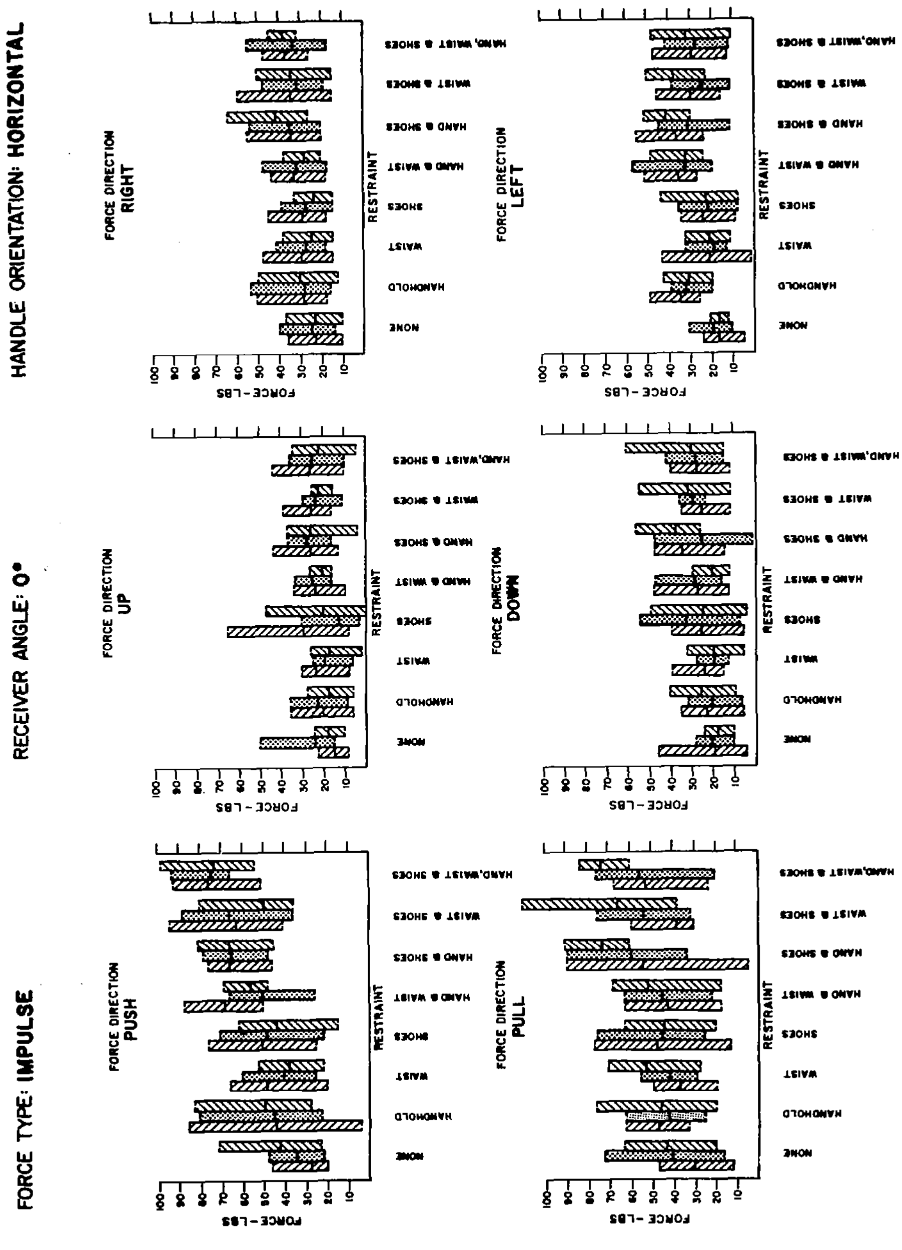
SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

g. Force Type: Impulse, Receiver Angle: 0°, Handle Orientation: Horizontal



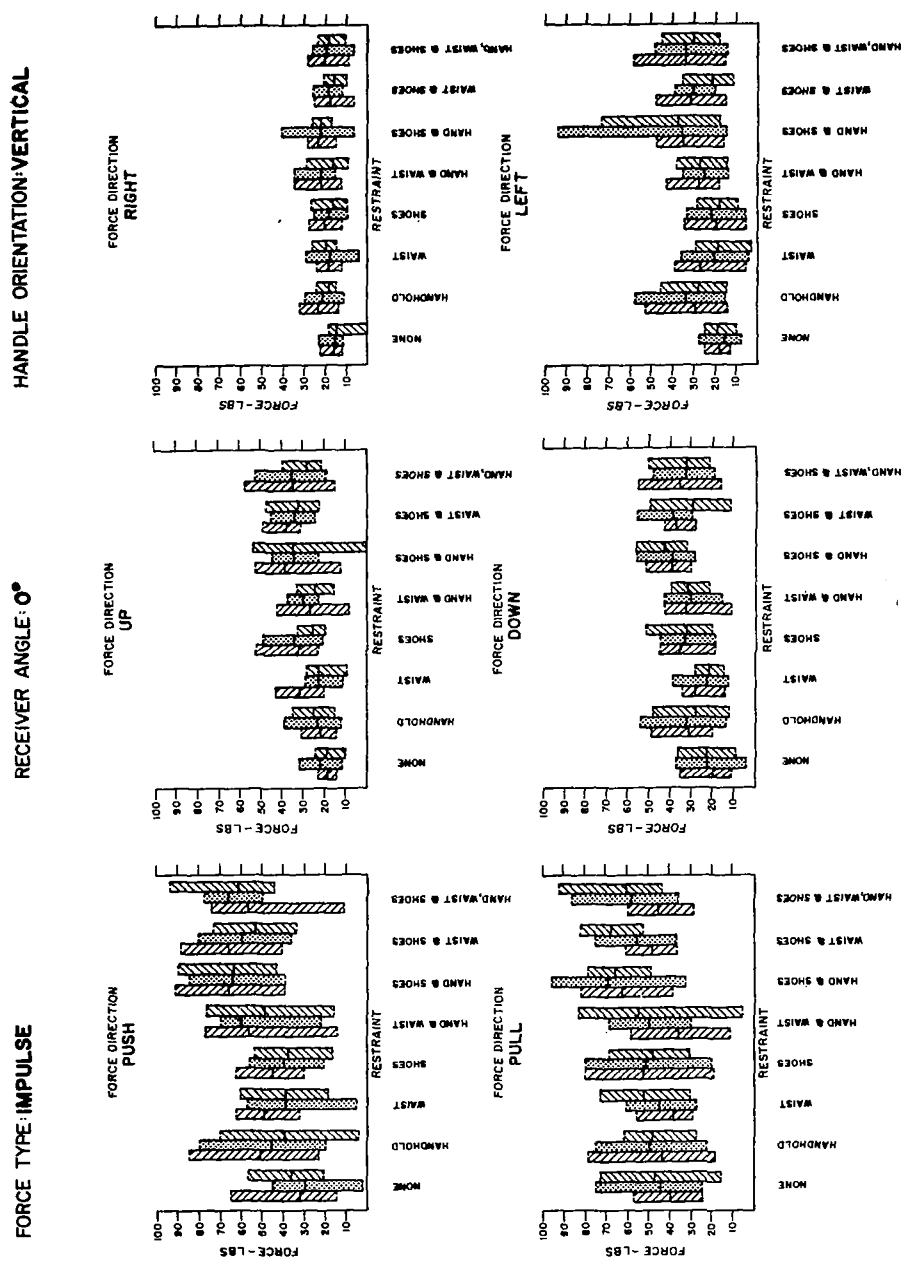
SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

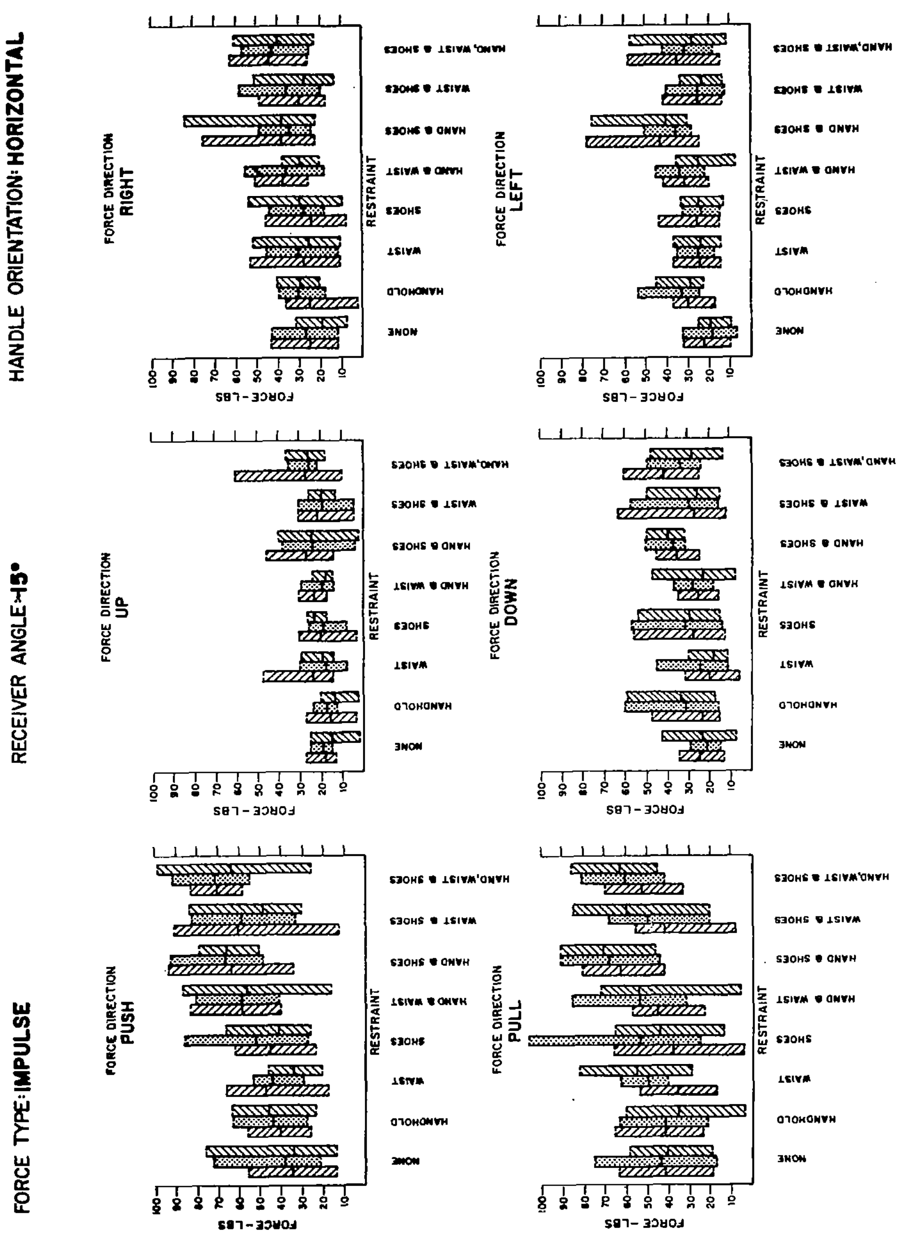
h. Force Type: Impulse, Receiver Angle: 0°, Handle Orientation: Vertical



SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

i. Force Type: Impulse, Receiver Angle: -15°, Handle Orientation: Horizontal



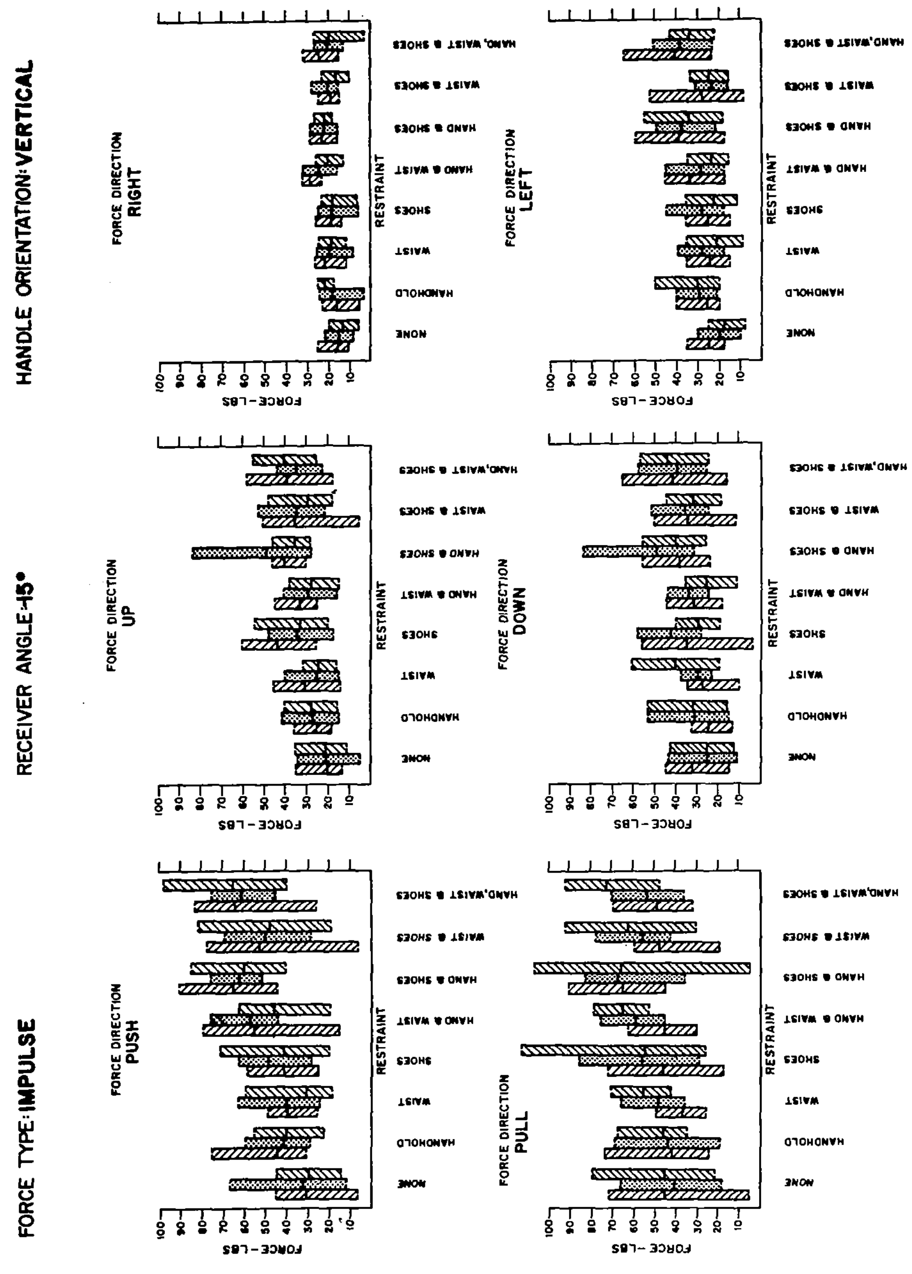
SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

j. Force Type: Impulse, Receiver Angle: -15°, Handle Orientation: Vertical

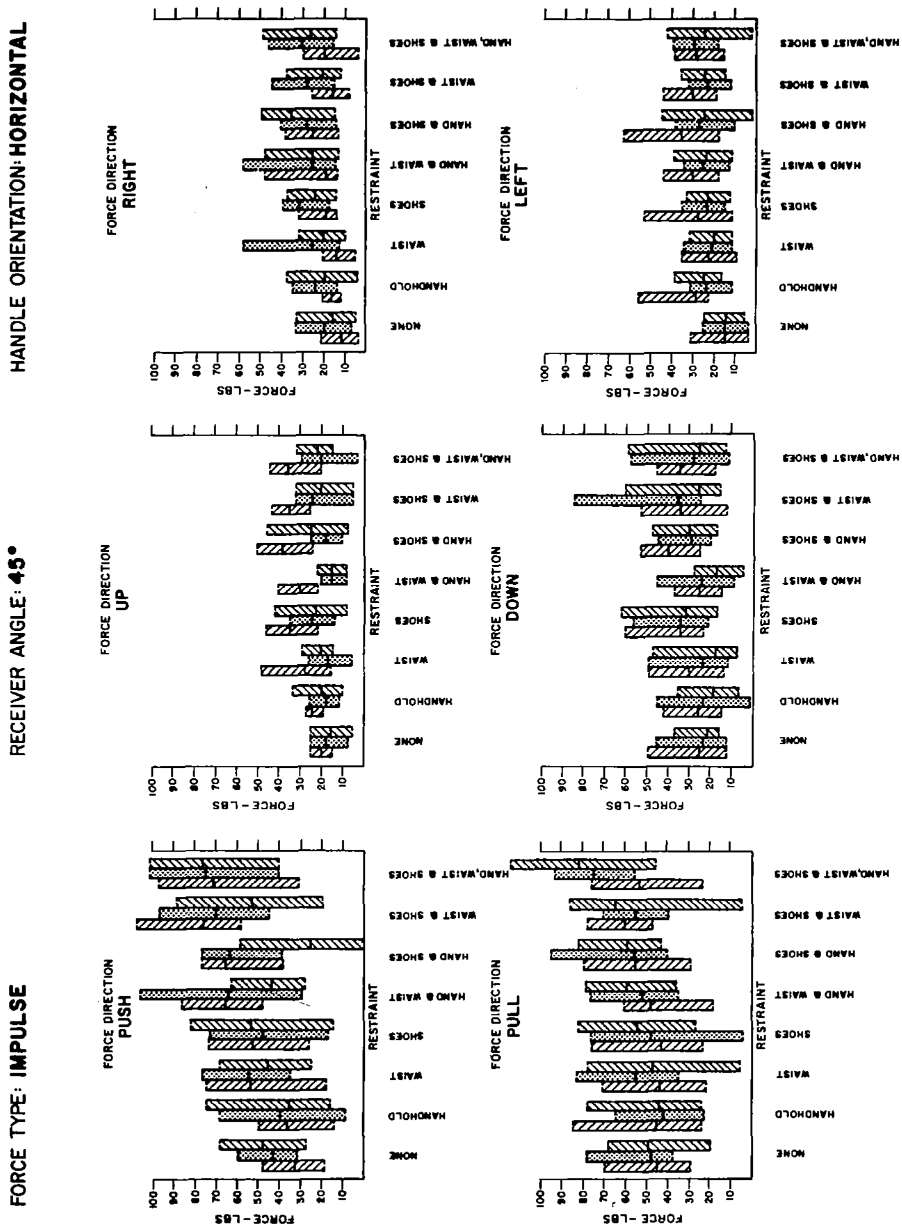


SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)



k. Force Type: Impulse, Receiver Angle: 45°, Handle Orientation: Horizontal

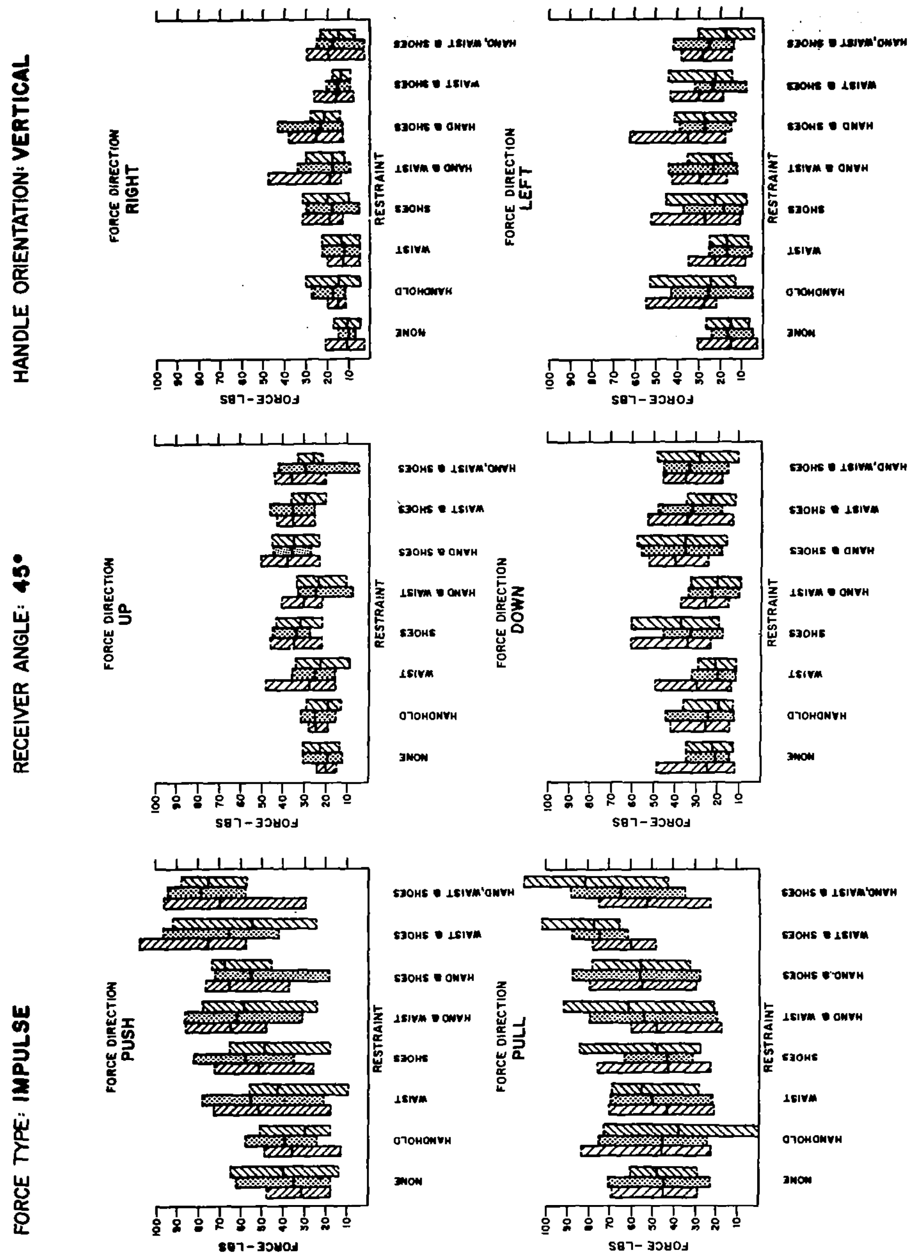
SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

FORCE EMISSION

SIMULATED ZERO GRAVITY (NEUTRAL BUOYANCY)

1. Force Type: Impulse, Receiver Angle: 45°, Handle Orientation: Vertical



SOURCE: Study for the Collection of Human Engineering Data for Maintenance and Repair of Advanced Space Systems, Vol. II (180).

PSYCHOMOTOR

REACTION TIME

EYE/HAND COORDINATION

Sense Organ Response. Any sense organ will react with the proper stimulus applied. Generally, only the three senses with the fastest reaction time, in the following order, are used:

1. Ear

2. Skin

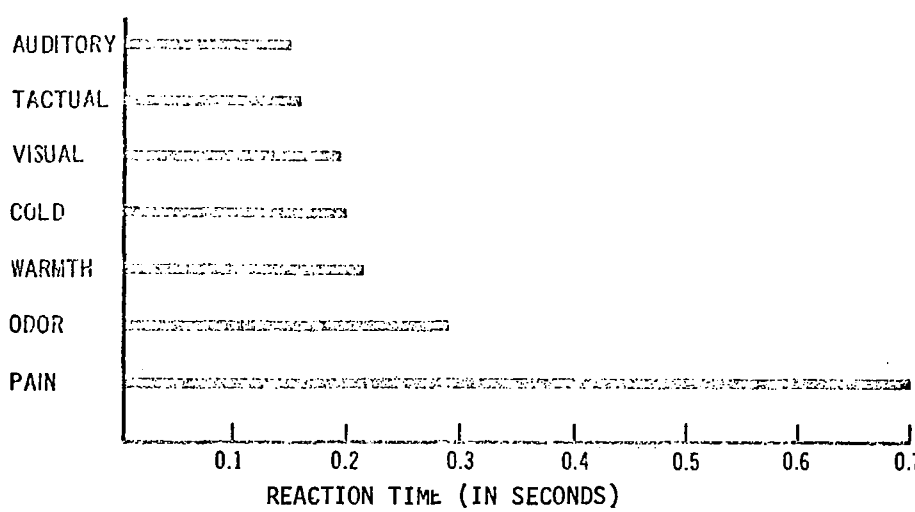
3. Eye

However, the differences are not significant for most applications.

The total man-machine response time includes the time lag of the machine to respond to the control and the time required to complete the machine response. Therefore the designer shall consider them in addition to the human lag time where it is important.

The illustrated reaction times are useful in making comparisons among senses. They are not necessarily representative of the reaction times in a practical situation where other factors may distract the operator.

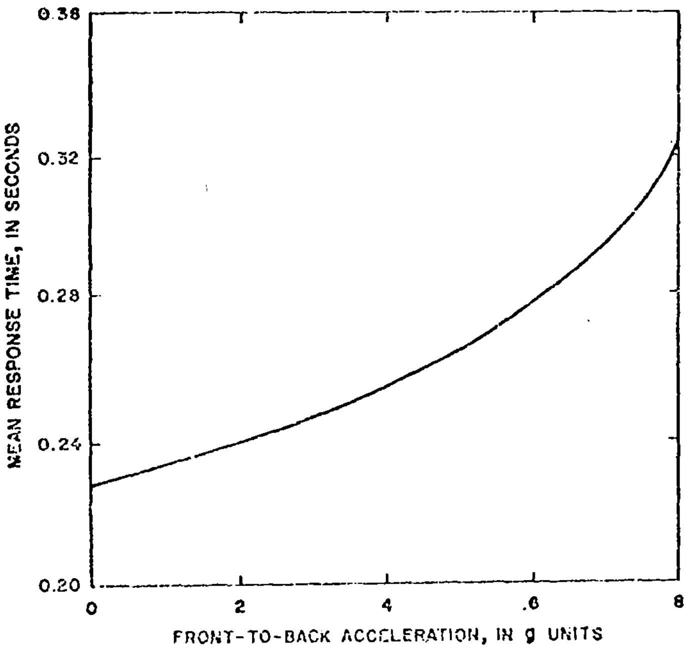
a. Reaction Time Lag for Seven Sense Modalities



SOURCE: Teichner (187) and Ely, et al (63).

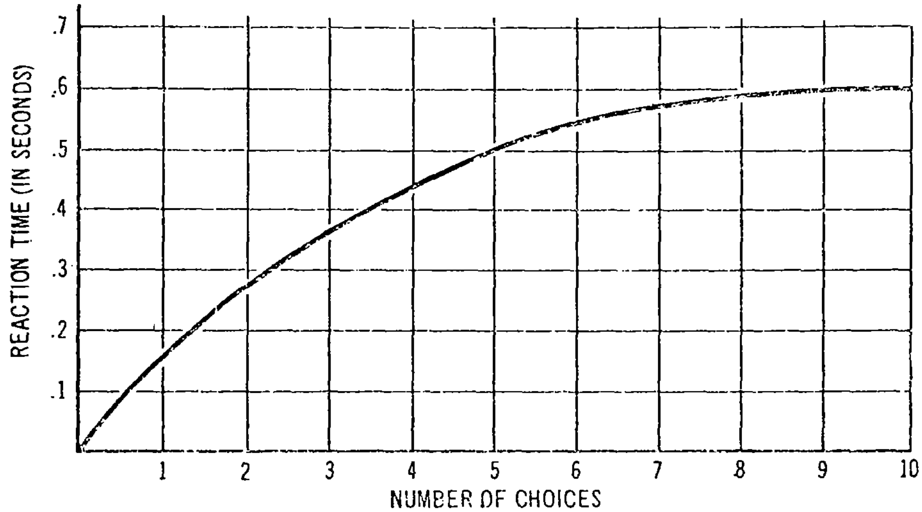
EYE/HAND COORDINATION

b. Reaction Time/Acceleration



Mean response time for combined left hand and right hand operations as a function of increased acceleration.

c. Reaction Time/Task Complexity



SOURCE: Kaehler, et al (99) and Human Engineering Design Criteria (88).

PSYCHOMOTOR

REACTION TIME

VISUAL PROBLEMS DUE TO SPEED

High speeds, altitudes, and accelerations, work load, airport density, complicated instrument panels, and the structure of the aircraft itself all create serious visual problems for the pilot and crew of high-performance aircraft. The most critical of these is high speed. At the speeds flown by today's jet aircraft, a perfectly ordinary situation, such as sighting an object a mile away, can turn into a calamity before the pilot can do anything about it. As speeds get higher, the problem will become worse in proportion. The trouble is simply that a man cannot see, identify, or act on an object the instant it comes into his field of view. Each of these things takes an interval of time--usually an exceedingly short interval, but worth hundreds or thousands of feet in a high-speed aircraft.

a. Time Intervals Required Between First Sighting of Object and Changing Flight Path to Avoid and Distances Traveled in These Intervals

Operation	Time, in sec		Distance Traveled, in feet			
			at 600 mph		at 1800 mph	
	For Operation	From 1st Sighting	During Operation	From 1st Sighting	During Operation	From 1st Sighting
Sensation (light travels from retina to brain)	0.10	0.10	88	88	264	264
Focusing with Central Vision						
Motor Reaction to Prearrange Eye Movement	0.175	0.275	154	242	462	726
Eye Movement	0.05	0.325	44	286	132	858
Focusing with Fovea	0.07	0.395	62	348	185	1043
Perception (minimum recognition)	0.65	1.045	572	920	1716	2759
Deciding What to Do (estimated min.)	2.0	3.045	1760	2680	5280	8039
Operating Controls	0.40	3.445	352	3032	1056	9095
Aircraft Changes Flight Path	2.0	5.445	1760	4792	5280	14,375

SOURCE: Byrnes (42), Moseley (135) and Wulfeck, et al (213).

VISUAL PROBLEMS DUE TO SPEED

b. Time Intervals Required to Shift Sight From Outside Aircraft to Instrument Panel and Back, and Distances Traveled in These Intervals.

	Time, in sec.		Distance Traveled, in feet			
			at 600 mph		at 1800 mph	
Operation	For Operation	From Beginning	For Operation	From Beginning	For Operation	From Beginning
To Panel						
Muscle Movement	0.175	0.175	154	154	462	462
Eye Movement	0.05	0.225	44	198	132	594
Foveal Perception	0.07	0.295	62	260	185	779
Accommodation	0.50	0.795	440	700	1320	2099
Recognition of Instrument Reading	0.80	1.595	704	1404	2112	4211
Back to Distance						
Reaction Time	0.175	1.770	154	1558	462	4673
Eye Movement	0.05	1.820	44	1602	132	4805
Relaxation of Accommodation	0.50	2.320	440	2042	1320	6125
Foveal Perception	0.07	2.39	62	2104	185	6310

SOURCE: Byrnes (42), Moseley (135) and Wulfeck, et al (213).

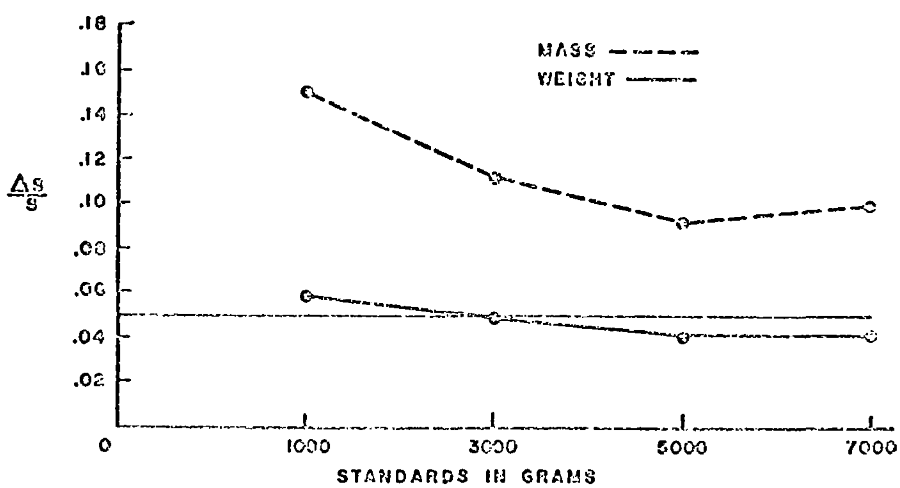
MASS DISCRIMINATION

WEIGHT AND MASS CONDITIONS

Absence of gravity results in the loss of many familiar kinesthetic cues of weight and friction necessary to man for object discrimination and manipulation. The chart below shows man's ability to discriminate small differences in mass as opposed to small differences in weight in a simulated weightless environment.

Results show that the mean difference threshold (DL), mean standard deviation, and Weber ratio ($\Delta S/S$) for each standard are much larger for mass than for weight. Thus to be detected under a weightless condition, mass increments must be at least twice as large as the weight increments required for discrimination in a normal weight-lifting situation.

a. Weber Ratios



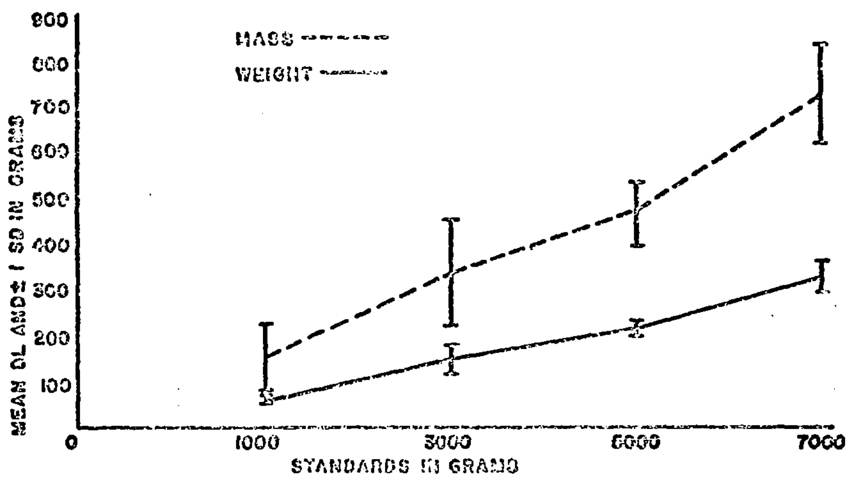
Comparison of Weber Ratios ($\Delta S/S$) between weight and mass conditions at each standard

Shown in the illustration are both mass and weight Weber Ratios ($\Delta S/S$), obtained by dividing as standard (S) into the stimulus increment (DL or Δ S) needed for difference discrimination around that standard. The horizontal line shown represents a ratio usually stated as the most accurate for weight-lifting experiments. The results for weight in this study tend to follow this line well.

SOURCE: Reco and Copeland (149).

WEIGHT AND MASS CONDITIONS

b. Mean Difference Thresholds



Mean difference thresholds (DL) and associated standard deviations (SD) plotted for each standard under both weight and mass conditions

DL points are connected by straight lines and SD's are given as ranges around these points. As can be seen, the difference between weight and mass grows larger with each increase in the standard. The DL's for mass are more than twice the size of those for weight. Also, the standard deviations of individual DL's at the various standards are much larger for mass.

SOURCE: Reco and Copeland (149).

WEIGHT AND MASS CONDITIONS

c. Summary of Statistics on Discrimination of Minimal Differences in Weight and Mass*

Standard in Grams	Condition	Mean PSE	Mean SD	Mean DL (.6745 $\hat{S}D$)	SD_{DL}	$\frac{\Delta S}{S}$
1000	Weight	1013.95	86.15	58.11	8.67	.050
	Mass	1019.40	222.60	150.14	75.78	.150
3000	Weight	3016.81	224.50	146.43	32.70	.049
	Mass	3014.47	497.40	335.50	116.59	.112
5000	Weight	5003.46	313.80	211.66	15.32	.042
	Mass	5010.69	683.00	460.69	66.12	.092
7000	Weight	7008.18	476.40	321.33	31.92	.048
	Mass	7018.90	1064.70	718.14	104.85	.103

* Using ten subjects for each standard.

SOURCE: Reco and Copeland (149).

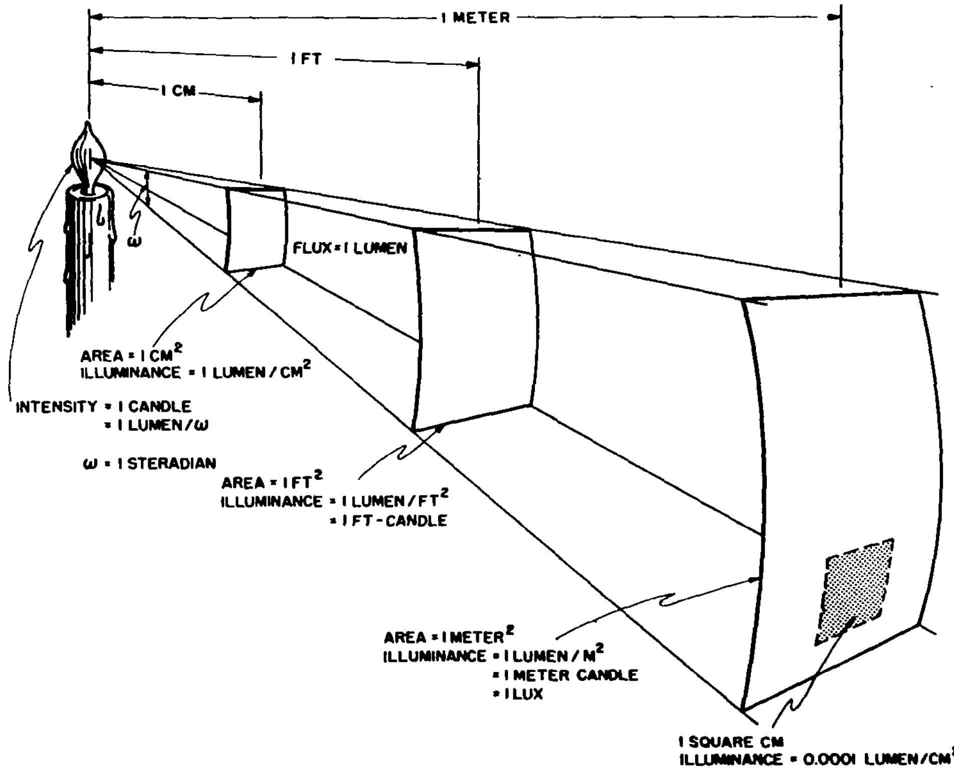
PSYCHOSENSORY

VISUAL

LUMINANCE

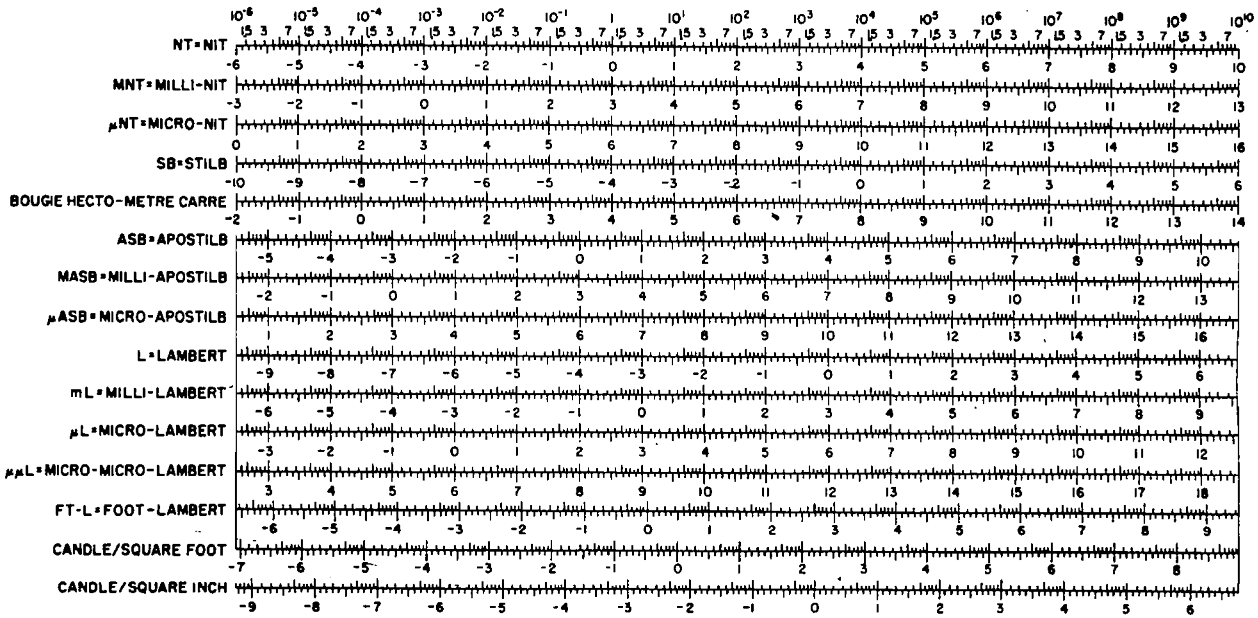
a. Relationships Between Intensity Units of Source and Illuminance Units on Surfaces at Various Distances

Intensity (I)	**1 lumen /steradian = 1 candle = 1 candle power** = 1.02 candelas
Illuminance (E)	**lumens/cm^2** **1 lumen/m^2 = 1 meter candle = 1 lux** **1 lumen/ft^2 = 1 ft-candle (ft-c)**
Luminous Emittance (L)	**lumens/cm^2** **lumens/m^2** **lumens/ft^2**
Luminance (B)	**lumens/steradian/m^2 (or cm^2)** **lamberts (L) = millilamberts (mL) $\times 10^3$ = microlamberts (μL) $\times 10^6$** **for a perfectly diffusing surface, 1 lambert = $1/\pi$ candles/cm^2. foot-lambert (ft-L) = 1.076 mL**



SOURCE: Sears(165) and Compendium of Human Responses to the Aerospace Environment, Vol. I (50).

b. Nomograph of Equivalent Values of Commonly Used Units of Luminance



Below each bar logarithmic units and their subdivisions are given. Above the Nit Bar natural figures and subdivisions are given. Above each bar subdivisions for natural figures are given.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Rose (152).

PSYCHOSENSORY

VISUAL

LUMINANCE

c. Conversion Factors - Absolute Values

To convert any quantity listed in the left most column to any quantity listed to the right, multiply by the factor shown.

Luminous Flux
(Intensity of a Source)

	Candle-power	Lumens	Watts	Ergs/second
Candlepower	1	4π	0.005882π (at 555mμ**)	$5.882\pi \times 10^4$ (at 555mμ**)
Lumens	$\frac{1}{4\pi}$	1	0.001471 (at 555mμ**)	1.471×10^4 (at 555mμ**)
Watts	$\frac{170}{\pi}$ (at 555mμ*)	680 (at 555mμ*)	1	10^7
Ergs/second	$\frac{170}{\pi} \times 10^{-7}$ (at 555mμ*)	680×10^{-7} (at 555mμ*)	10^{-7}	1

Illuminance
(Illumination Incident upon a surface)

	Foot-candles	Meter-candles	Lumens/ft²	Lumens/meter²
Footcandles	1	10.764	1	10.764
Meter-candles	0.0929	1	0.0929	1
Lumens/ft²	1	10.764	1	10.764
Lumens/meter²	0.0929	1	0.0929	1

Luminance
(Surface brightness or reflected light)

	Candles/foot²	Candles/meter²	Footlamberts	Apostilbs***	Lamberts (Lumens/cm²)
Candles/foot²	1	10.764	π	10.764π	$\frac{\pi}{929}$
Candles/meter²	0.0929	1	0.0929π	π	$\pi \times 10^{-4}$
Footlamberts	$\frac{1}{\pi}$	$\frac{10.764}{\pi}$	1	10.764	10.764×10^{-4}
Apostilbs***	$\frac{0.0929}{\pi}$	$\frac{1}{\pi}$	0.0929	1	10^{-4}
Lamberts (Lumens/cm²)	$\frac{929}{\pi}$	$\frac{10^4}{\pi}$	929	10^4	1

Quantity of Energy Received By a Surface

	Meter-candle-Seconds	Footcandle-Seconds	Ergs/cm²	Watt-seconds/cm² or Joules/cm²
Meter-candle-Seconds	1	0.0929	1.471 (at 555mμ**)	1.471×10^{-7} (at 555mμ**)
Footcandle-Seconds	10.764	1	15.83 (at 555mμ**)	15.83×10^{-7} (at 555mμ**)
Ergs/cm²	0.680 (at 555mμ*)	0.0632 (at 555mμ*)	1	10^{-7}
Watt-seconds/cm² or Joules/cm²	6.80×10^6 (at 555mμ*)	6.32×10^5 (at 555mμ*)	10^7	1

Quantity of Energy Emitted by a Source

	Lumen-Seconds	Candle-power-Seconds	Watt-seconds or Joules	Ergs
Lumen-Seconds	1	$\frac{1}{4\pi}$	0.001471 (at 555mμ**)	0.001471×10^{-7} (at 555mμ**)
Candlepower-Seconds	4π	1	0.005882 (at 555mμ**)	0.005882×10^{-7} (at 555mμ**)
Watt-seconds or Joules	680 (at 555mμ*)	$\frac{170}{\pi}$ (at 555mμ*)	1	10^7
Ergs	680×10^7 (at 555mμ*)	170×10^7 (at 555mμ*)	10^7	1

*True only for monochromatic light at 555mμ. For other wavelengths in the visible region, multiply by the relative visibility factor for that wavelength.

**True only for monochromatic light at 555mμ. For other wavelengths in the visible region, divide by the visibility factor for that wavelength.

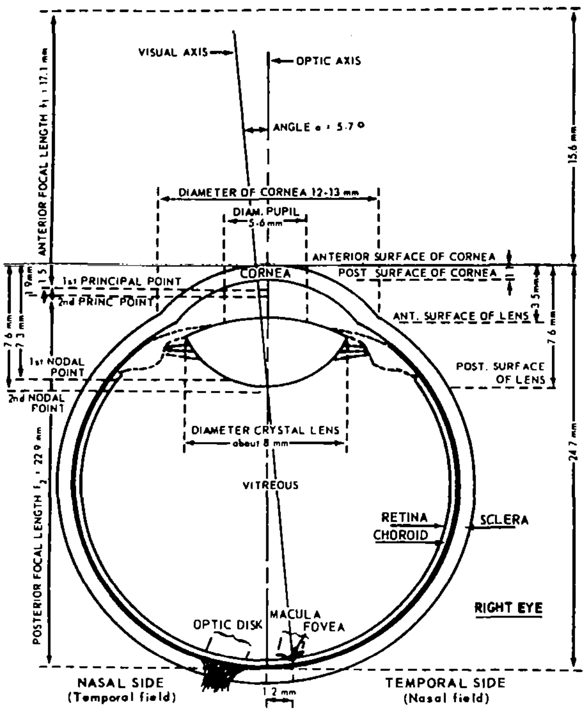
***Defined as 1 lumen per meter²; occasionally incorrectly called meter-lambert.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I(50) and Taylor and Silverman (184).

VISUAL

SCHEMATIC AND OPTICAL CONSTANTS OF THE EYEBALL

a. Human Eye Constants and Dimensions



Constant	Eye Area or Measurement	
Refractive index	Cornea	1.37
	Aqueous humor	1.33
	Lens capsule	1.38*
	Outer cortex, lens	
	Anterior cortex, lens	
	Posterior cortex, lens	
	Center, lens	1.41
	Calculated total index	1.41
	Vitreous body	1.33
Radius of curvature, mm	Cornea	7.7
	Anterior surface, lens	9.2-12.2
	Posterior surface, lens	5.4-7.1
Distance from cornea, mm	Post. surface, cornea	1.2
	Ant. surface, lens	3.5
	Post. surface, lens	7.6
	Retina	24.8
Focal distance, mm	Anterior focal length	17.1 [14.2]**
	Posterior focal length	22.8 [18.9]
Position of cardinal points measured from corneal surface, mm	1. Focus	-15.7 [-12.4]
	2. Focus	24.4 [21.0]
	1. Principal point	1.5 [1.8]
	2. Principal point	1.9 [2.1]
	1. Nodal point	7.3 [6.5]
	2. Nodal point	7.6 [6.8]
Diameter, mm	Optic disk	2-5
	Macula	1-3
	Fovea	1.5
Depth, mm	Anterior chamber	2.7-4 2

*Cortex of lens and its capsule
**Values in brackets refer to state of maximum accommodation

The diagram and table give dimensions and optical constants of the human eye. Values in brackets shown in the table refer to state of maximum accommodation. The drawing is a cross section of the right eye from above.

The horizontal and vertical diameters of the eyeball are 24.0 and 23.5 mm, respectively. The optic disk, or blind spot, is about 15 degrees to the nasal side of the center of the retina and about 1.5 degrees below the horizontal meridian.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and White (204).

PSYCHOSENSORY

VISUAL

PHYSIOLOGICAL AND PHYSICAL FACTORS EFFECTING VISUAL PERFORMANCE

a. Variables That Must Be Kept Constant or Carefully Controlled When Measuring Some of the Principal Kinds of Visual Performance

Type of Visual Performance	Variables to Be Controlled												
	Level of Illumination	Region of Retina Stimulated	Stimulus Size	Stimulus Color	Contrast Between Test Object and Background	Adaptive State of the Eye	Duration of Exposure	Distance at Which Measured	Number of Cues Available	Movement	Other Objects in Field	Monocular vs. Binocular	Stimulus Shape
Visual Acuity	X	X	(MV)*	X	X	X	X	X		X			X
Depth Discrimination	X		X	X	X	X	X	X	X	X	X	X	
Movement Discrimination	X	X	X	X	X	X	X	X		(MV)*	X		X
Flicker Discrimination	X	X	X	X	X	X	X						
Brightness Discrimination	X	X	X	X	(MV)*	X	X			X		X	X
Brightness Sensitivity		X	X	X	(MV)*	X	X			X			X
Color Discrimination	X	X	X	(MV)*	X	X	X	X	X		X		

*Variable being measured

There are several ways in which visual acuity has been defined and measured, each of which has significance for detection and recognition of detail. These are defined in Figure a. The luminance contrast between target and background determines the minimum visual angle which can be detected. Luminance contrast is a measure of how much target luminance (B_t) differs from background luminance (B_b). The equation for obtaining contrast is:

$$C_B = \frac{B_b - B_t}{B_b} \text{ and } C_B = \frac{B_t - B_b}{B_b} \text{ or } C_B \times 100 = \% \; C_B$$

Contrast can vary from zero to minus one for targets darker than their backgrounds, and from zero to infinity for targets brighter than their backgrounds. Most studies of this aspect of vision consider targets brighter than their backgrounds.

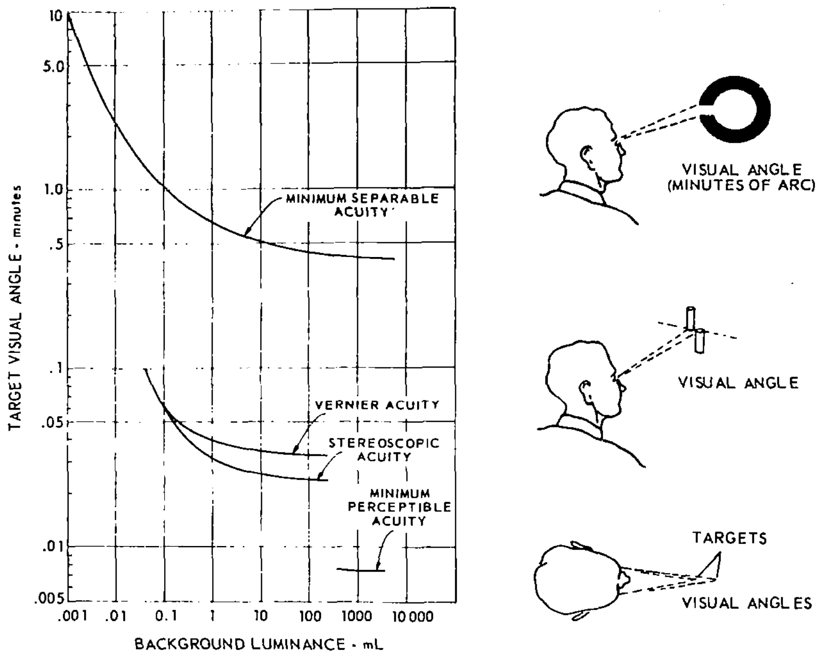
SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Wulfeck, et al (213).

PSYCHOSENSORY

VISUAL

PHYSIOLOGICAL AND PHYSICAL FACTORS EFFECTING VISUAL PERFORMANCE

b. Variation in Visual Acuity with Background Luminance



Definition of Terms: Minimum separable acuity defines the smallest space the eye can see between parts of a target. The relationship shown is for a black Landolt-ring on a white background. For white targets on black backgrounds, the relationship between acuity and luminance holds up to about 10 mL, above which acuity decreases because the white parts of the display blur. Vernier acuity is the minimum lateral displacement necessary for two portions of a line to be perceived as discontinuous. The thickness of the line is of little importance. Stereoscopic acuity defines the just perceptible difference in binocular parallax of two objects or points. Parallactic angle is one of the cues used in judging depth. Beyond 2500 feet, one eye does as well as two for perceiving depth. Minimum perceptible acuity refers to the eye's ability to see small objects against a plain background. It is commonly tested with fine black wires or small spots (either darker or lighter) against illuminated backgrounds. For all practical purposes, these numbers represent the limits of visual acuity. Another type of acuity, not shown in the graph, is minimum visible acuity. This term refers to the detection by the eye of targets of this kind. For instance, the giant red star Aldebaran (magnitude 1) can be seen even though it subtends an angle of 0.0003 minutes (0.056 sec) of arc at the eye.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I(50) and Webb (195).

PHYSIOLOGICAL AND PHYSICAL FACTORS EFFECTING VISUAL PERFORMANCE

Visual acuity is an important limiting factor in all human detection, target recognition, or other visual tasks. Acuity, like many other visual capacities, is measured and defined in terms of thresholds. The relation between the distribution of rods and cones near the horizontal meridian for various angular eccentricities is shown in the table. The last two columns of the table give visual acuity along the horizontal meridian of the temporal retina at different angles from the fovea (zero degrees) for two levels of luminance. At the highest luminance level, the fovea has the best acuity. At six degrees from the fovea, and at 100 mL, an object must be about twice as large to be seen as one in the central area. At the lowest level, acuity is best about five degrees away from the fovea. Scotopic peripheral acuity does not parallel the rod population or the light sensitivity of the retina. At lower luminance levels, visual acuity is fairly constant from 4 degrees to 30 degrees eccentricity.

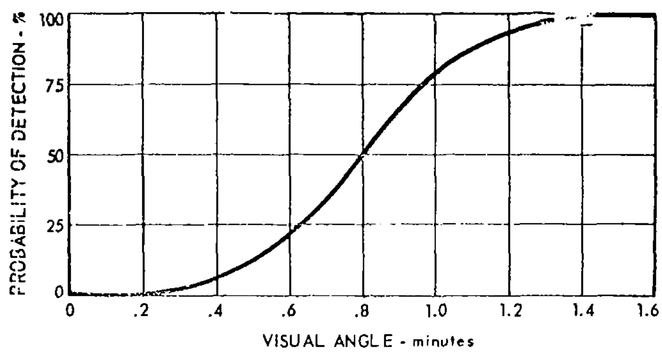
c. Visual Acuity and Density of Rods and Cones

Angular Eccentricity	Population Rods/sq mm	Population Cones/sq mm	Visual Angle 100 mL mean	Visual Angle 100 mL range	Visual Angle 0.002 mL
degrees	thousands		minutes		
			mean	range	
0.00	0	136.	0.7	(0.5-1.0)	12.5
0.25	0	84.4	0.8	(0.6-1.1)	-
0.50	7.22	57.5	1.0	(0.7-1.3)	-
1.00	34.2	41.3	1.2	(0.8-1.5)	22.2
5.00	88.	19.4	-	-	11.3
6.00	105.	12.1	4.5	(1.5-6.7)	-
10.00	118.	9.13	-	-	15.2
12.00	125.	7.64	6.1	(2.5-10)	-
12.50	126.	7.63	-	-	-
20.00	158.	7.08	10.	(5.0-17)	21.3
30.00	140.	6.52	-	-	31.2
40.00	132.	5.95	27.5	(14 - 48)	-
50.00	108.	5.79	42.5	(21 - 72)	-
70.00	80.4	5.47	100.	(47 - X*)	-
90.00	57.7	6.84	X*	(126 - X*)	-

* Unmeasurably poor acuity.

SOURCE: Morgan, Cook, et al (133), Spector (172) and Webb (195).

d. Example of Probability of Detection at Different Visual Angles for a Specific Test Case



One type of visual threshold is a value determined statistically at which there is a 50% probability of the target being seen. In most practical situations a higher probability of seeing, such as 95 or 100% is required. The general relation between threshold size and probability of detection is an ogive function of the general simplified form shown in Figure b. This curve covers a specific test case and should be used only as a very rough guide for estimating the relationship between visual angle and probability of detection under different conditions. It can be seen that doubling the visual angle for 50% probability of detection should give almost 100% detection if the location of the object is known. Threshold data are usually based on the 50% probability of detection. As a rough rule of thumb, these visual angle values should be doubled to give near 100% threshold values. More specific conversion factors for near 100% probabilities are available.

SOURCE: Morgan, Cook, et al (133), Spector (172) and Webb (195).

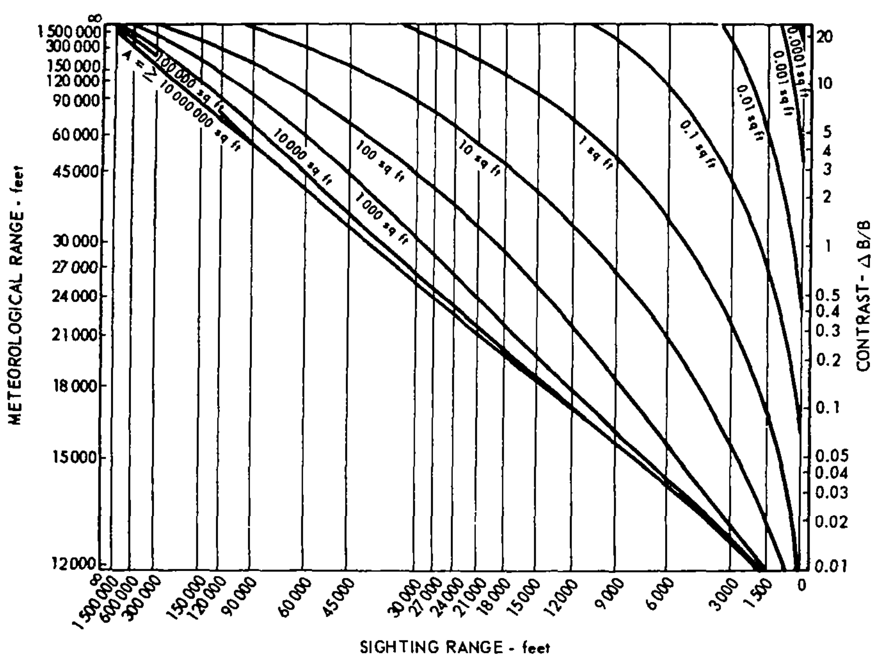
PSYCHOSENSORY

VISUAL

VISUAL ACUITY

This graph shows the sighting range of circular targets against the sky with a background luminance 0.0001 mL(starlight). The following is an example of the use of the nomogram: Find the range that an object 100 sq. ft. in area could be seen in starlight when the meteorological range is 150,000 feet and the contrast of the object and sky is 0.8. A straight line across meets the given range and contrast. The range is read off where the line intersects the 100 sq. ft. curve. Under these conditions a 100 sq. ft. target will be sighted with a probability of 95% at 1200 feet.

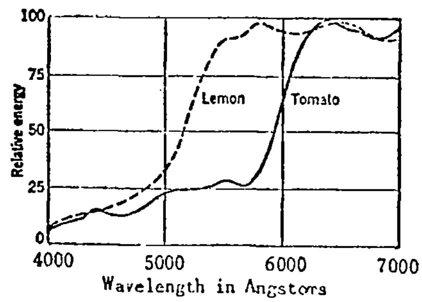
a. Visual Range in Natural Light - Starlight



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50), Dunthy (60) and Middleton (126).

VISUAL ACUITY

b. Reflectance and Transmittance



Reflectance Factor: The reflectance factor refers to the percentage of incident light that is reflected. Surfaces with compound reflectances may have reflectance factors for both diffuse and specular reflectance.

Transmittance Factor: As light passes through a medium some may be absorbed and some reflected back. The transmittance of such media (filters, etc.) is expressed as the percent of incident light transmitted.

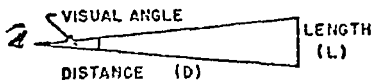
Selective Reflectance: Object color results from selective reflectance and selective absorption of particular wavelengths of incident light. A red object appears red because the longer wavelengths (red) are reflected and the shorter ones (blue) are absorbed in the surface. It is obvious, therefore, that perfect reflectors cannot have object color other than white. Selective or spectral reflectance is specified by the percent reflected light at arbitrary wavelength steps (usually 50 Angstroms) as seen in the diagram.

Selective Transmittance: A transparent or translucent medium may selectively absorb or transmit light as a function of wavelength. A red filter, for example, absorbs energy from the blue end of the spectrum and transmits the longer wavelengths. The spectral transmittance of a filter is usually plotted in a manner similar to the graph immediately above.

SOURCE: Baker and Grether (15).

VISUAL ACUITY

c. Visual Angle



Visual Angle: The visual angle is the angle subtended at the cornea of the eye by the viewed object. It is determined as follows:

Visual angle = 2 arctan $\frac{L}{2D}$ in which L is the size of the object measured perpendicularly to the line of sight. D is the distance from the eye to the object.

Visual Acuity: The size of detail which the eye is capable of resolving is used as a measure of visual acuity. Visual acuity is measured by determining the smallest visual angle that can be resolved. It is usually specified as the reciprocal of the minimum visual angle expressed in minutes of arcs.

$$\text{Visual acuity} = \frac{1}{\text{visual angle}}$$

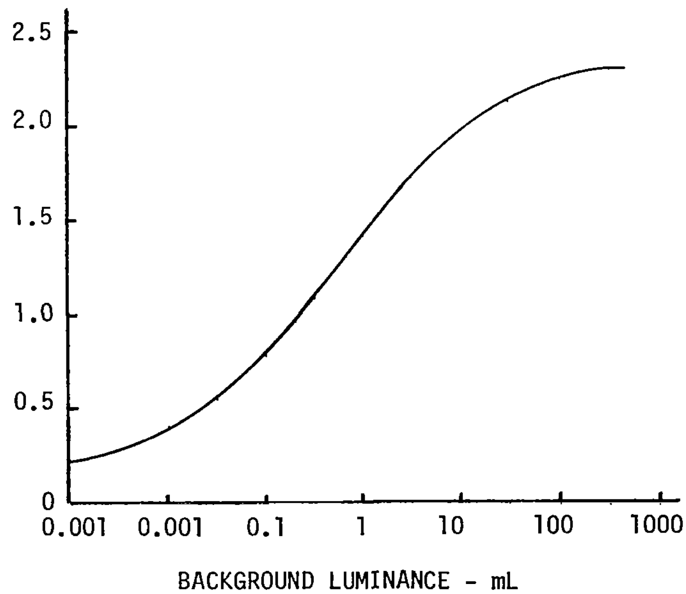
SOURCE: Baker and Grether (15).

VISUAL ACUITY

d. General Workplace Lighting

RECOMMENDED ILLUMINATION LEVELS	
WORKING CONDITION	FOOTCANDLES ILLUMINATION
Very difficult and prolonged visual tasks with objects of low brightness contrast such as sewing and inspection of dark materials.	100 or more
Fine machine work, detail drafting, watch repairing, and inspection of medium materials.	50 or more
Prolonged reading, assembly, general offices, ordinary bench work, and laboratory work.	25 or more
Occasional reading, washrooms, power plants, waiting rooms, and kitchens.	10 or more
No detail vision, restaurants, stairways, and bulk supply warehouses.	5 or more

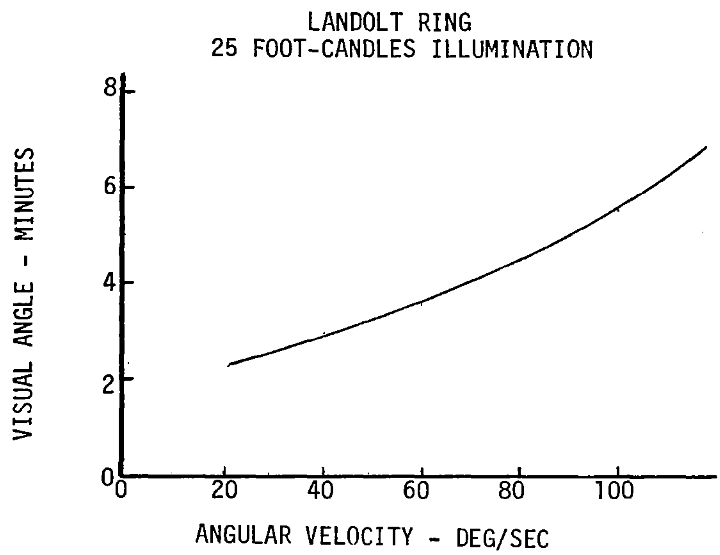
e. Visual Acuity as a Function of Luminance



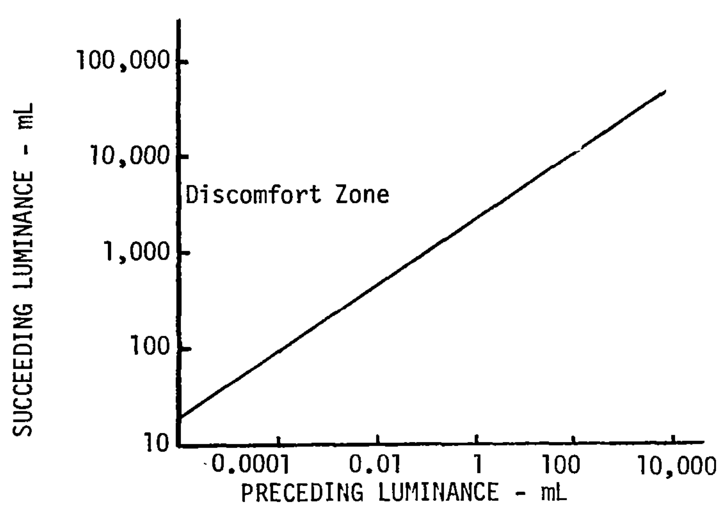
SOURCE: Baker and Grether (15), Chapanis, et al (46), Ludvigh and Miller (113), Moon and Spencer (130) and Scale, et al (160).

VISUAL ACUITY

f. Visual Acuity with Relative Motion



g. Successive Glare Effects



SOURCE: Chapanis, et al (46), Ludvigh and Miller (113), Moon and Spencer (130) and Scale, et al (160).

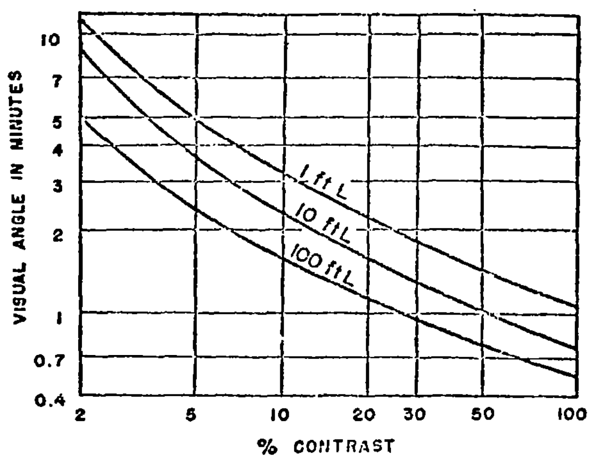
PSYCHOSENSORY

VISUAL

VISUAL ACUITY

The effect contrast has on minimum separable acuity is shown below for a dark Landolt-ring at three background brightnesses.

h. Minimum Visual Angles for Various Contrast Ratios

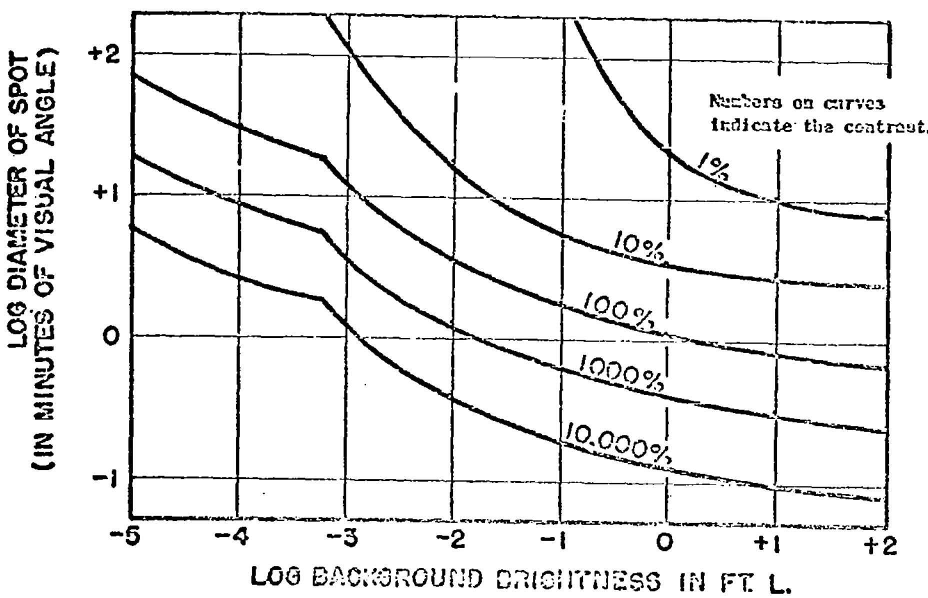


The most applicable type of visual acuity data which pertains to target detection is data concerning minimum perceptible acuity, i.e., where a spot is seen against a uniform background. The spot may be lighter or darker than the background. From the contrast formula, it is evident that contrast can range from 0 to 100% for targets darker than the background and from 0 to infinity for targets brighter than the background. Variation in minimum perceptible acuity with both background brightness and contrast is shown below. The contrast curves from 0 to 100% apply to signals both brighter and darker than the background. The curves with contrast above 100% apply only to signals brigher than the background. The thresholds are for 99% probability of detection.

SOURCE: Baker and Grether (15).

VISUAL ACUITY

i. Spot Detection (Minimum Perceptible Acuity)



There is no known lower limit of visual angle for bright targets on a dark background. The star, Mira, for example, is clearly visible and subtends a visual angle of only .056 seconds of arc. The visual angle subtended by visible lines and squares against bright backgrounds may be much smaller than those in the above graph if the background brightness is greater and if there is high contrast. A wire one degree long against a bright sky (2000mL) is visible 75% of the time if it subtends a visual angle of only 0.43 seconds in width. A dark square against a bright sky is visible 75% of the time if it subtends a visual angle of only 14 seconds.

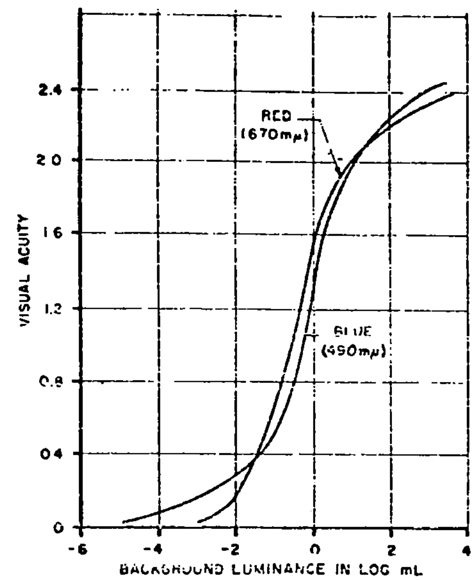
SOURCE: Baker and Grether (15).

PSYCHOSENSORY

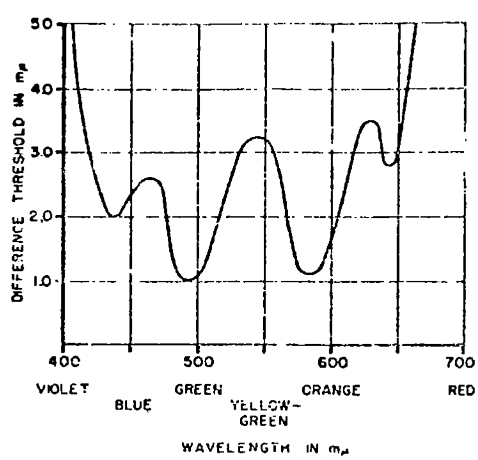
VISUAL

VISUAL ACUITY - COLOR EFFECT

a. Visual Acuity as a Function of Color of Illumination



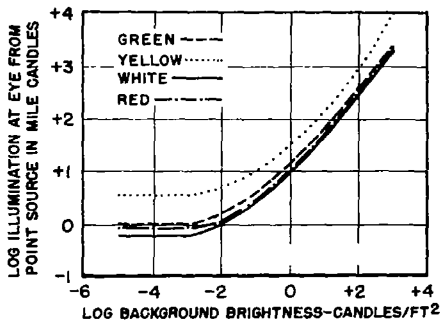
b. Smallest Difference in Wavelength That Can be Detected as a Difference in Hue When Two Fields are Presented for Comparison



SOURCE: Chapanis (45), Jones (96) and Steindier (173).

VISUAL ACUITY - COLOR EFFECT

c. Color Recognition of Point Sources of Light

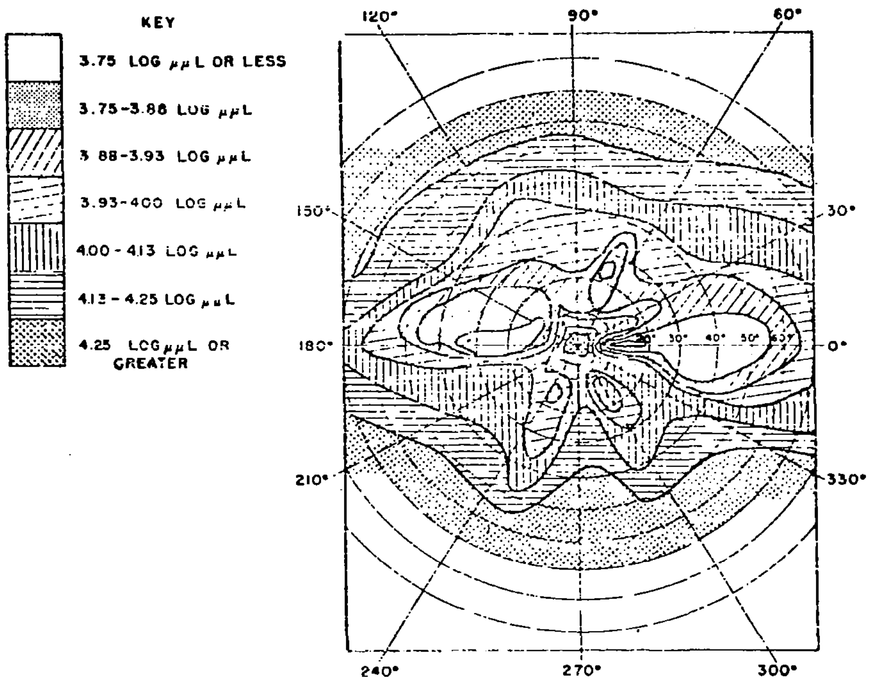


The illumination at the eye of a point source signal light that will be correctly identified 90 percent of the time for various colors viewed against various neutral background brightnesses.

SOURCE: Baker and Grether (15) and Compendium of Human Responses to the Aerospace Environment, Vol. I (50).

VISUAL FIELD SENSITIVITY - DARK ADAPTATION

a. A Map of Sensitivity to Light for the Visual Field of the Dark Adapted Right Eye



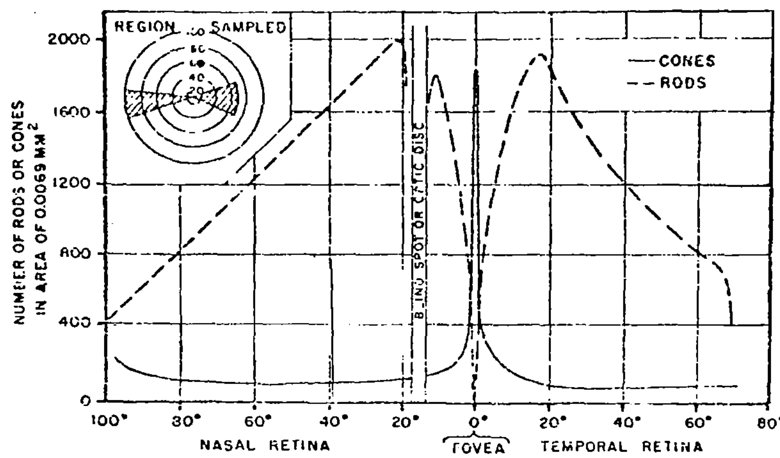
This phenomenon is due to the distribution of rods and cones in the retina, the rods, away from the fovea, being more light-sensitive than the cones.

PSYCHOSENSORY

VISUAL

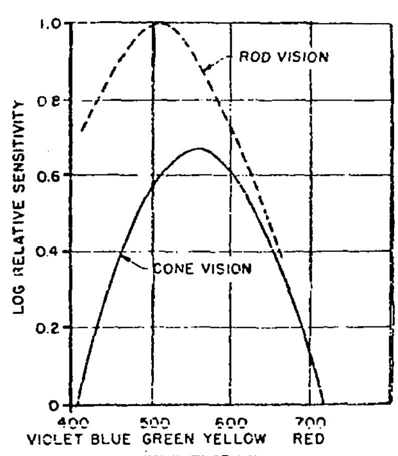
VISUAL FIELD SENSITIVITY - DARK ADAPTATION

b. Rod/Cone Population Curve - Density of Rods and Cones From Nasal to Temporal Edge of Retina



The cone system is largely responsible for detail and color vision, while the rod system provides for detection of small amounts of light. Different regions of the retina are specialized for these tasks. Detail vision is best in the fovea, where cones are dense, and poor in the periphery of the retina; here rods are more numerous than cones, and sensitivity to small amounts of light is higher than in the fovea.

c. Spectral Sensitivity Curve



SOURCE: Chapanis (45), Hecht and Williams (82) and Osterberg (141).

PSYCHOSENSORY

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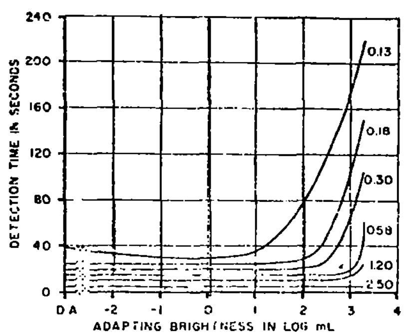
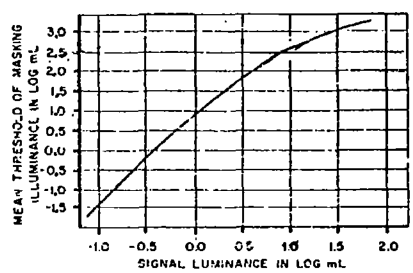
VISUAL FIELD SENSITIVITY - DARK ADAPTATION

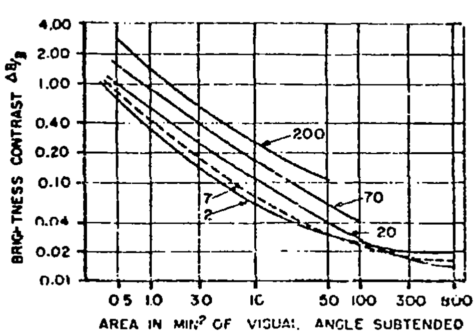
d. Time Required to Detect Signal as a Function of Previous Brightness to Which Subject has Been Adapted, for Several Different Contrasts



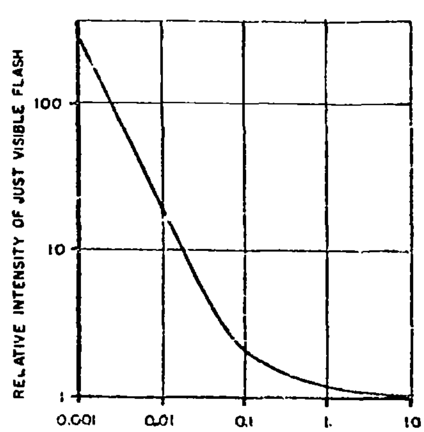
The Lowest Ambient Illuminance Required to Prevent a Radar Signal From Being Detected (I.E., Threshold Masking Luminance), Plotted as a Function of Signal Luminance



e. Effect of Area of Rectangular Stimulus on Threshold Contrast for Five Ratios of Length to Width of Rectangle



Intensity of Just Visible Flashes of Light as a Function of the Duration of the Flash



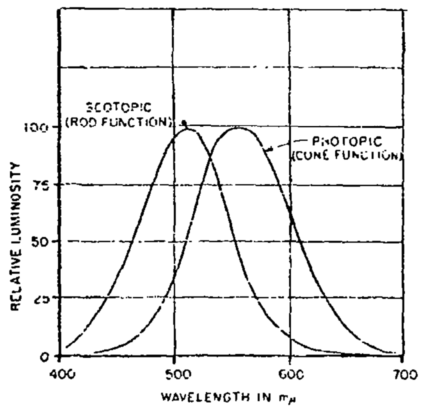
SOURCE: Adler, Kuhns, et al (2), Blondel and Rey (30), Chapanis (45), Hanes and Williams (80) and Lamar, Hecht, et al (107).

PSYCHOSENSORY

VISUAL

VISUAL FIELD SENSITIVITY - DARK ADAPTATION

f. Photopic and Scotopic Relative Luminosity Curves



The scotopic relative luminosity curve in this figure shows that if someone looked at a very dim, equal-energy spectrum (a light source emitting equal radiant energies at all wavelengths) after spending 30 to 45 minutes in the dark, the different parts of the spectrum would not appear to be equally luminous. The photopic curve shows the relative luminosity of the various wavelengths in an equal-energy spectrum when the intensity of the spectrum is well above cone threshold; the eye has been exposed to a fairly high luminosity level before the measurements or this curve are made. The curves show the sensitivity of the eye under extreme conditions. When the luminance is decreased gradually from photopic to scotopic levels, the transition from cone to rod vision is also gradual.

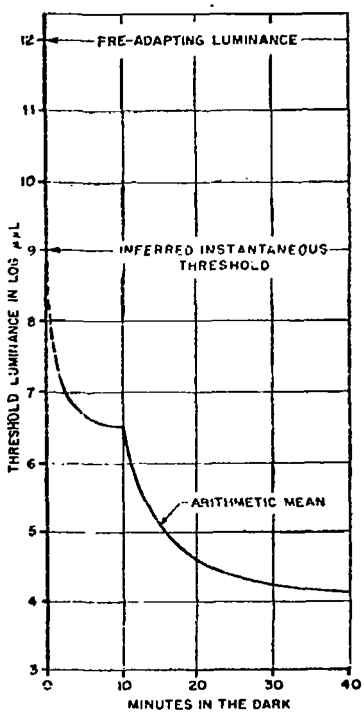
SOURCE: Chapanis (45).

PSYCHOSENSORY

VISUAL

VISUAL FIELD SENSITIVITY - DARK ADAPTATION

g. Dark Adaptation Curve

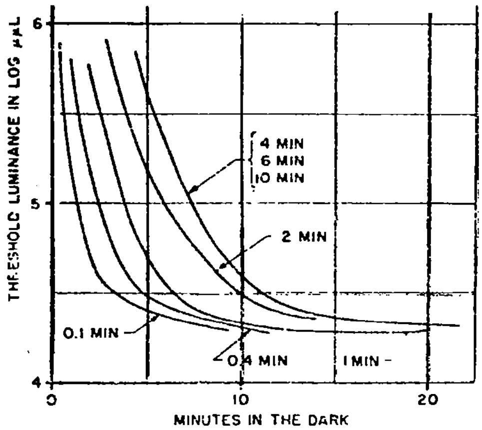


This dark-adaptation curve has been selected as one of the basic curves of visual performance, because it illustrates part of the tremendous sensitivity range of the eye, and also illustrates how the eye's sensitivity behaves as a function of time in the dark.

SOURCE: Chapanis (45) and Sloan (171).

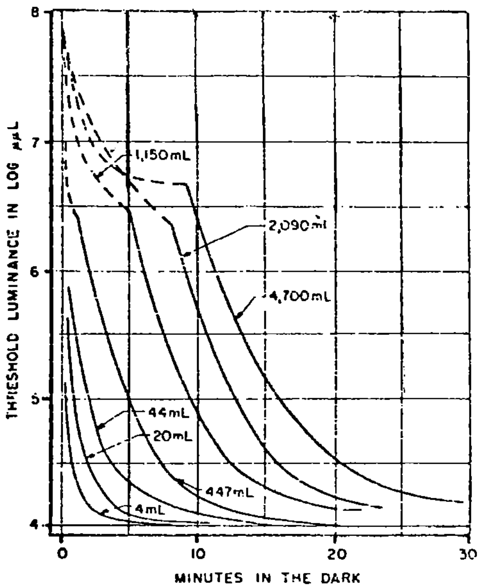
VISUAL FIELD SENSITIVITY - DARK ADAPTATION

h. Dark Adaptation as a Function of Duration of Previous Light



Dark-adaptation curves for one subject following exposure to light of 447 mL for various durations. Only the rod portions of the curves are shown here.

i. Dark Adaptation as a Function of Intensity of Previous Light



Dark-adaptation curves for one subject following exposures to lights of various luminances for four minutes. The broken lines indicate the color of the test light (violet) could be identified at threshold.

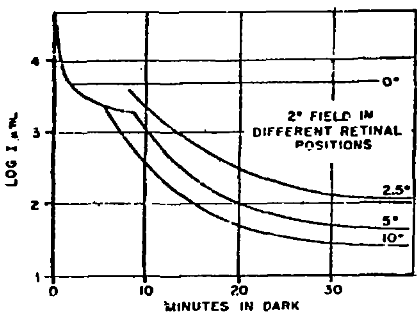
SOURCE: Chapanis (45) and Haig (78).

PSYCHOSENSORY

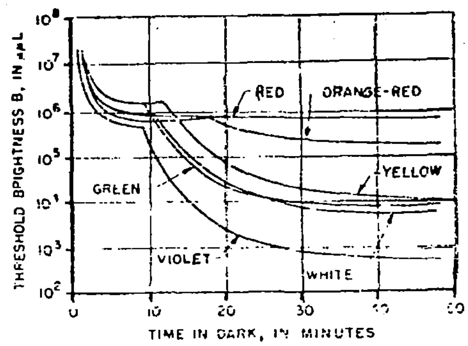
VISUAL

VISUAL FIELD SENSITIVITY - DARK ADAPTATION

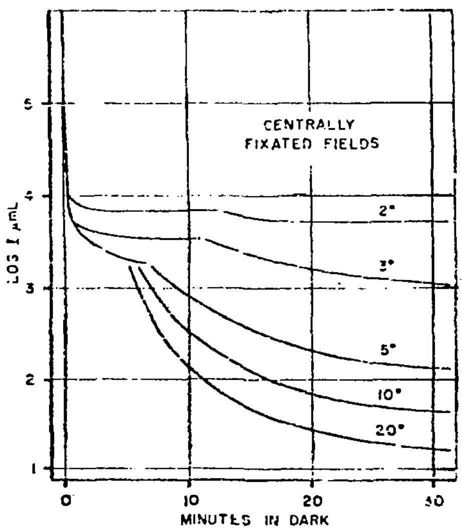
j. Dark Adaptation as a Function of the Region of the Retina Stimulated



k. Dark Adaptation as a Function of the Wavelength of the Test Stimulus



1. Dark Adaptation as a Function of the Area of the Test Object



SOURCE: Anon., (10), Journal Gen. Physiol. (98) and Stevens (174).

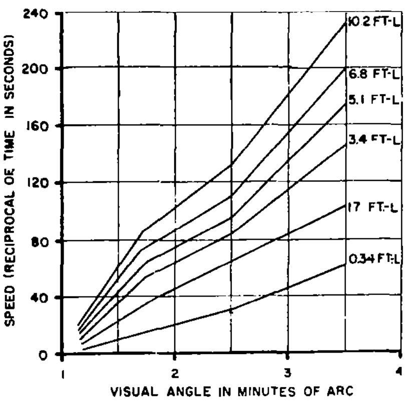
PSYCHOSENSORY

VISUAL

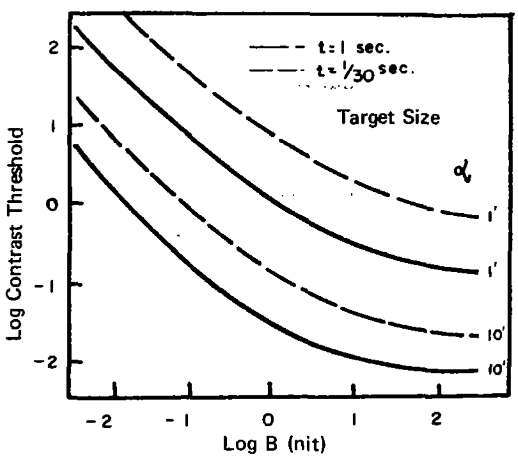
DURATION OF VISUAL EXPOSURE AND INTERMITTENT ILLUMINATION

When a target appears as a short flash up to about 0.1 sec. duration (this limit depending on the conditions), the effectiveness of the light increases linearly with exposure time. Above a critical time, the effect of a light becomes independent of the duration. These laws, which express the temporal summating ability of the visual system, may also be valid for a moving object as long as its image stimulates the same receptive fields of the retinal elements. Figures a and b are demonstrations of the effect of target size and target exposure on the contrast thresholds for stationary targets. At any luminance level, less time is required to see bigger objects. When size is held constant, less time is required to see at higher luminance levels.

a. Visual Acuity as a Function of Time Exposure to Viewed Object



b. Contrast Thresholds in Dependence of Target Size and Time of Exposure



Intermittent signal and warning lights are often more detectable than steady lights. This factor may be of value in space operations. Although a target may be bright enough to be visible, the pilot may not detect it against the star background -- particularly if its motion is very slow. Because the apparent motions at the initiation of rendezvous are, in general, very slow, this is an extremely important problem in acquisition. If the light is interrupted so as to flash off and on, it would be much more readily detected than a steady light. The problem then concerns the optimum flash rate and flash duration. The effect of flash duration on the apparent intensity of a light seen by the human eye is shown in Figure c. In this figure, a steady light which is just barely discernible is used as a datum reference with a relative intensity level of unity. The figure shows that little increase in relative intensity is required down to flash durations approaching 0.2 second. For flash durations less than one-tenth second, however, the required relative intensity increases as an inverse function of time. For example, if the flash

SOURCE: Blondel and Rey (30), Chapanis (45), Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Schmidt (164).

DURATION OF VISUAL EXPOSURE AND INTERMITTENT ILLUMINATION

duration is about 0.003 seconds, the intensity relative to the steady light must be increased by a factor of about 100. The curve of Figure c can be approximated by the equation:

$$E = E_0 \frac{(t + a)}{t}$$

where

E = intensity of flashing source required to appear as bright as E_0

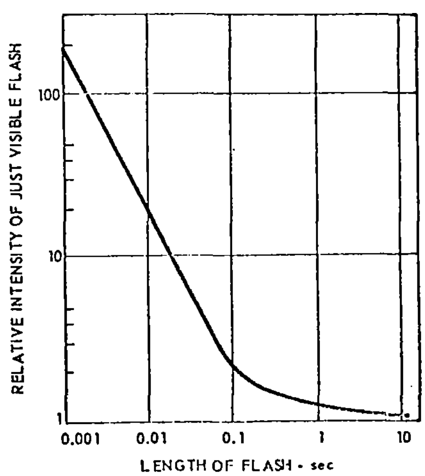
E_0 = intensity of steady source

t = duration of flash, sec.

a = curve fitting constant equal to 0.21 second

This expression is known as Talbot's law.

c. Intensity of Flash Required for Visibility at 50 Percent Level



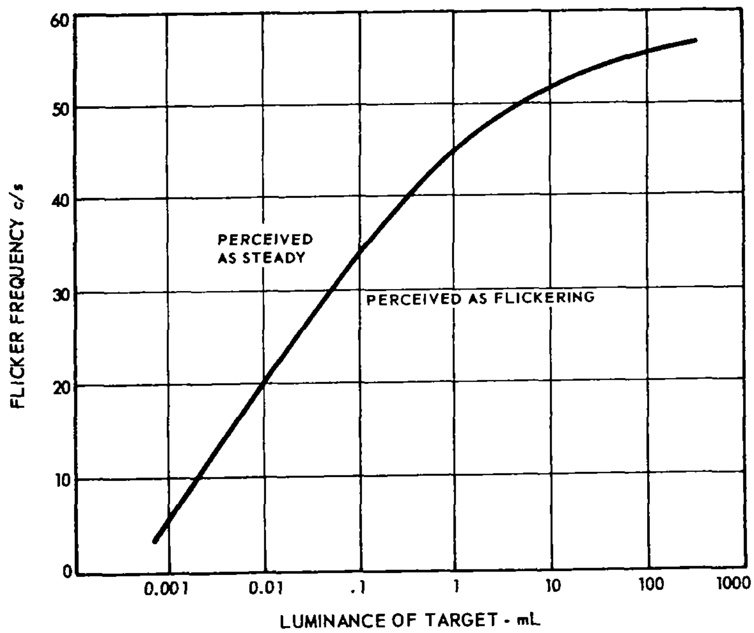
This figure shows how intense a flash of light must be in order to be seen at the 50% probability level. Note that very short flashes must be much more intense than long flashes if they are to be seen. The detection of colored lights requires about the same illumination at the eye as detection of white light.

SOURCE: Blondel and Rey (30), Chapanis (45), Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Schmidt (164).

DURATION OF VISUAL EXPOSURE AND INTERMITTENT ILLUMINATION

The flickering effect of intermittent light at around 8 pulses per second may be disturbing to some people. A small percent of the population may even develop epileptic seizures from the flicker. At high frequency of flicker, fusion of the image occurs and the light is perceived as steady. Figure d represents this phenomenon as a function of luminance. The data are valid only for white light on the fovea. The flicker fusion frequency is dependent on the functional state of the central nervous system.

d. Temporal Discrimination of White Light at the Fovea



The graph shows the relation between critical fusion frequency (CFF) and luminance. The curve defines the boundary between those combinations of target luminance and flicker frequency that are perceived as flickering and those perceived as steady. CFF is the lowest frequency (c/s) of flashing that can be perceived as steady. Luminance is the variable with the greatest influence on CFF. Other variables are target size, color, lengths of the light-dark cycle, brightness of the surround, region of the retina stimulated, and individual differences. The data shown in the graph are based on a two-degree, achromatic stimulus at zero degrees of angular eccentricity.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50), Hecht and Verrijp (81) and Webb (195).

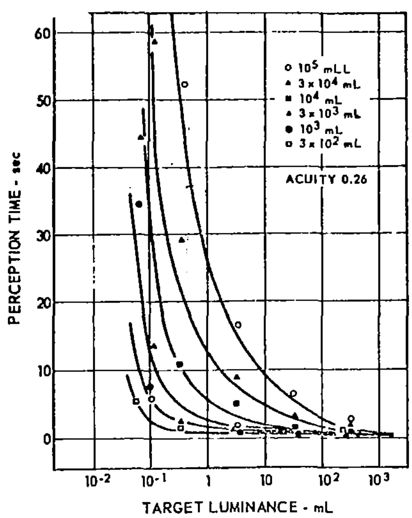
PSYCHOSENSORY

VISUAL

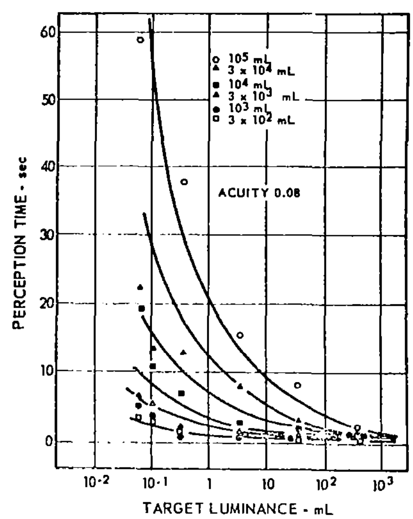
FLASH BLINDNESS

Flash blindness is the transient loss of vision for objects of low luminous intensity following an exposure to brief but intense general illumination. Figures a and b illustrate the times needed to perceive targets requiring two levels of visual acuity--0.26 for the upper curves, and 0.08 for the lower. Short "adapting" flashes were used, having various intensities as indicated by keying of the individual curves. Figure c shows the effect of 0.1 second flashes of much higher intensity on the ability of the eye to detect a large target, which subtended an angle of 17 min and which had a luminance of 0.7 mL. The brighter the flash, the longer was the recovery time.

a. Times to Perceive Targets - Acuity 0.26



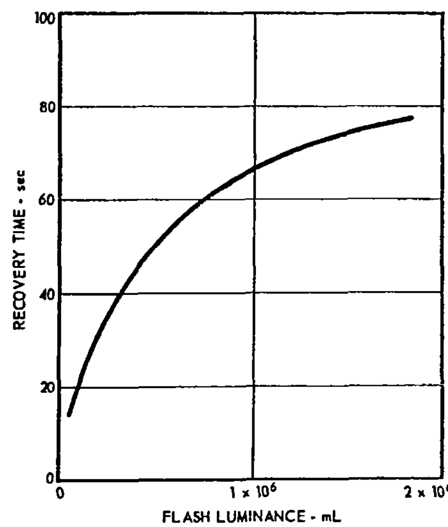
b. Times to Perceive Targets - Acuity 0.08



SOURCE: Brown (34), Metcalf and Horn (125) and Webb (195).

FLASH BLINDNESS

c. Effect of 0.1 Second Flashes on Ability to Detect a Large Target



SOURCE: Brown (34), Metcalf and Horn (125) and Webb (195).

PROBABILITY OF DETECTION

The visibility, or probability of detection, of visual signals depends upon five visual factors:

(1) The size, in visual angle, of the pip or signal.

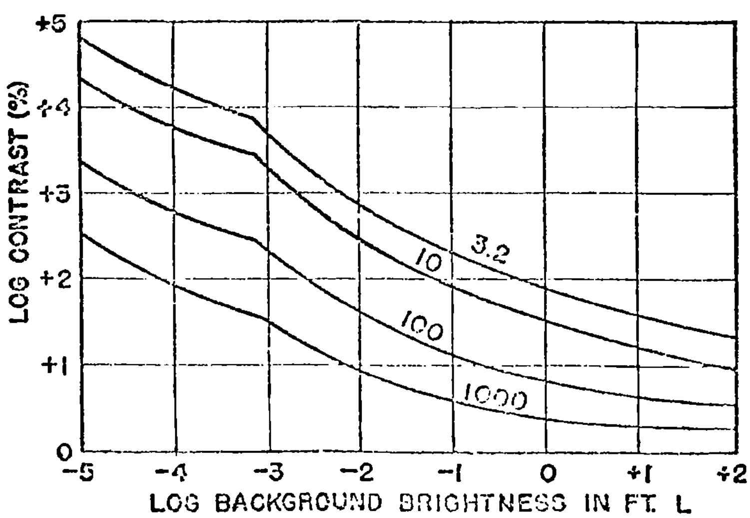
(2) The brightness of the background, including noise and clutter.

(3) The brightness of the pip.

(4) The length of time the signal is present.

(5) The state of adaptation of the eye.

a. Signal Size and Brightness Relationships



Numbers on curves indicate area of the signal in square minutes of visual angle.

This graph shows the signal-to-background contrast required for 99% probability of detection for:

(1) Signals of various sizes stated in visual angle.

(2) Various background brightnesses.

SOURCE: Baker and Grether (15).

PSYCHOSENSORY

VISUAL

PROBABILITY OF DETECTION

These data apply to situations where:

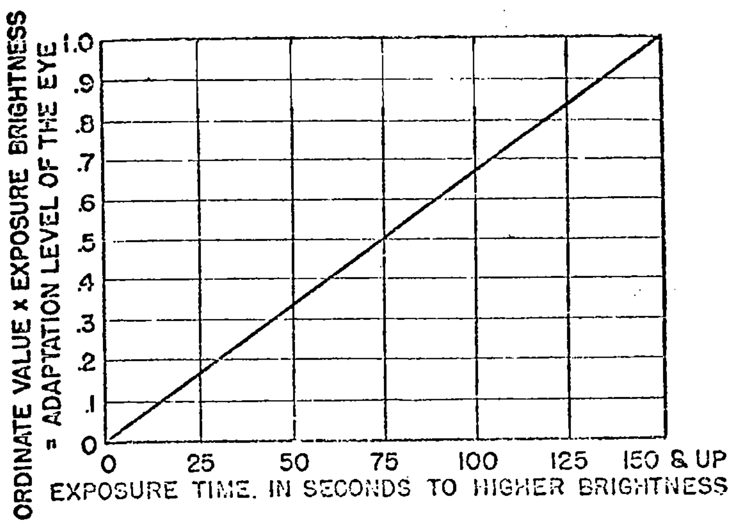
(1) The operator is adapted to the brightness level of the task.

(2) The signal is either brighter or darker than the background.

(3) The background brightness (noise) is distributed evenly.

(4) The operator has several seconds to detect the signal and is alerted to the task.

b. Duration of Pre-Exposure Brightness



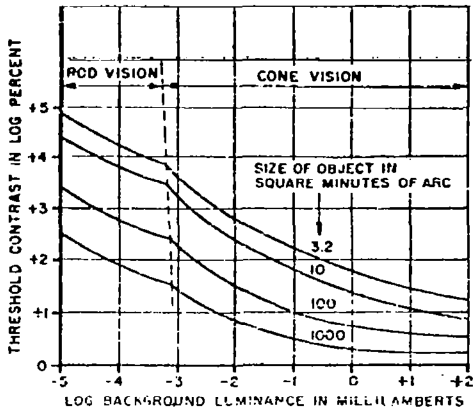
For any given exposure duration the value on the ordinate is used as a multiplier of the exposure brightness to give the steady state adaptation level of the eye.

We have seen that the eye is less sensitive to dim visual stimuli for some period after having been exposed to relatively high brightnesses. The data given above show the effect on visual sensitivity of adapting the eye to high brightnesses for five minutes or more. After the eye has been exposed to relatively high brightnesses for about 2-1/2 minutes it reaches, for all practical purposes, a "steady state" of adaptation. This means that longer periods of pre-exposure have little further effect upon the immediate subsequent sensitivity of the eye. However, if shorter periods of pre-exposure are used, the sensitivity is affected proportionately less. These relationships are shown above.

SOURCE: Baker and Grether (15).

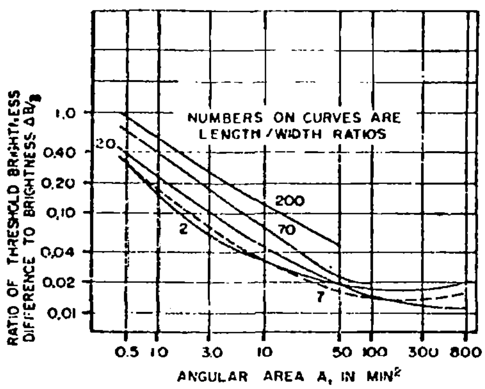
CONTRAST EFFECTS

a. Contrast Discrimination Curve



The smallest brightness contrast that can be seen, as a function of background luminance.

b. Contrast Threshold as a Function of Shape of the Stimulus

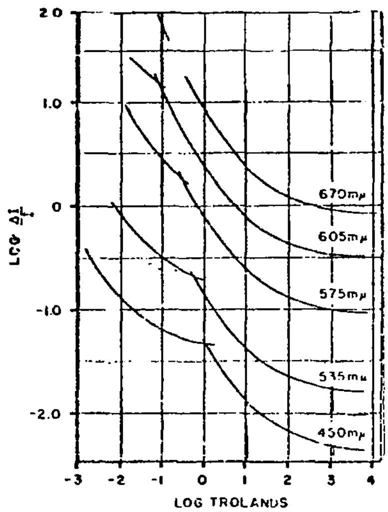


Effect of area of rectangular stimulus on threshold contrast B/B for 5 ratios of length to width of rectangle. For large areas, threshold contrast for fixed area decreases as shape approaches square. When area exceeds 100 min, shape again becomes unimportant.

SOURCE: Anon. (10) and Baker and Grether (15).

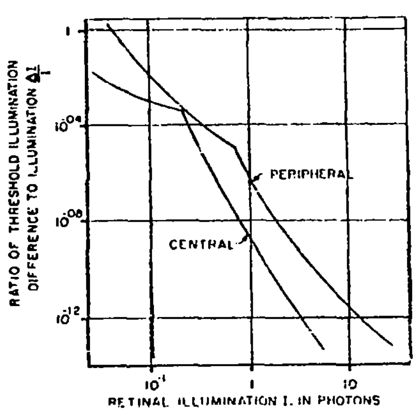
CONTRAST EFFECTS

c. <u>Contrast Threshold as a Function of Wavelength of Stimulus</u>



Brightness discrimination for the red, orange, yellow, green and blue parts of the spectrum. The labeling on the ordinate applies to the data for yellow (575 mμ). The orange and red curves have been raised 0.5 and 1.0 log unit respectively, and those for green and blue have been lowered 0.5 and 1.0 log unit respectively.

d. <u>Contrast Threshold as a Function of Region of the Retina Stimulated</u>

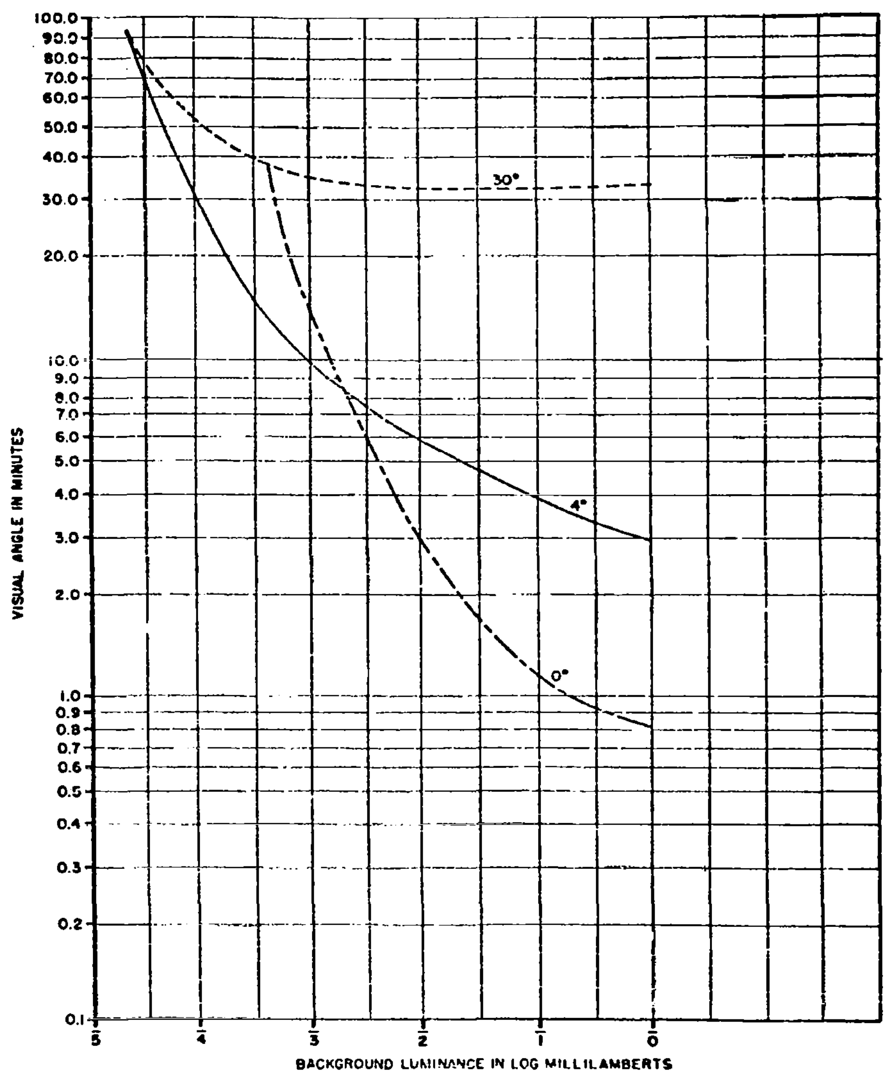


Just noticeable difference in retinal illumination as influenced by illumination for foveal and peripheral vision. In peripheral vision, where rods predominate, transition from rod to cone vision occurs at higher illumination level. Discrimination is generally poorer in periphery than in center of visual field.

SOURCE: Anon. (10) and Stevens (174).

CONTRAST EFFECTS

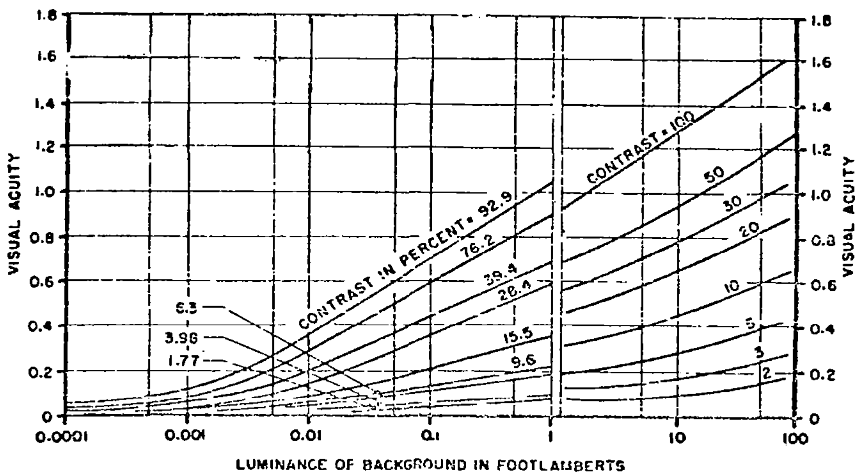
e. Visual Acuity Curve Plotted as a Function of Background Luminance



SOURCE: Mandelbaum and Rowland (123).

CONTRAST EFFECTS

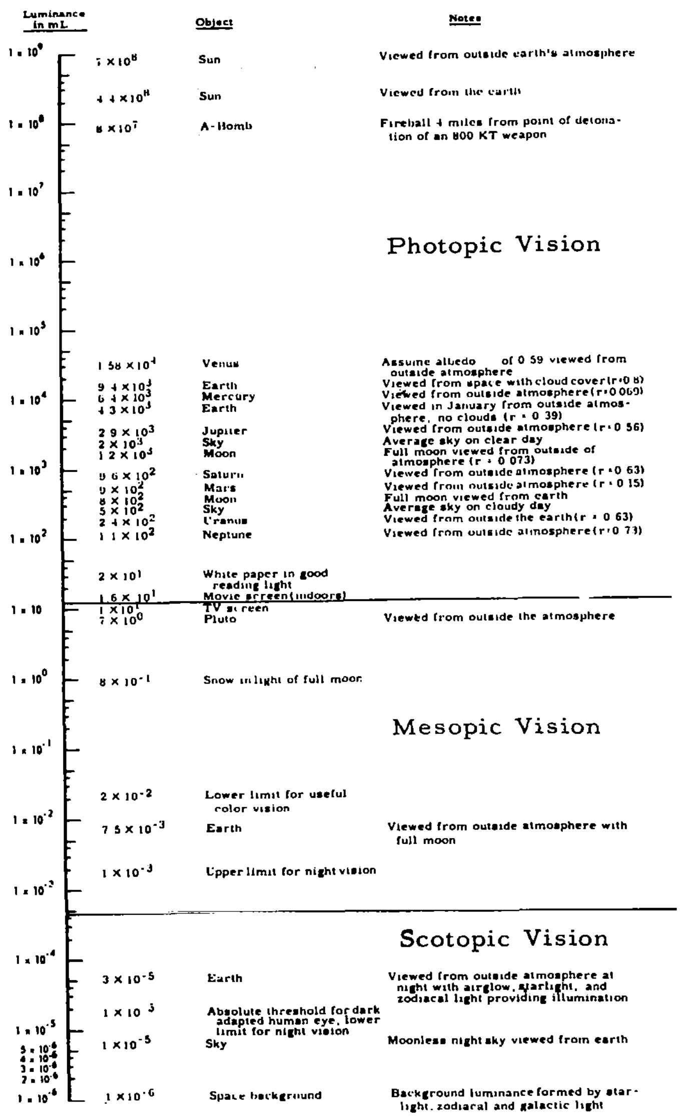
f. Visual Acuity as a Function of Contrast



SOURCE: Chapanis (45).

CHARACTERISTIC LUMINANCE VALUES

a. Characteristic Luminance on Earth and In Space



This enormous range of luminances is based on a solar illuminance of 12,700 Ft-c. A uniformly diffusing sphere at the earth's distance from the Sun would have a luminance of 13,655 mL and the apparent luminances of the Sun, Earth, Moon, Venus, and Jupiter have been recalculated on that basis. Albedo(r) as used in this figure is the ratio of the incident collimated light in a planetary body or spherical object to the light reflected and collected over 4 steradians and is considered to be invariant with wavelength. Only Jupiter and Venus are large enough to be characterized by their surface brightness.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and White (204).

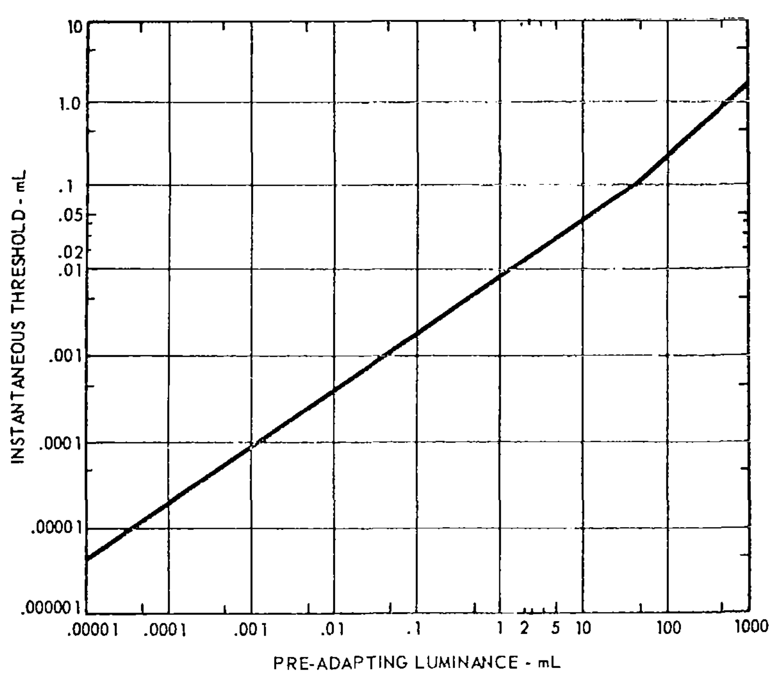
PSYCHOSENSORY

VISUAL

INSTANTANEOUS THRESHOLD FOR LIGHT

The luminance that is just visible immediately after the eye has been adapted to a given luminance is called the instantaneous threshold of the eye. The curve is a straight line except at the higher luminances where factors other than adaptation are present. This graph is for a square target that subtends 10 minutes of arc, and assumes that the observer is pre-adapted to a given wide field luminance. An observer adapted to a luminance of 1.0 mL can see a 10 minute square target about one hundredth as bright immediately after the pre-adapting field is turned off. Suppose, however, that the observer was exposed to a field luminance of 100 mL but the target luminance was 0.0001 mL, what can be said about the luminance threshold? The data on dark adaptation show that the observer must wait about 14 minutes after entering a dark room before he can see the target light. This graph is for simple light detection and does not permit a prediction of instantaneous visual acuity threshold, which requies discrimination of form.

a. <u>Instantaneous Threshold as a Function of Pre-Adapted Luminance</u>



SOURCE: Nutting (140) and Webb (195).

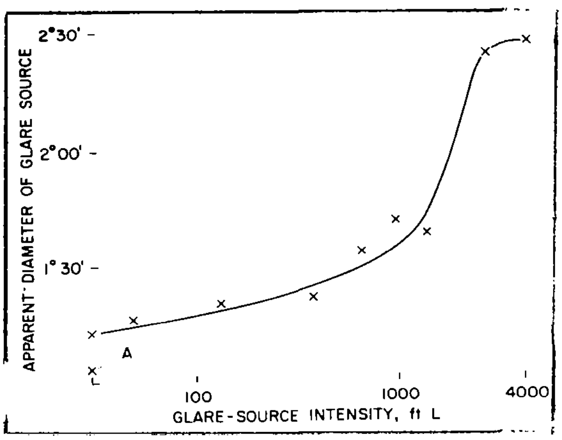
PSYCHOSENSORY

VISUAL

EFFECT OF GLARE ON APPARENT SIZE AND SHAPE

Visual identification of highly luminous objects in space, on the basis of their shape, may lead to incorrect identification. If navigational sightings are performed using high luminance sources as reference objects of approximately 2000 ft L apparent luminous intensity or greater, one must expect rather large errors in estimating star eclipse angles (from the edge of the luminous source). Under high luminance conditions one is likely to perceive size and shape characteristics of the glare source which may misrepresent the actual glare producing object. If a star is going to be chosen as a nvaigational referent with respect to either the perceived edge of the sun's photosphere, which is unlikely, or some man-made object having a high luminance (direct or reflected), optical filters will have to be used to reduce the photic flux to such a level that the physical edge of the referent can be accurately perceived.

a. Effect of Glare Source Intensity Upon Its Apparent Size*

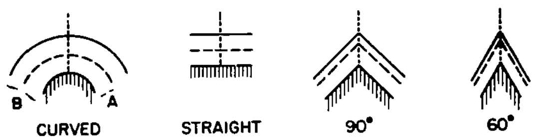


* A zero intensity or control condition.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Haines (79).

EFFECT OF GLARE ON APPARENT SIZE AND SHAPE

b. Effect of Glare Source Edge Geometry Upon Point Source Disappearance and Reappearance Position

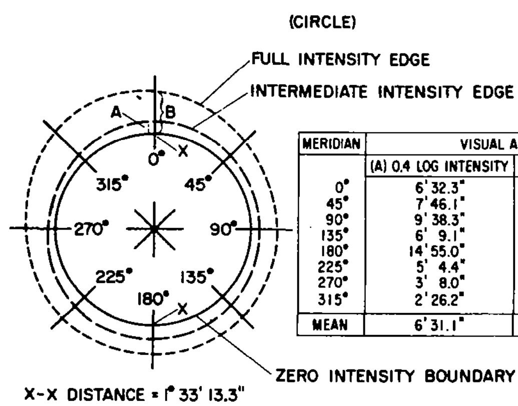


----- PATH OF POINT SOURCE
—— FULL INTENSITY
— — 0.4 LOG INTENSITY

EDGE GEOMETRY	VISUAL ANGLE	
	B	A
CURVED (16)*	12' 29.3"	6' 26.8"
90° (8)	8' 26.7"	5' 36.1"
60° (6)	8' 35.7"	6' 41.1"
STRAIGHT (14)	7' 33.8"	3' 31.8"

* INDICATES NUMBER OF SETS OF SIX IN AND SIX OUT TRIALS EACH VALUE IS BASED UPON

c. Effect of Glare Source Luminance Upon Perceived Size and Shape of Circles



MERIDIAN	VISUAL ANGLE	
	(A) 0.4 LOG INTENSITY	(B) FULL INTENSITY
0°	6' 32.3"	20' 35.9"
45°	7' 46.1"	13' 16.5"
90°	9' 38.3"	12' 39.2"
135°	6' 9.1"	12' 47.0"
180°	14' 55.0"	13' 8.0"
225°	5' 4.4"	12' 26.6"
270°	3' 8.0"	13' 8.0"
315°	2' 26.2"	20' 33.0"
MEAN	6' 31.1"	14' 29.5"

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Haines (79).

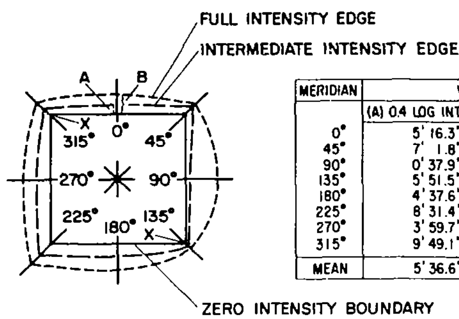
PSYCHOSENSORY

VISUAL

EFFECT OF GLARE ON APPARENT SIZE AND SHAPE

d. Effect of Glare Source Luminance Upon Perceived Size and Shape of Squares

(SQUARE)

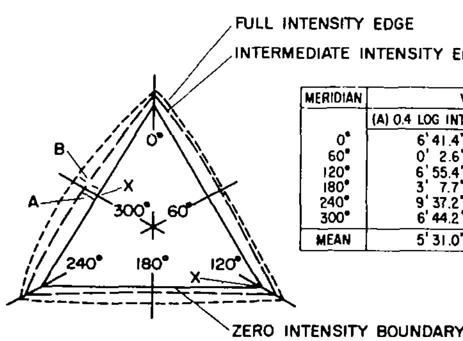


MERIDIAN	VISUAL ANGLE	
	(A) 0.4 LOG INTENSITY	(B) FULL INTENSITY
0°	5' 16.3"	8' 59.2"
45°	7' 1.8"	7' 57.4"
90°	0' 37.9"	12' 3.3"
135°	5' 51.5"	8' 50.0"
180°	4' 37.6"	11' 7.8"
225°	8' 31.4"	14' 9.2"
270°	3' 59.7"	9' 22.4"
315°	9' 49.1"	14' 18.3"
MEAN	5' 36.6"	10' 31.2"

X-X DISTANCE = 1°24'59"

e. Effect of Glare Source Luminance Upon Perceived Size and Shape of Triangles

(TRIANGLE)



MERIDIAN	VISUAL ANGLE	
	(A) 0.4 LOG INTENSITY	(B) FULL INTENSITY
0°	6' 41.4"	6' 58.3"
60°	0' 2.6"	8' 0.8"
120°	6' 55.4"	10' 8.7"
180°	3' 7.7"	7' 15.7"
240°	9' 37.2"	11' 5.1"
300°	6' 44.2"	13' 34.8"
MEAN	5' 31.0"	9' 22.2"

X-X DISTANCE = 1° 30' 50.7"

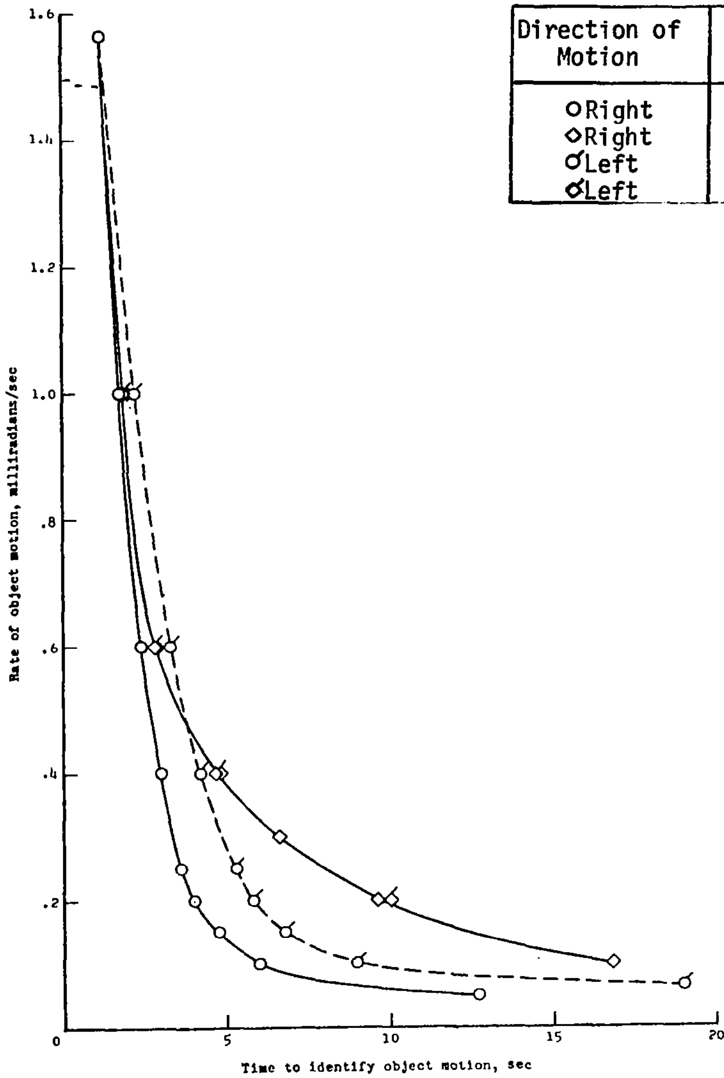
SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Haines (79).

PSYCHOSENSORY

VISUAL

DETECTION OF TARGET MOTION

a. Typical Visual Acuity Showing Effect of Reference Separation and Direction of Motion (Right and Left)*



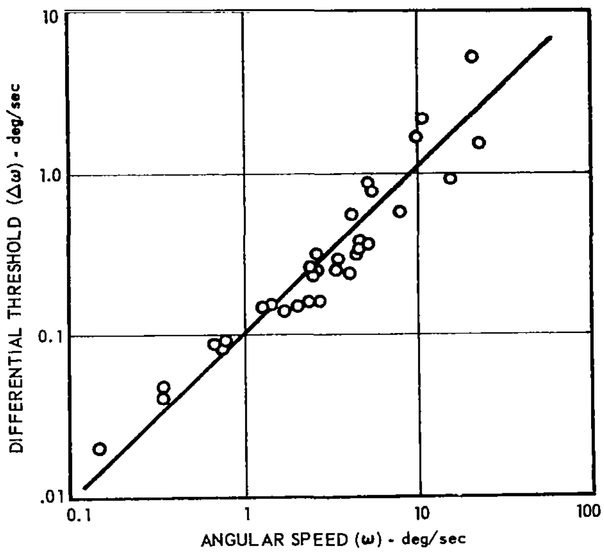
Direction of Motion	Initial Separation Distance, Milliradians
○Right	12.5
◇Right	34.0
♂Left	12.5
♂Left	34.0

* Slow speeds tested first.

SOURCE: Study of Human Pilots Ability to Detect Angular Motion with Application of Control of Space Rendezvous (181).

DETECTION OF TARGET MOTION

b. Differential Threshold of Motion Detection in the Frontal Plane



The differential threshold ($\Delta\omega$) is the amount that the angulár speed of an object moving at right angles to the line of sight must change to be detected as a new speed. Data points shown on the graph are thresholds gathered from eight different experiments, for abrupt changes in speed from ω_1 to ω_2.

When an object stationary in the visual field ($\omega_1 = 0$) is suddenly set in motion, the minimum speed which is perceived as motion ("rate threshold") varies from 1 to 2 minutes of arc per second (0.017 to 0.033 deg/sec).

Threshold for movement in peripheral vision is higher than the threshold in central vision. Effects of illumination and contrast on differential threshold are imperfectly known at this time. The rate threshold is higher at low illumination levels and when no fixed visual reference is available.

SOURCE: Brown (35), Graham (73) and Webb (195).

DETECTION OF TARGET MOTION

c. Perception of Movement in Depth of a Luminous Target

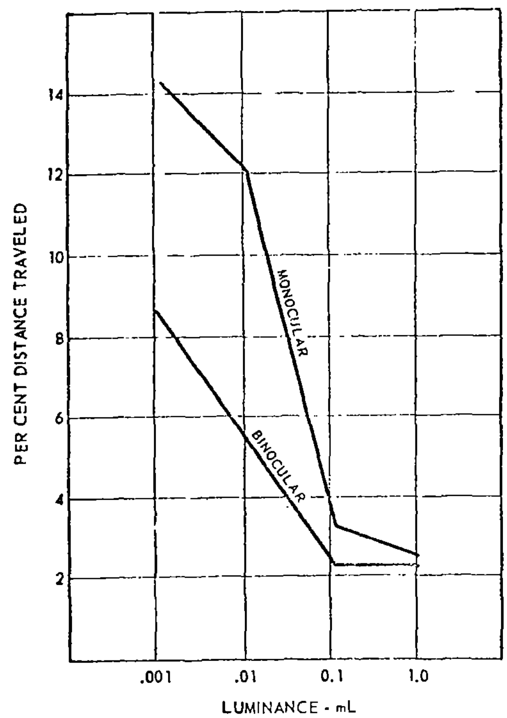


Figure c shows successful perception of movement in depth of a luminous target on a black field as a function of change in visual angle (percent distance traveled) and of luminance.

SOURCE: Baker and Steedman (16) and Webb (195).

DETECTION OF TARGET MOTION

d. Time to Perceive Movement in Depth

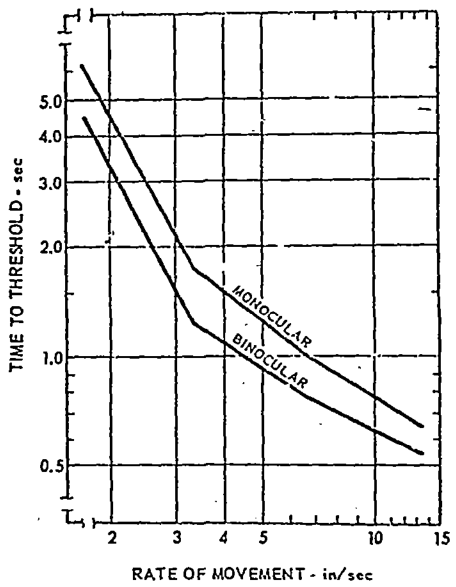


Figure d shows the time required to perceive movement in depth as a function of rate of change of visual angle (target speed). Both curves are for 75% correct responses, where 50% correct would be chance performance, since the target moved both toward and away from the observer, who had to choose the correct direction.

The target was a lamp measuring 3.5 inches in diameter which mas moved back and forth on a track from an initial distance of 25 feet. At the initial distance, the lamp subtended a visual angle of 40 minutes of arc. A 2% change in distance, which was detected as movement at the higher luminance levels, represented a 2% change in visual angle, or a change of about 0.8 minutes of arc. The range of target speeds from 1.65 to 13.2 inches per second produced initial changes in visual angle from about .25 minutes of arc to 2 minutes of arc.

SOURCE: Baker and Steedman (16) and Webb (195).

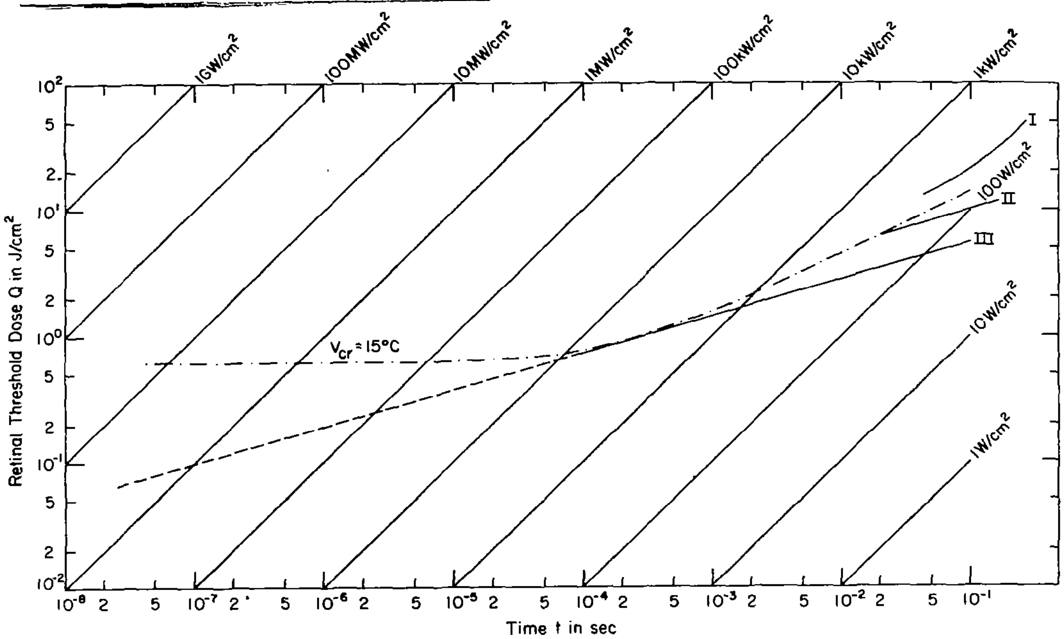
PSYCHOSENSORY

VISUAL

EYE PROTECTION - RETINAL BURN

The maximum dose Q (in J/cm^2) to produce retinal burn, as a function of time of irradiation, with the irradiated retinal area as parameter. Note that the threshold level is lower in the later experiment due to better diagnostic techniques.

a. Retinal Burn - Dose Parameters



For control of electromagnetic transmittance in the visor system, the following has been recommended:

a. Ultraviolet - The transmission of ultraviolet radiation in the range 220-320 nm be such that the total energy incident on the cornea and facial skin shall not exceed 1.0 x 10^5 ergs cm^{-2} in any 24 hours period.

b. Infrared Transmittance - The transmittance of infrared radiation beyond 770 nm not to exceed a total value of 10 percent with all visors in place.

c. Visible - The primary visor have a transmittance in the visible range of at least 85%. The maximum transmittance through the primary visor and the least dense sector of one secondary visor should be 60%. The maximum transmittance utilizing all visors should be 2%.

SOURCE: Compendium of Human Response to the Aerospace Environment, Vol. I (50) and Vos (193).

PSYCHOSENSORY

AUDITORY

TERMS, THRESHOLDS AND LEVELS

a. Terms and Units Used in Audition

Physical		Psychological	
Term	**Unit/Measure**	**Term**	**Unit/Measure**
Frequency	Cycles per second or Hertz	Pitch	Mel
Amplitude	Decibel $L=20 \log(p_1/p_2)$	Loudness	Phon
			Sone
Duration	Seconds/Minutes	Duration	Seconds/Minutes

The unit used to measure intensity, L, in physical units is the decibel (dB) and is expressed as:

$$L = 20 \log (p_1/p_0) \qquad (1)$$

where p_1 = the sound pressure level (SPL) to be measured;

p_0 = a reference pressure, usually 0.0002 bars or dyne/cm^2

The difference between two sound pressure levels is expressed as:

$$L_2 - L_1 = 20 \log (p_2/p_1) \qquad (2)$$

The speed of passage of the zones of compression or rarefaction represents the velocity of sound, which is characteristic of the medium of propagation in given conditions. The separation of corresponding points in successive zones is the wavelength, which is inversely proportional to the frequency, according to the relationship:

$$\text{Wavelength } (\tau) = \frac{\text{Velocity of Sound}(V)}{\text{Frequency } (\eta)} \qquad (3)$$

For example, taking the velocity of sound in air at 0°C to be 1087 ft/sec, a 100 Hz tone will generate a disturbance with a wavelength of 10.87 ft.

The measure of frequency is simply cycles per second or Hz. A range of frequency may be indicated by the octave, which is the interval between any two frequencies having a ratio of 2 to 1. The duration is expressed in seconds or minutes.

SOURCE: Compendium...Vol. II (51) and Sivian and White (170).

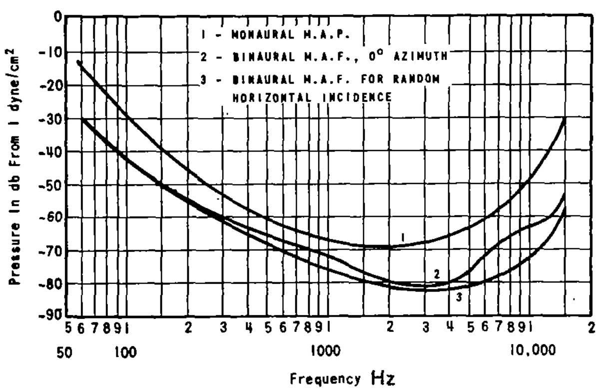
AUDITORY

TERMS, THRESHOLDS AND LEVELS

The psychological measures of loudness are the phon and sone. The phon is merely a transformation of the sone into a logarithmic scale related in specific ways to the sound pressure level of a reference sound. Sounds that have equal sone value or phon value or presumed to be equally loud, and discriminations between the loudness of sounds can be reported in either sone or phones.

b. Absolute Threshold for Intensity and Frequency

The auditory response to the frequency of pure tones is commonly accepted as falling between about 16 and 20,000 Hz.

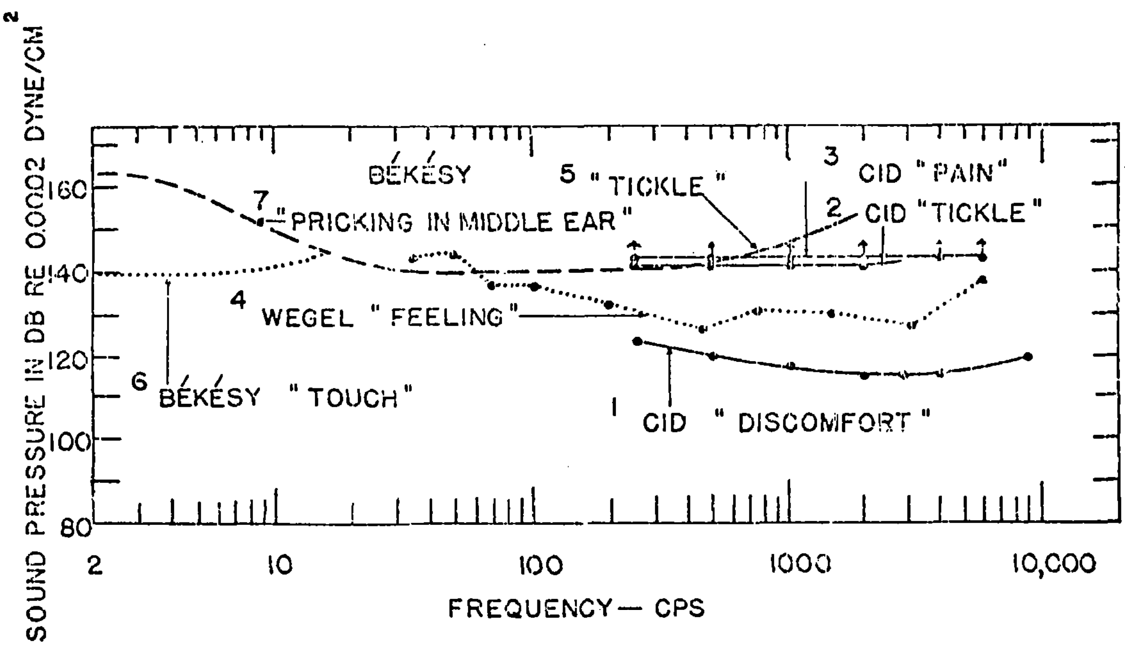


The limits for response to intensity vary as a function of frequency. They are often different for different individuals and the threshold may vary from time to time in the same individual. The limits for response to intensity extend from the minimum level (i.e., absolute threshold) at which a sound can be heard to intensities where feeling and discomfort begin. The minimum intensities to which the ear will respond vary as much as 80 dB with the greatest sensitivity between 2000 and 4000 Hz. Individual differences in absolute thresholds vary as much as 20 dB and can vary as much as 5 dB within a short period of time.

The audibility of a signal depends on the duration since the response of the ear is not instantaneous. For pure tones, about 200-300 msec. are required for buildup and approximately 140 msec. to decay.

SOURCE: Compendium...Vol. II (51) and Sivian and White (170).

c. Tolerance Thresholds for Pure Tones

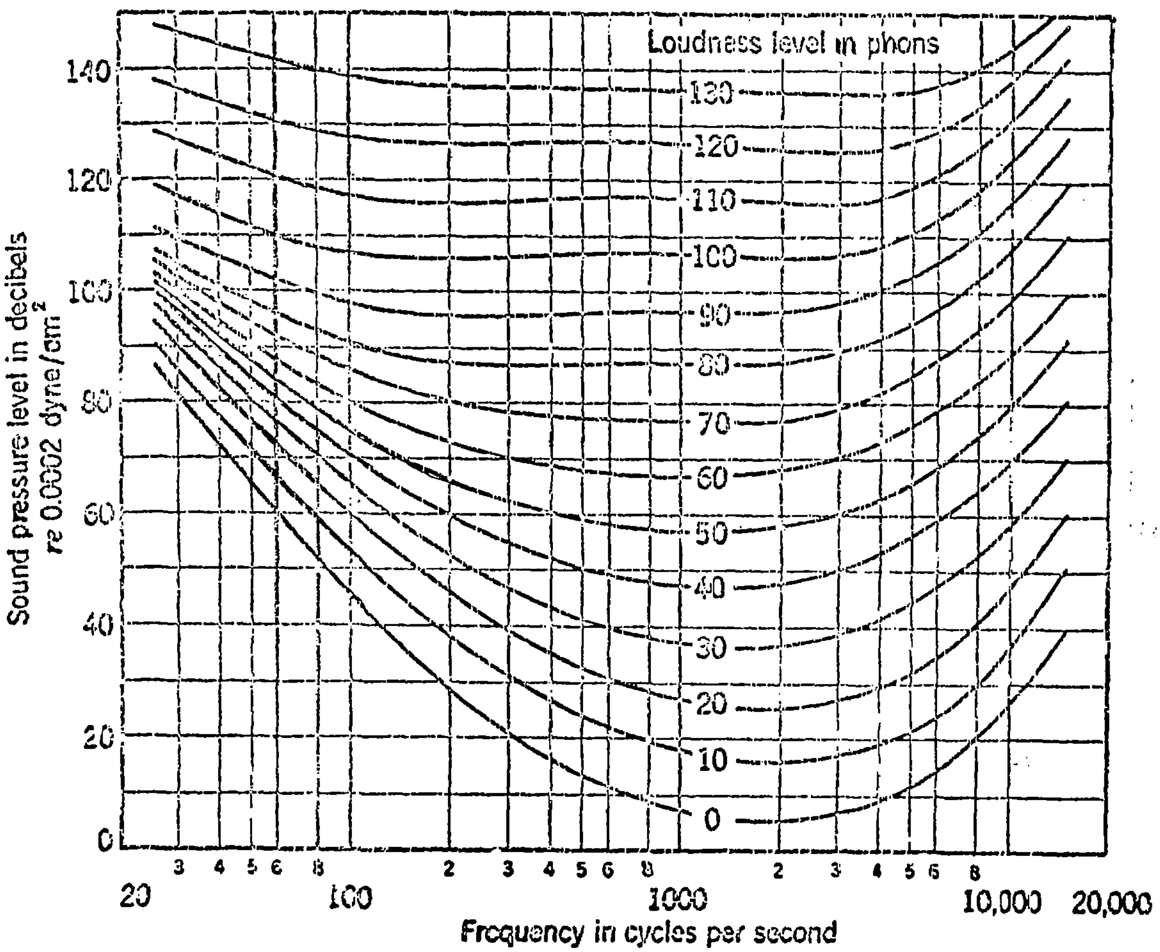


These curves show various determinations of tolerance thresholds for pure tones. Curves 1, 2 and 3 were reported by Silverman at the Central Institute for the Deaf (CID), in St. Louis. Curve 1 shows the intensity level at which, after an extended period of getting used to intense acoustic stimulation, the listeners reported "discomfort", and Curve 2 marks the onset of a "tickling sensation". The limit of the earphones was exceeded before some of the experienced listeners complained of "pain". Curve 4 is the "threshold of feeling" and Curve 5 is Bekesy's threshold of tickle. Bekesy found that at frequencies below 15 Hz his listeners could report consistently in terms of two criteria. Curves 6 and 7, labeled "touch" and "pricking in middle ear" show the central tendencies of the judgments.

SOURCE: Bekesy (20), Licklider (110), Silverman (167) and Wegel (199).

TERMS, THRESHOLDS AND LEVELS

d. Contours of Equal Loudness

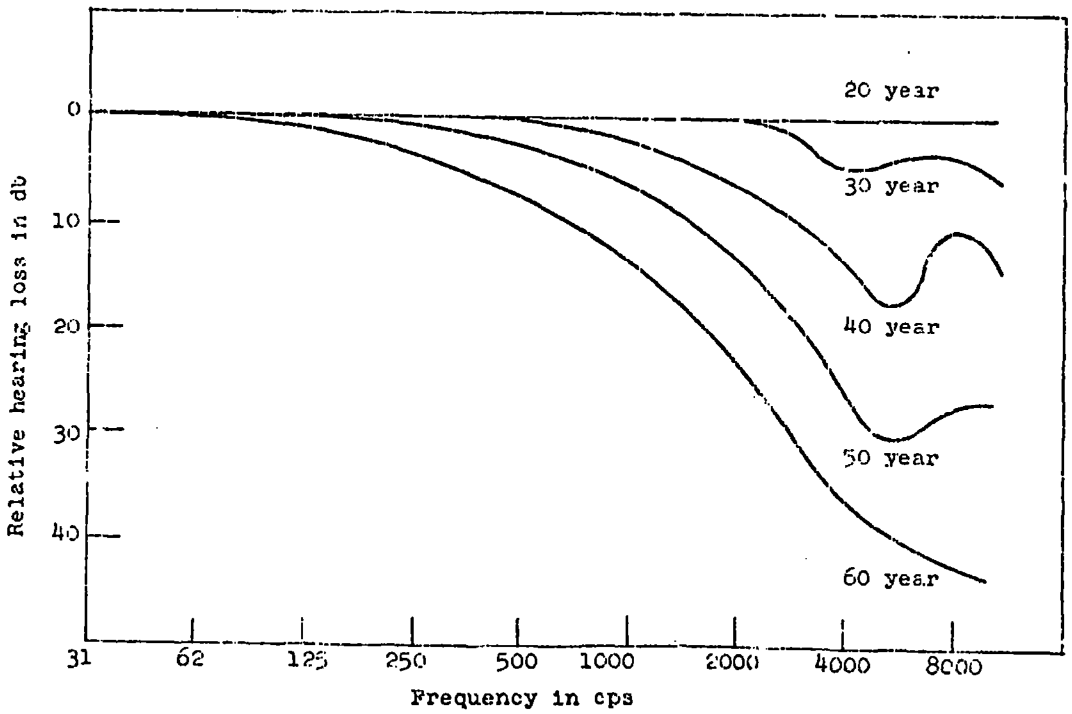


The sound pressure levels were measured at the eardrum, and an earphone was used to deliver the tone.

SOURCE: Fletcher and Munson (66) and Stevens and Davis (175).

TERMS, THRESHOLDS AND LEVELS

e. Progressive Hearing Loss with Increasing Age, as Reported by Bunch

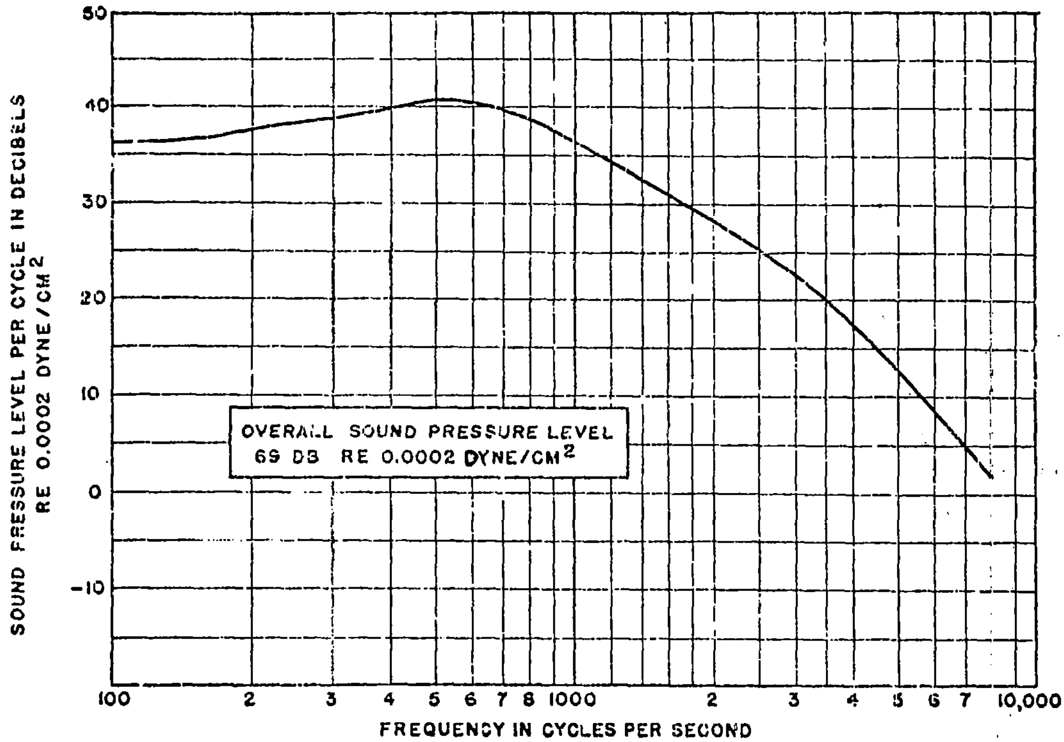


The audiogram at 20 years of age is taken as a basis of comparison (From Morgan).

SOURCE: Bunch (37).

TERMS, THRESHOLDS AND LEVELS

f. Average Spectrum Level of Speech



Average spectrum level of speech measured in one-cycle bands for young male voices talking at a level six decibels below the maximum they could sustain without straining their voices. Microphone placed on meter in front of talkers in an anechoic chamber. One decibel has been added to remove the effect of pauses between words in the total spectrum level.

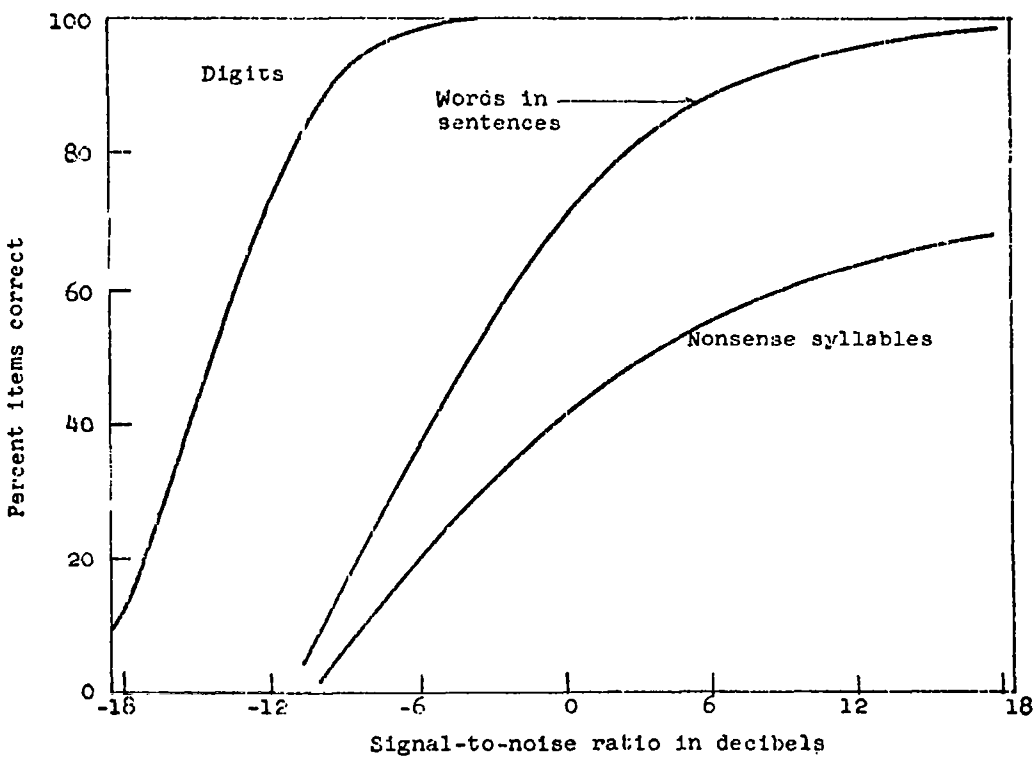
SOURCE: Beranek (20) and Clark, Rudmose, et al (48).

PSYCHOSENSORY

AUDITORY

TERMS, THRESHOLDS AND LEVELS

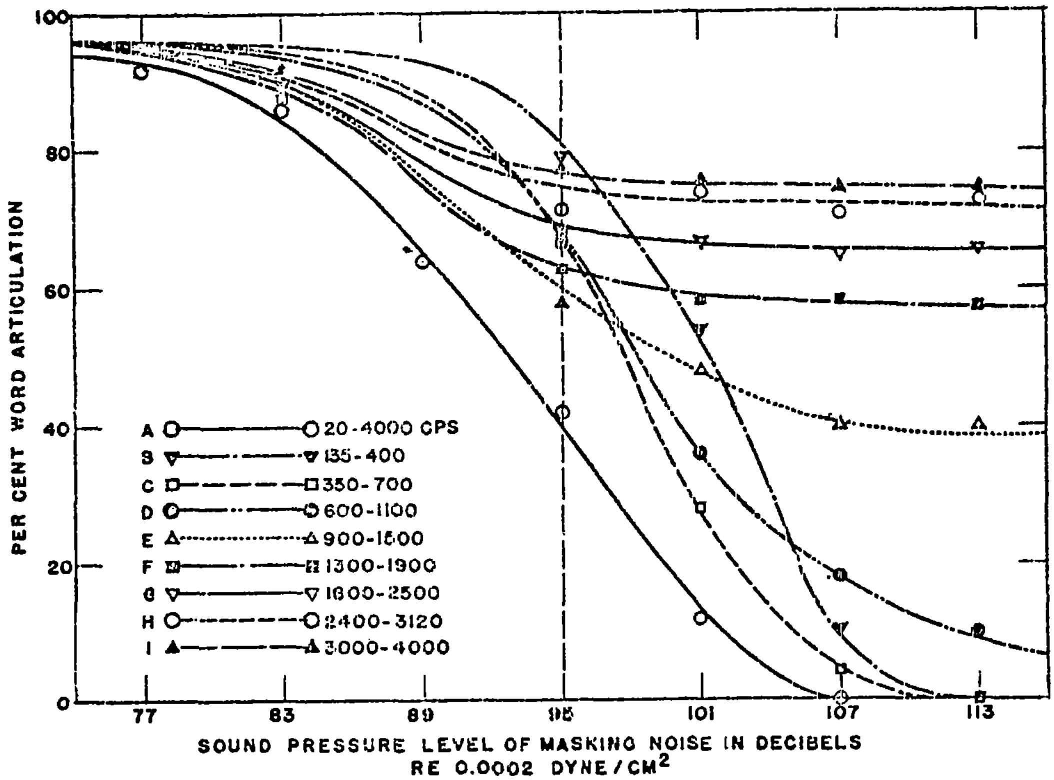
g. Articulation Scores for Three Different Types of Test Material



The test items were masked by white noise, and the percent items correct are plotted as a function of signal-to-noise ratio in decibels.

SOURCE: Miller, Heise, et al (128).

h. The Articulation Score for Monosyllabic Words as a Function of the SPL of the Masking Noise

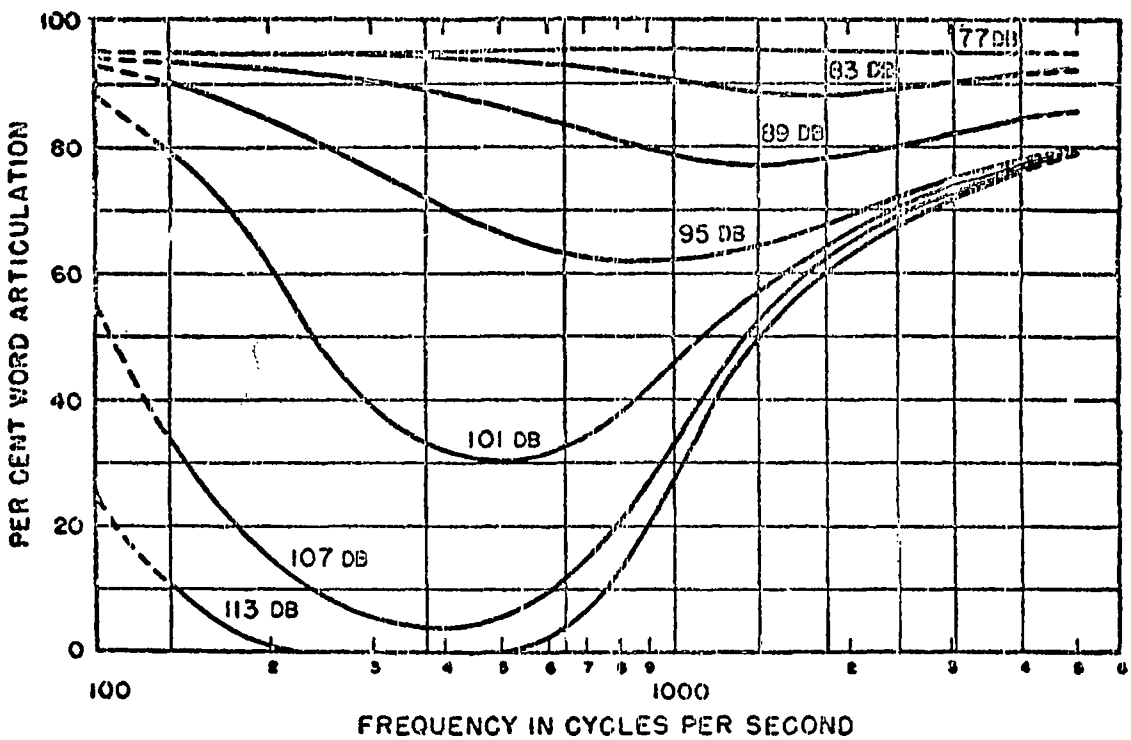


The different frequency bands of noise are parameters. The level of the speech was held constant at 95 db.

SOURCE: Miller (127).

TERMS, THRESHOLDS AND LEVELS

i. Articulation as a Function of the Component Frequencies of the Masking Noise

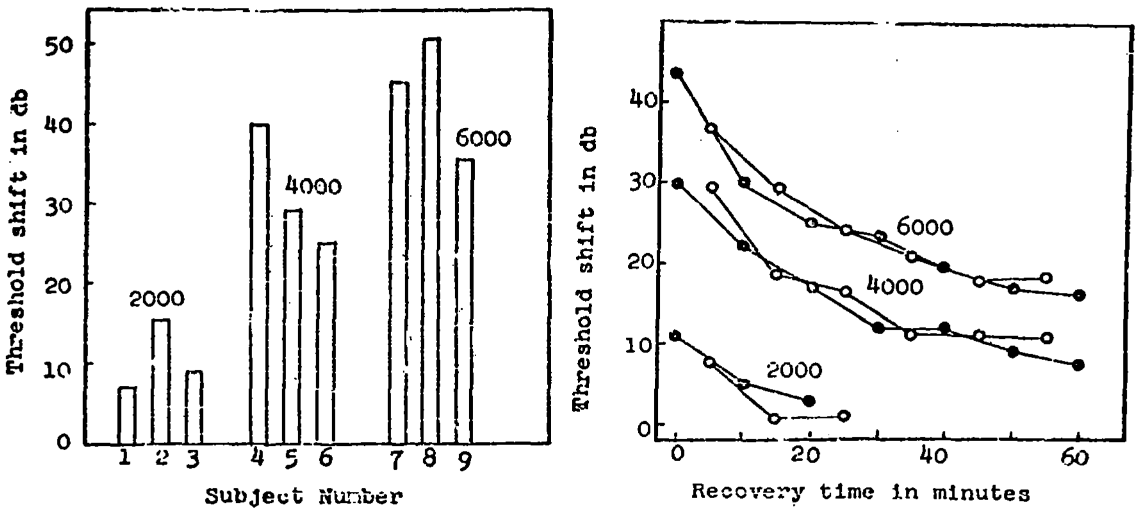


The parameter is the SPL of the masking noise.

SOURCE: Miller (127).

TERMS, THRESHOLDS AND LEVELS

j. Threshold Shifts and Recovery Times



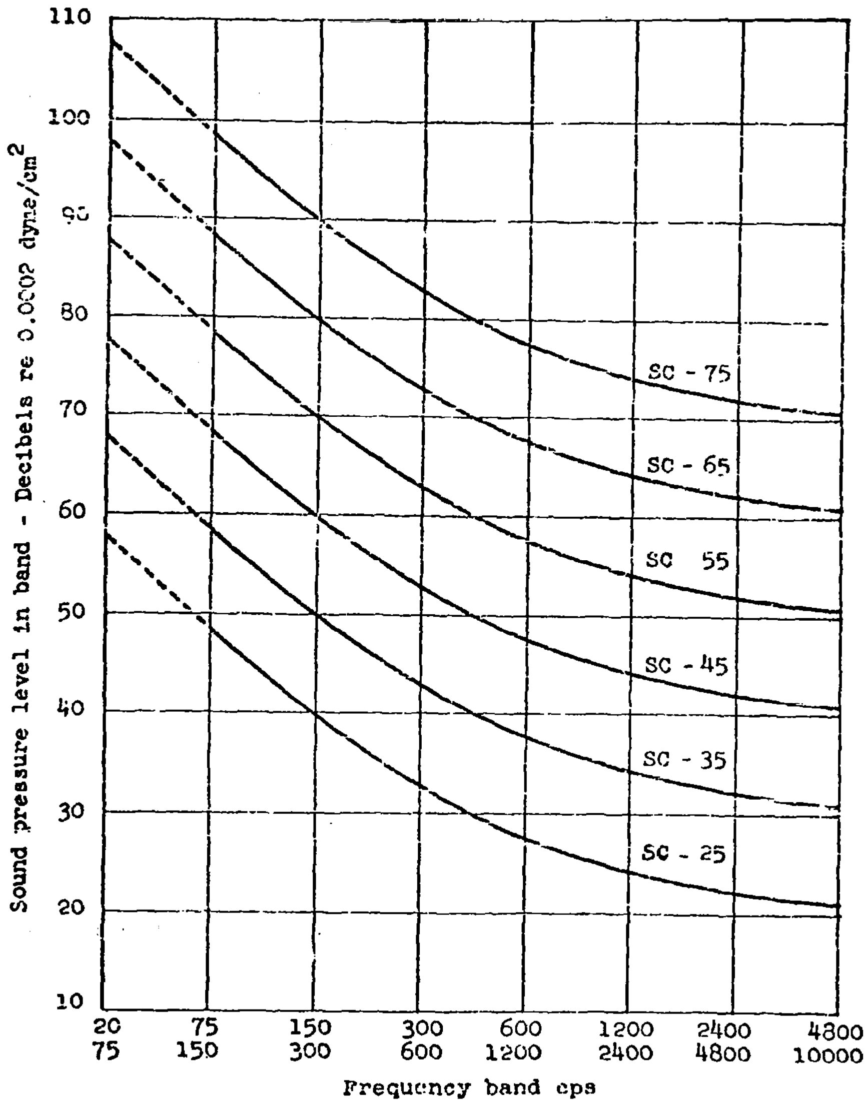
A. Initial threshold shifts at different frequencies, observed after exposure to 30 minutes of thermal noise at 105 db SPL. The exposure stimulus was delivered over a loudspeaker. Each bar represents the mean of three exposures for a different subject.

B. Recovery curves for nine subjects (three at each frequency). Open circles are threshold shifts for right ears, while solid circles indicate threshold shifts for left ears. Each experimental point is the mean of nine post-exposure thresholds.

SOURCE: Wheeler (201).

TERMS, THRESHOLDS AND LEVELS

k. Speech Communication (SC) Criteria



The curves are labeled with numbers equal to the speech interference levels they represent. Each curve specifies the octave-band pressure levels that must not be exceeded if a certain quality of speech communication is to be guaranteed.

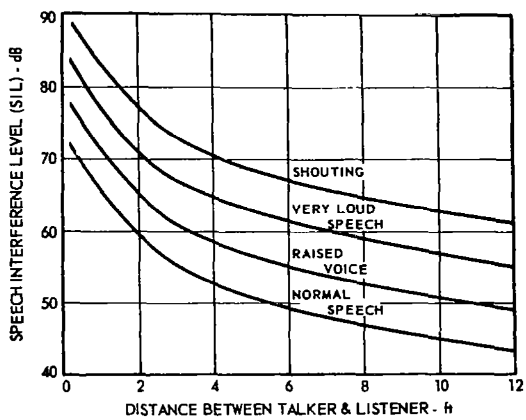
SOURCE: Wheeler (201).

PSYCHOSENSORY

AUDITORY

TERMS, THRESHOLDS AND LEVELS

1. Speech Interference Levels



Speech Interference Level (SIL) is a readily calculated index of the degree to which a complex sound or noise will interfere with speech. It is also often used as a rough estimate of the comfort or acceptability of a potentially annoying noise. SIL is defined as the arithmetic mean of the sound pressure levels (dB re 0.0002 dyne/cm^2) within three octave bands: 600-1200 Hz, 1200-2400 Hz, and 2400-4800 Hz. Table 1 shows the maximum permissible SIL for normal and raised speech associated with various distances between speaker and listener. It should be kept in mind that the SIL is accurate only for broad-band noises with fairly typical spectra.

SIL of the noise estimated at the astronaut's ear during lift-off may be calculated from the dB levels within the three octave bands between 600 and 4800 Hz as shown. These are 81, 60, and 41 dB. SIL is the arithmetic mean of these numbers; therefore, SIL = (81 + 60 + 41)/3 = 61 dB. For the Century fighter overflight, SIL = (118 + 113 + 108)/3 = 113 dB.

Speech communication criteria associated with various SIL levels are shown in table m.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Jerison (94).

TERMS, THRESHOLDS AND LEVELS

m. Speech Communication Criteria

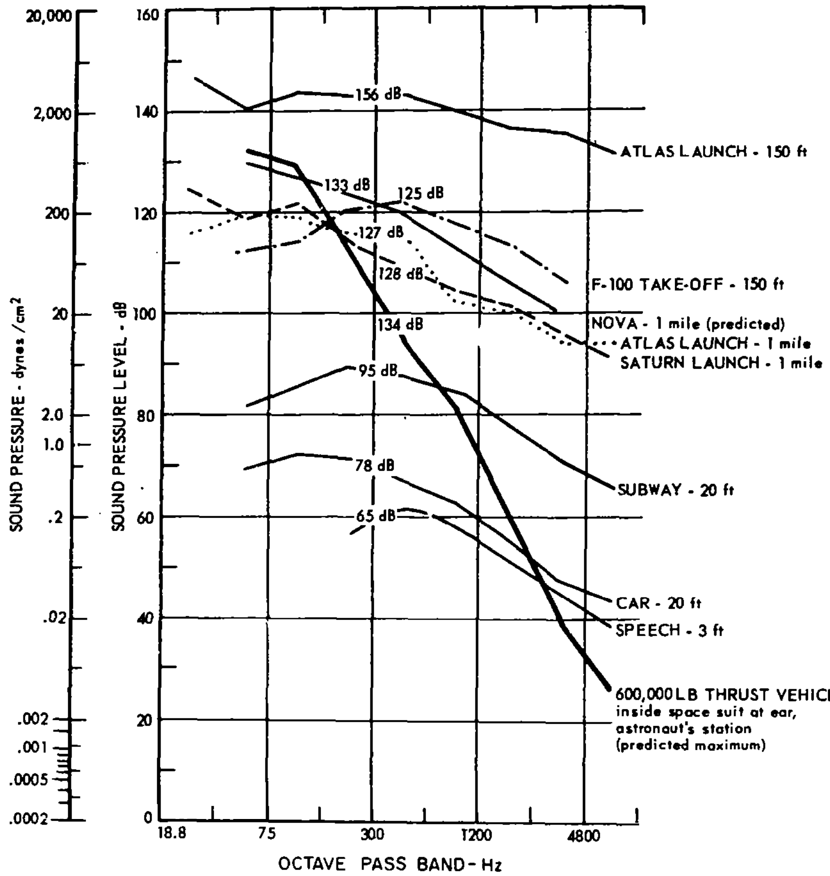
Speech Communication Criteria

SIL dB	Voice Level and Distance	Nature of Possible Communication	Type of Working Area
45	Normal voice at 10 ft.	Relaxed conversation	Private offices, conference rooms
55	Normal voice at 3 ft; raised voice at 6 ft; very loud voice at 12 ft.	Continuous communication in work areas	Business, secretarial, control rooms of test cells, etc.
65	Raised voice at 2 ft; very loud voice at 4 ft; shouting at 8 ft.	Intermittent communication	
75	Very loud voice at 1 ft; shouting at 2-3 ft.	Minimal communication (danger signals; restricted prearranged vocabulary desirable)	

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Jerison (94).

TERMS, THRESHOLDS AND LEVELS

n. Rocket Noise and Everyday Sounds



This graph shows physical descriptions of some common and uncommon sounds. Measurements with commerical sound level meters and octave band analyzers give sound pressure level (SPL) in decibels (dB) relative to the reference level, and the ordinate can serve as a nomogram for converting from one measure to the other. (The conversion is logarithmic.) Overall sound pressure level of each curve is shown numerically on the curve. The source of each curve and the distance between the point of measurement and the noise source are indicated at the right. Major differences between rocket noises from either Atlas, Saturn, or (predicted) Nova and other sources are in the very high energies of the rockets at frequencies below 75 Hz. The very unusual spectrum of noise predicted for the Mercury astronauts was based on the sound shielding properties of the capsule, space suit, helmet, and earphones of the Mercury configuration. These attenuate higher frequency sound more effectively than lower frequency sound.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Jerison (94).

PSYCHOSENSORY

AUDITORY

SOUND DISCRIMINATION

a. Difference Thresholds for Intensities of Signals

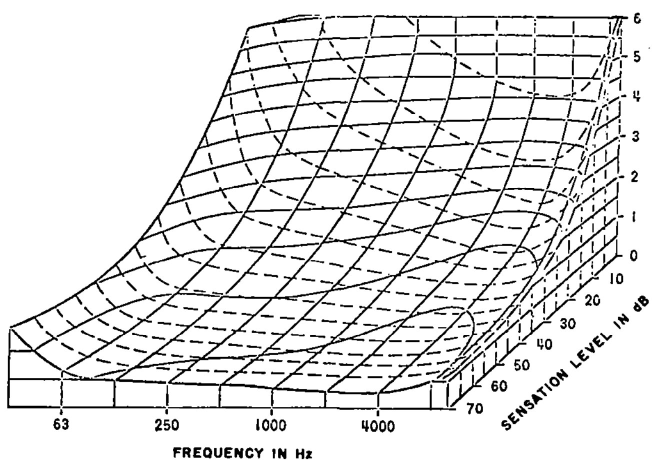


Figure a presents a three-dimensional surface showing the differential intensity thresholds as a function of the frequency and the intensity of the standard tone. The threshold is represented as the difference in decibels between the standard intensity and the standard plus the increment. Following the contour lines from 1000 Hz and 30 dB, one sees, by way of illustration, that the intensity of a 1000 Hz tone must be raised 1.0 dB from a level of 30 dB above threshold before the average observer can detect the change. If one starts with levels 60 or 70 dB above threshold, he finds that an increment of less than 0.5 dB is detectable.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Stevens (174).

SOUND DISCRIMINATION

b. Difference Thresholds for Frequency of Signals

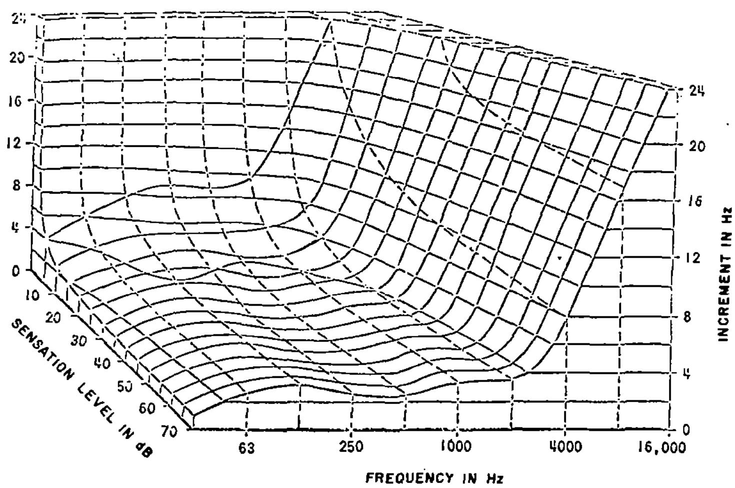


Figure b presents a three-dimensional surface showing the differential frequency threshold as a function of the frequency and the intensity of the standard tone. Frequency discrimination is poor at intensity levels near the absolute threshold (rear part of figure) and at high frequencies (right-hand part of figure). At sensation levels above 30 dB and at frequencies below 1000 Hz, however, a change of about 3 Hz can be detected.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Stevens (174).

SOUND DISCRIMINATION

c. Message Perception

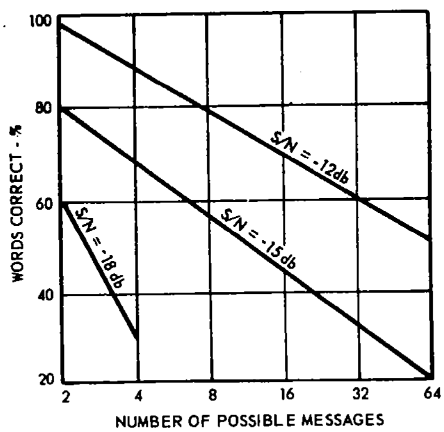


Figure c shows how the correct perception of spoken messages is affected by the diversity of responses required of the observer. As the number of possible messages (standard, two-syllable words) increases from 2 to 64, the percentage of correct reports about the messages drops. The relationship is poorer when the signal signal/noise ratio, shown here in dB, is lower.

d. Message Intelligibility

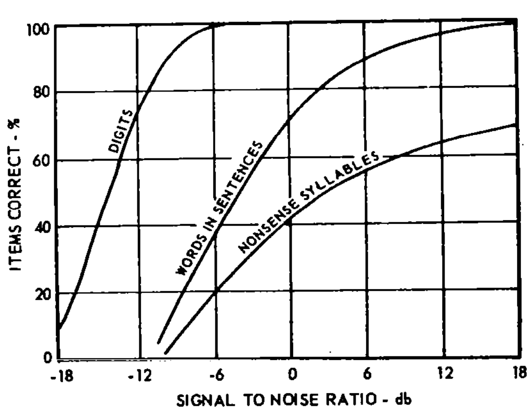


Figure d shows similar effects with other materials graphed in a different way. It shows that single numbers (digits) are detected correctly more easily than are words in sentences, and words in sentences are detected correctly more easily than nonsense syllables. This is a special case of the effect shown in figure c. In general, the less "information" the sender-receiver system has to process, the more accurate the processing. In figure c, the system is processing from 1 to 6 "bits" of information (that is, 64 messages = 2^6 message = 6 "bits"). In figure d, the amount of information processes varies from a little over 3 "bits" for digits to unknown but higher amounts for the other categories. It is clear that communications can be improved by using a limited vocabulary; the smaller the vocabulary, the better the system.

SOURCE: Compendium...Vol. II (51), Gale, Morgan, et al (69), Jerison (93), Miller, Heise, et al (128) and Pollack (145).

SOUND DISCRIMINATION

e. Effects of Visual Cues on Intelligibility

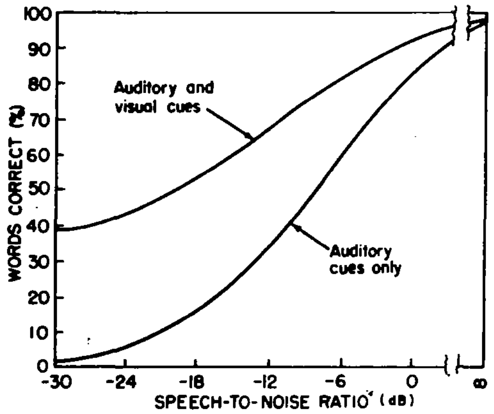


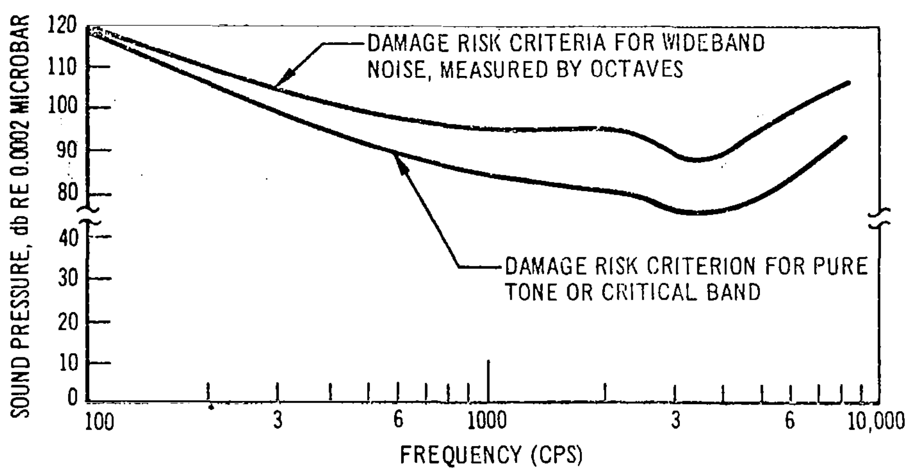
Figure e shows that the increment of intelligibility contributed by visual cues is a function of the prevailing speech-to-noise ratio; if the speech-to-noise ratio is high, the listeners hear the words clearly and therefore cannot take advantage of the cues provided by lip reading; if the speech-to-noise ratio is low, they need, and they in fact use, the visual cues.

SOURCE: Compendium...Vol. II (51), Gale, Morgan, et al (69), Jerison (93), Miller, Heise, et al (128) and Pollack (145).

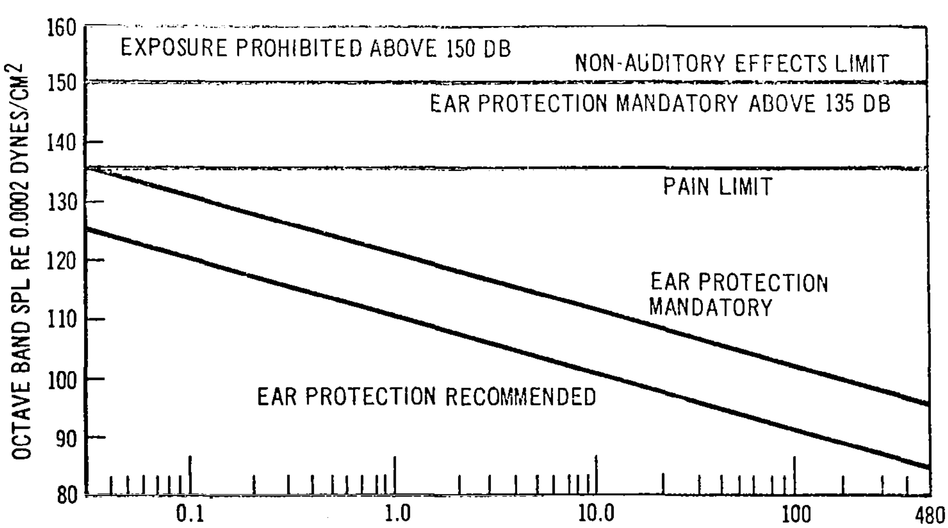
SOUND/NOISE

DAMAGE TO HEARING

a. Pure Tone and Wide Band Noise Damage Risk Criteria



b. Short Term Damage Risk Criteria (Wideband Noise)

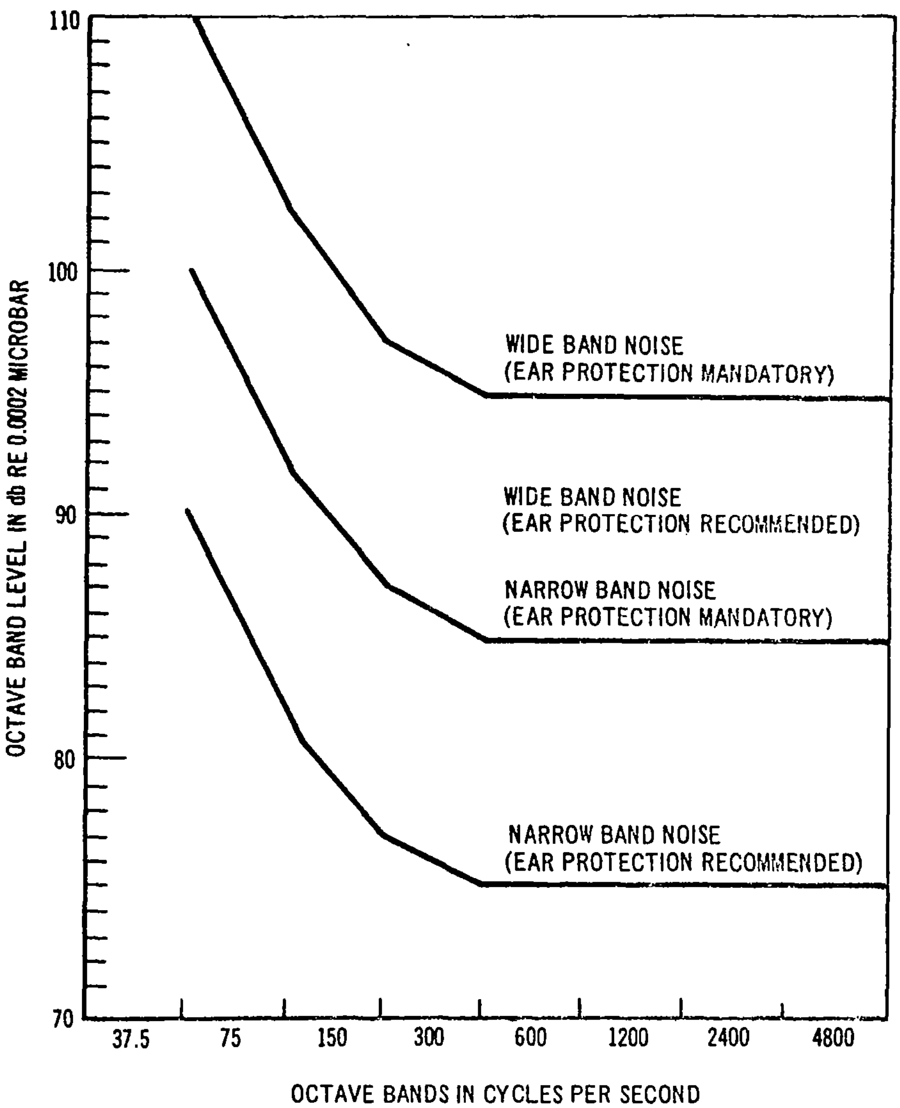


EXPOSE EXPOSURE TIME - MINUTES

SOURCE: Beranek (22), Human Engineering Design Criteria (88), Kryter(104) and Rosenblith, Stevens, et al (153).

DAMAGE TO HEARING

c. Long Term (8 Hour) Damage Risk Criteria



SOURCE: Human Engineering Design Criteria (88).

SOUND CONTROL RECOMMENDATIONS

a. SIL Criteria

SPEECH INTERFERENCE LEVEL(db)	PERSON-TO-PERSON COMMUNICATION
30-40	Communication in normal voice satisfactory.
40-50	Communication satisfactory in normal voice 3 to 6 ft; and raised voice 6 to 12 ft; telephone use satisfactory to slightly difficult.
50-60	Communication satisfactory in normal voice 1 to 2 ft; raised voice 3 to 6 ft; telephone use slightly difficult.
60-70	Communication with raised voice satisfactory 1 to 2 ft; slightly difficult 3 to 6 ft. Telephone use difficult. Ear plugs and/or ear muffs can be worn with no adverse effects on communications.
70-80	Communication slightly difficult with raised voice 1 to 2 ft; slightly difficult with shouting 3 to 6 ft. Telephone use very difficult. Ear plugs and/or ear muffs can be worn with no adverse effects on communications.
80-85	Communication slightly difficult with shouting 1 to 2 ft. Telephone use unsatisfactory. Ear plugs and/or ear muffs can be worn with no adverse effects on communications.
OVERALL SPEECH LEVEL(db)MINUS SIL(db)*	Communications via earphones or loudspeaker.
+10 db OR GREATER	Communication satisfactory over range of SIL 30 to maximum SIL permitted by exposure time.
+5 db	Communication slightly difficult. About 90 percent of sentences are correctly heard over range of SIL 30 to maximum SIL permitted by exposure time.
0 db TO -10 db	Special vocabularies (i.e., radio-telephone voice procedures) required. Communication difficult to completely unsatisfactory over range of SIL 30 to maximum SIL permitted by exposure time.

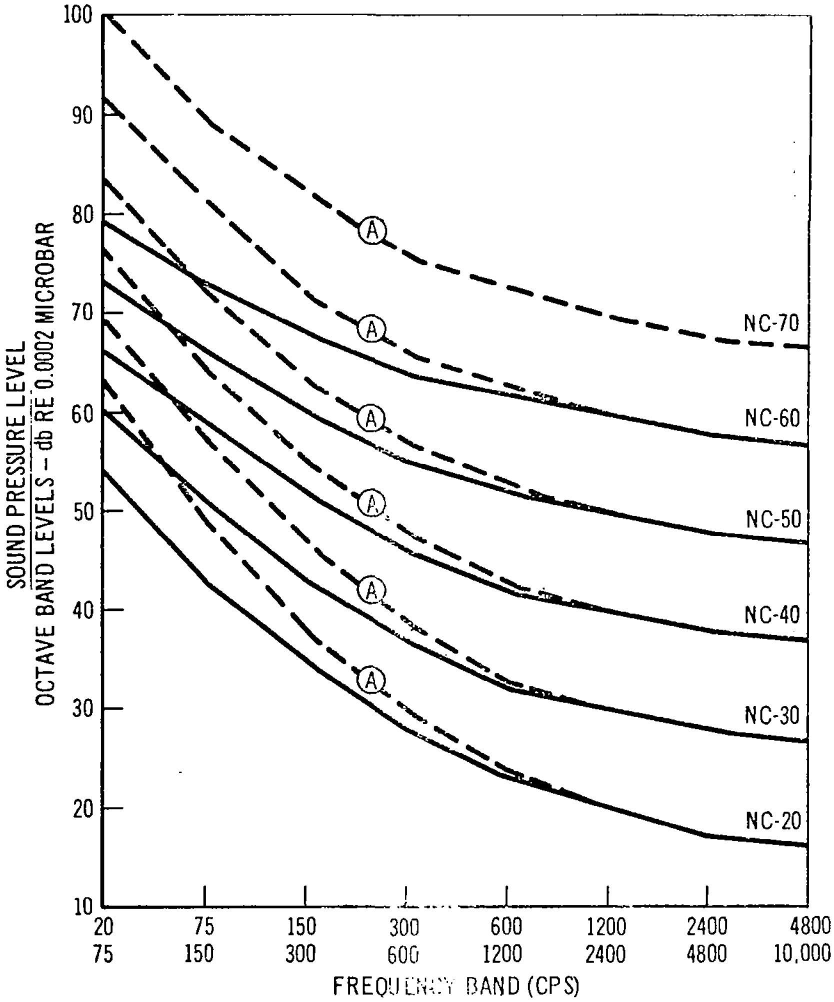
*The overall long-time RMS sound pressure level of speech and the SIL for the noise must be measured at or estimated for a position in the ear canal of the listener. The long-time RMS value of speech can be approximated by subtracting 4 db from the peak VU meter readings on monosyllabic words.

**Ear plugs and/or muffs worn in noise having SIL's above 60 db will not adversely affect communication and will extend maximum permissible SIL in accordance with protection provided.

SOURCE: Human Engineering Design Criteria (88) and Von Gierke and Pietrasanta (192).

SOUND CONTROL RECOMMENDATIONS

b. Noise Criteria Curves



The NC curves (solid lines) are recommended for specifications whenever a favorable relation between the low and the high frequency portion of the spectrum is desired. The NCA curves are the maximum recommended deviation from the NC curves whenever economy dictates a maximum compromise and where, in addition, the noise is steady and free of beats between low frequency components.

SOURCE: Beranek (23) and Human Engineering Design Criteria (88).

SOUND CONTROL RECOMMENDATIONS

c. Frequency Bands that Contribute Equally to Speech Intelligibility

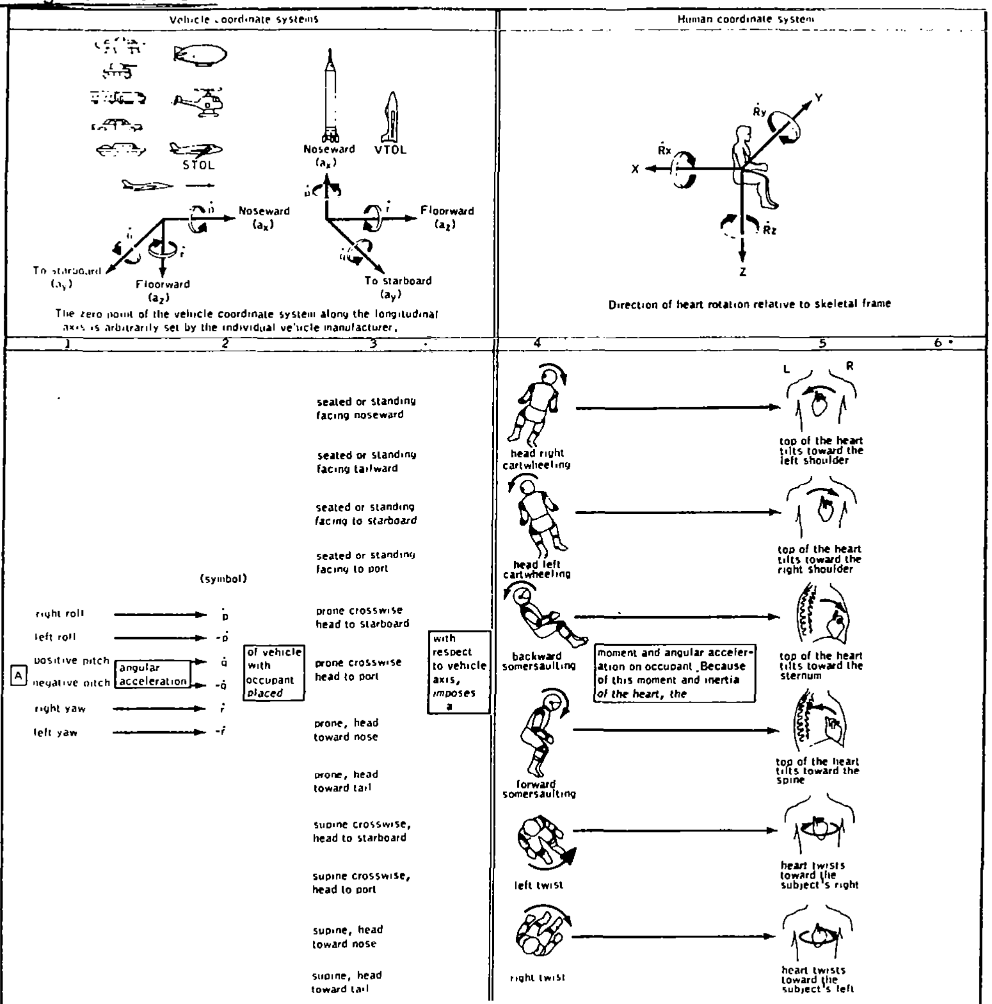
BAND NUMBER	FREQUENCY (CPS)			BANDWIDTH
	LOWER	MIDDLE	UPPER	
1	200	270	330	130
2	330	380	430	100
3	430	490	560	130
4	560	630	700	140
5	700	770	840	140
6	840	920	1,000	160
7	1,000	1,070	1,150	150
8	1,150	1,230	1,310	160
9	1,310	1,400	1,480	170
10	1,480	1,570	1,660	180
11	1,660	1,740	1,830	170
12	1,830	1,920	2,020	190
13	2,020	2,130	2,240	220
14	2,240	2,370	2,500	260
15	2,500	2,660	2,820	320
16	2,820	2,900	3,200	380
17	3,200	3,400	3,650	450
18	3,650	3,950	4,250	600
19	4,250	4,650	5,050	800
20	5,050	5,600	6,100	1,050

SOURCE: French and Steinberg (67) and Human Engineering Design Criteria (88).

DESCRIPTIVE STANDARD NOMENCLATURES

These tables develop in greater physical and anatomical detail, the equivalence of the different nomenclatures for the vehicular and human coordinate systems.

a. Angular Motion



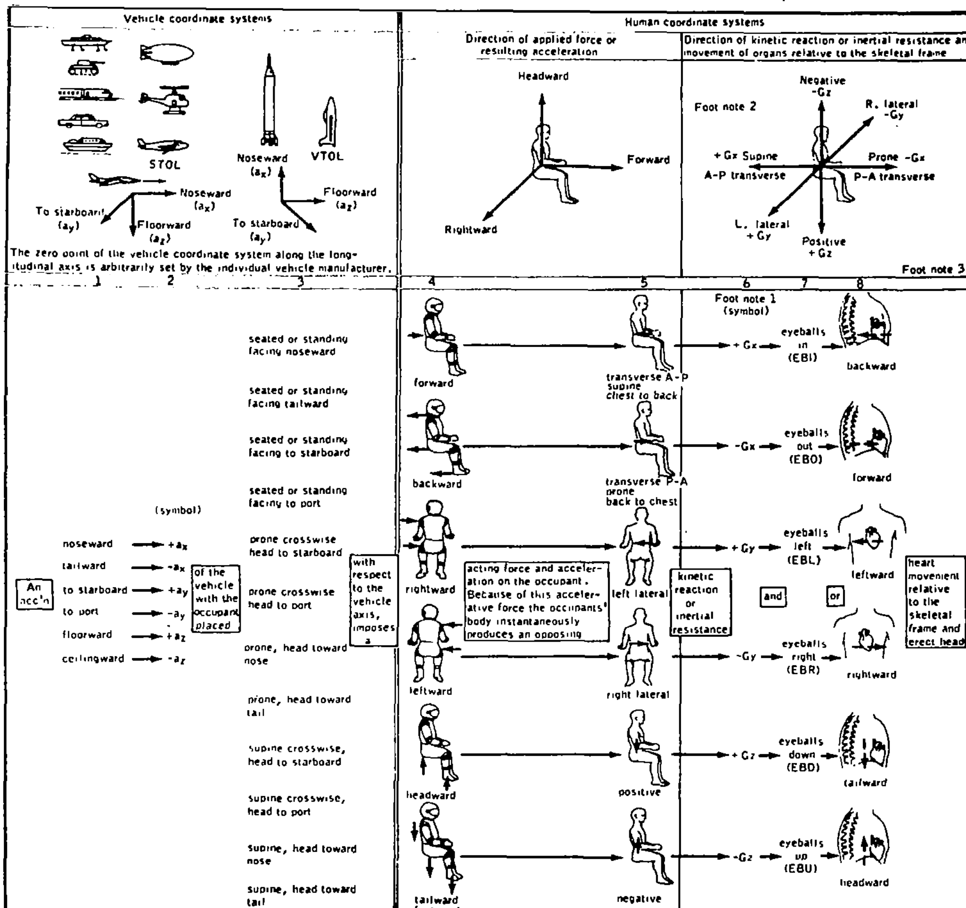
The inter-relationships between vehicle acceleration, the consequent force acting on occupant, and terms used to describe directions of these variables are shown in table. These various possible inter-relationships are derived as follows Direction of *vehicle acceleration, based on above vehicle coordinate systems, is selected in column 1. Position of occupant with respect to* vehicle is selected in column 3. Direction of force acting on vehicle, column 1, combined with occupant's position with respect to vehicle, column 3, determines direction of force with respect to occupant. This result then determines proper relationship to be selected in column 4. Once correct selections have been made, the two sentences, reading from left to right, list terms and symbols in present use to describe the directions of forces and accelerations of body and organ movement relative to skeletal frame. Sentences also describe relationships that must exist because of Newton's laws of motion.

* Footnote
Statements true only when intersection of axes is below heart.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Pesman (144).

DESCRIPTIVE STANDARD NOMENCLATURES

b. Linear Motion



Inter-relationships between vehicle acceleration, the consequent force acting on the occupant, and terms used to describe directions of these variables are shown in the table. Possible inter-relationships are derived as follows: Direction of the vehicle acceleration, based on the above vehicle coordinate system, is selected in column 1. Position of an occupant with respect to the vehicle is selected in column 3. Direction of force acting on vehicle, column 1, combined with the occupant's position with respect to vehicle, column 3, determines direction of force with respect to occupant. Result then determines proper relationship to be selected in column 4. Once correct selection has been made, the two sentences, reading from left to right, list terms and symbols in present use describing directions of forces and accelerations of body, and organ movement relative to skeletal frame. Sentences also describe relationships that must exist because of Newton's laws of motion.

Footnotes:

1. Large letter, G, used as unit to express whole body acceleration in multiples of the acceleration of gravity. Acceleration of gravity, $g_0 = 980.665$ cm/sec^2 or 32.1739 ft/sec^2.
2. A-P, P-A refers to anterior-posterior, posterior-anterior.
3. *Symbols (±Gxyz) represent orthogonal directions of kinetic reaction opposing applied force and thus units must be pounds* of reaction force per pound of involved object. Laws of motion indicate that "G" may not represent an acceleration in situations and context depicted, and statement "a + Gx acceleration" would be a misnomer.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II(51) and Pesman (144).

FACTORS EFFECTING HUMAN G TOLERANCE

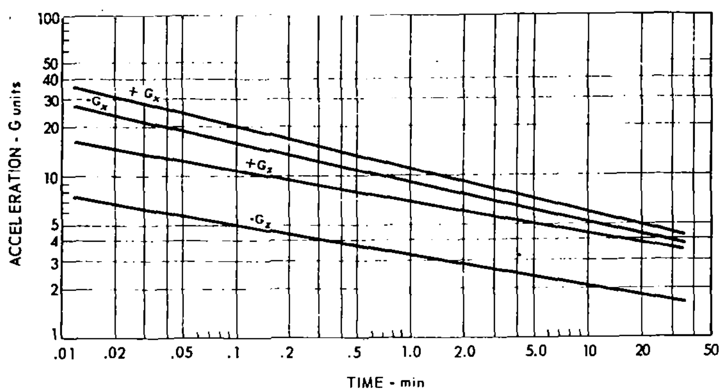
a. Typical Human G Tolerance Considerations

- Magnitude of the peak or peaks of of acceleration
- Duration of the peak or peaks of acceleration
- Total duration of the acceleration from time of onset to completion of offset
- Direction of the primary or resultant acceleration with respect to the body axes (vector)
- Gradient of inertial effects along body in short-armed centrifuges
- Rate of onset and offset
- Types of end points used in determining tolerance (physiological and performance limits may be related but need not be same; portion of G profile when test performed)
- Types of G-protection devices and body restraints used; also the coupling between the individual and the vehicle of application (seat, couch, etc.)
- Body position, including specific back, head, and leg angles
- Environmental conditions such as temperature, ambient pressure and lighting
- Anthropomorphic form of the specific test animal's body and its components which modify the transmission of force (impedance)
- Age of subject
- Emotional factors such as fear and anxiety, confidence in self and apparatus, and willingness to tolerate discomfort and pain
- Motivational factors such as competitive attitude, desire to be selected for a particular space project, or specific pay, recognition, or awards
- Previous acceleration training and accumulative effects
- Techniques of breathing, straining, and muscular control; and G-protection devices

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II(51).

FACTORS EFFECTING HUMAN G TOLERANCE

b. Crude Comparison of G-Tolerance in Four Vectors of G



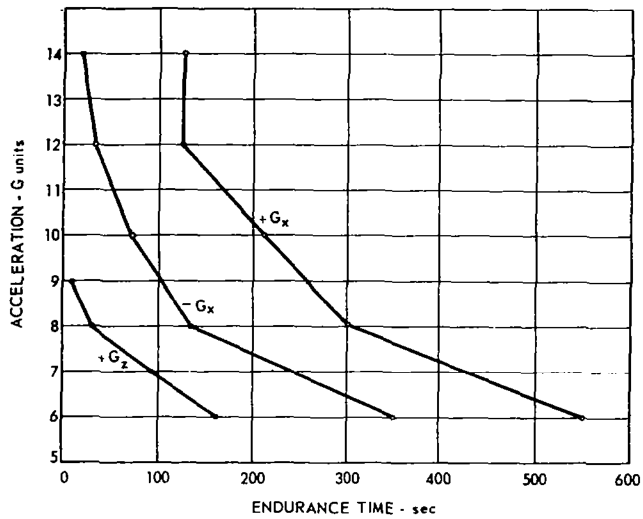
AVERAGE TOLERANCE

Acceleration tolerance is shown for ($+G_Z$), ($-G_Z$), ($+G_X$), and ($-G_X$). The end point criteria are different for each of the vectors, and back angle may be different within each curve.

SOURCE: Chambers (43) and Compendium of Human Responses to the Aerospace Environment, Vol. II (51).

FACTORS EFFECTING HUMAN G TOLERANCE

c. G-Tolerance for Test Pilots



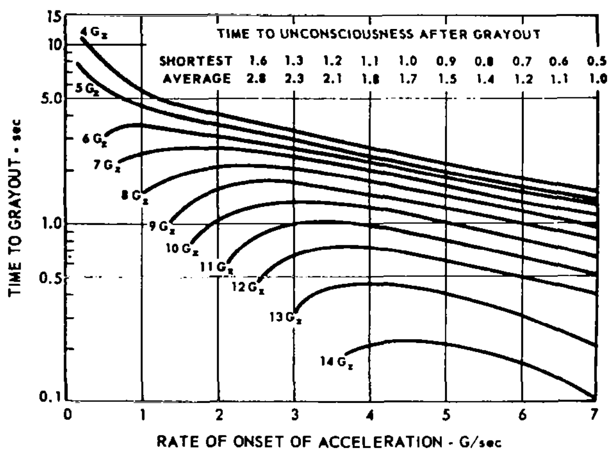
VOLUNTARY ENDURANCE

Upper limits (as contrasted with average tolerances shown) are plotted for a group of highly motivated test pilots, preconditioned to the effects of acceleration and suitably restrained. The pilots were able to operate satisfactorily a side-arm control device to perform a tracking task throughout the times indicated.

SOURCE: Chambers (43) and Compendium of Human Responses to the Aerospace Environment, Vol. II (51).

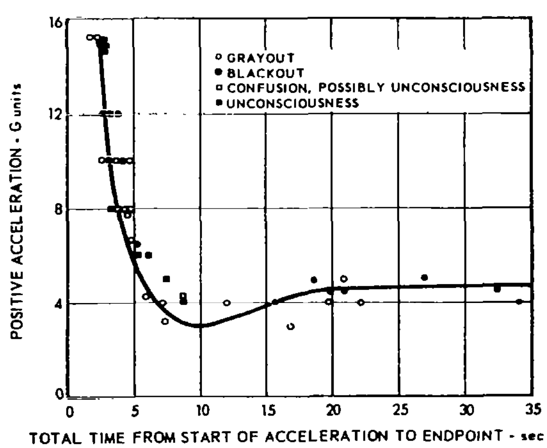
FACTORS EFFECTING HUMAN G TOLERANCE

d. Gray Out Tolerance Time as a Function of Rate of Acceleration Onset



This graph relates the onset rate of acceleration to time-to-end-point. It shows that for any given positive acceleration (G_Z) from 4 to 14G, the time to grayout depends on how rapidly the acceleration level was reached. Further, the table inset in the graph shows the shortest times and the average times for unconsciousness to develop following grayout, each pair of values being related to an onset rate. For example, at onset rate of 4G/sec, the shortest time to unconsciousness was 1.1 sec, and the average 1.8 sec.

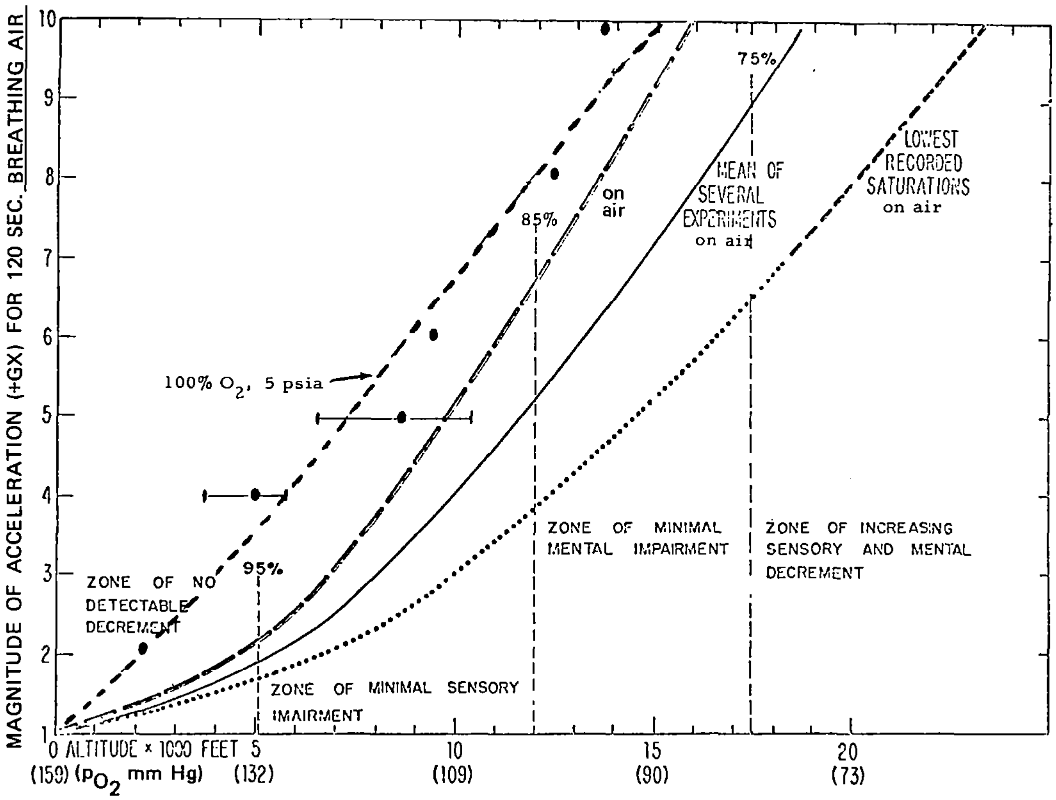
e. Human Tolerance to Positive G_Z for Varying Rates of Onset, G Amplitudes, and Exposure Times.



SOURCE: Chambers (43) and Compendium of Human Responses to the Aerospace Environment, Vol. II (51).

FACTORS EFFECTING HUMAN G TOLERANCE

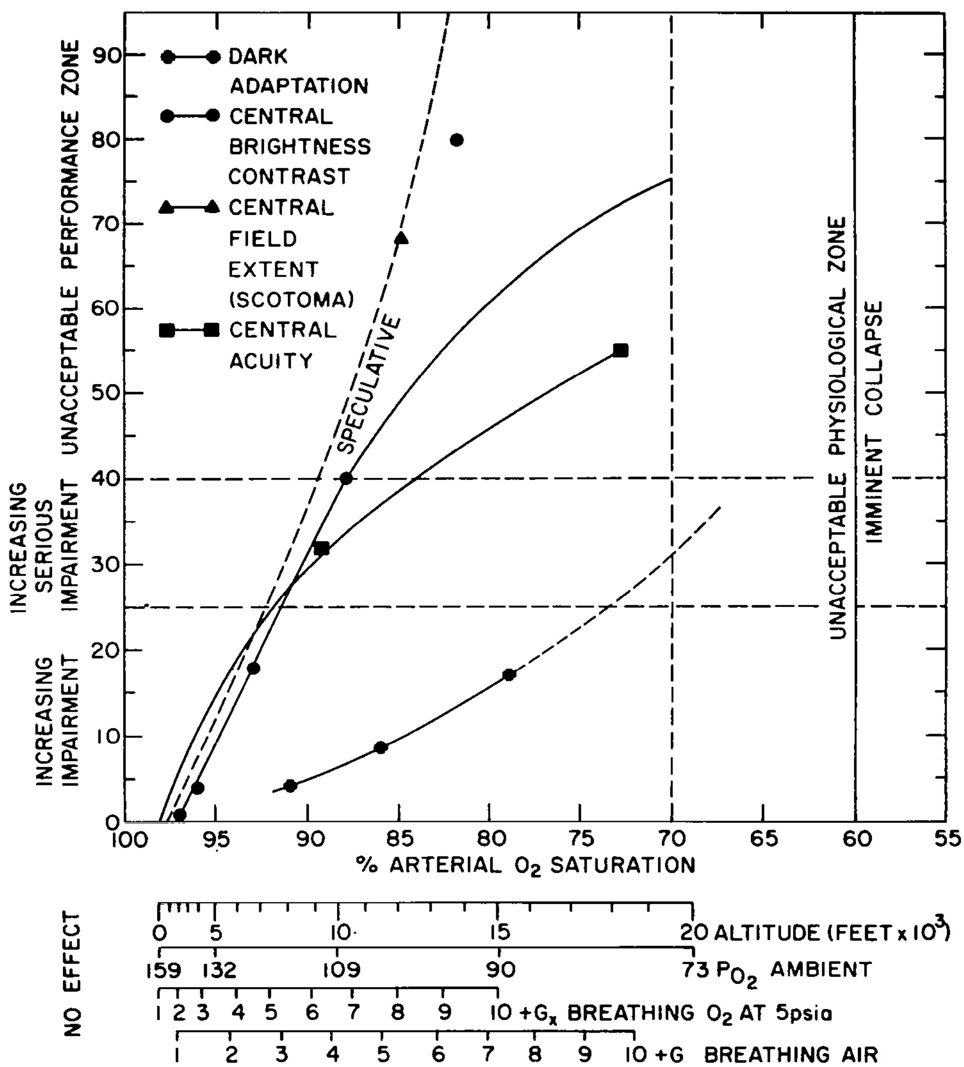
f. Impairment of Performance Predicted for Different $+G_X$ Levels Breathing Air and Oxygen at 5 PSIA Equated to Performance at Different Altitudes



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Teichner and Craig (188).

FACTORS EFFECTING HUMAN G TOLERANCE

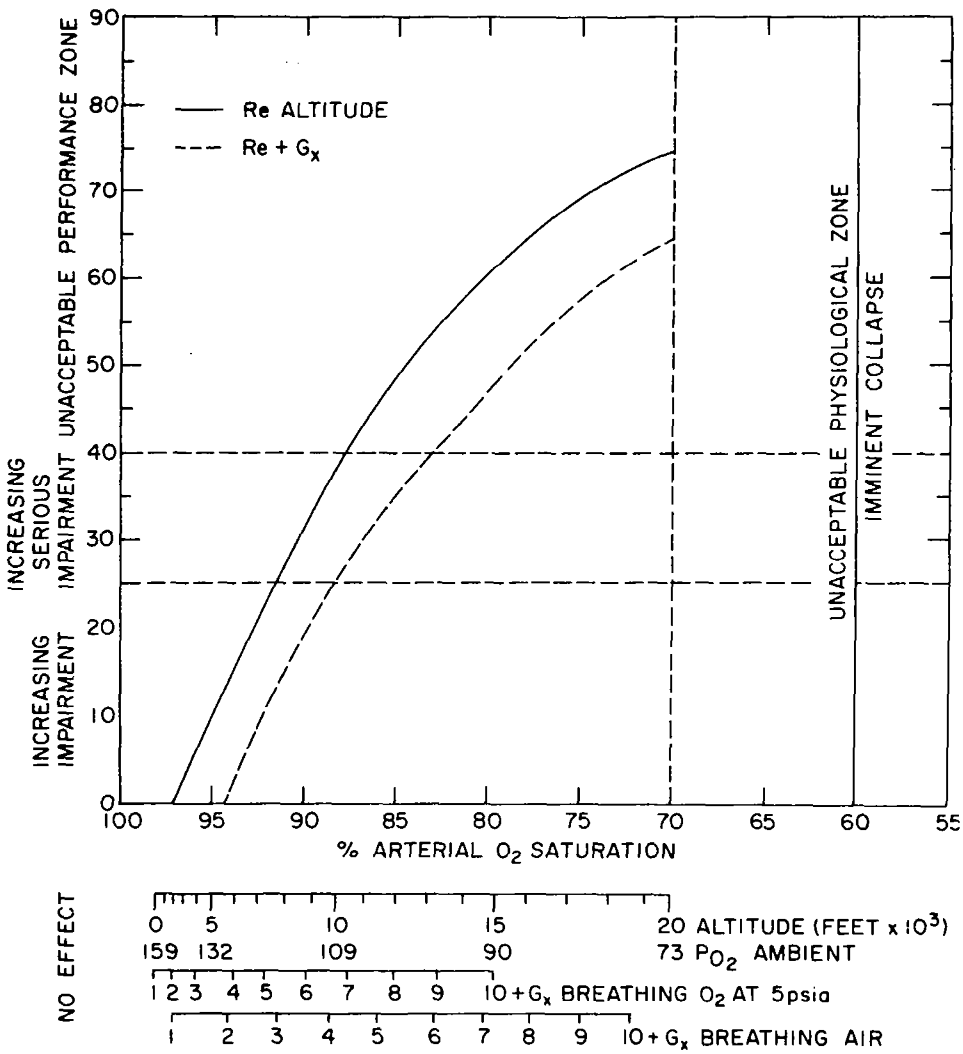
g. Response of Several Visual Functions of Hypoxemia



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

FACTORS EFFECTING HUMAN G TOLERANCE

h. Comparison of Visual Contrast Sensitivity Decrements Induced by Reduced Partial Pressure of Oxygen and Acceleration



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III(52).

DYNAMICS - ACCELERATION

FACTORS EFFECTING HUMAN G TOLERANCE

i. Maximum Tolerance to Prolonged Accelerations $-G_X$

VECTOR MAGNITUDE (G)	DURATION AT G (SECONDS)	AVERAGE ONSET (G/SECONDS)	BACK ANGLE (DEGREES)	CAUSE OF TERMINATION*	TRAUMA	NUMBER OF SUBJECTS ATTAINING
COMPLETE RESTRAINT n=1						
12.0	6	0.5	-17°	S	None	1
11.0	11	0.2	-20°	S?	None	1
10.0	90	0.2	-20°	S	None	1
10.0	71	?	Approx. 5°	S?	None	1
10.0	18	0.5	-17°	S	None	1
8.0	65	0.5	-17°	S	None	1
7.0	300	?	Approx. 5°	S?	None	1
7.0	240	?	Approx. 5°	S?	None	1
7.0	210	?	0°	S?	None	1
6.0	140	0.5	-17°	S	None	1
5.0	180	0.5	-17°	A	None	1
4.0	300	0.5	-17°	A	None	1
3.0	1223	0.5	-17°	S	None	1
PARTIAL RESTRAINT n=1						
5.0	18	0.5	-17°	S	None	1
3.0	450	0.5?	-17°	S	None	1
2.0	3600	?	-17°	A	None	1
2.0	1800	0.5?	-17°	A	None	1
COMPLETE RESTRAINT n >1						
15.0	5	8.10	Approx. 0°	Voluntary Limit	None	5 of 5
12.0	30	0.2	-20°	A	None	2 of 2
12.0	≧ 3	0.5	-17°	S	None	4 of 4
10.0	120	0.2	-20°	A	None	4 of 9
10.0	≧10	0.5	-17°	S	None	3 of 4
8.0	120	0.2	-20°	A	None	13 of 13
8.0	>30	0.5	-17°	S	None	3 of 4
6.0	>50	0.5	-17°	S	None	4 of 4
5.0	≧80	0.5	-17°	S	None	4 of 4
4.0	>240	0.5	-17°	S	None	3 of 4
3.0	≧1200	0.5	-17°	A	None	2 of 4
3.0	900	0.2	-20°	A	None	10 of 13
2.0	1200	0.5	-17°	A	None	2 of 2

*S = Physiological end point
A = Arbitrary time limit end point

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II(51) and Hyde and Raab (90).

FACTORS EFFECTING HUMAN G TOLERANCE

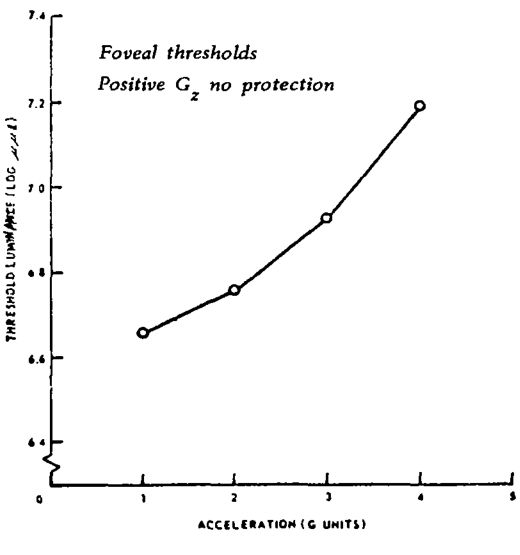
i. Maximum Tolerance to Prolonged Accelerations $-G_x$ (Cont.)

VECTOR MAGNITUDE (G)	DURATION AT G (SECONDS)	AVERAGE ONSET (G/SECONDS)	BACK ANGLE (DEGREES)	CAUSE OF TERMINATION	TRAUMA	NUMBER OF SUBJECTS ATTAINING
PARTIAL RESTRAINT n > 1						
5.0	≧ 5	0.5	-17°	S	None	4 of 5
3.0	> 300	0.5?	-17°	S	None	4 of 4
2.0	>1000	0.5?	-17°	S	None	2 of 3

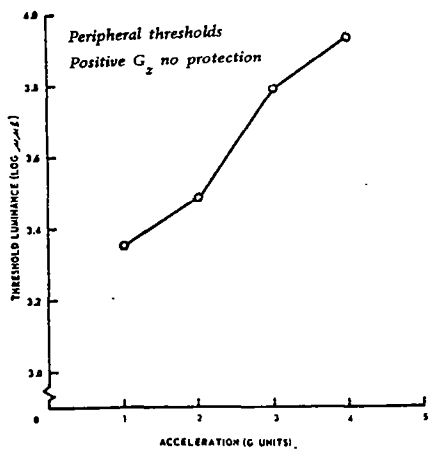
*S = Physiological end point
A = Arbitrary time limit end point

j. Foveal and Peripheral Thresholds Under Acceleration

FOVEAL



PERIPHERAL



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51), Vol. III (52) and Hyde and Raab (95).

FACTORS EFFECTING HUMAN G TOLERANCE

k. Visual Tolerance to Accelerative Stress

VISUAL TOLERANCE TO $+G_z$ (N = 1000); RATE OF G DEVELOPMENT IS 1 G/SEC.

CRITERION	MEAN THRESHOLD (G UNITS)	STANDARD DEVIATION (G UNITS)	RANGE (G UNITS)
Loss of Peripheral Vision	4.1	± 0.7	2.2 - 7.1
Blackout	4.7	± 0.8	2.7 - 7.8
Unconsciousness	5.4	± 0.9	3.0 - 8.4

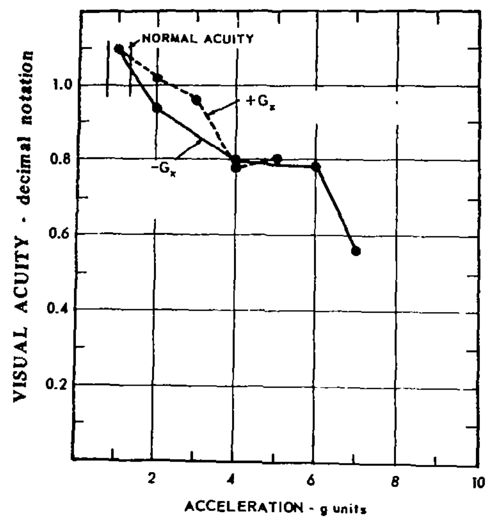
l. Frequency of Symptoms Reported By Subjects Exposed to Negative G_z for 10 Sec

SYMPTOMS	ACCELERATION IN G				
	1	2	3	4	5
	NO PROTECTION				
Conjunctival Hemorrhage	0	0	40%		
Diminished Vision	0	0	40%		
	PROTECTED BY FULL PRESSURE HELMET				
Diminished Vision	0	0	10%	20%	30%
Conjunctival Hemorrhage	0	0	0	0	0

SOURCE: Cochran, et al (49), Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Sieker (166).

FACTORS EFFECTING HUMAN G TOLERANCE

m. Binocular Visual Acuity/Acceleration

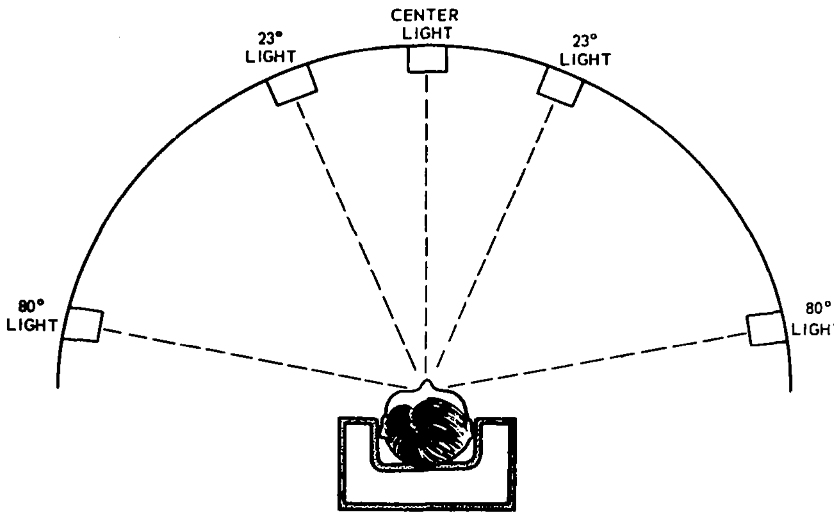


This graph shows binocular visual acuity as a function of acceleration. If a target is to be seen at 7 $-G_x$, it must be twice the size of the threshold target at 1 G.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51), Webb (195), and White and Jorve (205).

FACTORS EFFECTING HUMAN G TOLERANCE

n. Grayout Threshold During +G Acceleration



One hundred fifteen subjects exposed to positive acceleration (+G_Z) with a light array as shown in the diagram almost invariably lost the 80° light before loss of the light of 23° (23° LL). After completing the experiment it was decided to quantitate this in 30 subjects, and it was found that the 80° light loss (80° LL) occurred at a mean of 4.2 G_Z, standard deviation $\pm$ 0.7 G; and in the same subjects, the 23° LL occurred at a mean of 4.5 G_z, S.D. $\pm$ 0.8 G. Central light loss (CLL) occurred at 5.3 G_z, $\pm$ 0.8 G.

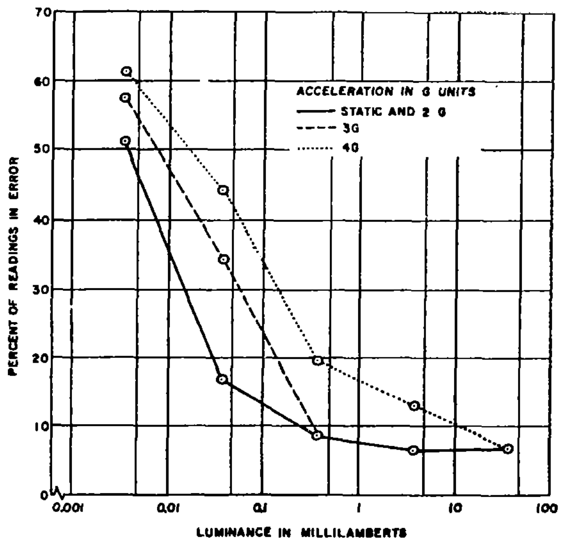
Comparison of 80° Light Loss, 23° Light Loss, and 0° Light Loss

	Symptoms			
	Clear	80° LL	23° LL	CLL
Mean (G_z level)	3.8	4.2	4.5	5.3
Range (G_z level)	2.3-5.1	2.7-5.7	2.9-6.4	3.6-7.0
Standard Deviation	0.7	0.7	0.8	0.8
Duration of symptom-Mean (sec)		5.4	5.1	6.8
Duration of symptom-Range (sec)		1.9-17.0	1.9-11.9	2.1-23.4

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Webb (195).

FACTORS EFFECTING HUMAN G TOLERANCE

o. Effect of Acceleration ($+G_z$) on Dial Reading Accuracy as a Function of Luminance



The reduction in acuity can be compensated for by increasing the luminance as indicated in this figure.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and White and Riley (206).

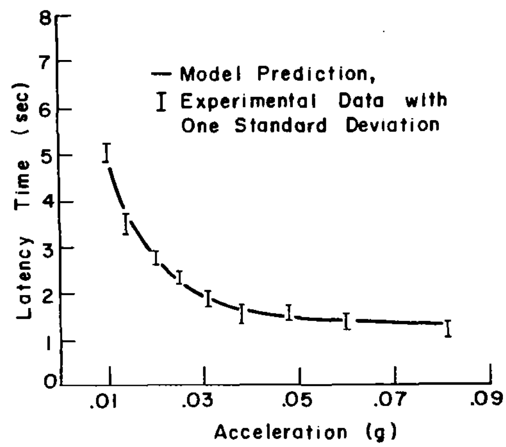
PHYSIOLOGICAL STANDARDS AND TOLERANCES

DYNAMICS - ACCELERATION

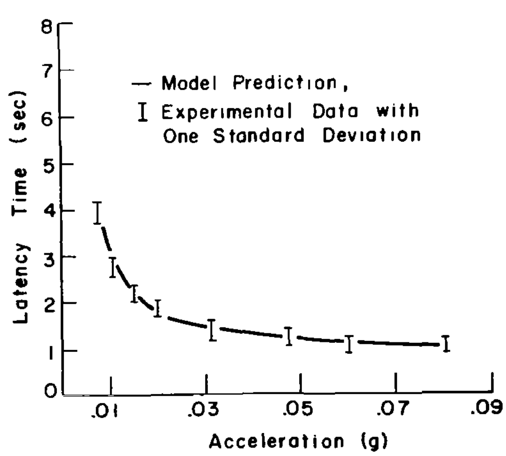
PERCEPTION OF ACCELERATION

a. Perception of Horizontal Linear Acceleration as a Function of Subject Position

SUPINE POSITION



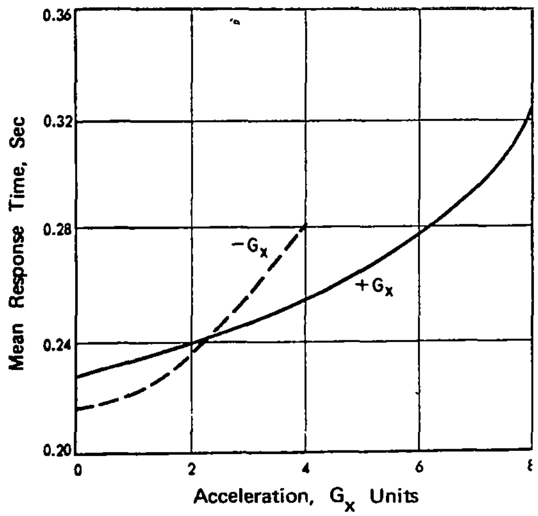
UPRIGHT POSITION



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51), Meiry (124).

PERCEPTION OF ACCELERATION

b. Response Time During Transverse Acceleration



The two curves show mean response times (the time from appearance of a red signal light to the movement of the subject's hand from his lap) for five male college students, 20-25 years old, exposed to transverse accelerations. The solid line shows the combined response times for both right and left hand operation in more than 900 ($+G_x$) exposures up to +8 G_x. The dashed line shows the combined response times for both right and left hand operation in more than 500 ($-G_x$) exposures up to -4 G_x. The times required to reach and operate a horizontal lever, a toggle switch and a push button were longer as the accelerations increased, and variable times were recorded for left and right hand operation. Still longer times were needed for adjusting a rotating knob and a vertical "trim" wheel.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Kaehler and Meehan (99).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

DYNAMICS - SUBGRAVITY

WEIGHTLESSNESS

a. Physiological Effects of Weightlessness (Vertebrates)

	Animal	Dynamic Conditions	Effects
			Sensory and Neurophysiological Effects
1	Man	Subgravity tower	Upward deviation when aiming a stylus and attempting to hit a bull's-eye ("overshoot")
2			Increased tapping rate and distribution of marks in "upper right" sector of test chart
3	Man	Aerodynamic flight parabola[1,2]	Upward deviation when aiming a stylus and attempting to hit a bull's-eye ("overshoot")
4			Difficulty in placing crosses in diagonally arranged squares, especially when blindfolded ("overshoot")
5			Apparent motion and displacement of a real target in the direction of gravity ("oculogravic illusion")
6			Apparent motion and displacement of an afterimage in the direction opposite to that of gravity ("oculoagravic illusion")
7			Retardation in speed of execution of motor functions in the absence of discoordination symptoms
8			Loss of gravitational vertical; sensation of floating, being lifted, and flying upside down
9			Shortening of illusions of counterrotation and afterrotational nystagmus after a series of parabolic flights
10			Mass-weight discrimination changed in weight-lifting task
11			Recovery from acceleration stress impaired before and after weightless state
12		Cargo aircraft	23 of 45 subjects became motion sick
13		Fighter aircraft	5 of 16 subjects became motion sick
14			6 of 18 subjects became motion sick
15		Suborbital flight, MR 4[1,2]	Grissom: tumbling sensation during transition from accelerated flight to weightlessness
16		Orbital flight[1,2] MA 6	Glenn: brief forward tumbling sensation
17		MA 8	Schirra: sensation of traveling upside down
18		MA 9	Cooper: sensation of traveling upside down
19		Vostok 2	Titov: vertigo, nausea, rolling, sensations of illusion
20		Vostok 3	Nicolayev: sensations of illusion and traveling upside down
21		Vostok 4	Popovich: sensations of illusion and traveling upside down
22		Vostok 5	Bykovsky: decreased oculomotor activity; asymmetry of nystagmoid movement
23		Vostok 6	Tereshkova: decreased oculomotor activity; asymmetry of nystagmoid movement
24		Voskhod 1	Feoktistov and Yegorov: sensations of illusion and traveling upside down. Yegorov: mild nausea
25	Cat	Aerodynamic flight parabola	Labyrinthine posture reflex (righting *reflex) ceased to function after several* seconds of weightlessness
26	House mouse	Aerodynamic flight parabola	Mice without labyrinthine function less disoriented than normal mice

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Gerathewahl and Von Becker (72).

WEIGHTLESSNESS

a. Physiological Effects of Weightlessness (Vertebrates) (Cont.)

	Animal	Dynamic Conditions	Effects
27	Rabbit	Subgravity tower	Righting reflex inhibited when subjects blindfolded
28		Aerodynamic flight parabola	Oculomotor reflex opposite to direction of gravity
29	Pigeon	Aerodynamic flight parabola	Posture reflex failed whether subjects were blindfolded or not; random movements and floating
30	Water turtle	Aerodynamic flight parabola	Inability to project head when attempting to aim accurately at offered bait. Turtles without labyrinthine function have advantage.
31	Goldfish	Aerodynamic flight parabola	Swimming upside down, on the side, etc.
		Respiratory Effects	
32	Man	Aerodynamic flight parabola	Recovery from acceleration stress impaired before and after weightless state
		Orbital flight	
33		Mercury flights	Slightly decreased pulmonary activity
34		Vostok 3, 4	Nicolayev, Popovitch: slightly decreased pulmonary activity
35		Voskhod 2	Velyayev, Leonov: two- to threefold increase in pulmonary ventilation
36	Dog	Orbital flight, Sputnik II	Laika: decrease in frequency of respiration
		Cardiovascular Effects	
37	Man	Aerodynamic flight parabola	Recovery from acceleration stress impaired before and after weightless state
		Orbital flight[3]	
38		Mercury flights	Cardiac activity increased
39		Vostok 1-6; Voskhod 1	Increased pulse fluctuations in the duration of cardiac cycle; cardiac activity reorganized; tendency toward lowered cardiac activity
		Postorbital flight	
40		MA 8	Schirra: orthostatic hypotension persisted several hours after landing
41		MA 9	Cooper: orthostatic hypotension, accompanied by accelerated pulse and blood pressure responses, persisted 9-19 hr after landing
42		Vostok 1-6	Orthostatic hypotension
43	Dog	Orbital flight, Sputnik II	Laika: heart rate took 3 times longer to return to normal than in preflight laboratory experiments in which the dog was exposed to G profiles similar to those of the launching acceleration
		Metabolic Effects	
	Man	Orbital flight	
44		MA 7	Carpenter: mobilization of skeletal minerals
45		Gemini IV	White, McDivitt: bone mass losses
46		Voskhod I, II	Some strain on lipid metabolism; increase in cholesterol levels

1 Disorientation, which can be extreme without visual cues, was prevented during orbital flights by maintenance of visual control. 2 Since these short exposures (> 1 minute) to weightlessness were necessarily preceded and followed by phases of G loads, the experiments revealed the effects of alternating acceleration and weightlessness rather than the effects of weightlessness per se. 3 The extent to which weightlessness alone is responsible for the deconditioning phenomenon is difficult to assess, since astronauts are also exposed to multiple stresses, such as dehydration, high temperature, recumbency, and muscular inactivity during orbital flights.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Gerathewahl and Von Becker (72).

WEIGHTLESSNESS

b. Weightlessness Response Found in Early Experiments

	Short-term Effects	Orbital Flight Data	Submersion Effects	Bed-rest Effects
	Free-fall, frictionless devices, Keplerian trajectory,* Mercury ballistic flights	Project Mercury (441) primarily (Vostok flights V1 and V2 (638))	Head-out submersion (HOS) Complete submersion (CS)	Normal subjects
General Metabolism				
Metabolic rate	--	Low-residue balanced diet pre-flight; low-caloric intake inflight	Decreased	Decrease 6 - 9%
Body weight	--	Observed losses due to low-caloric intake and dehydration	Variable	Variable depending on caloric balance
Body temperature	--	Elevated due to thermal stress	Depends on water temperature	No effect
Water Balance	--	Diuresis in one, low intake and low or normal urine volume in three Mercury astronauts	Diuresis during both HOS and CS	Diuresis
Electrolyte balance	--	Post-flight Na+ and Cl- retention with rehydration	Na+ losses, HOS	Equilibrium
Muscoloskeletal System				
Nitrogen balance	--	Not measured	Equilibrium or negative	Equilibrium or negative, depending on method of calculation
Muscle girth and strength	--	No change	Little or no change reported	Only slight wasting, little or no loss in strength
Calcium excretion	--	No increased excretion	--	Sustained loss despite supine bicycle exercise
Cardiovascular System				
Resting responses Pulse	Abrupt decrease in heart rate on transition to weightlessness*	Normal values at rest, work, and sleep	--	+0.5 beats/minute per day
Pressure	Influenced by prior G; resting value decreased while weightless*	Normal values at rest, work, and sleep	Reduced pulse pressure	Increase
Stroke volume	--	--	--	Probable decrease
Cardiac output	--	--	--	No major change
Peripheral resistance	--	--	--	No marked change
Blood volume	--	Reduced in dehydration	Plethora, elevated hematocrit	-9.3%
Tilt-table response	Abrupt decrease in heart rate on transition to weightlessness*.	Transient faitness due to orthostasis on capsule egress with elevated heart rate--188; confirmed by tilt-table test post-flight	Deterioration	Deterioration
Acceleration tolerance	No change	No apparent effect; good performance on reentry	Decreased--small but significant	--
Exercise tolerance Work capacity	--	Maintained; work subjectively easier; pulse rate response slightly greater and slightly slower in return to normal	Decreased	Decreased, but capacity can be maintained by supine exercise
Vasomotor activity	--	--	--	Response to supine exercise indicates effective arterial vasomotor activity but decreased venomotor tone

* In the body of the table, those data taken under the conditions of the Keplerian trajectory are marked with an asterisk.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Gerathewahl and Von Becker (72).

WEIGHTLESSNESS

b. Weightlessness Response Found in Early Experiments (Cont.)

	Short-term Effects	Orbital Flight Data	Submersion Effects	Bed-rest Effects
	Free-fall, frictionless devices, Keplerian trajectory,* Mercury ballistic flights	Project Mercury--MA-9(441) Vostok flights V1 and V2(638)	Head-out submersion (HOS) Complete submersion (CS)	Normal subjects
Mechanical Effects				
Swallowing	No problem with proper food containers and training*	No problem with proper food containers and training	--	--
Urination	No problem	No problem; bladder sensation normal	--	--
Free objects	Dust, droplet, and food crumb problem*	Dust, droplet, and food crumb problem	--	--
Sensations				
Falling	Induced by prior G; absent when free-floating*	Not experienced	--	--
Motion sickness	Related to G-transition*	One subject (Titov)	--	--
Orientation	Orientation unrestrained decays in dark, and tactile sensations become important; any surface can become floor for the individual*	Perceives earth or vehicle relative to self	Otolithic sensitivity decreased in certain postures	--
Illusions	"Oculoagravic" illusion observed* no significant difference in semicircular canal sensitivity when weightless compared to 1G-- Oculogyral illusion*	Change in apparent position of objects in peripheral visual fields; head motion not disorienting	Illusions related to sensory monotony	--
Vision	Small decrement in visual acuity*	Sightings indicate importance of pattern vision; no apparent decrement in acuity, color vision, or light sensitivity	--	--
Performance				
Mass discrimination	Difference threshold twice as large for masses as compared to weights	--	--	--
Motor	Body restraint, hand-holds, tethers and adhesive footgear required for effective performance, closed force tools recommended; eye-hand coordination and object positioning shows overshooting, slight decrement in switch operation; rapid adaptation to altered motor requirements*	No operational decrement in restrained subject, as evidenced by reentry performance	Vigilance, discriminative reaction time, and complex task performance show small decrements, HOS overshooting and applied force changes related to water displaced, CS	--
Sleep	Disorientation on sudden awakening*	Frequent dozing; oriented rapidly on awakening (one subject)	Diminished requirement	--

* In the body of the table, those data taken under the conditions of the Keplerian trajectory are marked with an asterisk.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Gerathewahl and Von Becker (72).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

DYNAMICS - SUBGRAVITY

WEIGHTLESSNESS

c. Factors Detected While Free-Floating in Large Aircraft Cabins

(X = conditions affecting factor)

Subjective Sensations (subject's observations)	Light Conditions: Light Cabin	Light Conditions: Dark Cabin and Moon	Light Conditions: Dark Cabin	Weightless Conditions: Low Friction	Weightless Conditions: Free Body	Weightless Conditions: G-Free Support and Stimulation	Maneuver Conditions: Rapid G Transition	Maneuver Conditions: Stress	Maneuver Conditions: Short Time Period	Maneuver Conditions: Aircraft Rotation	Summary, Applications and Hazards
1. *Exhilaration* from surface freedom	x	x	x	x		x	x	x			Enjoyment increased in light cabin (knowledge of freedom), *G*-free support tends to induce an exciting and enjoyable environment. *G*-free training should be based on the advantages of such an environment.
2. *Comfort* of non-tactual support					x	x					Simpler bed and chair required, exercise required. Emphasis should be on man's position as focus, rather than cabin orientation within a vehicle.
3. Lack of *falling* sensation					x	x	x				Sudden vehicle accelerations induce falling sensations, while *G*-free training quickly dispels anticipated falling sensations. Slow *G* transitions reduce sensations during this phase.
4. Knowledge and control of *limb position* (orientation)	x				x	x	x		x		Positions were known during all conditions. Overshooting occurs in darkness but knowledge of results aids quick adjustment. Rapid motions perceived as weight.
5. Knowledge and control of *body position* in aircraft (orientation)	x				x	x	x		x		Posture orientation proposed as *basic reference plane*, for visual-gravitational conflict of subjective vertical is not a problem with posture identification. Man rather than vehicle should be design focus. The cockpit is 'floor oriented' whereas our space position may be 'man oriented.' Attitude and position information necessary to flight path knowledge can be related to basic reference plane. False rotation and loss of rotation knowledge noted.
6. Knowledge of *vehicle attitude* (orientation)	x	x	x				x		x	x	Knowledge of surface location decreased in darkroom and apprehension and accidents increased because of inability to prepare for surface contact. Observers often unable to differentiate between subject motion and aircraft motion about subject without comparative *G*-free mass. *G*-free posture indoctrination (item 5) reduces need for vehicle information.
7. *Concern* over collisions	x	x	x	x	x	x		x			Difficulty in self rotation produces collision anxiety. Padding requirements are extensive, open machinery absolutely taboo. Training flights excellent for reducing overcontrol.
8. Illusions (target motion)		x				x	x	x		x	The apparent upward displacement of the visual target (oculo-agravic illusion) may not be a design problem with proper display information. Self propulsion units must have low thrust (low *G*) levels due to line of sight and deceleration program requirements. Autokinesis should be investigated with subjects moving in still visual field.
9. Sense of *zero, partial* and *excessive G's*	x	x	x	x	x	x	x				Lack of visual stimulation (dark cabin) increased sensitivity to *G*; *G*-free body systems tend to pick up strong sensations with minute stimulations (?) (Weber-Fechner law). Development of *G* cues may aid worker handling materials where small accelerations of mass and man are important factors.
10. Sense of *heaviness* after zero-*G* period					x	x	x		x	x	Variable control forces may aid psychomotor adjustment upon re-entry.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II(51) and Gerathewahl (71).

WEIGHTLESSNESS

c. Factors Detected While Free-Floating in Large Aircraft Cabins (Cont.)

Subjective Sensations (subject's observations)	*Light Conditions*			*Weightless Conditions*			*Maneuver Conditions*				*Summary, Applications and Hazards*
	Light Cabin	*Dark Cabin and Moon*	*Dark Cabin*	*Low Friction*	*Free Body*	*G-Free Support and Stimulation*	*Rapid G Transition*	*Stress*	*Short Time Period*	*Aircraft Rotation*	
11. Decrease in *clothing pressure*					×	×	×				Movies of loose clothing reveal that apparel tends to oscillate out of phase on moving limbs. Crews in shirt sleeve environments should wear form fitting, easily flexed clothing with elastic cuffs on limb extremities. The sensation could serve as a tactile perception of weightlessness.
12. Nausea and *motion sickness*	×			×	×	×	×	×	×	×	Rapid *G* transition and perceptual-sensation conflicts cause discomfort; may be valuable crew selection criterion.
13. Decrease in *span of attention*	×					×	×	×	×	×	During the excitement of the moment subjects forget their task. Criterion for crew selection might be their adaptation rate to unusual environment over short periods. Emergency tasks should be assigned to restrained workers. Task analyses should include a reorientation constant for free-floaters; omnidirectional displays should be developed.
14. Harness irritations					×	×					Harnesses tightened for 1-*G* behavior tend to limit *G*-free limb activity.
15. Change in *cabin pressure*										×	Changing cabin pressures were mistaken for weightless stimulations of the ear organs.
Performance Factors (Observable by subject or observer)											
16. *Swimming* motions	×			×	×	×			×		These 'swimming in air' motions were unsuccessful attempts to translate, stabilize and turn; however, they tended to interfere with attitude control and disappeared after a few exposures (self rotation). Rotation training can be accomplished on simple swivel chairs.
17. *Body resilience* motions				×		×	×				Passive subjects tend to leave surfaces following sudden relaxation of excessive *G*-compressed tissues. Compressible objects should be tethered. Sleeping subjects should be restrained against their own accelerations.
18. *Cross-coupled* motion				×	×	×					3-d spinning subjects should extend limbs and thus reduce rpm. Any external force adds a linear component to the tumble. Stabilization gyros must be available for controlled rotation, before, during and after translation. Moments of inertia computed from segmented man models should include the transfer of energies between the muscular interactions of the various segments.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Gerathewahl (71).

WEIGHTLESSNESS

c. Factors Detected While Free-Floating in Large Aircraft Cabins (Cont.)

Subjective Sensations (subject's observations)	*Light Conditions*			*Weightless Conditions*			*Maneuver Conditions*				*Summary, Applications and Hazards*
	Light Cabin	*Dark Cabin and Moon*	*Dark Cabin*	*Low Friction*	*Free Body*	*G-Free Support and Stimulation*	*Rapid G Transition*	*Stress*	*Short Time Period*	*Aircraft Rotation*	
19. ***Sloppy,* pendulous motion**					×	×					Self induced accelerations tend to oscillate a *G*-free body causing unstable work performance, poor translation, and poor attitude and position control. Unharnessed operators should not be required to perform gross motions requiring discriminating movements. Open force systems must be avoided and man should work against himself.
20. Ease of *self propulsion*				×	×	×					Improper launches cause excessive motions, inadvertent tumbling, and rotating translations. Subjects can train for accomplishing straight and stable flight paths.
21. Difficulty in *walking*				×	×	×	×				Attempts at walking propel the worker from the surface. Handholds, rails, and foot devices are being developed.
22. Change of *relaxed posture*					×	×	×				Subjects' limbs tend to contract toward the center of mass (fully relaxed subjects). Bed, chair, and control position designs should be affected.
23. Difficulty in *absorbing inertia* against a surface	×	×××	×××								The inability to self-rotate accurately and prepare for impact compels workers to absorb their previous launching forces haphazardly (lighted cabin). Exhilaration promotes overcontrol, which decreases with exposure. Cautious training, padded living areas, and attitude control aids are basic requirements.
24. Helplessness *between surfaces* (light cabin served as base line)		×	×	×	×	×					Suspended subjects are often incapable of surface return. Training methods should include proper methods of expending mass to achieve translation.
25. Rigidity of *powered tools*				×	×	×					Tools may be a source of stabilization, but are difficult to align and reposition. Motors impart forces to *G*-free capsules.
26. Suspension of dust and objects				×		×					Filters, screens, air circulation are required; smooth configuration of objects is a necessity.
27. Inadequacy of open containers, tethers		×	×	×		×	×				Covers, mounts, and tethers must be designed.

Note: × Indicates conditions affecting factor.

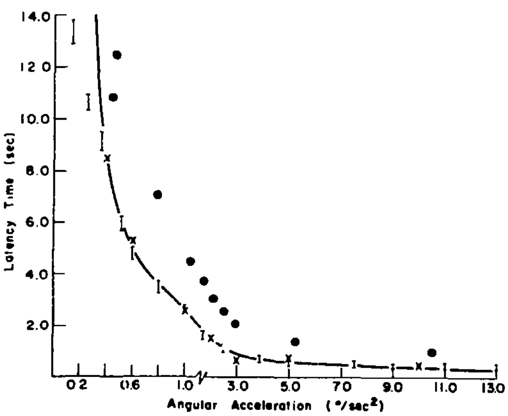
SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Gerathewahl (71).

TUMBLING

The data points in Figures a and b are measurements of the time required by human subjects to sense and signal a response to low angular accelerations. They are directly predictive of the mean time elapsing between onset of an acceleration and motor response of an alerted individual, located close to the axis of rotation. Figures a through d show comparative data using different ground rules.

Because time for a decision and a motor output is included in the time to respond, these data cannot be used to find a_{min} directly. However, analysis of the data on the assumption that the total decision and motor response time is a constant on the order of 1 second yields an inferred value for threshold, a_{min}, of 0.1 to 0.5 deg/sec^2, the least acceleration which, applied for an unlimited time, can be detected. Higher accelerations will be detected in less time, and combinations of time and acceleration lying in the quadrant above the curve will be detected with higher probability or by more of the population. Figure a shows variation in data for yaw axis or horizontal canals; the threshold of the latest model being 0.14 deg/sec^2. Figure b shows the threshold for the roll axis or vertical canals to be 0.5 deg/sec^2.

a. Latency Times for Perception of Angular Acceleration About the Vertical Axis (Y_h)*



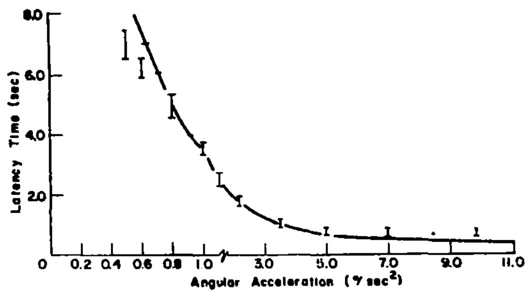
— Model Prediction
I Experimental data with one standard deviation
X Data from Clark and Stewart
• Data from Guedry and Richmond

* Note scale change of angular acceleration

SOURCE: Clark and Stewart (47), Compendium of Human Responses to the Aerospace Environment, Vol. II(51), Guedry and Richmond(75) and Meiry (124).

TUMBLING

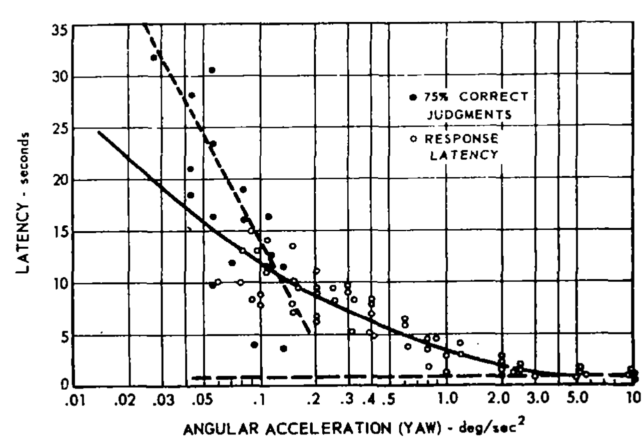
b. Latency Times for Perception of Angular Acceleration About the Roll Axis (X_h)*



— Model Prediction
I Experimental data with one standard deviation

* Note scale change of angular acceleration

c. Perception of Angular Acceleration

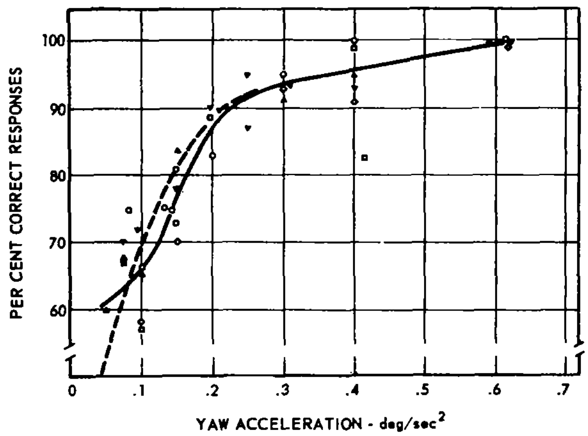


The times required to make judgments of the direction of rotation about the yaw axis are plotted as a function of the angular acceleration. The solid points indicate the time required to make judgments that are correct 75% of the time, as determined by Mann and Ray. The open points represent the time required to make judgments, whether the judgments are correct or not, and are redrawn from the data of Clark and Stewart.

SOURCE: Clark and Stewart (47), Compendium...Vol. II(51), Guedry and Richmond (75) Meiry (124) and Webb (195).

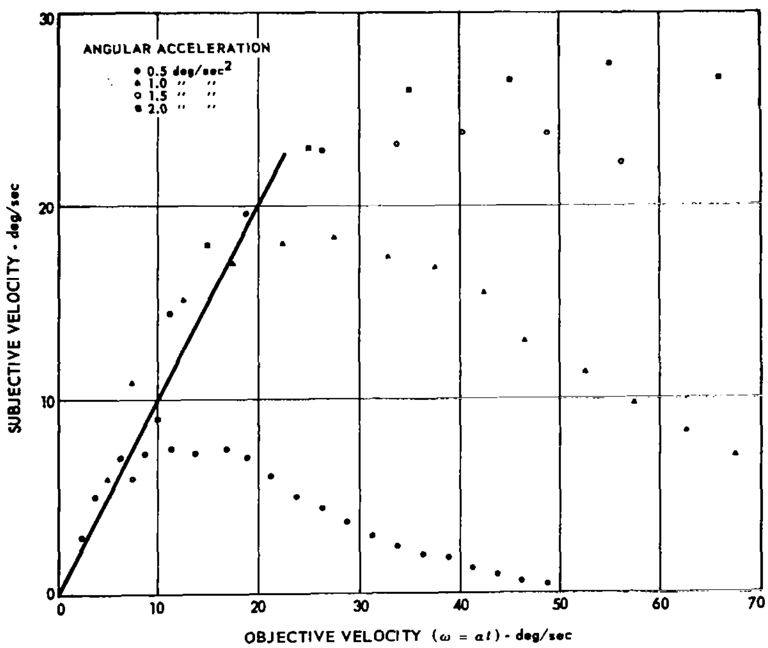
TUMBLING

d. Correct Perception of Direction of Rotation



The percent of direction of rotation judgments that are correct is plotted as a function of the level of angular acceleration. The 75% point is considered to be the threshold point. Also included are the 75% points (dashed line).

e. Perceived Versus Actual Rotation

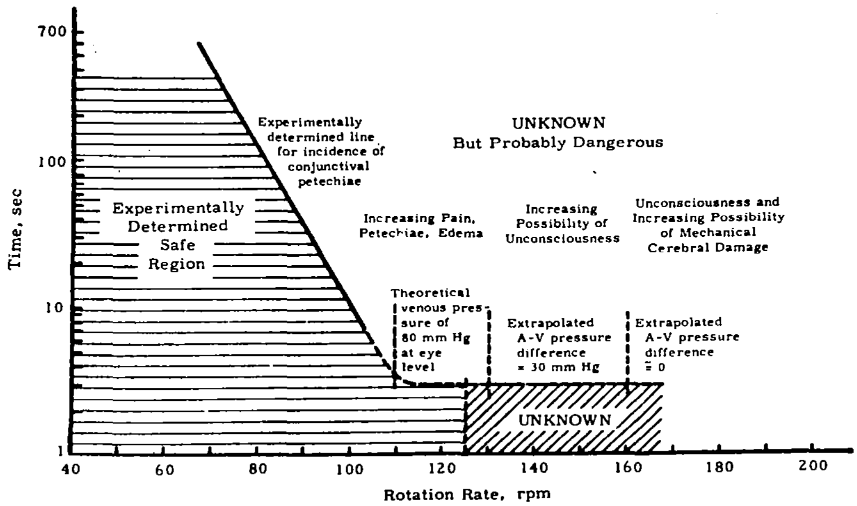


Points on this graph are values of angular velocity computed from subjects' reports of perceived 45° increments in displacement while subjected to constant angular acceleration on a turntable. Each point is the average of readings during four trials by each of ten subjects. A trial consisted of one acceleration and one deceleration, with sufficient time at constant velocity in between for sensations to decay. The average values mask a 25% decrease in response between the first and fourth trials, ascribed to habituation.

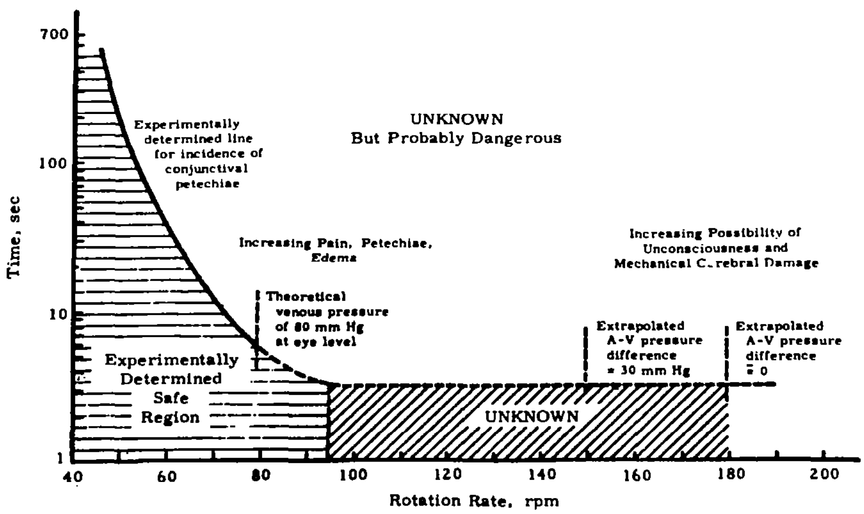
SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Webb (195).

TUMBLING

f. Man's Tolerance to Simple Tumbling - Center of Rotation at Heart



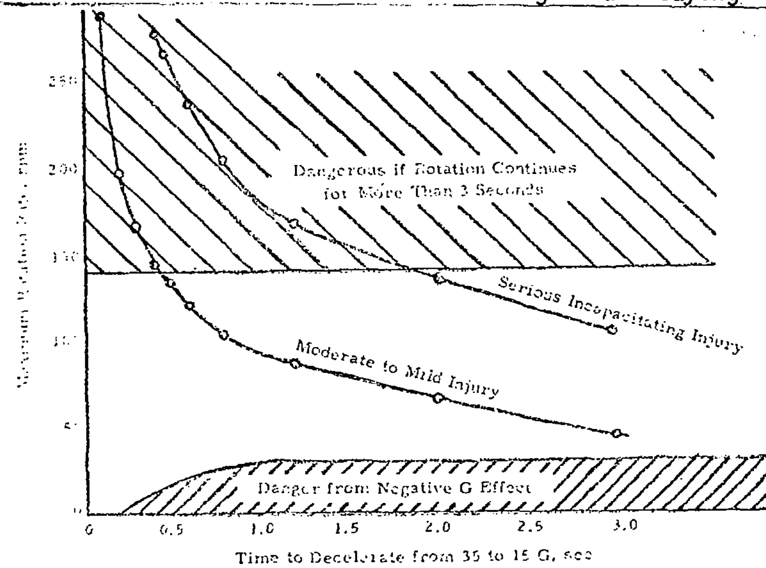
g. Man's Tolerance to Simple Tumbling - Center of Rotation at Iliac Crest



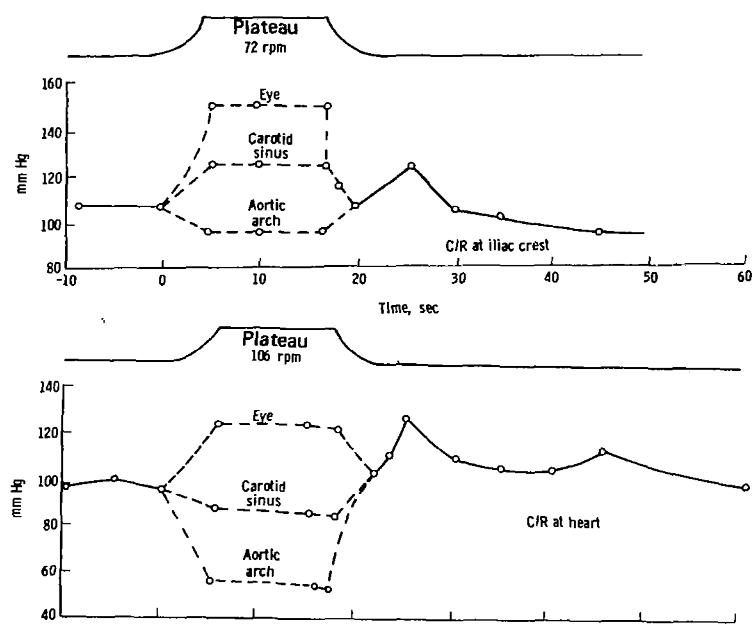
SOURCE: Edelberg (62).

TUMBLING

h. Man's Tolerance to Constant Rate of Tumbling in a Decaying "G" Field



i. Mean Arterial Pressures at Various Points With Center of Rotation at Heart and Iliac Crest

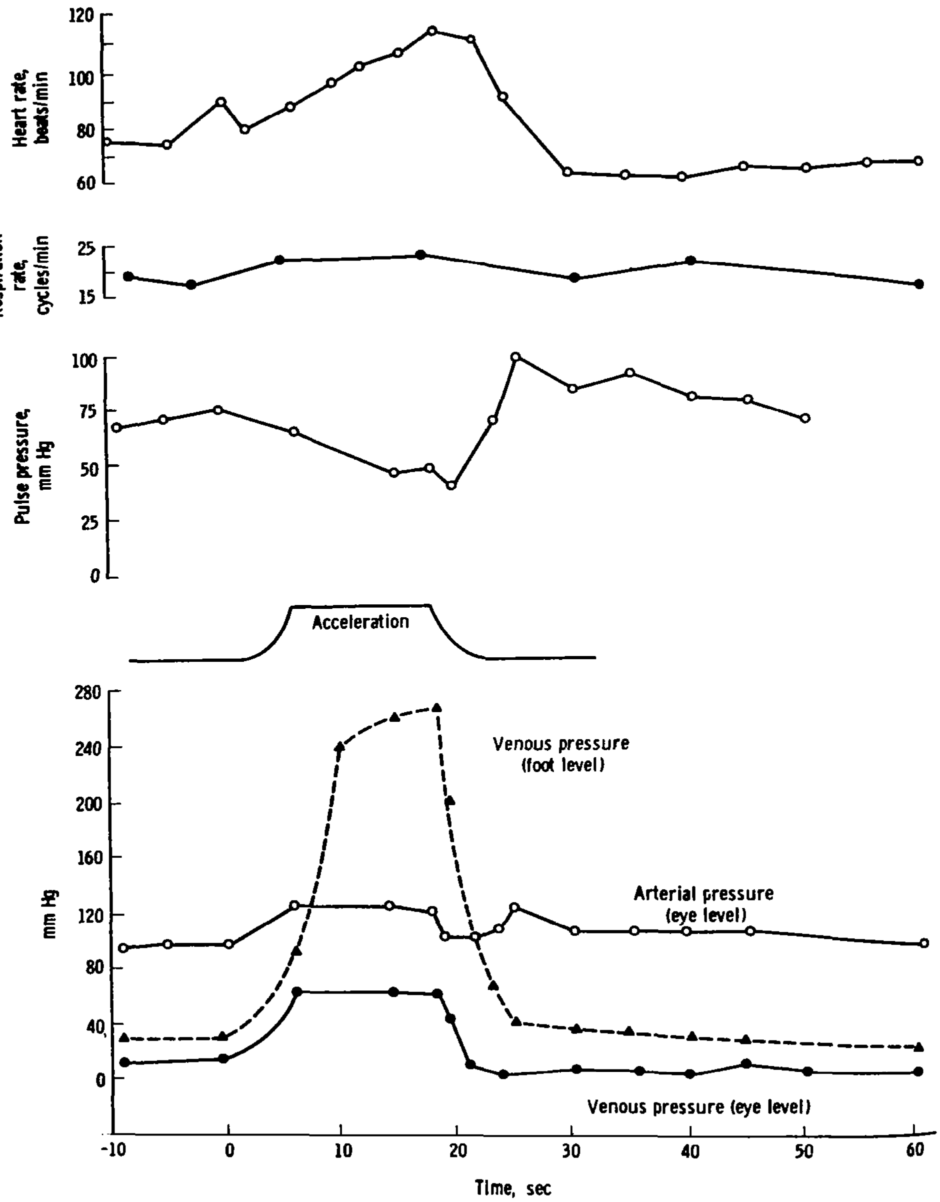


SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51), Edelberg (62) and Weiss, et al (200).

TUMBLING

j. Physiological Effects of Spinning a Human About a Center of Rotation Through the Heart

Resources at 106 rpm.



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Weiss, et al (200).

IMPACT TOLERANCES

a. Tentative Criteria for Limiting Impact Velocities in Humans

CONDITION CRITICAL ORGAN OR EVENT	RELATED IMPACT VELOCITY FT/SEC
Standing Stiff-legged Impact	
Mostly "safe"	
No significant effect	< 8(?)
Severe discomfort	8 - 10
Injury	
Threshold	10 - 12
Fracture threshold (heels, feet and legs)	13 - 16
Seated Impact	
Mostly "safe"	
No effect	< 8(?)
Severe discomfort	8 - 14
Injury	
Threshold	15 - 26
Skull Fracture	
Mostly "safe"	10
Threshold	13
50 percent	18
Near 100 percent	23
Total Body Impact	
Mostly "safe"	10
Lethality threshold	20
Lethality 50 percent	26
Lethality near 100 percent	30

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and White, et al (202).

IMPACT TOLERANCES

b. Tentative Criteria for Indirect Blast Effects Involving Impact From Secondary Missiles

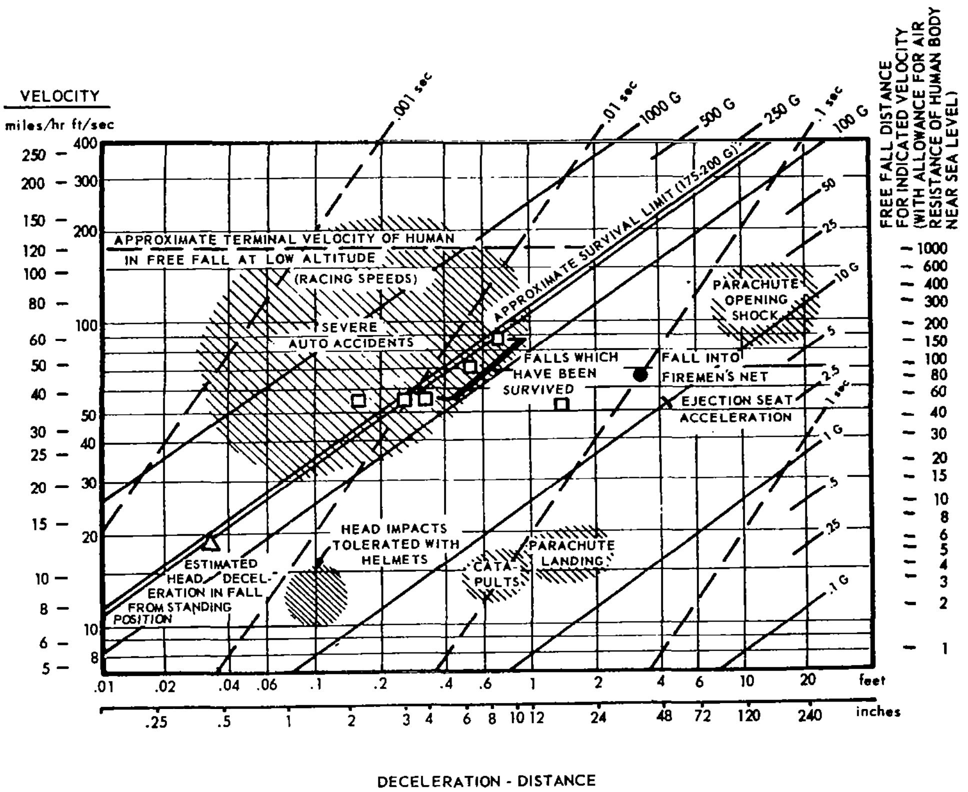
KIND OF MISSILE	CRITICAL ORGAN OR EVENT	RELATED IMPACT VELOCITY FT/SEC
Nonpenetrating 10-lb. object	Cerebral Concussion:	
	Mostly "safe"	10
	Threshold	15
	Skull Fracture:	
	Mostly "safe"	10
	Threshold	15
	Near 100%	23
Penetrating 10-gm glass fragments	Skin Laceration:**	
	Threshold	50
	Serious Wounds:**	
	Threshold	100
	50%	180
	Near 100%	300

** Represent impact velocities with unclothed skin. A serious wound arbitrarily defined as a laceration of the skin with missile penetration into the tissues of depth of 10 mm or more.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and White, et al (202).

IMPACT TOLERANCES

c. Empirical Effects of Impact Levels



This chart brings together a variety of impact and deceleration experiences by plotting the data from a number of sources on the common axes of deceleration distance and velocity. Stopping time and impact force in G units are shown as secondary scales. The data points with hollow squares are for free falls of 50-150 ft. with survival. There are many other cases of more extreme and less extreme impacts with survival, for free falls from 5 to 275 ft., but deceleration distance is not always available. The line labeled "approximate survival limit" must be used with caution, since many biophysical factors influence the injury due to deceleration.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and White, et al (202).

ILLUSIONS RESULTING FROM PERCEIVED OR EXPERIENCED DYNAMIC MOVEMENT

Vestibular Illusions

At the conscious level, motion sickness leads to illusions. As with the other symptoms, illusory phenomena arise when vestibular, kinesthetic, and visual cues are in conflict giving rise to "cross modality" interactions. During aircraft flight, many kinds of illusions occur because of sudden changes in linear acceleration or departure of the aircraft from a straight path. These may be compounded by adverse weather or night flight conditions which restrict visibility and add fear and anxiety.

The Visual Illusions

This class of illusions usually involves error in interpreting the visual environment, which gives the pilot information about the horizon, altitude, location of other vehicles and obstacles, position in formation, vehicle attitude, and so on. Lights form the major portion of his night visual field. Errors in the perception of lights include those of recognition, position, and movement. Fatigue may cause loss of binocular vision, a single light may split and appear as two or more lights.

(1) Autokinetic Illusions

A single fixed point of light may appear to move in random fashion when viewed steadily against a dark background. This can be demonstrated by staring fixedly at a fairly bright, isolated star. A subject asked to localize such a light usually reports this to be impossible, be-because of the apparent movement of the star. After a short delay before onset, movement is reported in apparently random directions. Median duration of the movement is about 10 seconds, and voluntary control over it is slight. The effect is abolished only with difficulty. Alternately blinking lights used on current vehicles tend to destroy the illusion. Moving the eyes and avoiding steady fixation also tends to prevent it. Eye muscle imbalance rather than vestibular factors appear at fault.

(2) Oculogyral Illusions (OGY)

These visual illusions may result when a pilot is subjected to rotary motion. It is caused by a reflex response consisting of movements of the eyeball following semicircular canal stimulation. The direction of apparent motion is in accord with the sensation of rotation during acceleration. If the subject is rotated to the right, a visual target fixed in relation to the subject appears to move in that direction. Movement gradually comes to a standstill after which it may appear to shift slowly to the left. When rotation rate is stabilized, apparent motion ceases. Sudden deceleration causes the visual target to have

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51).

(2) Oculogyral Illusions (OGY) (Cont.)

rapid apparent motion to the left, with a successive stage in which apparent motion is to the right. The pilot may interpret this as motion of the craft. After recovering from a spin to the left which involves large accelerations, a pilot will sense a turning to the right, and if he attempts to correct for this illusory turning, he will cause the airplane to spin to the left again. This reflex response of the eyeballs cannot be eliminated, and the only remedy is to train the pilot to ignore the sensations it produces.

The threshold for the OCY is ppproximately 0.2° to 0.3° of angular acceleration per second however, reported threshold values vary from $2.0°/sec^2$ to $0.035°/sec^2$.

(3) Oculogravic Illusions (OGI)

Conflicting sensory information supplied by the eye and otolithic sense organs can cause an illusion consisting of the apparent displacement of objects in space as well as body displacement. Upon change of gravitational vector, dimly illuminated objects in the visual field will move and assume new positions in space after a lag period. Presence of a strong visual framework will tend to prevent the change from primary visual orientation to vestibular, and diminish the effect; but there is little adaptation or habituation effect upon repreated exposure.

The illusion may be described as follows: If a subject faces toward the line of the resultant force, he perceives an apparent change in body position as though he were being tilted backwards. An object on the horizon will appear to shift above the horizon. Conversely, facing away from the resultant force results in the sensation of being tilted forward and an object will appear below the horizon. If a subject is at right angles to the resultant force, a horizontal line will appear to rotate clockwise if the direction of the resultant force is from the left and counterclockwise if the direction of the resultant force is from the right. For example, if a subject faces the center of a centrifuge while viewing a fixed light during exposure to acceleration which attains 3.0 G within three seconds, with onset of rotation, he feels he is changing position and the light is rising. The apparent change is described as a sensation of being slowly tilted backward along with the chair and centrifuge platform; thus, the illusion includes both apparent exterior motion and body displacement. When centripetal acceleration reaches 1.5 G, the subject reports a sensation of being on his back in a horizontally placed chair fixed to a vertical platform with walls of the centrifuge rotating around him. The opposite sensation occurs when the centrifuge is stopped.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II(51).

ILLUSIONS RESULTING FROM PERCEIVED OR EXPERIENCED DYNAMIC MOVEMENT

(3) Oculogravic Illusions (OGI) (Cont.)

The threshold for a perceived change in direction of horizontal or vertical is 1.5°. This is equal to a G increase of 0.00034; however, calculations reveal that this corresponds to 0.02 G at right angles to the gravity vector. Further work is needed to better establish the quantitative value of the OGI threshold.

A linear acceleration increment of about 0.1 $+G_x$ is interpreted as a climb at a 20° to 25° angle. A deceleration of about the same magnitude may be interpreted as a dive at a 15° angle below horizontal. Static tilt of the body laterally from vertical can also displace the visual localization of the horizontal. Kinesthetic cues from a horizontal floor may abolish this effect.

The Non-Visual Illusions

Illusions of this type may result solely from accelerative stimulation of vestibular and kinesthetic sense organs. Such illusions are marked by perceived rotation during and following actual rotation and by changes in linear acceleration. A subject may sense the onset of rotation but lose the sensation when rotation becomes constant.

(1) The Audiogyral Illusion

The ears also return faulty information as a result of rotary deceleration. A sound source in front of the subject was reported as arising from left of center following left spin. The audiogyral illusion might affect a pilot who has become oriented to the afterburner or rocket sound. Following spin to left, the pilot might perceive the sound as coming from right of rear. Similarly, spin to right would dislocate the sound to left of rear.

(2) Vertigo

Vertigo may be defined as the subjective loss of spatial orientation with respect to the direction of "up." Vertigo may be induced by many physiological and/or psychological factors often related to the conflicting vestibular and local visual cues to verticality. These result from a combination of the illusions noted above.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51).

ILLUSIONS RESULTING FROM PERCEIVED OR EXPERIENCED DYNAMIC MOVEMENT

(2) Vertigo (Cont.)

(a) Sensation of Climbing While Turning

In a properly banked turn, acceleration tends to force the body firmly into the seat in the same manner as when the aircraft is entering a climb or pulling out of a dive. Without visual references, an aircraft making a banked turn may be interpreted as being in a climbing attitude, and the pilot may react inappropriately by pushing forward on the control column.

(b) Sensation of Diving While Recovering from a Turn

The positive G-forces sustained in a banked turn are reduced as the turn is completed. This reduction in pressure gives the flyer the same sensation as going into a dive and may be interpreted in this way. He may overcorrect by pulling back on the control column and cause the aircraft to stall.

(c) Sensation of Diving Following Pull-out from a Dive

The accelerative forces on the body during the pull-out from a dive are reduced after recovery is complete. This reduction in G-forces may be falsely identified as originating from another dive.

(d) Sensation of Opposite Tilt While Skidding

If skidding of the aircraft takes place during a turn, the body is pressed away from the direction of turning. This may be falsely perceived as a tilt in the opposite direction.

(e) The Coriolis Phenomenon

This is a severe loss of equilibrium in which vertigo results. When the pilot is rotating with the aircraft and then moves his head out of the plane of rotation, there is a differential stimulation of two sets of semicircular canals. For example, if during a spin the pilot moves his head forward or backward, an additional pair of semicircular canals is stimulated and extreme dizziness and nausea may be suddenly produced. Constant angular velocity of less than 1°/sec with the appropriate head movement may permit the Coriolis response. Training by repeated exposure of the Coriolis effect can produce resistance.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51).

ILLUSIONS RESULTING FROM PERCEIVED OR EXPERIENCED DYNAMIC MOVEMENT

(2) Vertigo (Cont.)

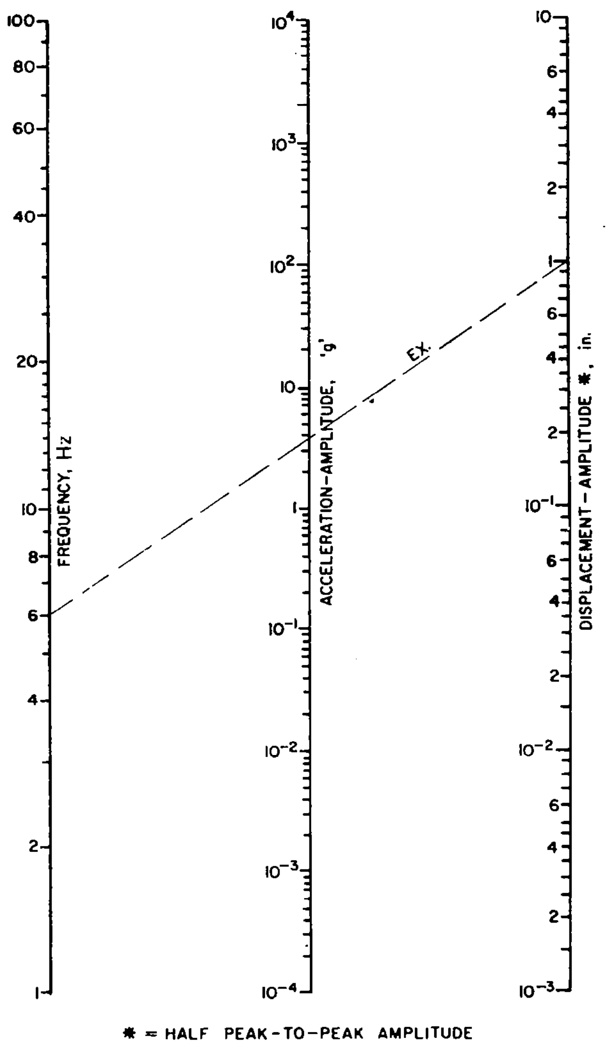
(f) Sensation of Reversed Rotation

If a rotary motion persists for a short period and is then discontinued, there is a sensation of rotation in the opposite direction. This occurs in a spinning aircraft when the pilot has poor visual reference to the Earth. After recovery from a spin to the left, there is a sensation of turning to the right. In attempting to correct for this, the pilot puts the aircraft back into the spin to the left. Flyers have given this illusion the sinister name of "graveyard spin."

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51).

VIBRATION

a. Nomogram of Frequency, Displacement-Amplitude and Acceleration-Amplitude for Sinusoidal Vibration

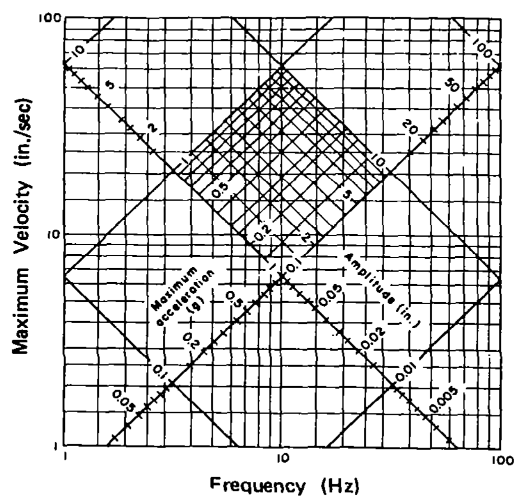


To determine the acceleration-amplitude of a vibration of 6 Hz at 1 in. (half-wave) amplitude (i.e. 2 in. peak-to-peak), lay a straight-edge across the chart joining 6 Hz with 1 in. amplitude. The acceleration-amplitude is 4 g (approximately).

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Guignard (76).

VIBRATION

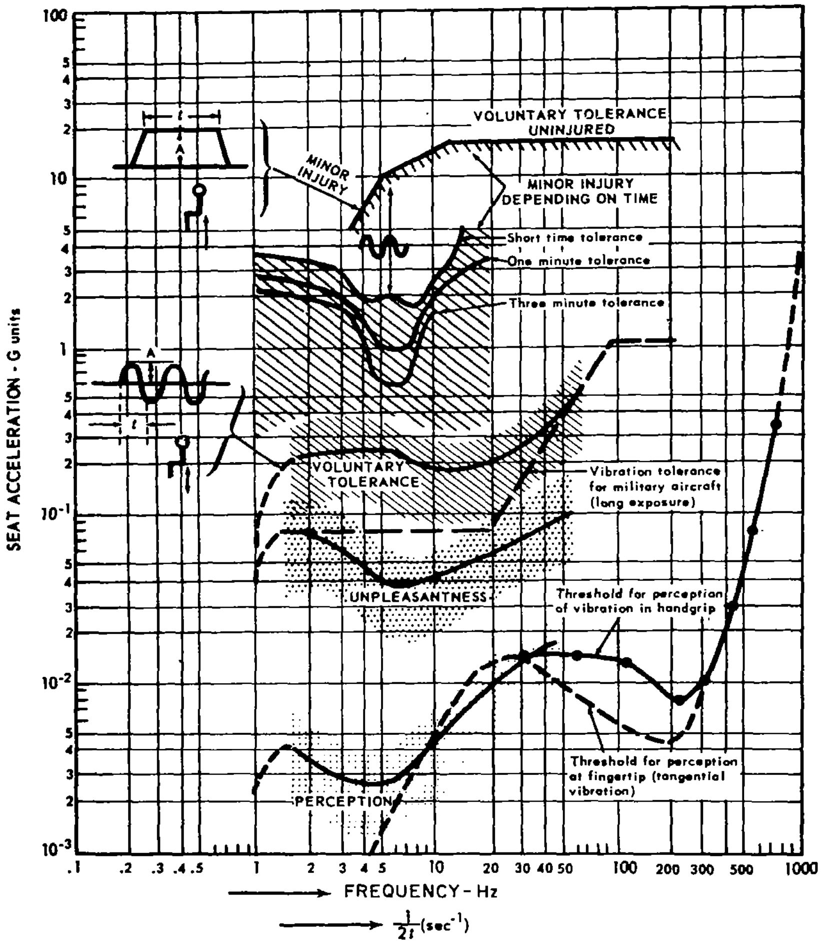
b. Conversions Between the Parameters of Vibration

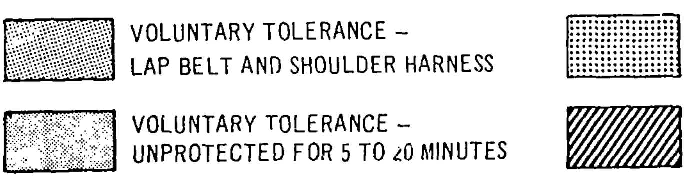


SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Morgan, et al (134).

VIBRATION

c. Criteria for Vibration Tolerance



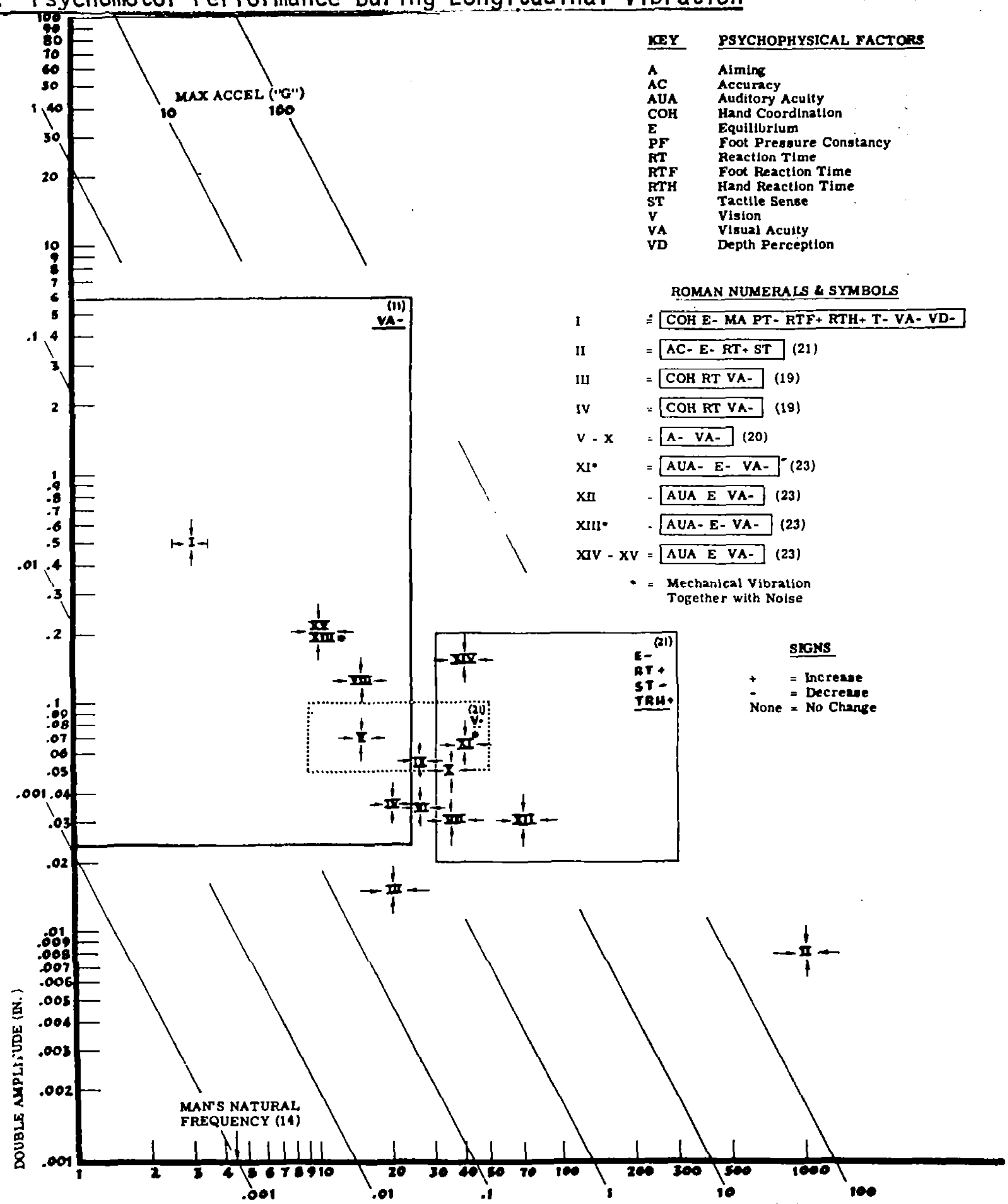


	VOLUNTARY TOLERANCE – LAP BELT AND SHOULDER HARNESS		UNPLEASANTNESS
	VOLUNTARY TOLERANCE – UNPROTECTED FOR 5 TO 20 MINUTES		PERCEPTION

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Human Engineering Design Criteria (88).

VIBRATION

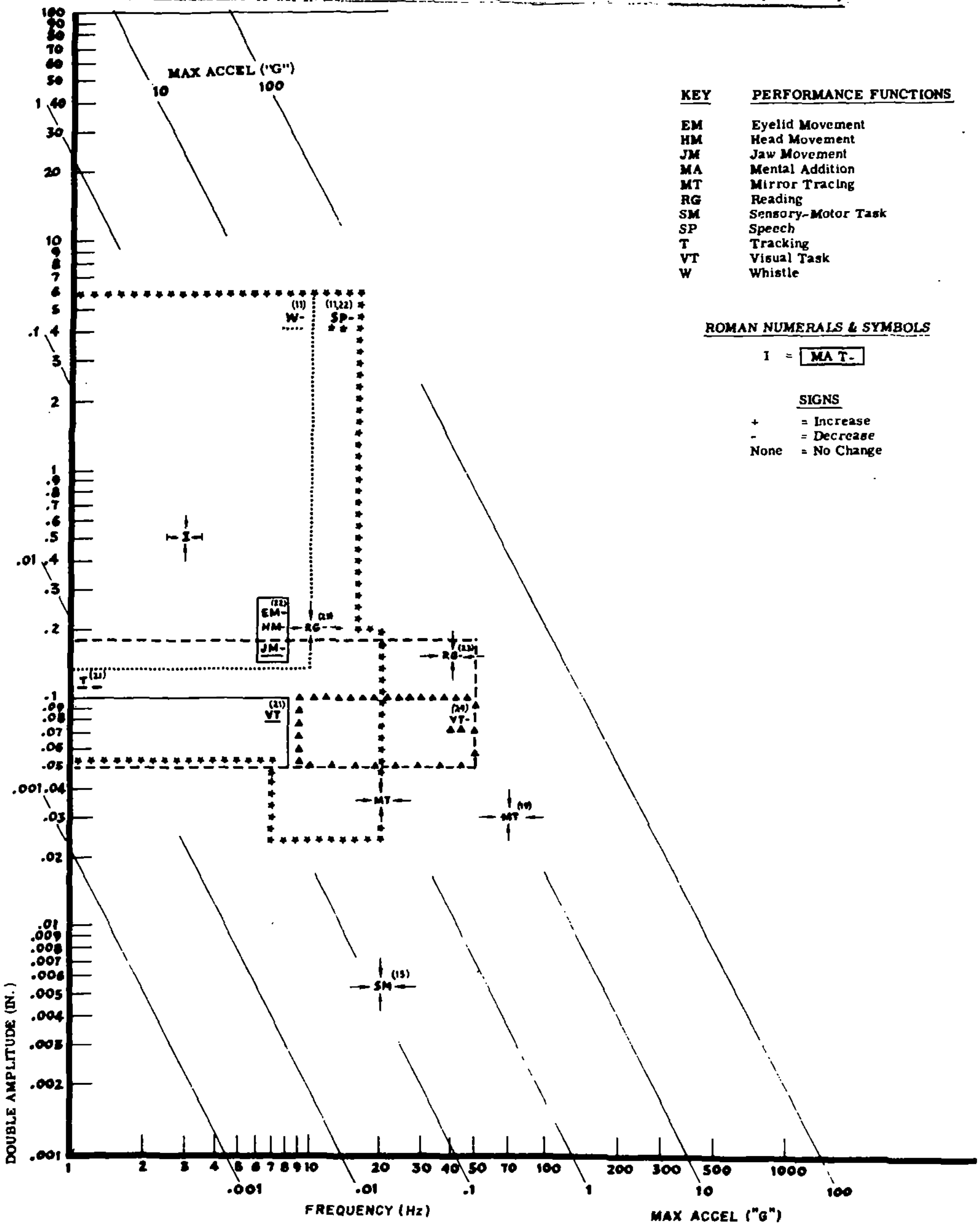
d. Psychomotor Performance During Longitudinal Vibration



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Linder (112).

VIBRATION

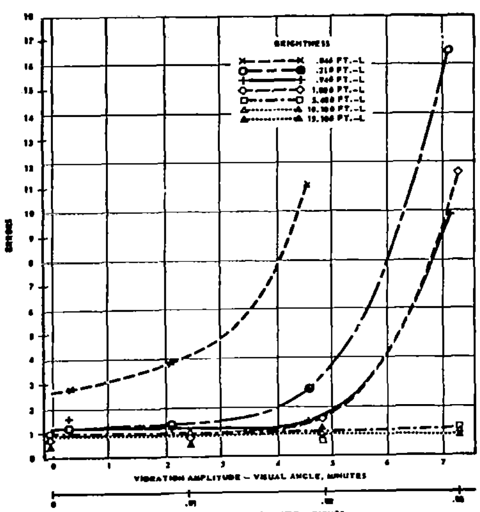
d. Psychomotor Performance During Longitudinal Vibration (Cont.)



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Linder (112).

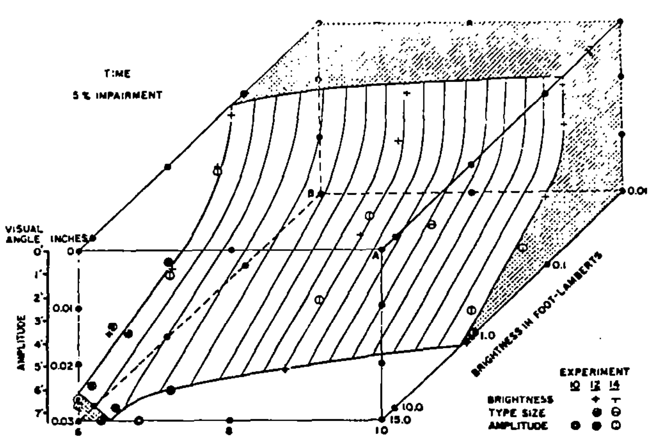
VIBRATION

e. Effect of Vibration Amplitude(1050 cpm) on Reading Accuracy for Various Luminances



Increase in the level of illumination reduces the amount of impairment of visual acuity. The visual acuity decrements produced by vibration can be compensated for by increased luminance of the displays. This chart indicates that as luminance of the displays. This chart indicates that as luminance increases from 0.046 ft-L to 15.0 ft-L, performance is significantly improved, although the difference in errors between luminances of 5.4 ft-L and 15.10 ft-L is not marked.

f. Effects of Amplitude, Brightness, and Type Size on Visual Performance During Vibration



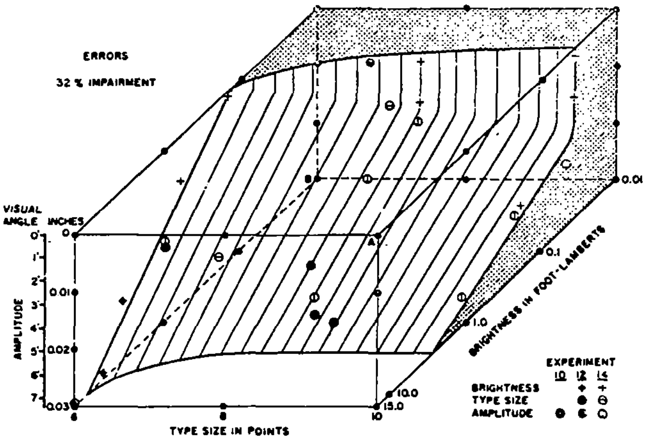
Combinations of Amplitude, Brightness, and Type Size Producing a Constant Impairment in Time Scores.

In the solid figure, corner A represents the most favorable conditions, B the least favorable. The curved surface is the boundary at which time is increased 5% as conditions become less favorable. Based on results from 12 subjects each.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II(51), Cook, et al (54) and Urmer and Jones (191).

VIBRATION

f. Effects of Amplitude, Brightness, and Type Size on Visual Performance During Vibration (Cont.)



Combinations of Amplitude, Brightness, and Type Size Producing a Constant Impairment in Error Scores

In the solid figure, corner A represents the most favorable conditions, B the least favorable. The curved surface is the boundary at which errors are increased 32% as conditions become less favorable. Based on results from 12 subjects each.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Cook, et al (54).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

TEMPERATURE TOLERANCES

THERMAL COMFORT REQUIREMENTS

a. Physiological and Thermal Characteristics of the Average Man

CHARACTERISTIC	METRIC UNITS	ENGLISH UNITS
Weight	68-72 kg	150-160 lbs.
Height	170 cm.	68-69 inches
Total Body Surface Area	1.8 sq. meters	19.5 ft^2
Volume	0.07 $meters^3$	2.5 ft^3
Specific heat	0.8 cal/gm-°C	0.8 Btu/lb-°F
Heat Capacity (using 160 lb. man)	57.6 cal/°C	128 Btu/°F
Body temperature (rectal)	37°C	98.6 0.5°F
Body surface temp.	33-34°C	91-93°F
Body and clothing Surface temperature (ave. - 1 Clo)	28°C	82.2°F
Body temperature ($2/3\ t_r + 1/3\ t_s$)	35.6°C	96.1°F
Body percent water	70%	70%
	HUMAN SKIN	
Weight	4.0 kg	8.8 lbs.
Surface Area	1.8 $meters^2$	19.5 ft^2
Volume	3.6 liters	3.7 Quarts
Water Content	70-75%	70-75%
Specific Gravity	1.1	1.1
Thickness	0.5 mm (Eyelids) to 5 mm (back)	0.02 to 0.2 inches
Heat production	13% (Body's Metabolic Heat Prod.)	13%
Conductance	9 → 30 kgCal/m^2-hr.-°C	
Thermal Conductivity (k)	1.5 ± 0.3 X 10-3 Cal/cm-sec-°C at 23-25°C Ambient	

SOURCE: Breeze (32) and Compendium of Human Responses to the Aerospace Environment, Vol. I (50).

THERMAL COMFORT REQUIREMENTS

a. Physiological and Thermal Characteristics of the Average Man (Cont.)

CHARACTERISTIC	METRIC UNITS	ENGLISH UNITS
Diffusivity $(k/_{\rho} C_p)$	7×10^{-4} cm^2/sec (Surface Layer 0.26 mm Thick)	
Thermal Inertia $(k/_{\rho} C_p)$	90-400 X 10^{-5} cal^2/cm^4-sec-°C^2	
Heat Capacity (Cp)	0.8 cal/gm-°C	0.8 Btu/lb-°F
Emissivity (Infrared) Skin and Clothing	- 0.99 - 0.94	
Reflectance (Wave Length Dependent)	MAX. 0.5→1.1μ MIN. 0.3 and 1.2μ	
Transmittance (Wave Length Dependent)	MAX. 1.2, 1.7, 2.2, 6, 11μ MIN. 0.5, 1.4, 1.9, 3, 7, 12μ	

TERM	DEFINITION
Clo	Insulation value of that quantity of clothing that will maintain comfortable thermal equilibrium in a man sitting at rest in an environment of: (a) 70°F air and wall temperature, (b) less than 50% rel. humidity, and (c) 20 ft/min air movement.
$1 \text{ Clo} = \frac{0.18 \text{ Deg. F}}{\text{kg-cal/Hr}}$	{In combined units {For 1.8 m^2 Surface Area
$1 \text{ Clo} = \frac{0.04536 \text{ Deg. F.}}{\text{Btu/Hr}}$	{1 kg-cal = 3.968 Btu
Heat Capacity of Body Periphery 40 Btu/°F	Outer layer to skin as opposed to body core. Approximately 1.0 inches thick.
Resistance of Periphery	Function of body activity and is equivalent to 0.16 to 0.70 Clo

Pain threshold for any area of skin 113°F (45°C)

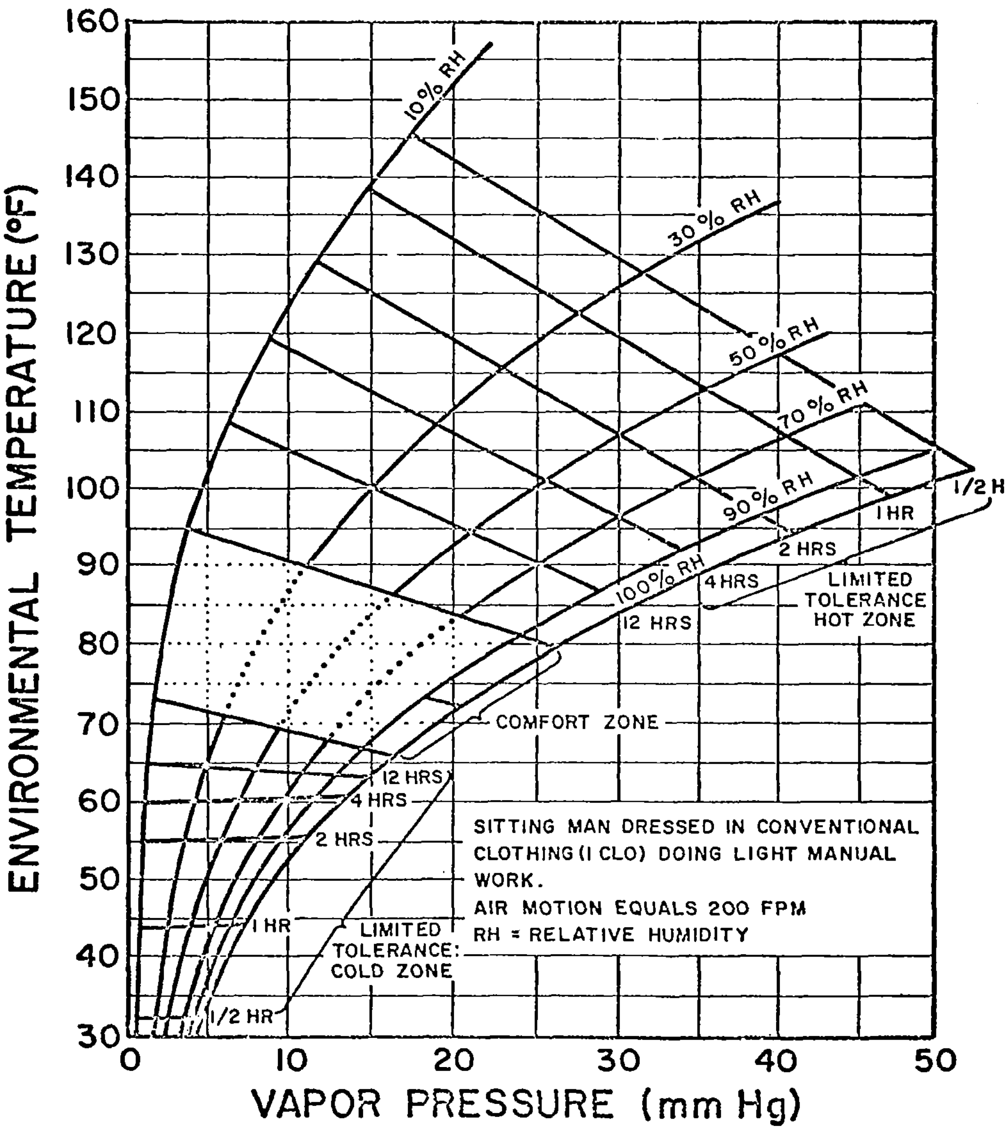
When mean weighted skin temperature is:	The typical sensation is:
above 95°F (35°C)	unpleasantly warm
93°F (34°C)	comfortably warm
below 88°F (31°C)	uncomfortably cold
86°F (30°C)	shivering cold
84°F (29°C)	extremely cold

When the hands reach:	When the feet reach:	They feel:
68°F (20°C)	73.5°F (23°C)	uncomfortably cold
59°F (15°C)	64.5°F (18°C)	extremely cold
50°F (10°C)	55.5°F (13°C)	painful and numb

SOURCE: Breeze (32) and Compendium of Human Responses to the Aerospace Environment, Vol. I (50).

THERMAL COMFORT REQUIREMENTS

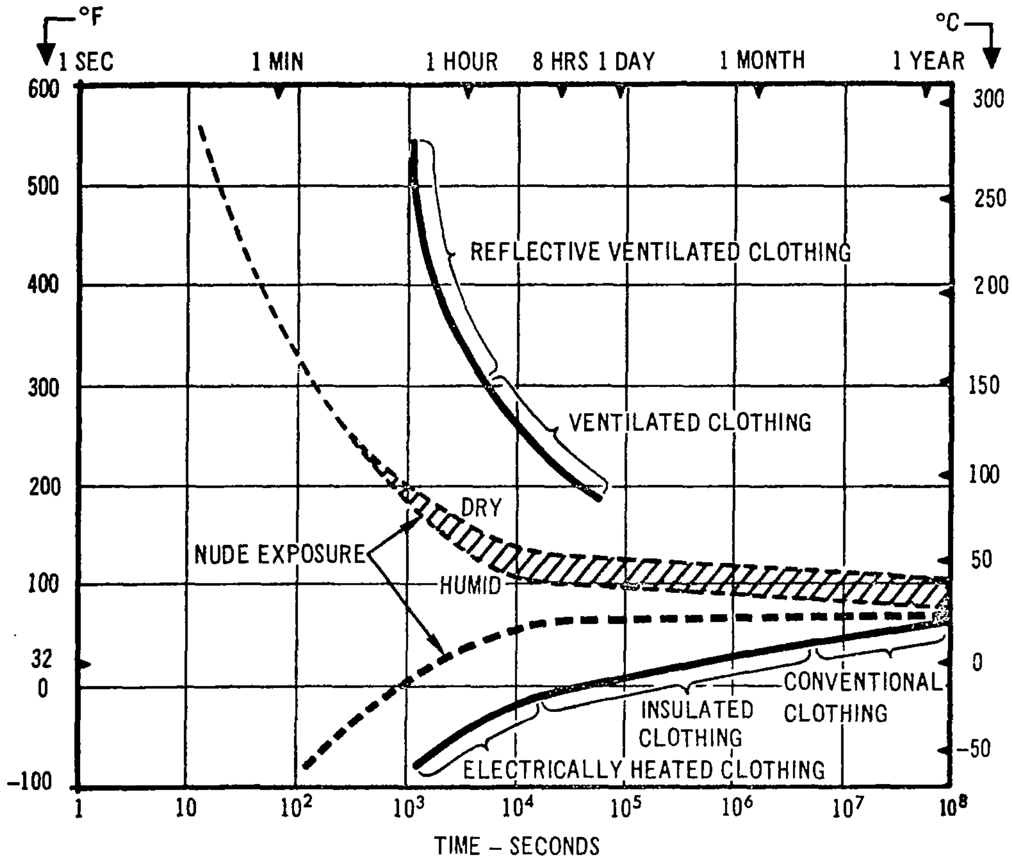
b. Temperature/Humidity Relationship



SOURCE: Human Engineering Design Criteria for Military Systems (89).

EXTREME TEMPERATURE TOLERANCES

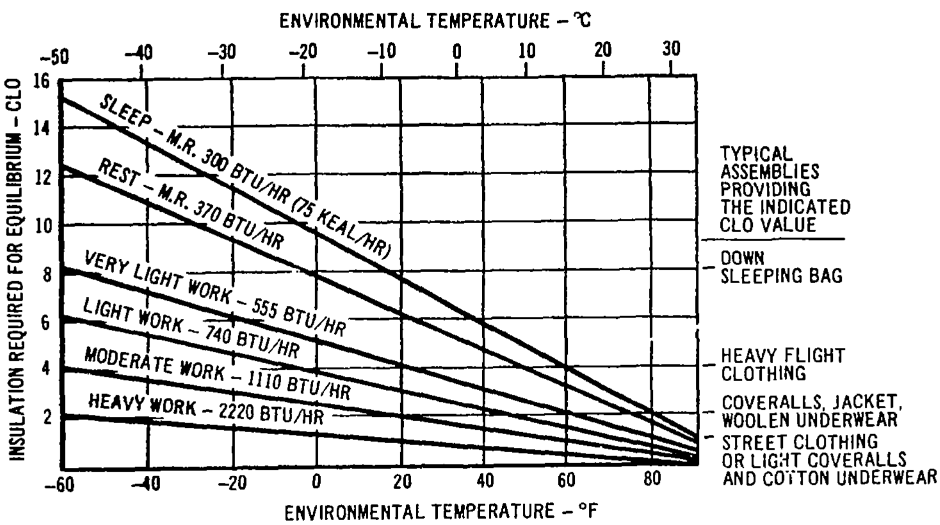
a. Human Thermal Tolerance Limits



SOURCE: Human Engineering Design Criteria (88), Webb (195).

EXTREME TEMPERATURE TOLERANCES

b. Low Temperature Limits for Different Activity Levels

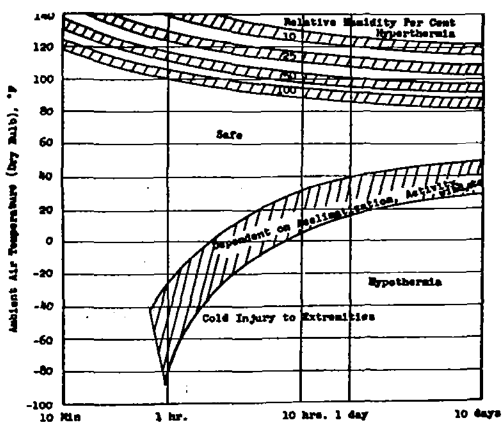


SOURCE: Human Engineering Design Criteria (88) and Webb (197).

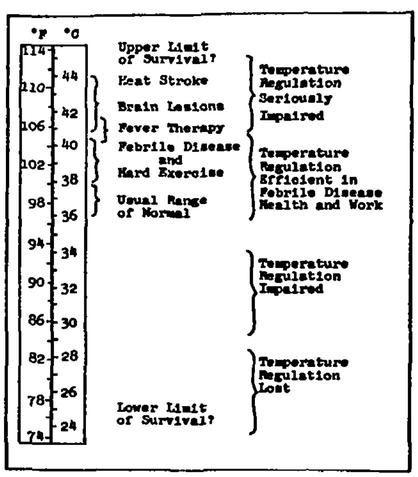
TEMPERATURE TOLERANCES

EXTREME TEMPERATURE TOLERANCES

c. Approximate Human Time-Tolerance Temperature with Optimum Clothing



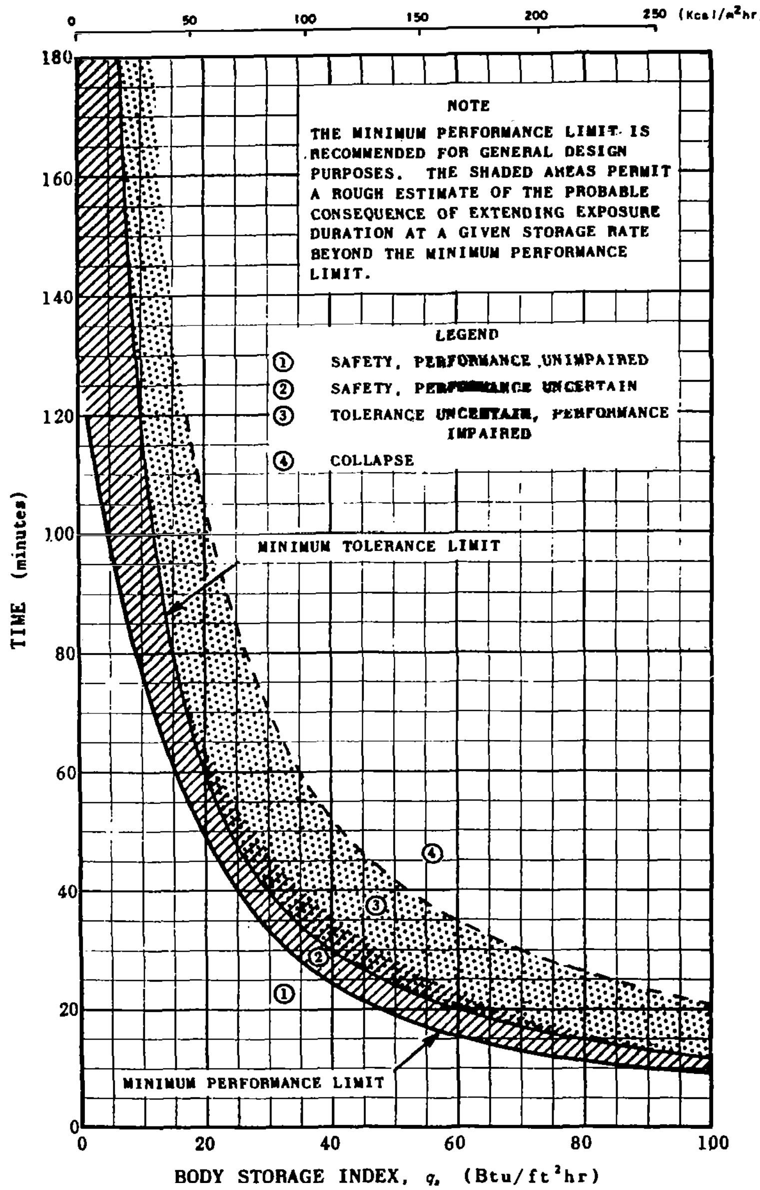
d. Human Body Temperature Extremes Defining Zones of Temperature Regulations



SOURCE: Breeze (32) and Compendium of Human Responses to the Aerospace Environment, Vol. I (50).

EXTREME TEMPERATURE TOLERANCES

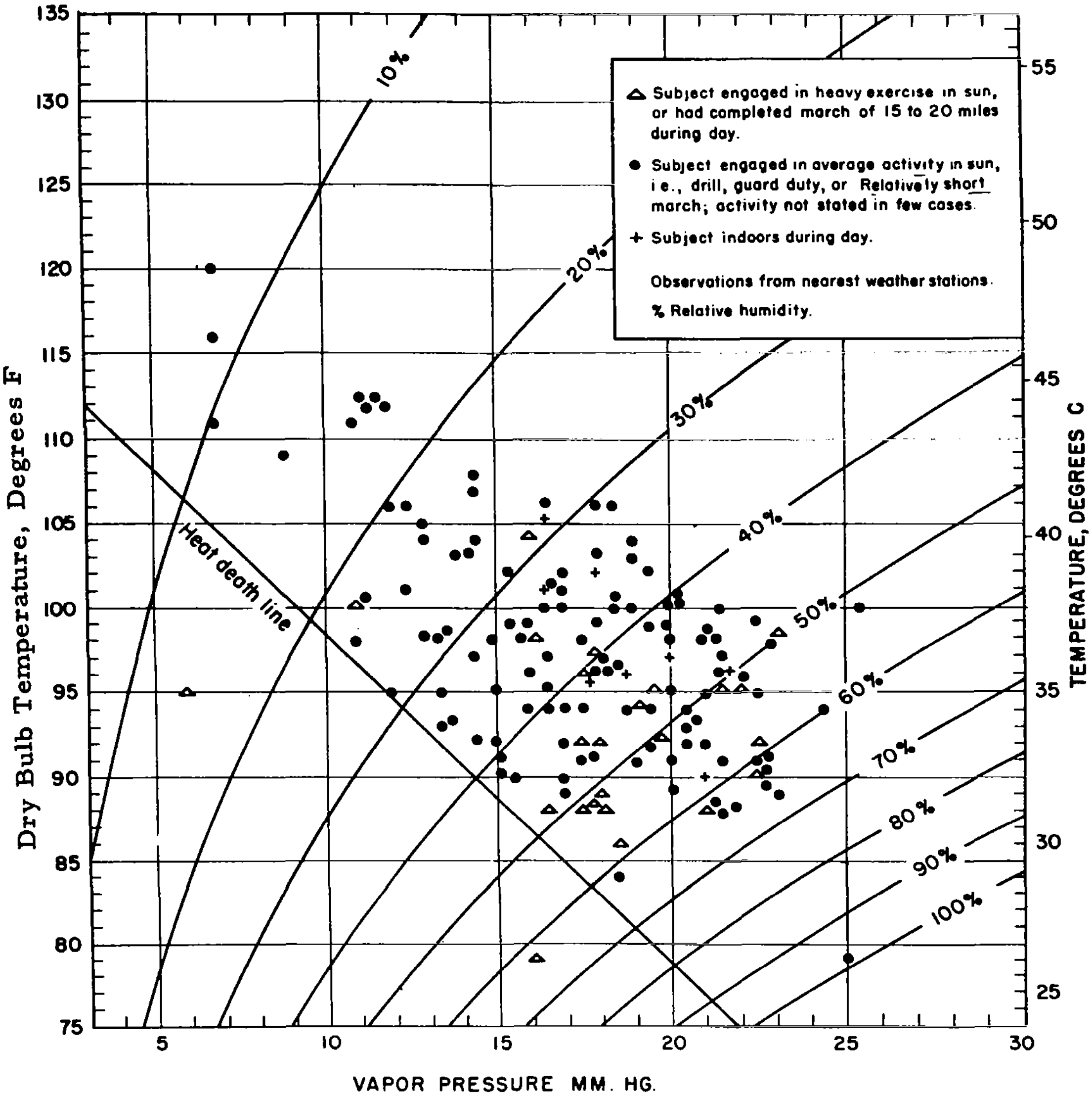
e. Performance and Tolerance Limits: Transient Zone



SOURCE: Blockley, McCutchan, et al(29), and Compendium of Human Responses to the Aerospace Environment, Vol. I (50).

EXTREME TEMPERATURE TOLERANCES

f. Humidity and Maximum Temperature on Day on Onset of 157 Cases of Fatal Heat Stroke in the U. S. Army, 1942-44.



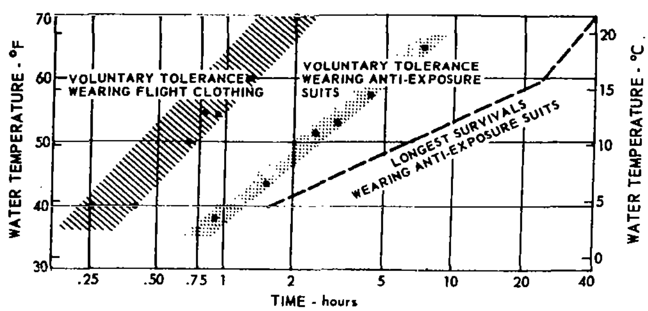
SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Schieckele (163).

EXTREME TEMPERATURE TOLERANCES

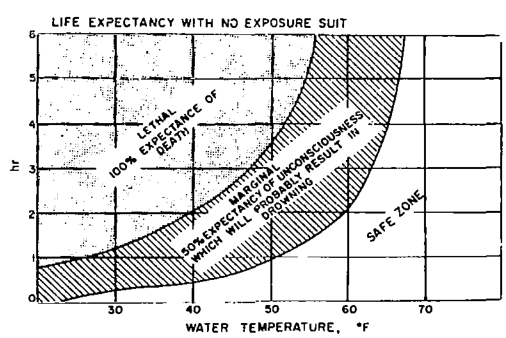
The "voluntary tolerance, flight clothing" zone in figure g shows the average results from numerous experimental studies, including a recent one using a diver's "wet suit" in conjunction with a flight suit and long underwear. Such experiments are typically terminated when the subject declines to accept the discomfort any longer, or reaches a skin temperature below 50°F. The second limit shown, pertaining to men protected by potentially waterproof garments, reflects the fact that hands and feet cannot be adequately insulated and remain functional. Nude men in 75°F water reach within 12 hours one or another tolerance limit (rectal temperature below 95°F, blood sugar below 60 mg/100 ml, or muscle cramps).

The extent to which real survival time would exceed this limit is difficult to predict, due to the importance of injury, equipment available, and such psychological factors as belief in the possibility of rescue. An analysis of over 25,000 personnel on ships lost at sea during 1940-44 showed that of those who reached life rafts, half died by the sixth day if the air temperature was below 41°F (5°C); survival time increased with increasing air temperature.

g. Voluntary Tolerance to Cold Water



h. Life Expectancy in Cold Water with No Exposure Suit

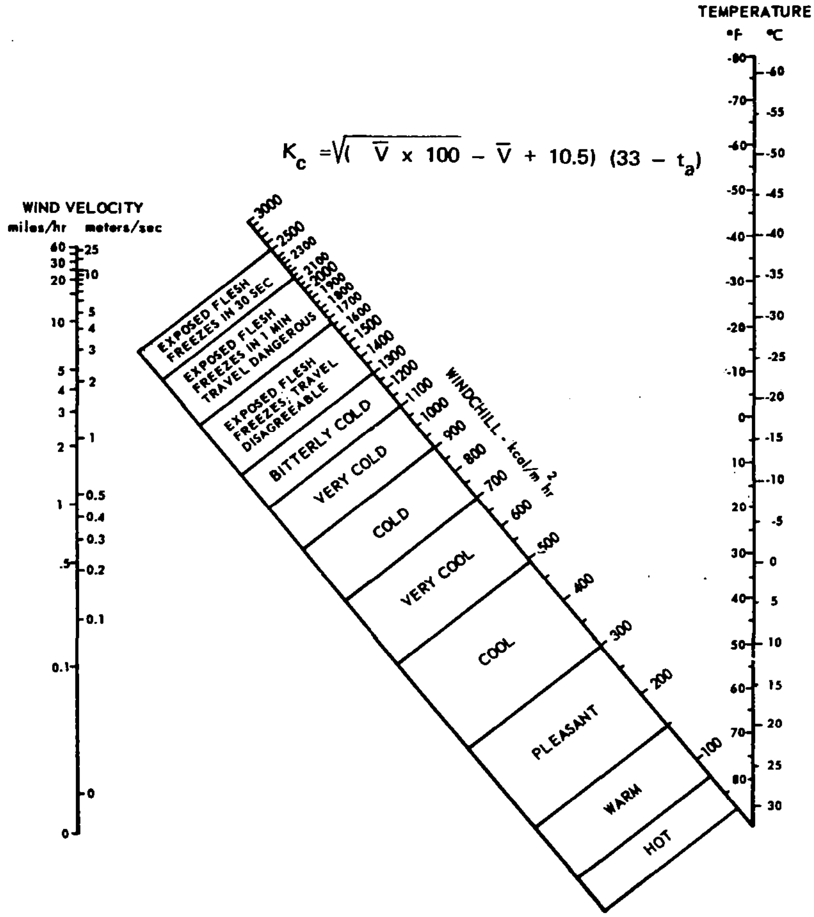


The expectation of life following cold water immersion. The data is that of Molnar.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Webb (195).

EXTREME TEMPERATURE TOLERANCES

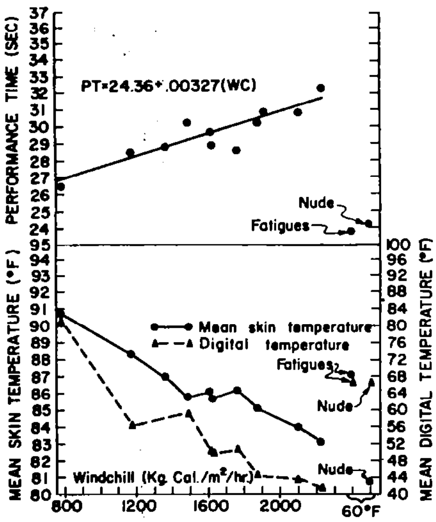
i. Windchill Index



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Webb (195).

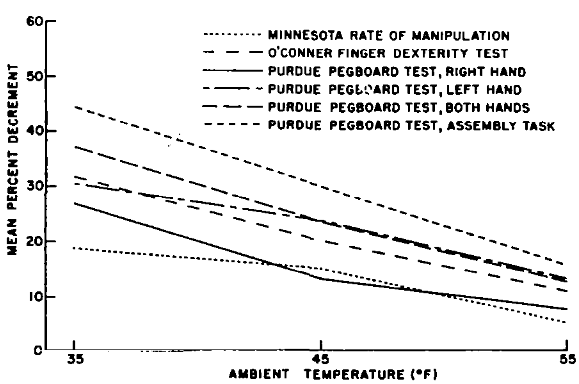
TEMPERATURE RELATED HUMAN PERFORMANCE

a. Performance Time, Skin, and Digital Temperature as a Function of Windchill



Arctic clothing was worn except where indicated. hand exposed during performance only. Follows approximately 35 minutes of exposure.

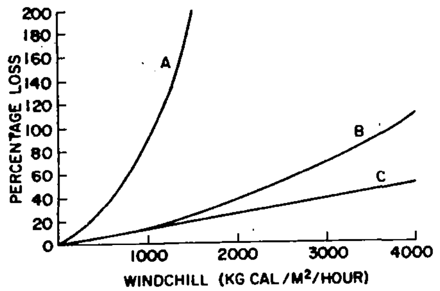
b. Percent Decrement in Performance as a Function of Ambient Temperature at Sea Level



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50), Dusek (61) and Teichner (185).

TEMPERATURE RELATED HUMAN PERFORMANCE

c. Minimum Effects of the Cold on Selected Functions



Each curve is an estimated percentage loss of the indicated type of performance for appropriately dressed but unacclimatized men.

a. Tactual sensitivity of the bare hand
b. Simple visual reaction time
c. Manual skill

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Teichner (186).

TEMPERATURE TOLERANCES

PAIN FROM RADIANT AND CONVECTIVE HEATING

a. Time Required to Reach Strong Skin Pain as a Function of Radiant Heat

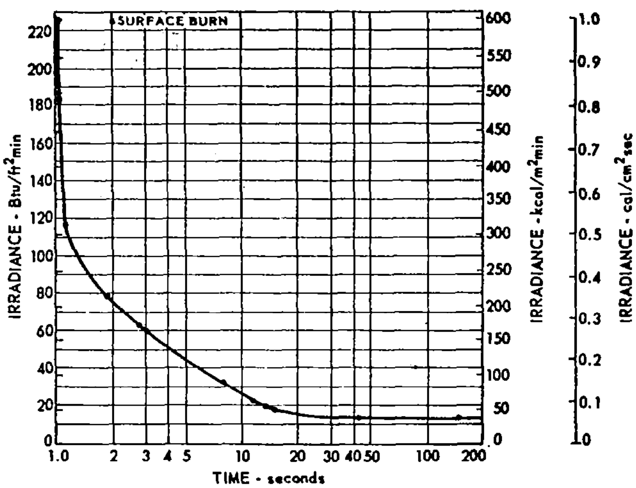


Figure a shows the time to reach strong skin pain from radiant heating, with radiation sources ranging from the simulated intense thermal flash of a nuclear weapon (approximately 100 Btu/ft^2 min) to the slow heat heat pulse associated with re-entry heating, where the heating is partly convective as well. The curve is derived from experiments involving heating of single small areas of forehead or forearm or exposed areas of skin of a subject in flight clothing, and of the whole body surface. The pain threshold is reached when the skin temperature comes to 45°C, and a skin temperature of 46°C is intolerably painful. For small skin areas the curve becomes asymptotic at about 18 Btu/ft^2 min, which means that at this level and below, the blood supply to the skin is carrying off the heat as fast as it arrives, and heat is stored in the body; how long this can go on with the total body exposed is not established.

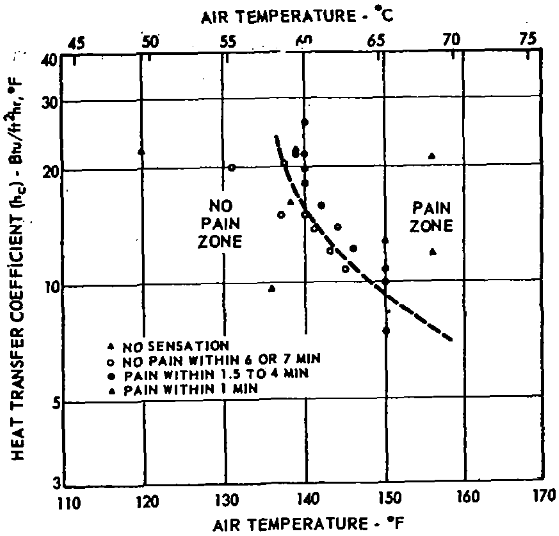
SOURCE: Buettner (36), Stoll and Greene (176) and Webb (195, 197).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

TEMPERATURE TOLERANCES

PAIN FROM RADIANT AND CONVECTIVE HEATING

b. Painful and Nonpainful Heating of Air as a Function of the Heat Transfer Coefficient



These data in Figure b indicate the dividing line between painful and nonpainful heating for air at various temperatures, versus the heat transfer coefficient, which depends on air density, air velocity, and surface areas and shape. The data were obtained by exposing a small segment of the cheek to a flowing air stream through a padded hole in the wall of a cylindrical tube. h_c was computed from air velocity and duct geometry.

SOURCE: North American Aviation (139) and Webb (195).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

TEMPERATURE TOLERANCES

COMPUTATION OF THE HEAT BALANCE

Characteristics of the environment which determine the level of heat stress are the following: air temperature, density, and rate of movement; wall temperature, emissivity, and geometry; radiation sources and sinks; water vapor concentration and diffusion resistance between the skin and the surrounding atmosphere. These determine respectively the convection (C), radiation (R), and evaporation (E) exchange of the body; together with the heat production of the body itself (metabolism, M), these quantities determine the heat balance of the body. This can be represented in simple notation as: M - (E + C + R) = S, where S is storage. The bracket encloses quantities which are normally heat losses from the body (i.e., when the surrounding environment is lower in temperature than the body). A sixth possible term, which may be significant in special situations, is conductive heat exchange. The following equations and charts permit determination of each term in the heat balance equation. All heat flows are expressed per unit body surface area.

CONVECTION (C) $= h_c(t_{surface} - t_{air})$ Btu/ft^2, hr

$$h_c = 0.57 \left(\frac{t_{air} + 460}{536}\right)^{0.5} (V\rho)^{0.5} \qquad \text{Btu/ft}^2\text{, hr, °F}$$

RADIATION (R) $= h_r\,(t_{surface} - t_{mean\ radiant})$ Btu/ft^2, hr
(exclusive of solar)

$$h_r = \sigma F_{ae}\, f_r \left[\frac{(t_{surface} + 460)^4 - (t_{mean\ radiant} + 460)^4}{t_{surface} - t_{mean\ radiant}}\right]$$

where t = temperature in °F
V = mass velocity lb/ft^2 min
h_c = the convective conductance
h_r = radiant conductance
σ = Stefan-Boltzmann universal radiation constant; 0.173 x 10^{-8} Btu/ft^2, hr, °R^4
F_{ae} = shape and emissivity factor
f_r = ratio of radiation area to total body surface area

EVAPORATION. No general formula is possible due to dependence on sweat response and clothing characteristics (wicking, diffusion resistance, etc.). The following formula pertains only to the special case of the totally wet body. (Achievable for nude men only at severe levels of heat strain and in humid environments; feasibility unknown but unlikely for clothed men):

SOURCE: Blockley, McCutchan, et al (29) and Webb (195).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

TEMPERATURE TOLERANCES

COMPUTATION OF THE HEAT BALANCE

$$E = 3.6\ h_c\ (p_s - p_a) \qquad \text{Btu/ft}^2\text{, hr}$$

where p_s and p_a are vapor pressures (in mm Hg) at the evaporating surface and in the air respectively. For cases where the surface (skin or garment) is not completely wet, a factor must be introduced to represent the "degree of wettedness" of the surface. In the case of a partially dry clothing layer, complex adjustments must be made to account for the resistance to vapor transfer of textiles and of still air. E may be obtained by experimental measurement of weight change in a given environment.

$$\text{STORAGE (S)} = 0.83\ \frac{W}{A}\ \frac{d}{dt}\ (t_{body}) \qquad \text{Btu/ft}^2\text{, hr}$$

where $t_{body} = \frac{1}{3}\ t_{skin} + \frac{2}{3}\ t_{rectal}$
W = body mass in lbs
A = body surface area
0.83 = average heat capacity for body tissues

S is a rate, like the other terms in the heat balance, and is computed from the linear rate of change of the weighted mean body temperature (slope of the time history), not from a finite difference quantity.

METABOLISM (M) can be estimated from activity description or determined by measuring oxygen consumption

For equilibrium, S must equal zero. When M is changed substantially, 45 minutes or more may be required to reach a new equilibrium. Solving for E will permit an estimate of the magnitude of the sweat rate required. For most non-compensable heating conditions, a steady state of heat transfer can be assumed after about 10 minutes. Solving the equation for S permits prediction of "tolerance time" (time to collapse) from the following equation:

$$T_{tol} = \frac{1700}{S}\ \text{minutes}$$

where T_{tol} = average tolerance time, and S is expressed in Btu/ft^2 hr;

Or: $$T_{tol} = \frac{4600}{S}\ \text{minutes}$$

where S is expressed in $kcal/m^2$ hr.

The above equations are based on average experimental data taken on unacclimatized men. The corresponding constants for minimum predicted tolerance time are: 1200 and 3300 for English and metric respectively.

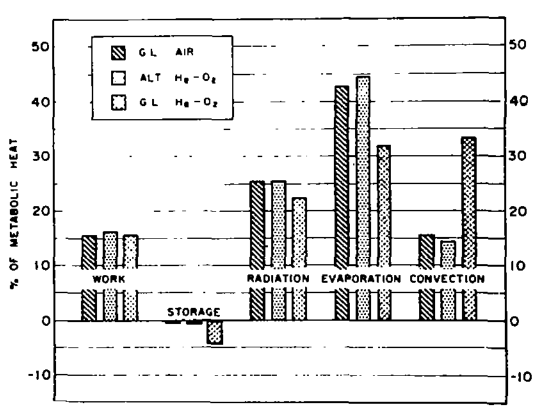
SOURCE: Blockley, McCutchan, et al (29) and Webb (195).

COMPUTATION OF THE HEAT BALANCE

a. Summary of the Contribution Made by Each Mechanism of Heat Loss Under Normal, Comfortable Environmental Conditions.

MECHANISM	PERCENT OF TOTAL	HEAT LOSS (Cal/24 Hrs)
1. Direct Radiation	60.0%	1,800
2. Conduction-Convection		
a. Direct contact with air	10.0%	300
b. Warming inspired air	2.5%	75
c. Urine and feces	1.5%	45
3. Insensible Perspiration		
a. Via skin	14.5%	435
b. Via lungs	8.0%	240
4. CO_2 Liberation	3.5%	105
TOTAL	100.0%	3,000

b. Avenues of Heat Exchange as Percentages of Total Metabolic Heat for a 150-Minute Test Period with 1 Hour of Exercise at 26°C.



Dewpoints are:

G.L. Air = 7.4°C

Alt. He - 0_2 = 5.0°C

G.L. He - 0_2 = 4.0°C

G.L. = Ground Level at 745 min Hg

G.L. He - 0_2 = 0_2 at 159 mm Hg He at 579 mm Hg

Alt. He - 0_2 = 0_2 at 165 mm Hg He at 206 mm Hg

SOURCE: Air Force Manual AFM 160-5 (4), Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Epperson, et al (64).

COMPUTATION OF THE HEAT BALANCE

c. Conditions for Prediction of Body Thermal Status

Environment			
External (Natural)	Internal (Induced)	Body State	Clothing
Solar radiation (q_{sr})	Wall temperature (t_w)	Metabolic rate (q_m)	Thermal resistance (R_g)
Earth radiation (q_{er})	Atmospheric temperature (t_a)	Weight (W)	Vapor resistance (R'_g)
Lunar radiation (q_{lr})	Atmospheric pressure (P)	Posture	Wind permeability
Shadow cones (day/night)	Atmospheric velocity (V)	Area of body (A_b)	Weight
Atmospheric composition	Atmospheric composition	Skin temperature (t_s)	Color (emissivity absorptivity)
Vehicle velocity (if > C/7) (C = vel. of light)	Absolute humidity (p_a)	Rectal temperature (t_r)	Wicking efficiency
	Diffusivity (D_v)	Mean body temperature (t_b)	Effective clothing absorbtance
Vehicle attitude or orientation	Specific heats (C_p, C_v)	Respiration rate ($\dot{V}$)	
Vehicle altitude	Surface Area (surroundings) A	Insensible water loss	
	Shape emissivity factor F_{ae}	Sweat rate (sensible (W_e) water loss)	
	Crew operating mode	Wetted area (ω)	
		Activity/work efficiency	
	Stress Factors	Physical condition	
	System failure	Degree of heat stress resistance (acclimatization)	
	G-loads (weightlessness)	Water/electrolyte balance	
	Toxicity (CO_2 etc.) effects	Radiation area factor (fr)	
	Radiation effects	Radiating area of body (A_r)	
	Decompression (emergency)	Area of body irradiated	
	Hypoxia	Effective skin absorbtance	
	Psychological (morale, anxiety)		
	Vibration		

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol I (50).

EVAPORATIVE COOLING CONSIDERATIONS

a. Recruitment of Sweating

AREA	USUAL (BUT NOT INVARIABLE) ORDER OF RECRUITMENT
Dorsum foot	1
Lateral calf	2
Medial calf	3
Lateral thigh	4
Medial thigh	5
Abdomen	6
Dorsum hand	7 or 8
Chest	8 or 7
Ulnar forearm	9
Radial forearm	10
Medial arm	11
Lateral arm	12

b. Increments in Mean Regional Evaporative Rates in Environmental Temperature

REGION	EVAPORATIVE RATE			INCREMENT IN EVAPORATIVE RATE	
	T_A 29°C.	34°C.	38°C.	29-34°C.	34-38°C.
	gm/m²/hr.			gm/m²/hr/°C.	
Calf	18.0	86.5	169.0	13.7	20.4
Thigh	14.4	58.7	144.0	8.0	21.3
Abdomen	12.0	60.0	156.0	9.6	24.0
Chest	9.6	37.2	120.0	5.5	20.7
Forearm	12.0	21.6	96.0	1.9	18.6
Arm	10.8	14.4	65.0	0.7	13.0
Cheek	24.0	36.0	108.0	2.4	18.0
Forehead	24.0	60.0	240.0	7.2	45.0

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50), Hertzman, et al (85) and Randall and Hertzman (148).

EVAPORATIVE COOLING CONSIDERATIONS

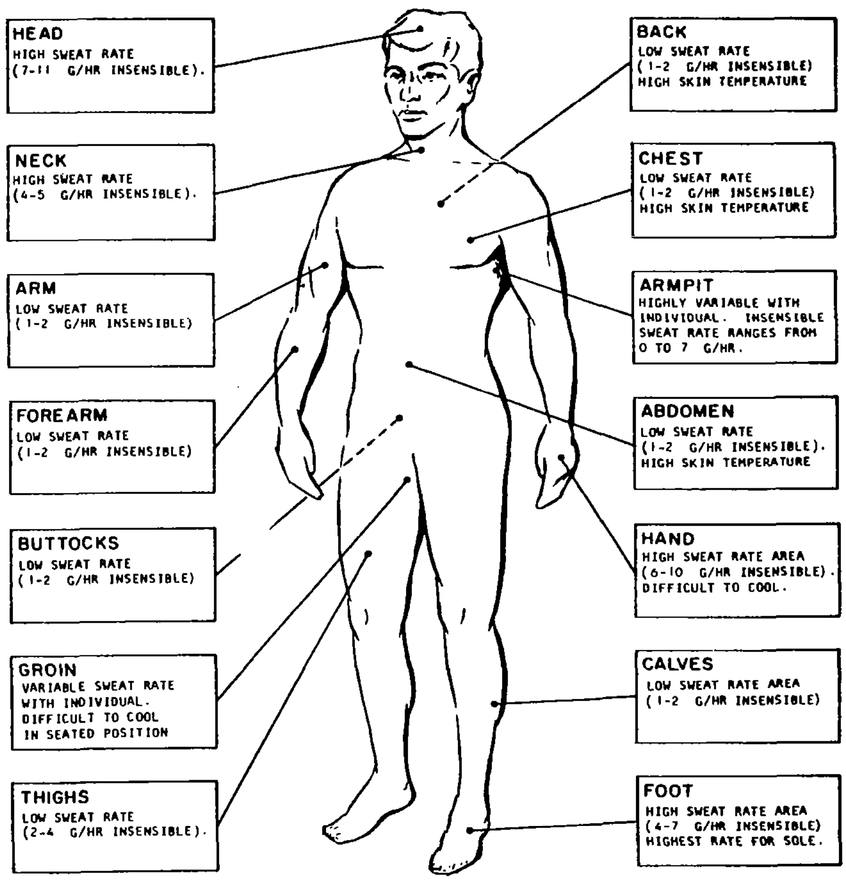
c. Regional Fractions of Total Cutaneous Evaporation Expressed as Percentage of Total

REGION	AIR TEMPERATURE							
	24°C.	26°C.	28°C.	30°C.	32°C.	34°C.	36°C.	37°C.
Head	11.8	12.1	11.9	9.7	8.0	7.0	8.5	8.4
Arm	4.6	4.4	4.2	3.4	2.6	2.2	3.1	3.3
Forearm	8.2	7.2	6.0	4.3	3.2	3.1	4.4	4.3
Trunk	22.8	23.0	22.2	22.2	30.0	33.0	43.0	38.2
Thigh	13.6	13.1	17.1	20.2	22.6	23.8	25.5	22.3
Calf	8.5	9.0	11.9	16.0	20.3	22.8	24.1	19.8
Palm	15.6	15.3	13.1	9.6	6.8	4.6	3.5	2.5
Sole	14.7	15.1	13.5	9.9	6.4	3.7	2.3	1.5

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Hertzman, et al (85).

COOLING - SKIN EVAPORATION

a. Regional Cooling Requirements of the Human Body in Air at Sea Level at Rest



SOURCE: Berenson(24) and Compendium of Human Responses to the Aerospace Environment, Vol. I (50).

COOLING - SKIN EVAPORATION

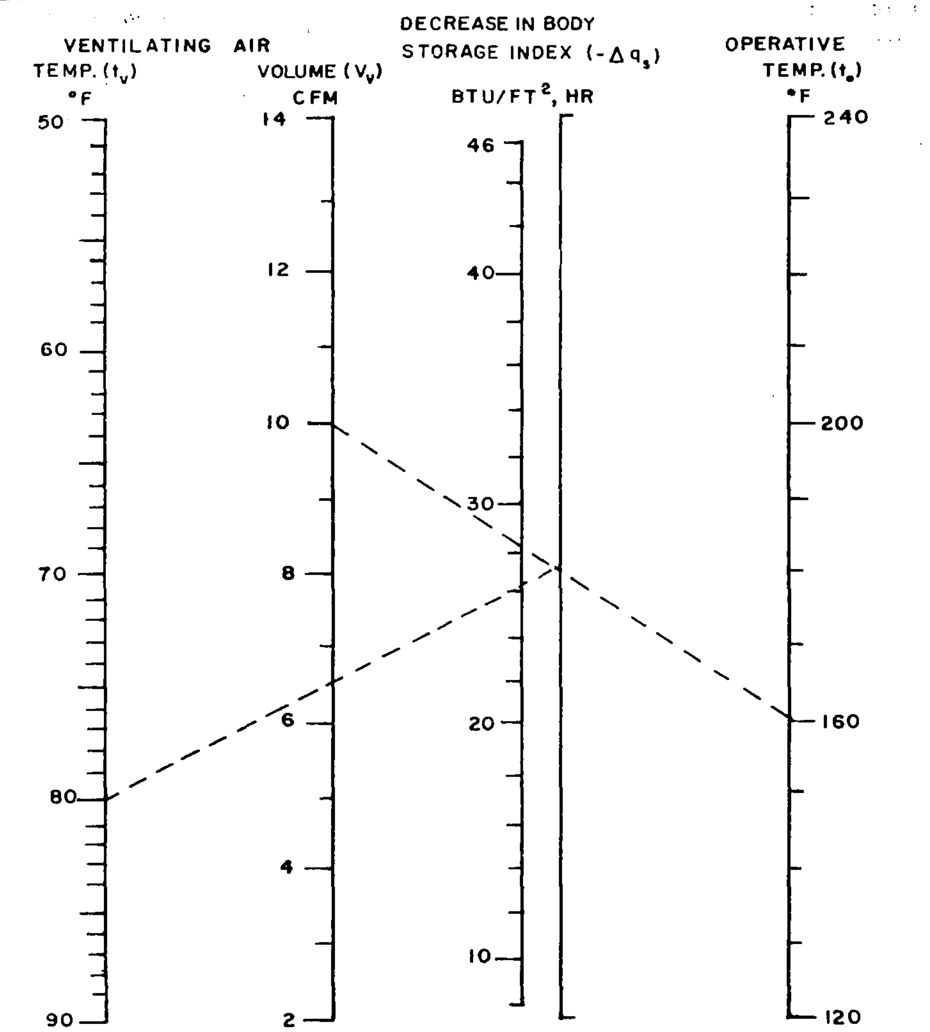
b. Regional Temperature Heat Transfer Relationship

REGION	PREFERRED TEMPERATURE (°F)	HEAT LOSS BTU/HR	AREA FT^2	SKIN CONDUCTANCE $BTU/FT^2/HR/°F$
Head	94.4	15.9	2.15	1.61
Chest	94.4	32.6	1.83	3.87
Abdomen	94.4	17.9	1.29	3.02
Back	94.4	49.3	2.48	4.31
Buttocks	94.4	33.0	1.94	3.70
Thighs	91.4	47.7	3.55	1.76
Calves	87.5	58.0	2.15	2.35
Feet	83.5	39.7	1.29	1.98
Arms	91.4	33.4	1.07	4.10
Forearms	87.5	34.2	0.86	3.45
Hands	83.5	63.5	0.75	5.45

SOURCE: Berenson (24) and Compendium of Human Responses to the Aerospace Environment, Vol. I (50).

VENTILATING GARMENT COOLING CHARACTERISTICS

a. Nomograph for Computing Cooling Power of Ventilating Garment

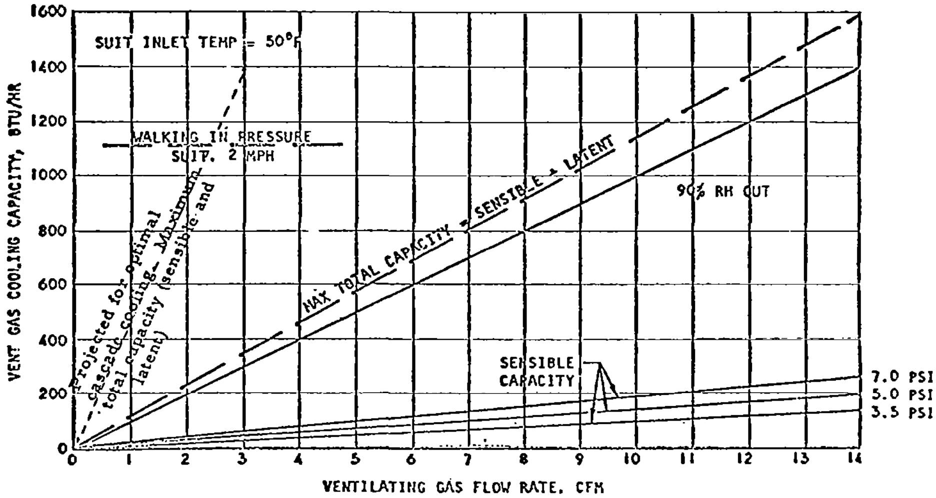


EXAMPLE: GIVEN t_o = 160°F, V_v = 10 CFM, t_v = 80°F; $-\Delta q_s$ = 26.2 BTU/FT²/HR

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and McCutchan and Isheewood (120).

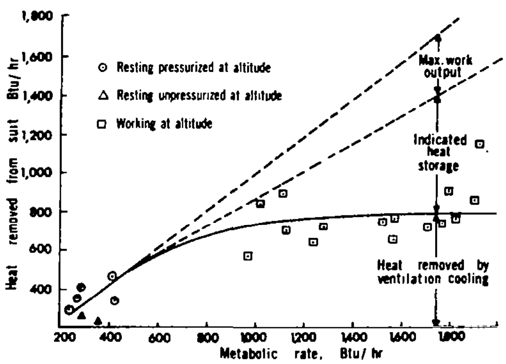
PRESSURE SUIT VENTILATION

a. Pressure Suit Ventilating Gas Cooling



The dashed line represents the addition to cooling capacity of the ventilating suit theoretically possible by optimum function of a cascade cooling system proposed for the Apollo system.

b. Thermal Energy Removed from an International Latex Prototype Apollo Suit Pressurized at 3.5 psia Above Ambient with Air Flow at 15 ft^3/min.

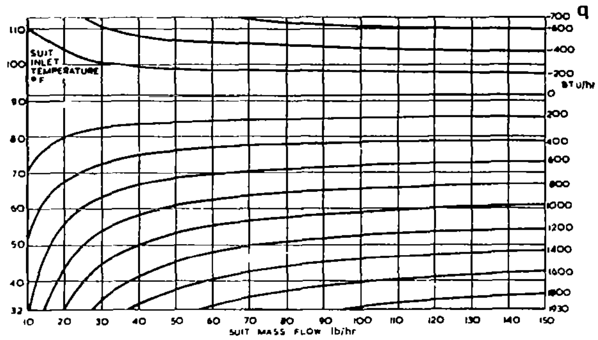


SOURCE: Burris, et al (38), Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Roth (154).

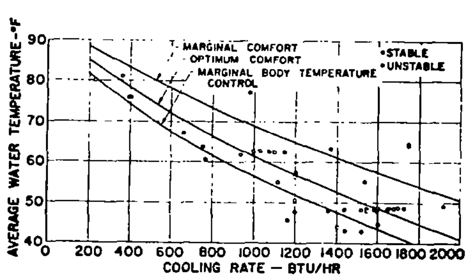
TEMPERATURE TOLERANCES

LIQUID COOLING GARMENT PERFORMANCE

a. Effect of Water Temperature on the Performance of Prototype Liquid-Cooled Suit



SUIT PERFORMANCE FOR AN EARLY PROTOTYPE LIQUID-COOLED SUIT



COOLING GARMENT OPERATING LIMITATIONS OF AVERAGE WATER TEMPERATURE AND COOLING RATE FOR SEVERAL PROTOTYPE APOLLO SUITS

SOURCE: Burton (40), Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Jennings (92).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

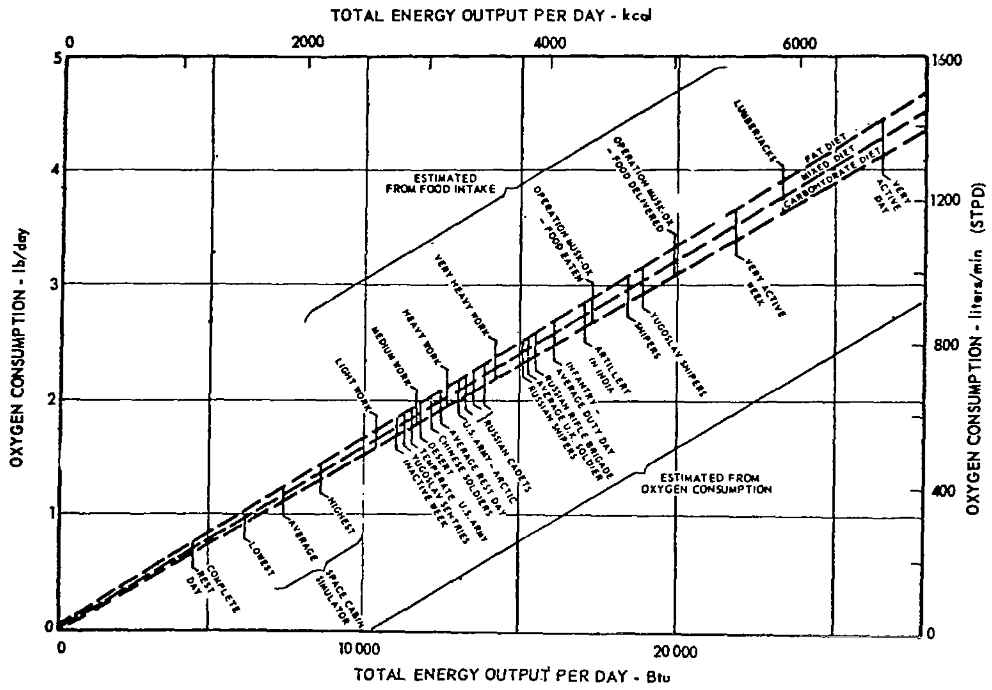
METABOLISM

OXYGEN COSTS

There are two methods of calculating daily energy exchange. The preferred method is by indirect calorimetry, in which oxygen consumptions are measured and a complete time-activity study is made. Representative figures for soldiers, derived by using this technique, are given on the lower half of the diagram as an indication of the wide day-to-day and week-to-week variation within a uniform group, and of occupation-to-occupation variations.

The alternative method is by precise estimation of food intake and body weight change. Since not all food is absorbed, and since changes in body weight are not all due to energy storage or liberation, this is a difficult technique to use accurately. Representative figures obtained from food intake are given in the upper half of the diagram as an indication of light, medium, heavy and very heavy work in industry on a year-round basis. Also given are the approximate food-supply and food-eaten figures for Operation Musk-Ox, which was a 4-month, 3400-mile motorized journey across Northern Canada in winter. Long distance journeys across the moon will require special planning for food and oxygen supplies. Values obtained in space cabin simulator trials have been added as a guide to in-flight requirements. Highest values regularly recorded are for lumberjacks, whose food intake contains much fat.

a. Total Metabolic Energy Exchange



SOURCE: Webb (195).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

METABOLISM

OXYGEN COSTS AS A FUNCTION OF WORK LOAD

These tables give typical values for the oxygen cost of everyday activities and of certain special activities, which may be useful in the bioastronautics program. The values were selected from the literature and adjusted for a man 69 inches tall and weighing 167 pounds (average values for the Mercury astronauts).

The first column of each table gives values for oxygen consumed, which can be regarded as the most direct estimate of energy expenditure generally available to us. Large men consume more oxygen than small men, and it is suggested that the values given be increased by 7.5% for large astronauts and reduced by 6% for small astronauts, based upon the size range of the men in current NASA programs.

Evidence is accumulating that important subject-to-subject differences exist even in men of the same size. These commonly give rise to variations as high as 60% when different men are performing the same task, as high as 30% when adjustments for body size are made, and as high as 10-15% when repeated measurements are taken on the same man.

The efficiency with which external work is produced also varies widely. It is lowest in the work of respiration (less than 5%), is 10-20% for common tasks, and highest in bicycling and walking on the inclined treadmill (up to 35% and occasionally 40% in trained men). Variations of these magnitudes must be allowed for in using the tables. To obtain closer estimates, measurements must be made on each astronaut.

The amount of energy that is produced when a given weight of oxygen is consumed depends on the fuel. On an average mixed diet, 0.1 lb. of oxygen is used for every 613 Btu or 154 kcal. On a fat diet, however, this drops to 591 Btu. On a carbohydrate diet, and during prolonged physical work, the total energy produced is equivalent to 636 Btu per 0.1 lb.

Presented first is a useful table given as an indication of the severity of physical work in terms of oxygen cost, energy expenditure, and heat output. The tables can be used to give an approximate value of the energy exchanges in a day by working out how many hours and minutes are spent on each activity. Thus, if 8 hours are spent asleep at 0.045 lb/hr., 4 hours are spent walking at 0.147 lb/hr., and 12 hours are spent in aircrew activities at 0.066 lb./hr., the total oxygen consumption in 24 hours is:

$$(8 \times 0.045) + (4 \times 0.147) + (12 \times 0.066) = 1.74 \text{ lb.}$$

Several discrepancies in the tabulated values are indicative of the imprecision of such data. This sort of variation is to be expected. For example, "shoveling sand" occurs twice; once under "Moderate activity--standing," and again under "Heavy activity--standing", with an appropriately higher level of energy cost. Both measurements shown have been reported in the literature, and both are probably valid for the subjects and activities measured. These disparities may be due to the wide range of subject-to-subject differences mentioned

OXYGEN COSTS AS A FUNCTION OF WORK LOAD

in the introductory paragraph above, differences in the rate of work, or to some variation in experimental technique.

a. Classification of Physical Work by its Severity

	LB O_2/HR	KCAL/MIN	BTU/HR
Very light work	below 0.10	below 2.5	below 595
Light work	0.10 - 0.19	2.5 - 5.0	595 - 1190
Moderate work	0.19 - 0.28	5.0 - 7.5	1190 - 1785
Heavy work	0.28 - 0.38	7.5 - 10.0	1785 - 2380
Very heavy work	0.38 - 0.47	10.0 - 12.5	2380 - 2975
Unduly heavy work	over 0.47	over 12.5	over 2975

b. Everyday Activities

	Typical values for		
Asleep	lb O_2/hr	kcal/min	Btu/hr
Sleeping, men over 40	0.04	1.1	260
Sleeping, men aged 30-40	0.05	1.2	280
Sleeping, men aged 20-30	0.05	1.2	280
Sleeping, men aged 15-20	0.05	1.3	300
Resting			
Lying fully relaxed	0.05	1.2	290
Lying moderately relaxed	0.05	1.3	320
Lying awake--after meals	0.06	1.4	340
Sitting at rest	0.07	1.7	400
Very light activity--seated			
Writing	0.07	1.8	430
Riding in automobile	0.08	2.0	480
Typing	0.09	2.3	550
Polishing	0.09	2.4	570
Very Light activity--standing			
Relaxed	0.07	1.8	440
Drafting	0.07	1.9	460
Taking lecture notes	0.08	2.0	480
Peeling potatoes	0.08	2.1	510

SOURCE: Webb (195).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

METABOLISM

OXYGEN COSTS AS A FUNCTION OF WORK LOAD

b. Everyday Activities (Cont.)

	Typical values for		
	lb O_2/hr	kcal/min	Btu/hr
Light activity--seated			
Playing musical instruments	0.11	2.9	690
Repairing boots and shoes	0.12	3.0	720
At lecture	0.12	3.0	730
Assembling weapons	0.14	3.6	860
Light activity--standing			
Entering ledgers	0.10	2.6	610
Washing clothes	0.15	3.7	890
Ironing	0.17	4.4	1040
Scrubbing	0.18	4.7	1130
Light activity--moving			
Slow movement about room	0.10	2.5	600
Vehicle repairs	0.13	3.4	820
Slow walking	0.15	3.8	900
Washing	0.16	4.2	1000
Moderate activity--lying			
Creeping, crawling, prone resting maneuvers	0.22	5.7	1360
Crawling	0.24	6.1	1450
Swimming breast stroke at 1 mph	0.26	6.8	1620
Swimming crawl at 1 mph	0.27	7.0	1670
Moderate activity--sitting			
Rowing for pleasure	0.20	5.0	1190
Cycling at 8-11 mph	0.22	5.7	1360
Cycling rapidly	0.27	6.9	1640
Trotting on horseback	0.28	7.1	1690
Moderate activity--standing			
Gardening	0.23	5.8	1380
Chopping wood	0.24	6.2	1480
Baseball pitching	0.25	6.5	1550
Shoveling sand	0.27	6.8	1620
Moderate activity--moving			
Golf	0.21	5.4	1290
Table tennis	0.23	5.8	1380
Tennis	0.25	6.3	1500
Army drill	0.28	7.1	1690
Heavy activity--lying			
Leg exercises, average	0.29	7.5	1790
Swimming breast stroke at 1.6 mph	0.32	8.2	1950
Swimming backstroke at 1.0 mph	0.32	8.3	1980
Lying on back, head raising	0.34	8.8	2100

SOURCE: Webb (195).

OXYGEN COSTS AS A FUNCTION OF WORK LOAD

b. Everyday Activities (Cont.)

	Typical values for		
	lb O_2/hr	kcal/min	Btu/hr
Heavy activity--sitting			
Cycling rapidly--own pace	0.32	8.3	1980
Cycling at 10 mph--heavy bicycle	0.35	8.9	2120
Cycling in race (100 mi in 4 hr 22 min)	0.38	9.8	2340
Trotting on horseback	0.38	9.8	2340
Heavy activity--standing			
Chopping wood	0.29	7.5	1790
Shoveling sand	0.30	7.7	1830
Sawing wood by hand	0.31	8.0	1900
Digging	0.35	8.9	2120
Heavy activity--moving			
Skating at 9 mph	0.30	7.8	1860
Playing soccer	0.32	8.3	1980
Skiing at 3 mph on level	0.35	9.0	2140
Climbing stairs at 116 steps/min	0.38	9.8	2340
Very heavy activity--sitting			
Cycling at 13.2 mph	0.39	10.0	2380
Rowing with two oars at 3.5 mph	0.43	11.0	2620
Galloping on horseback	0.44	11.4	2720
Sculling (97 strokes/min)	0.49	12.6	3000
Very heavy activity--moving			
Fencing	0.41	10.5	2500
Playing squash	0.41	10.5	2500
Playing basketball	0.44	11.4	2720
Climbing stairs	0.47	12.0	2860
Extreme activity			
Wrestling	0.51	13.0	3100
Marching at double	0.52	13.3	3160
Endurance marching	0.58	14.8	3520
Harvard Step Test	0.63	16.1	3830

SOURCE: Webb (195).

OXYGEN COSTS AS A FUNCTION OF WORK LOAD

c. Special Activities

		Typical values for		
Engineering tasks		lb O_2/hr	kcal/min	Btu/hr
Medium assembly work		0.11	2.9	680
Welding		0.12	3.0	720
Sheet metal work		0.12	3.1	760
Machining		0.13	3.3	800
Punching		0.14	3.5	840
Machine fitting		0.17	4.5	1060
Heavy assembly work--noncontinuous		0.20	5.1	1210
Driving vehicles and piloting aircraft				
Driving a car in light traffic		0.05	1.3	300
Night flying--DC-3		0.06	1.6	380
Piloting DC-3 in level flight		0.07	1.7	400
Instrument landing--DC-4		0.10	2.5	590
Piloting light aircraft in rough air		0.11	2.7	640
Taxiing--DC-3		0.11	2.9	680
Piloting bomber aircraft in combat		0.12	2.9	700
Driving car in heavy traffic		0.12	3.2	760
Driving truck		0.13	3.3	790
Driving motorcycle		0.14	3.5	840
Moving over rough terrain on foot				
Flat firm road	2.5 mph	0.11-0.19	2.8-4.9	660-1140
Grass path	2.5	0.12-0.20	3.2-5.1	760-1240
Stubble field	2.5	0.16-0.23	4.0-6.1	960-1440
Deeply plowed field	2.0	0.19-0.27	4.9-6.9	1160-1640
Steep 45° slope	1.5	0.19-0.27	4.9-6.9	1160-1640
Plowed field	3.3	0.30	7.8	1850
Soft snow, with 44 lb load	2.5	0.79	21.0	4850
Load carrying				
Walking on level with 58 lb load, trained men	2.1 mph	0.07	1.9	450
	2.7	0.11	2.9	690
	3.4	0.18	4.6	1100
	4.1	0.32	8.3	1980
Walking on level with 67 lb load, trained men	2.1	0.09	2.3	550
	2.7	0.11	2.9	690
	3.4	0.20	5.1	1210
	4.1	0.33	8.4	2000
Walking on level with 75 lb load, trained men	2.1	0.10	2.5	600
	2.7	0.13	3.4	810
	3.4	0.20	5.2	1240
	4.1	0.34	8.6	2100
Walking up 36% grade with 43 lb load, sedentary men	0.5	0.26	6.7	1590
	1.0	0.47	12.3	2910
	1.5	0.62	16.0	3800

SOURCE: Webb (195).

OXYGEN COSTS AS A FUNCTION OF WORK LOAD

c. Special Activities (Cont.)

			Typical values for	
Swimming on surface		lb O_2/hr	kcal/min	Btu/hr
Breast stroke	1 mph	0.27	7.0	1650
	2	1.13	29.0	6900
	3	3.78	97.0	23100
Crawl	1	0.35	9.0	2150
	2	0.70	18.0	4200
	3	1.87	48.0	11400
Butterfly	1	0.47	12.0	2900
	2	1.13	29.0	6900
	3	2.92	75.0	17850
Walking under water				
Walking in tank	minimal rate	0.11	2.9	700
Walking on muddy bottom	minimal rate	0.21	5.5	1300
Walking in tank	maximal rate	0.28	7.2	1700
Walking on muddy bottom	maximal rate	0.33	8.4	2000
Movement in snow				
Skiing in loose snow	2.6 mph	0.32	8.1	1930
Sled pulling--low drag, hard snow	2.2	0.34	8.6	2020
Snowshoeing--bearpaw type	2.5	0.34	8.7	2070
Skiing on level	3.0	0.35	9.0	2140
Sled pulling--low drag, medium snow	2.0	0.38	9.7	2310
Snowshoeing--trail type	2.5	0.40	10.3	2460
Walking, 12-18"snow, breakable crust	2.5	0.50	12.7	3010
Skiing on loose snow	5.2	0.52	14.6	3800
Snowshoeing--trail type	3.5	0.59	14.8	4200
Skiing on loose snow	8.1	0.80	20.6	4900
Measured work at different altitudes				
Bicycle ergometer 430 kg-m/min	720 mm Hg	0.20	5.1	1230
Bicycle ergometer 430	620	0.19	4.9	1170
Bicycle ergometer 430	520	0.21	5.4	1290
Mountain climbing 880-1037 kg-m/min	610 mm Hg	0.36-0.43	9.2-11.0	2200-2640
Mountain climbing 566- 786	425	0.30-0.37	7.7- 9.5	1840-2260
Mountain climbing 393- 580	370	0.25-0.41	6.4-10.5	1530-2520

SOURCE: Webb (195).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

METABOLISM

OXYGEN COSTS IN VARYING "G" FIELDS

This chart summarizes previous data and shows why the oxygen requirement in space and on the moon surface cannot be estimated more accurately than to say it will lie in the range 1 to 5 lb per day per man. Starting at the top and reading across each row, comparisons are made between the oxygen requirements for specific functions on earth, in the flight capsule, in free space, and on the moon surface. At the end of each row is a note on some important aspect of the function under study--tissue maintenance, temperature regulation, body position, body movement, movement of controls, walking and carrying, or total daily oxygen cost.

a. Comparison of Oxygen Costs in Various Environments

FUNCTION	ENVIRONMENT AND GRAVITATION				NOTES
	Earth – 1 g	Capsule – 0 g	Free Space – 0 g	Moon Surface – 1/6 g	
Tissue Maintenance-- Circulatory, Respiratory, and Other Functions	0.8-1.4 lb O_2 (250-450 liters)	-- -- same as Earth requirement -- --			No reduction expected in subgravity environments.
Temperature Regulation	Add 3% to tissue maintenance values for every 18° F of mean temperature below 50°, subtract 5% for every 18° above 50°		May be sharp changes due to temperature.	May be sharp changes due to low shade temperature and high radiation in open.	Energy costs raised in heat, but men more relaxed. Oxygen intake raised in cold.
Maintenance of Body Position Position	Sitting at rest involves 25% higher O_2 cost than lying. Standing requires further 10%.	In zero gravity, posture maintenance may cost more or less, according to restraint equipment.			In water at neutral temperature, O_2 costs drop toward cost lying horizontally.
Movement of Body Parts	In sitting and standing positions, movement of body parts can increase O_2 cost by up to 0.07 and 0.15 lb/hr respectively	In zero gravity, the inertial work of a given movement is unchanged, but the difficulties of moving and operating controls without traction or fixation may increase oxygen costs.			Training for zero gravity operations may be very important. Clumsy movements have high O_2 costs.
Movement of External Objects (levers, pushing, lifting)	Heavy engineering work raises O_2 cost by up to 0.12 lb/hr.	For controls unaffected by gravity, this increase is likely to hold. Use of powered tools and controls will naturally reduce the effect, assuming that controls are properly redesigned for use when gravity and traction are absent or reduced.			The O_2 cost of wearing a pressurized suit needs measuring, especially in respect to this type of operation.
Walking and Carrying	O_2 consumptions up to 0.015 liters per hr per lb total weight are commonly found.	Not applicable	Not applicable	O_2 consumptions up to and exceeding 0.015 liters/hr per lb total weight must be expected frequently if moon surface is rough and steep.	See also O_2 costs of movement in the snow.
TOTAL DAILY OXYGEN COST	2 lb of O_2 per man per day is common. On strenuous days, this may rise to 3-4 lb.	1-1.5 lb expected consumption.	Requires simulated or actual measurement		Highest recorded daily cost was in lumberjacks, and was about 5 lb.

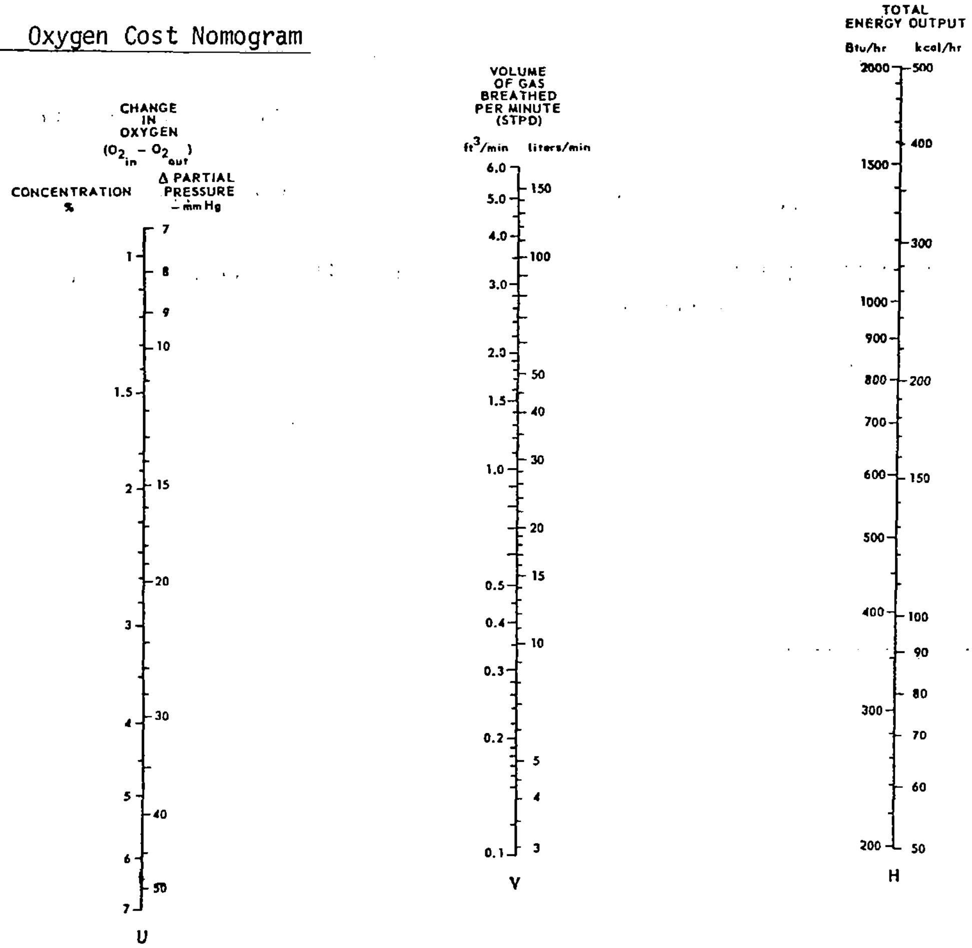
SOURCE: Webb (195).

OXYGEN COSTS - NOMOGRAMS

Heat output is determined from respiratory data in four stages. First the oxygen cost is calculated from the respiratory ventilation rate of the subject and the change in oxygen concentration of the expired air. Second, the volume is corrected to 0°C, 760 mm Hg, dry (STPD); this is particularly important at reduced atmospheric pressures. Third, the heat output corresponding to each unit volume of oxygen is selected, either by approximation or from a knowledge of the subject's diet or from his measured respiratory quotient. For simplicity in calculations, the following two nomograms have been constructed.

Nomogram a uses the standard values: RQ = 1.00 and 1 liter of oxygen is equivalent to 5.0 kcal. It permits direct calculation of heat output (H) in Btu/hr and kcal/hr from oxygen uptake (U) and ventilation rate(V). Alternatively, U can be calculated from H and V, or V from U and H.

a. Oxygen Cost Nomogram



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Webb (195).

OXYGEN COSTS - EQUATIONS

a. Formulas for Calculating the Energy Equivalent of Any Given Oxygen Consumption:

If breathing oxygen, $K = \theta \times 0_{cons}$

where K is the energy expenditure,

θ is the energy equivalent per unit volume of oxygen consumed, and

0_{cons} is the volume of oxygen consumed, STPD (0°C, 760 mm Hg, dry).

If breathing gas mixtures, $K = \theta\, x(0_{in} - 0_{out})$

where 0_{in} is the volume of oxygen (STPD) supplied to the mask, suit, or cabin, and

0_{out} is the volume of oxygen (STPD) leaving the mask, suit, or cabin.

If breathing air, 0_{in} = 20.93% and $K = V(1.0429 - 0.0498\ 0_{exp\%})$ with error less than 1%

where V is the volume of air (STPD) exhaled, and

$0_{exp\%}$ is the percentage of oxygen in the expired air.

Values for θ:	Pure fat diet; during extreme exhaustion:	θ = 525.3 Btu/ft^3, 4.686 kcal/liter
	Mixed diet:	θ = 545.0 Btu/ft^3, 4.825 kcal/liter
	Pure carbohydrate diet; heavy exertion:	θ = 565.8 Btu/ft^3, 5.047 kcal/liter

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III(52) and Webb (195).

OXYGEN COSTS - EQUATIONS

b. Formulas for Calculating Gross and Net Oxygen Costs and Efficiencies:

Gross values

--below maximum aerobic capacity*

$$C_{gross} = \frac{O_{work}}{T_{work}} \qquad E_{gross} = \frac{W \times 100}{C_{gross}}$$

--above maximum aerobic capacity

$$C'_{gross} = \frac{O_{work} + O_{debt}}{T_{work}} \qquad E'_{gross} = \frac{W \times 100}{C'_{gross}}$$

Net values

--below maximum aerobic capacity

$$C_{net} = \frac{O_{work} - O_{rest}}{T_{work}} \qquad E_{net} = \frac{W \times 100}{C_{net}}$$

--above maximum aerobic capacity

$$C'_{net} = \frac{O_{work} + O_{debt} - O_{rest}}{T_{work}} \qquad E'_{net} = \frac{W \times 100}{C'_{net}}$$

Oxygen debt

$$O_{debt} = O_{recovery} - O_{rest}$$

(measured over the same time interval, which must be adequate for the oxygen consumption to return to normal)

where C_{gross}, C'_{gross}, C_{net}, and C'_{net} are rates of oxygen consumption,

O_{work}, O_{rest}, O_{debt}, and $O_{recovery}$ are quantities of oxygen consumed

E_{gross}, E'_{gross}, E_{net}, and E'_{net} are efficiencies (in percentage units,

W is the quantity of external work produced, and

T_{work} is the time during which work is performed.

*The maximum aerobic capacity is a characteristic measurement for each individual; it is influenced by the individual's state of training, his age, and other factors.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III(52) and Webb (195).

OXYGEN COSTS - EQUATIONS

c. Formulas for Calculating Energy Cost and Variance of Walking on a Level with Load

For speeds between 2.0 and 4.5 mph, the following equations give predictions for the energy cost of marching and its variance:

$$E = K + Y$$

$$K = 0.0083\ (10 + W + L)\ e^{v/50}$$

$$Y = 0.56 \pm 0.0091\ W$$

$$\sigma 2 = 0.017\ e^{v/25}$$

where E = total energy expenditure in kilocalories per minute,

K = energy expenditure in kilocalories per minute above resting expenditure,

Y = resting energy expenditure in kilocalories per minute,

$\sigma 2$ = variance in K,

W = body weight in kilograms,

L = load carried in kilograms,

v = marching velocity in meters/min, and

e = exponential constant

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Webb (195).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

METABOLISM

METABOLIC COST OF WORK - CONVERSION FACTORS

Estimates of the expenditure of energy during various activities are useful for computing dietary requirements, for assessing the overall physiological severity of activities, and for determining optimum means and rates of work for any mission.

Some pertinent metabolic factors to be used are:

$$
\begin{aligned}
1 \text{ kcal} &= 3.9685 \text{ Btu} \\
&= 426.9 \text{ kg m} \\
&= 3087.4 \text{ ft lb} \\
&= 0.00156 \text{ hp hr}
\end{aligned}
$$

$$Q = 5.0 V_{O_2}$$

where

Q energy expenditure, kcal/min
V_{O_2} oxygen consumption, liters/min
Standard external work efficiency $\approx$ 20%
Average body surface area = 1.85 m^2 (unless otherwise indicated)

In general, the values of energy expenditure for specific tasks in trained subjects are accurate from person to person within 15% as an outside figure. In the past, energy requirements for specific tasks have been presented as "net calories" after deducting the basal or resting metabolic rate determined from standard tables. Since exercise itself may change the energy requirement for body maintenance, it appears more significant to record the values as gross or total calories as determined for each task. Wherever possible, the values will be expressed as kilocalories (Calories) or Btu/m^2 of body surface per min, or the weight of exercising subjects will be recorded along with the rate of energy expenditure. No attempt is made to separate the specific dynamic action (SDA) of food from these figures. To what extent SDA is available for external work is still uncertain, and in most cases the times of studies relative to meals are not recorded.

The problem of the efficiency of energy conversion to external work is of interest. Factors which must be considered in appraisal of overall efficiency of performance include the rate of work, the load, the duration and quality of work, and the speed of recovery in intermittent tasks. It is, of course, quite difficult to assess all these variables independently for any given task. Efficiency is expressed by the formulas:

$$\text{Gross efficiency (\%)} = \frac{\text{External work performed}}{\text{Energy used}} \times 100$$

$$\text{Net efficiency (\%)} = \left(\frac{\text{External work performed - Basal energy}}{\text{Energy used}}\right) \times 100$$

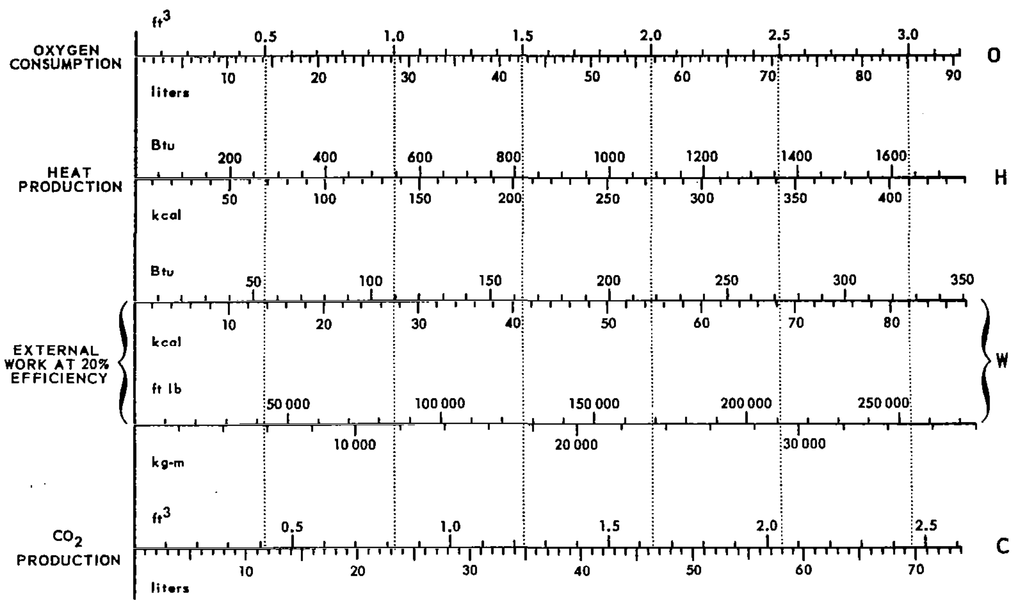
SOURCE: Roth (154).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

METABOLISM

METABOLIC COST OF WORK - CONVERSION FACTORS

a. Relationships of Oxygen Consumption, Heat Output, External Work, and Carbon Dioxide Production



The nomogram above uses the standard values: RQ (Respiratory Quotient) = 0.82 and 1 liter of oxygen is equivalent to 4.825 kcal. This nomogram allows one to interrelate, by drawing straight vertical lines, the values for oxygen consumption (O), heat output (H), external work output (W), and carbon dioxide production (C), at typical conversion rates. Note that H may be as much as 3% lower or 5% higher than the quoted value at any specific oxygen consumption, depending on the RQ, which equals 0.7 for a pure fat diet and 1.00 for a pure carbohydrate diet. Values given in the third and fourth lines have to be modified if the efficiency changes. Typical ranges are 5 to 35%, average 20%, so that the listed work output may increase by three-quarters if the task is one that can be performed at high efficiency (e.g., bicycling). Conversely, the true value may be reduced by three-quarters if the function is inefficiently performed, (e.g., high speed walking).

SOURCE: Webb (195).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

METABOLISM

METABOLIC COST OF WORK - 1 G

a. Energy Expenditures for Different Types of Progression at Various Speeds and Grades*

Type of progression	Speed, mph	Grade, %	Energy expenditure of 154-pound man kcal/hr	Energy expenditure of 154-pound man kcal/mile
Horizontal walking	2.3	0	210	90
	3.5	0	290	85
	4.6	0	470	100
Grade walking	2.0	5.0	250	125
	2.5	5.0	290	115
	2.3	5.5	350	150
	3.5	5.5	450	130
	2.4	8.6	430	180
	3.5	8.6	560	160
Horizontal walking carrying 43-lb load	1.0	0	210	210
	2.0	0	270	135
	3.0	0	350	115
	4.0	0	540	135
(Running)	5.0	0	820	165
Grade walking carrying 43-lb load	0.5	35.8	370	740
	1.0	35.8	680	680
	1.5	35.8	890	595
Skiing along level	3.0	0	540	180
	5.0	0	720	145
	7.5	0	950	125
Swimming (breast stroke)	1.0		410	410
	1.6		490	305
	1.9		820	430

* The figures in this table were calculated from Harvard Fatigue Laboratory data for a 150-lb. man.

A dominant factor in human energy efficiency is the time spent in performing the work. The longer the work period, the lower the energy efficiency. In order to achieve the highest energy efficiency, work should be performed at the most rapid rate within the limits of skill and endurance. The reason for the low economy of progression at a slow rate is that a large part of the energy used during the work is required for the maintenance of body functions (digestive, glandular, etc.) which do not contribute directly to the performance of the work. When the distance is traversed in a shorter time, the energy cost of these supportive functions is correspondingly reduced. Net efficiency, therefore, does not change significantly with exercise rate.

The increase in energy cost when work is performed at slow rates is shown in the table. The 1 mile climb at 0.5 mph requires 2 hours. At 1.5 mph the climb can be completed in 40 minutes. At the slow rate of work the energy cost of maintaining the human machine must be met for 80 minutes longer than at the faster rate of work. This increased energy cost, amounting to 145 kcal, reduces the work efficiency from 24% to 6%.

SOURCE: Morehouse and Miller (131) and Roth (154).

METABOLIC COST OF WORK - 1 G

b. Relation of Efficiency to Rate and Load of Work*

[154-pound man carrying 43-pound load up 35.8% grade]

SPEED, MPH	CLIMBING 1 HOUR		CLIMBING 1 MILE	
	KCAL/HR	EFFICIENCY	KCAL/MILE	EFFICIENCY
0.5	370	13%	740	6%
1.0	680	14%	680	14%
1.5	890	16%	595	24%

*Data from table on preceding page.

An additional factor in work efficiency is the work load. When the speed was increased from 0.5 to 1.0 mph, the work load was increased by 145, 548 foot-pounds per hour and the efficiency improved from 13% to 14%. At 1.5 mph the work load was 436, 444 foot-pounds per hour and the efficiency was 16%. However, work which requires an energy expenditure greater than 700 kcal per hour cannot be continued for much longer than 1 hour by an untrained man. Unless the man carrying the 43-pound load up the 35.8% grade was well trained, he could not be expected to climb at 1.5 mph for more than an hour, as the energy expenditure at this rate is 890 kcal her hour. If the speed is reduced to 1.0 mph, the energy requirement is reduced to 680 kcal per hour and the work can be sustained for a longer period. If the distance is great, the speed should be reduced so that the climber is not exhausted by the work. Efficiency must be sacrificed for endurance in order to accomplish work of long duration. When the distance is short, greater speed or heavier loads are necessary if the work is to be performed with the greatest efficiency. The well-trained individual is able to carry on work at a higher level of energy expenditure; thus he is able to perform work at higher speeds for longer periods.

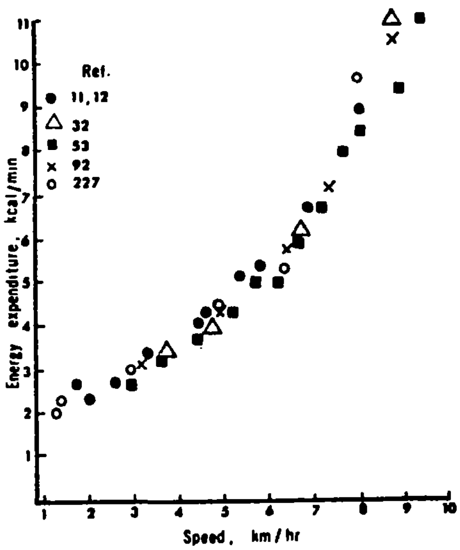
SOURCE: Morehouse and Miller (131) and Roth (154).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

METABOLISM

METABOLIC COST OF WORK - 1 G

c. Energy Expenditure Walking on a Level at Various Speeds



d. Energy Cost of Walking and Running

Speed of walking and running, mph	Energy cost kcal/m²min	Btu/hr
1.2	1.7- 2.0	735- 870
2.0	1.5- 1.9	650- 820
2.4	1.6- 2.7	690-1,150
2.8	1.9- 2.4	820-1,040
3.0	2.2- 3.1	950-1,340
3.2	2.1- 3.3	910-1,430
3.6	2.4- 3.8	1,040-1,640
4.0	2.5- 4.0	1,080-1,730
4.3	3.6- 5.5	1,560-2,480
4.8	4.6- 7.6	1,990-3,290
5.0	5.6- 8.3	2,420-3,580
6.0	6.5-11.4	2,810-4,940
6.5	6.6-13.3	2,850-5,750

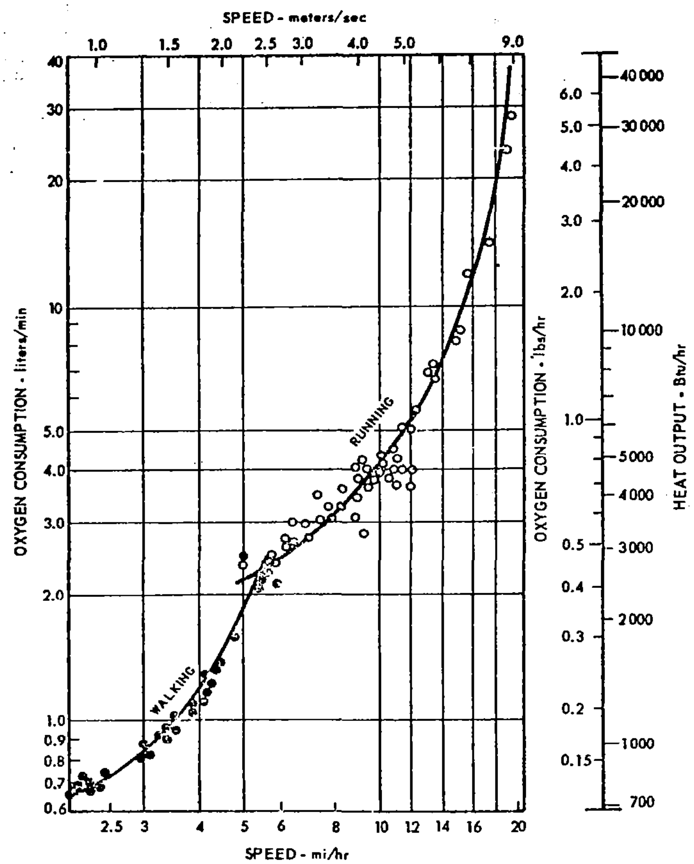
e. Relation of Speed and Body Weight to Energy Expenditure

Speed of walking mph	Energy expenditure, kcal/min, for gross body weight of— 80 lb	100 lb	120 lb	140 lb	160 lb	180 lb	200 lb
2.0	1.9	2.2	2.6	2.9	3.2	3.5	3.8
2.5	2.3	2.7	3.1	3.5	3.8	4.2	4.5
3.0	2.7	3.1	3.6	4.0	4.4	4.8	5.3
3.5	3.1	3.6	4.2	4.6	5.0	5.4	6.1
4.0	3.5	4.1	4.7	5.2	5.8	6.4	7.0

SOURCE: Passmore and Durnin (143) Roth (154) and Webb (195).

METABOLIC COST OF WORK - 1 G

f. Oxygen Requirement at Various Speeds for Men Walking and Running

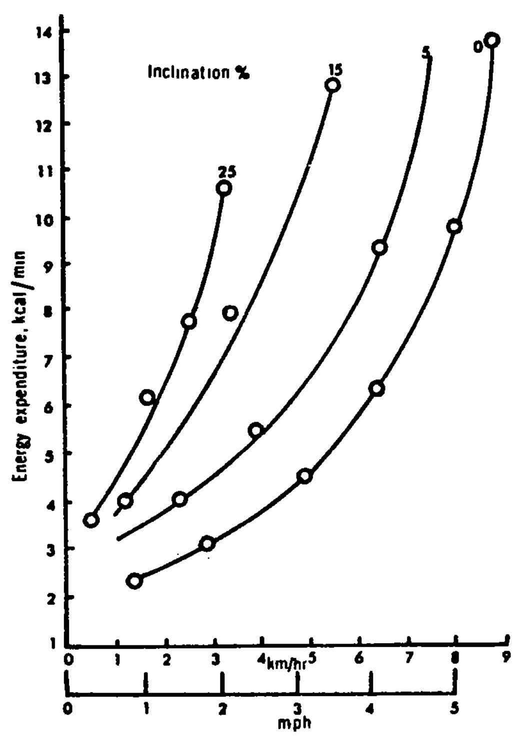


To convert oxygen requirement to energy units: multiply liters/min. by 4.825 to get kcal/min. or by 19.3 to get Btu/min.

SOURCE: Dittmer and Grebe (56), Passmore and Durnin (143) and Roth (154).

METABOLIC COST OF WORK - 1 G

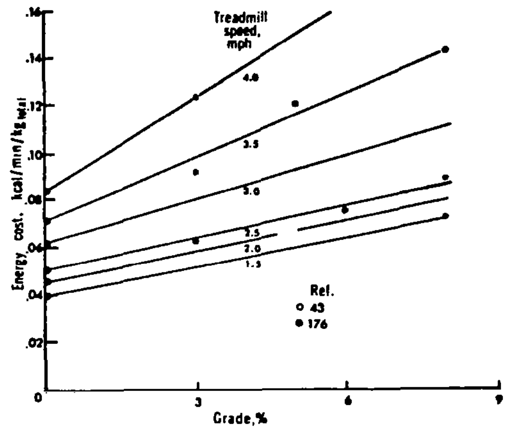
g. Energy Expenditure Walking Uphill at Various Speeds



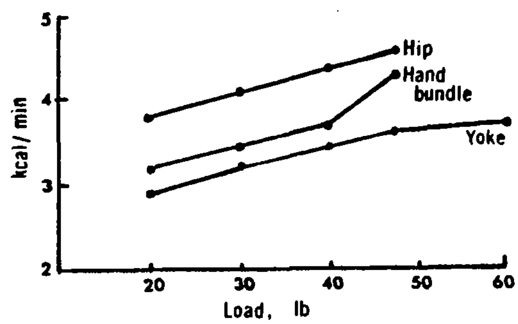
SOURCE: Passmore and Durnin (143) and Roth (154).

METABOLIC COST OF WORK - 1 G

h. Graph for Estimating Energy Cost for Rates of Progression Between 1.5 and 4.0 MPH and Grades Up to 9% With Loads Up to 30 KG.



i. Energy Expenditure When Carrying Loads in Various Ways



j. Energy Expenditure When Walking With Load at 1.5 MPH on Firm Flat 10% Grade

Load		Energy expenditure			
lb	kg	kcal/hr	kcal/min	Btu/hr	Btu/min
0	0	500	8.3	2,000	33
22	10	550	9.2	2,200	37
44	20	630	10.5	2,500	42
66	30	730	12.2	2,900	48
88	40	830	13.9	3,300	55
110	50	950	15.8	3,800	63

SOURCE: Atzler and Herbst (14) Iampietro and Goldman (91) and Roth (154) and Passmore and Durnin (143).

METABOLIC COST OF WORK - 1 G

k. Energy Expenditure as a Function of Rate of Progression, Load Carried, and Grade

Grade, %	Load, kg	kcal/min/kg subject wt. without load (a)	kcal/min/kg total wt. (b)	Mean kcal/ min/kg total wt.	Standard error
Speed = 1.5 mph					
9	10 20 30	0.088 .091 .096	0.077 .073 .070	0.073	±0.007
Speed = 2.5 mph					
3	10 20 30	0.071 .078 .088	0.063 .063 .064	0.063	±0.007
6	10 20 30	0.084 .093 .107	0.074 .075 .077	0.076	±0.004
9	10 20 30	0.106 .114 .121	0.093 .090 .087	0.090	±0.004
Speed = 3.5 mph					
3	10 20 30	0.103 .116 .128	0.091 .094 .091	0.092	±0.006
6	10 20 30	0.136 .160 .166	0.120 .125 .119	0.121	±0.008
9	10 20	0.165 .182	0.145 .143	0.144	±0.014
Speed = 4.0 mph					
3	10 20	0.142 .148	0.125 .123	0.124	±0.017

[a] The 5-subject mean value of: $\frac{\text{Individual calculated energy cost (kcal/min)}}{\text{Individual subject dressed weight}}$

[b] The 5-subject mean value of: $\frac{\text{Individual calculated energy cost (kcal/min)}}{\text{Individual subject dressed weight + load}}$

SOURCE: Iampietro and Goldman (91) and Roth (154).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

METABOLISM

METABOLIC COST OF WORK - 1 G -

1. Energy Cost of Progression for Adult Males

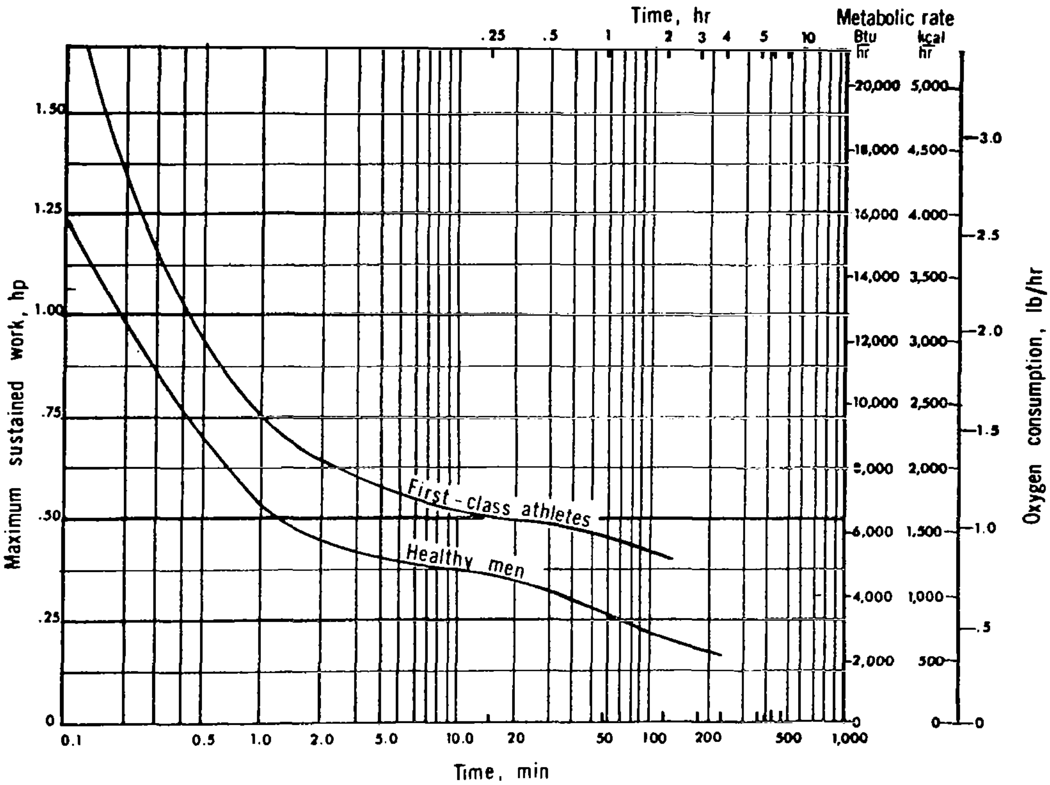
Activity		Subjects			Speed		Energy expenditure		O_2 requirement, liters/min (b)
		No.	Wt, kg (a)	Remarks	mi/hr	km/hr	kcal/min	Btu/min	
Walking, level, on:									
Hard-surface road		2	68–69	Carrying 9 kg clothing and apparatus	3.5	5.5	5.6	22.4	1.13
Grass-covered road					3.5	5.6	6.3	25.2	1.28
Furrow in field					3.4	5.4	7.0	28.0	1.43
Harvested field					3.3	5.2	6.9	27.6	1.41
Plowed field					3.3	5.3	7.7	30.8	1.57
Harrowed field					3.2	5.1	10.0	40.0	2.05
Hard snow		1	83		3.8	6.0	11.9	47.6	2.29
					5.7	9.1	15.8	63.2	3.22
Soft snow		1	83	Carrying 20-kg load	2.5	4.0	20.2	80.4	4.13
Walking, grade, uphill	2.7%	2	70	Soldiers	3.5	5.6	6.1	24.4	(1.23)
	5.0%	1	70	Trained individual	2.0	3.2	4.1	16.4	(0.83)
	5.0%	1	70	Trained individual	2.5	4.0	4.8	19.2	(0.97)
	5.5%	1	70	Soldier	3.5	5.6	7.5	30.0	(1.50)
	6.2%	2	70	Soldiers	3.5	5.6	7.8	31.2	(1.56)
	7.3%	2	70	Laboratory workers	3.5	5.6	8.6	34.4	(1.73)
	8.3%	1	70	Soldier	3.5	5.6	9.3	37.2	(1.87)
	8.6%	2	70	Laboratory workers	2.4	3.8	7.2	28.8	(1.43)
	8.6%	64	70	1 marathon runner, 23 sharecroppers, 40 trained individuals	3.5	5.6	9.3	37.2	(1.87)
	9.0%	2	70	Soldiers	3.5	5.6	9.3	37.2	(1.87)
	10.0%	7	70	Civilian public service workers	3.5	5.6	9.7	38.8	(1.93)
	11.8%	2	70	Soldiers	3.5	5.6	11.0	44.0	(2.20)
	14.4%	2	70	Soldiers	3.5	5.6	12.3	49.2	(2.47)
Walking, grade, treadmill, uphill	0%	2	70–79		2.6	4.2	3.9–4.4	15.6–17.6	0.80–0.90
	5.0%						5.4–5.9	21.6–23.6	1.10–1.20
	10.0%						7.4–7.8	29.6–31.2	1.51–1.60
	15.0%						9.7–10.3	38.8–41.2	1.98–2.10
	20.0%						12.2–13.0	48.8–52.0	2.48–2.65
	25.0%						14.7–15.8	58.8–63.2	3.00–3.23
Walking, grade, treadmill, downhill	0%	2	70–79		2.6	4.2	3.9–4.4	15.6–17.6	0.80–0.90
	5.0%						3.4–3.7	13.6–14.8	0.70–0.76
	10.0%						3.3–3.6	13.2–14.4	0.68–0.73
	15.0%						3.7–3.8	14.8–15.2	0.75–0.77
	20.0%						4.2–4.3	16.8–17.2	0.85–0.88
	25.0%						4.8–4.9	19.2–19.6	0.97–1.00

[a] Values for all subjects listed as weighing 70 kg are proportional calculations from values for subjects of other weights.
[b] Values in parentheses are calculations, assuming 1 liter of oxygen is equivalent to 5 kcal. The oxygen requirement per minute for a given rate of energy expenditure may exceed the oxygen uptake during any given minute if an oxygen debt is being accumulated, resulting in very high values for level running and swimming.

SOURCE: Dittmer and Grebe (56) and Roth (154).

METABOLIC COST OF WORK - 1 G

m. Maximum Sustained Work Capacity of Men

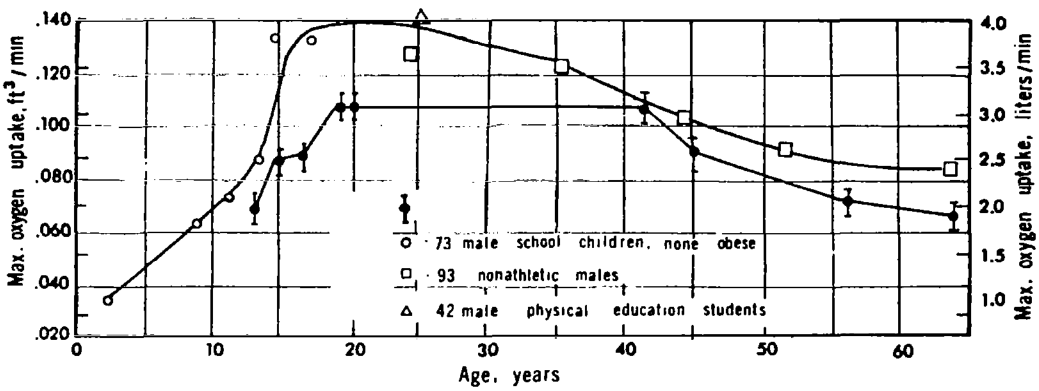


In emergency situations, the maximum sustained work capacity of men is of importance. The graph above illustrates that the maximum work which men can sustain until exhausted is greatest for periods of less than 1 minute. When the oxygen demand exceeds the intake of oxygen, an oxygen debt is incurred. The graph has rather special data in that the kind of work chosen to yield the highest power for a given metabolic rate; the efficiency is 20%. Data beyond 1 hour are sparse, and the maximum level that can be sustained for 4 to 8 hours is not precisely known. It must be emphasized that these curves represent the very maximum levels for the most select individuals and are far above what even the average astronaut would probably be able to accomplish. The curves should, therefore, be used only as extreme upper limits of endurance.

SOURCE: Webb (195).

METABOLIC COST OF WORK - 1 G

n. Maximum Oxygen Intake of Males



The maximum aerobic work capacity decreases from an average of 3.0 to 2.2 liters/min. from ages 35 to 63, or by a factor of 26% (21% when calculated per kg body weight). The graph above presents a summary of the aging data for males showing the variations expected in the athletic subjects and the more general population.

RANGE OF PHYSICAL FITNESS DETERMINED VIA TREADMILL TESTS

The graph in Figure o on the following page presents peak oxygen consumptions as found in a treadmill test at 3.4 mph with slopes increasing by 1% each minute. The performance rating is arbitrary. These values define upper limits of aerobic capacity to be expected from a select and average population of military personnel.

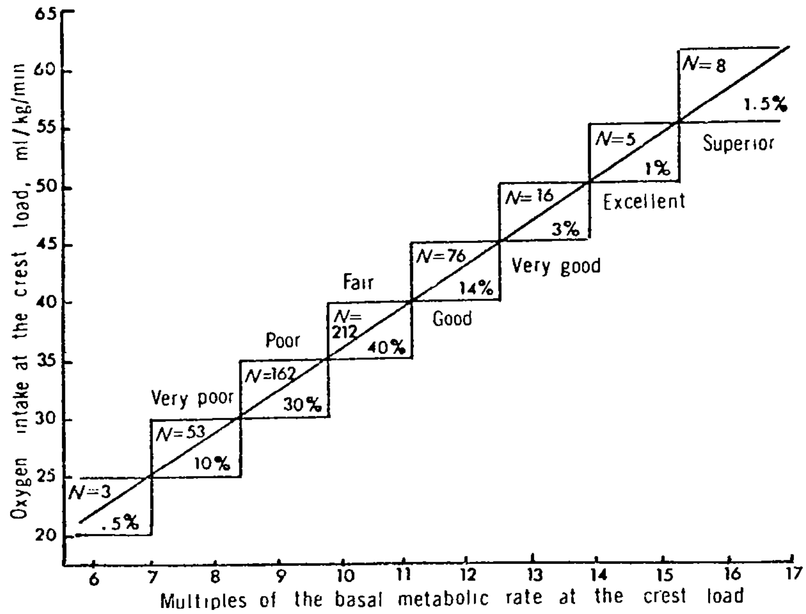
The specific physiological effects of training have also been covered. Such factors as the decreased basal metabolic rate at rest, slower pulse at rest and during exercise, increased heart volume, increased muscular mass, increased vascularization and glycogen deposition in muscles, slight increase in blood volume, and decreased lactic acid level after severe work have been noted as resulting from training.

From determination of respiratory quotients it was concluded that while trained athletes can utilize carbohydrate and fat indifferently during rest and light work, they increase the percentage of carbohydrate used when performing heavy work.

SOURCE: Webb (195).

METABOLIC COST OF WORK - 1 G

o. Range of Physical Fitness Determined by a Standardized Treadmill Test of 535 Male Adults



That a reduction in ambient oxygen pressure reduces work capacity is a well-studied phenomenon. The recent Himalayan Scientific and Mountaineering Expedition determined the graduated effects of oxygen depletion at different altitudes on men well acclimatized to these altitudes. In reviewing the data, it must be kept in mind that these subjects were as well acclimatized to their environment as any group of subjects doing work at altitude would probably ever be.

Table p presents a summary of these studies. Control studies were carried out in London before the expedition. As on a previous Mt. Everest expedition, the higher levels of work intensity, oxygen intake, and ventilation were observed than in previous studies on nonmountaineers. The data for maximum 5-minute exercise are given in the table which shows that maximum work, maximum oxygen intake, maximum ventilation STPD, and maximum heart rate declined with increase in altitude. Maximum ventilation BTPS, on the other hand, was higher at altitude than at sea level, except at the highest camp. There was no significant difference in the values obtained at heights between 15,000 and 21,000 ft. (4,600 and 6,400 m). One obvious factor affecting ventilation at altitude is the reduced work of breathing air of low density. In spite of this reduction, the ventilation BTPS fell at 24,400 ft. This result may be due to the hypoxia of respiratory muscles or a failure of subjects to exert maximum effort.

SOURCE: Balke (17) and Roth (154).

METABOLIC COST OF WORK - 1 G

It appears that exercise at 20,000 ft (6,090 m) and above is halted by factors other than those operating at sea level. Subjectively, the overwhelming sensation which brings work to a close is breathlessness. Very high ventilation rates of about 200 liters/min BTPS --in fact, values approaching the resting 15-second maximum voluntary ventilation (MVV test) --were sometimes observed just before the breaking point at 21,000 ft (6,400 m) on Mt. Everest and again on the 1960-61 expedition.

p. Graduated Effects of Oxygen Depletion at Different Altitudes on Men Well Acclimatized to These Altitudes

Altitude, ft	Barometric pressure, mm Hg	No. of subjects	Weight, kg	Ventilation, liters/min		Oxygen intake		Heart rate, beats/min	Work rate, kg m/min
				STPD (a)	BTPS (b)	STP, liters/min (c)	ml/kg/min		
Sea level	750	6	72.7	97.9 ± 18.4	119.7 ± 22.6	3.40 ± 0.23	46.8 ± 3.2	192 ± 6	1,500-1,800
15,000	440	5	68	75.0 ± 7.3	164.8 ± 15.9	2.58 ± 0.12	37.9 ± 1.8	159 ± 17	1,500
19,000	380	4	65.5	61.4 ± 14.3	159.1 ± 37.2	2.14 ± 0.23	32.7 ± 3.5	144 ± 13	900-1,200
21,000	340	4	65.2	56.7 ± 8.6	168.8 ± 25.4	1.95 ± 0.11	29.6 ± 1.7	146 ± 11	900-1,050
24,400	300	2	67.5	35.2 ± 2.3	119.8 ± 7.7	1.40 ± 0.09	20.7 ± 1.3	135 ± 8	600

[a] STPD = Standard temperature and pressure, dry.
[b] BTPS = Body temperature and pressure, saturated with water.
[c] STP = Standard temperature and pressure.

SOURCE: Pugh (146) and Roth (154).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

METABOLISM

METABOLIC COST OF WORK - SUBGRAVITY STATE

Work and Locomotion in Zero and Subgravity States

The increase in degress of freedom of movement in the zero gravity of orbital flight is probably a factor in the difficulty of accomplishing extravehicular tasks in the Gemini program. No specific data are available on energy consumption in orbital tasks; however, on Gemini IX-A, X, XI, and XII, preflight and postflight exercise tests using the bicycle ergometer were performed on the pilots. During these tests, the subject performed a measured amount of work in increasing increments, while heart rate, blood pressure, and respiration rate were monitored and periodic samples of expired gas were collected for analysis. These data were translated into oxygen utilization curves and Btu plots. An increase of about 0.02 beats per minute for each work increment of 1 Btu/hr. was noted for the ranges of 100 to 180 beats/minute and 1000 to 4000 Btu. Rough estimates of EVA work loads were thus attained from heart rate data, but these derived data were considered inaccurate, because changes in heart rate caused by thermal, carbon dioxide or other environmental problems could not be taken into consideration.

Periods of exercise were included in both of the standup EVAs. These exercises consisted of moving the arms away from the neutral position of the pressurized space suit. Both arms were brought from the neutral position to the sides of the helmet once each second for 60 seconds. An attempt was made to correlate heart rate data during these inflight exercise periods with preflight exercise tests. When compared in this manner, no significant difference appeared in the response to exercise performed before and during flight. It must be remembered, however, that only qualitative conclusions can be drawn from these data. Valid quantitative conclusions must await the results of more precise inflight medical experimentation in which controlled conditions and additional data collection are feasible.

Several other factors were significant in the energetics aspects of Gemini EVA. One of these was the art of conserving energy as demonstrated in Gemini XII. The pilot of Gemini XII was able to condition himself to relax completely within the neutral position of the space suit. He reported that he systematically monitored each muscle group. When a group of muscles was found to be tense while performing no useful work, he was able to relax these muscles consciously. All of his movements were slow and deliberate. When a task could be performed by small movement of the fingers, he would use only those muscles necessary for this small movement. This technique of conserving energy contributed to the low indicated work levels in the Gemini XII umbilical EVA.

For the final Gemini XII EVA, the oxygen allotment for umbilical EVA was 25 pounds, with 2.9 pounds scheduled for egress preparation and 22.1 pounds for a projected 2-hour and 10-minute EVA timeline. The pilot stated that he felt that his work rate had not taxed the capability of the system and that he could have worked somewhat harder without discomfort. Total ELSS oxygen usage for the 126-minute EVA period was 18.9 pounds, which indicated a usage rate of 8.9 lb/hr,

METABOLIC COST OF WORK - SUBGRAVITY STATE

as compared to the measured value of 8.5 lb/hr obtained during preflight testing. The EVA pilot performed several tasks intended to evaluate any forces acting on him from either thrust or pressure forces from the ELSS outflow. He reported that that he was unable to detect any forces which might be attributable to the ELSS. There was no noticeable float-out or float-up tendency when he was standing in the cockpit with the hatch open. Study of oxygen consumption in Apollo is planned.

The energy balance for upper torso work under all tractive conditions may be expressed by the following equations relating energy, Q, and efficiency, E:

$$\Delta Q_m (E) = Q_w$$

or

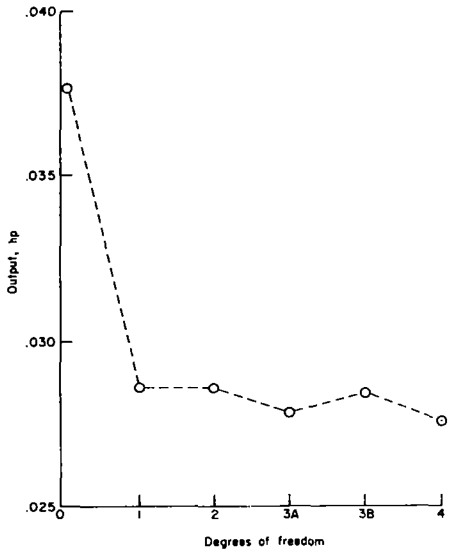
$$\Delta Q_m = Q_w + Q_{wc} + Q_{wr} + Q_s + Q_n$$

Where ΔQ_m is the metabolic cost of work, Q_w is the amount of energy utilized in performing useful work, Q_{wc} is the energy spent in supplying the counteractive force, Q_{wr} is the energy required to restore the body to the prework position, Q_s is energy stored as body heat, and Q_n is the net heat loss. As traction is reduced for a given task, the muscular energy required to supply the counterforce must increase. The total energy required to accomplish a given task is increased as traction is reduced.

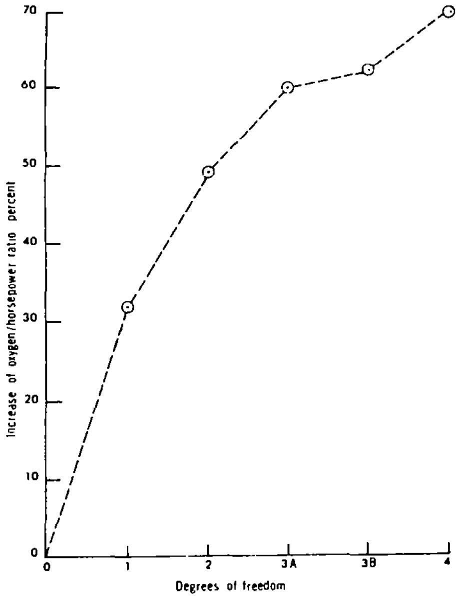
SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

METABOLIC COST OF WORK - WEIGHTLESSNESS SIMULATION

a. Horsepower Output with Various Degrees of Freedom on Reciprocating Task; 15-Pound Load and 22-Inch Stroke



b. Percentage Increase of Oxygen/Horsepower Ratio for a Reciprocating Task; 15-Pound Load and 22-Inch Stroke



c. Comparison of Metabolic Rates During Construction and Maintenance Work (Btu/hr)

SIMULATION	REST	MAXIMUM MEASURED
One-g	697	3243
Neutral Buoyancy	1035	2170
Zero-g six-degree-of-freedom	478	3489

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III(52), Streimer, et al (179) and Wortz, et al (210).

METABOLIC COST OF WORK - PRESSURE SUIT - GENERAL CONSIDERATIONS

a. Metabolic Rate in Pressure Suit Operations

Task	Suit Type	Suit Pressure PSIG	Heat Production BTU/HR			Number of Subjects	Vent Flow CFM	Trials
Treadmill	Street		15 Mins	30 Mins	60 Mins			
0.8 mph	Clothes	0.0	510	576	562	5	—	20
0.8 mph	Gemini	0.0	—	811	780	3	11.5	4
	(G-1c-4)	3.7	—	1159	1171	3	11.5	4
1.5 mph	Gemini	0.0	—	953	996	3	11.5	6
	(G-1c-4)	3.7	—	1775	1979	3	11.5	6
0.8 mph	Apollo	0.0	810	804	—	2	13.5	8
	(021)	3.7	1126	1062	—	2	13.5	8
0.8 mph	Apollo	0.0	—	814	826	2	10.5	5
	(024)	3.7	—	926	944	2	10.5	5
Arm [1]	Apollo	0.0	644	649	—	2	13.5	6
Exercise	(021)	3.7	723	730	—	2	13.5	6
Switch [2]	Gemini	0.0	425	—	—	5	11.5	11
Flipping	(G-1c-4)	3.5	625	—	—	5	11.5	11

Task	Suit Type	Suit Pressure PSIG	Heat Production BTU/HR		Number of Subjects	Vent Flow CFM	Trials
Treadmill	Gemini		15 Mins	30 Mins			
1.2 mph	G-1c-4	0.0		824	2	11.5	2
	G-1c-4	3.7		1453	2	11.5	2
2.5 mph	G-1c-4	0.0	1256	1263	1	11.5	1
2.0 mph	G-1c-4	3.7		2079	2	11.5	2
2.0 mph	G-2c-24	0.0	1027		4	11.5	4
2.0 mph	G-2c-24	0.0	1125		4	4.0	4
3.0 mph (6% GD)	G-2c-24	0.0	2309		4	11.5	6
0.8 mph	G-2c-24	3.7	1163		4	11.5	4
0.8 mph	G-2c-24	3.7	1338		2	4.0	2
1.8 mph	G-2c-24	3.7	1929		3	11.5	3

1. The Arm Exercise consisted of lifting an 11.5 lb. weight thru a distance of 18 inches every 5 seconds, alternating between left and right arms.
2. The Switch Flipping task consisted of activating a switch at arms length once every 5 seconds while the subject was sitting in the Gemini mockup couch.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III) (52).

METABOLIC COST OF WORK - PRESSURE SUIT - GENERAL CONSIDERATIONS

b. Caloric Requirements

Activities	Heat production, Btu/hr
Treadmill walking at 0.8 mph:[a]	
Light clothing (normal dress)	520
Space suit, unpressurized	860
Space suit, pressurized 3.5 psi	1520
Space suit, pressurized 5.0 psi	2020
Sitting in mockup activitating switches:[b]	
Space suit, unpressurized	420
Space suit, pressurized 3.5 psi	590

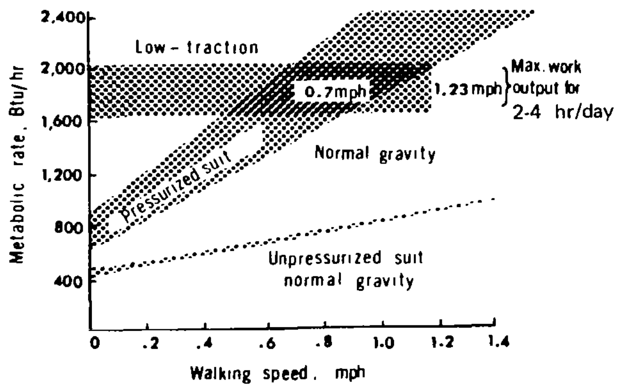
[a]At sea level.
[b]Activating switch once every 5 seconds at sea level.

An effective method of testing the energetics of locomotion on the lunar surface is to reduce traction, on a six-degree-of-freedom simulator, and to add weights to the subjects to return them to their 1-g weight. As the simulated level of gravity is reduced, a pronounced decrease in energy expenditure occurs. When weights are added to the subjects to return them to their original (presimulation) weight, only slight increase in metabolic rate occurs, despite the substantial increments in the total weight being transported. This substantiates the concept that weight reduction is a primary mechanism in producing walking metabolic rates that are lower at reduced gravity than at 1 g. Current studies of elastic fabric or foam-sponge counter-pressure suits may lead to considerable reduction in the energy requirement of extravehicular locomotion. The effect of inflated space suits is especially significant in this task. Tables c, d, and e and Figures c and d indicate locomotion in an inflated suit may more than double the energy requirement over that in an uninflated suit in Earth gravity. Figures c, d, and e represent the sensitivity of metabolic rate of progression to gravitation and to suit pressure.

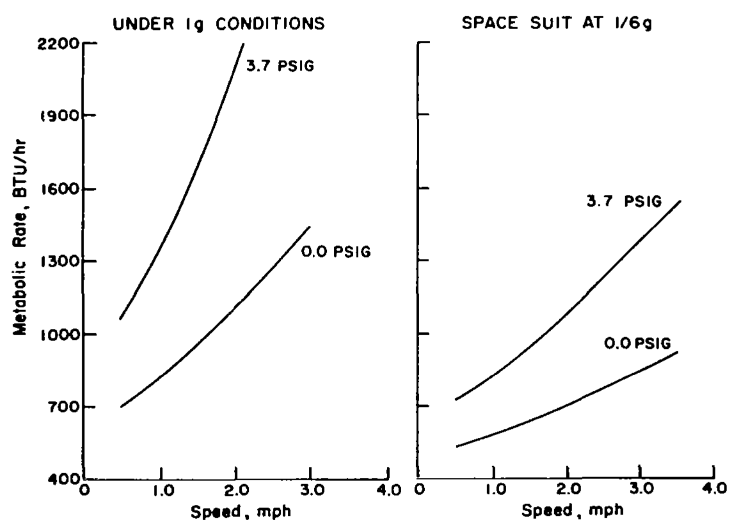
SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and LaChance (106).

METABOLIC COST OF WORK - PRESSURE SUIT - GENERAL CONSIDERATIONS

c. Metabolic Cost of Walking in Pressurized Space Suits Under Normal Earth Gravity



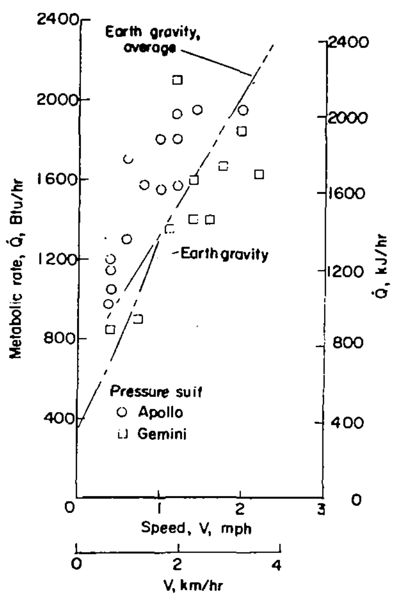
d. Metabolic Rate Comparison



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Kincaide (102).

METABOLIC COST OF WORK - PRESSURE SUIT - GENERAL CONSIDERATION

e. Comparative Test Data of Metabolic Cost of Locomotor Work in Subgravity with Pressurized Suits from Various Sources and for Different Conditions



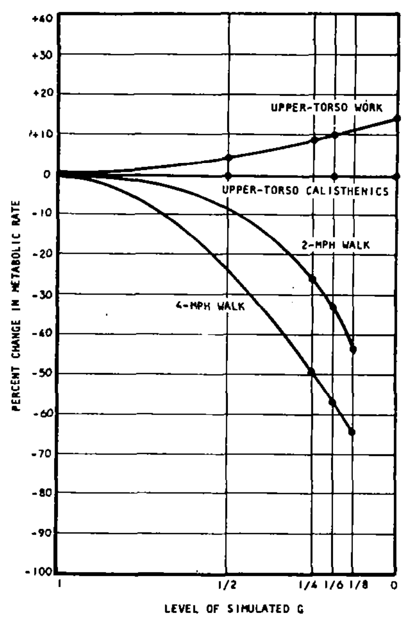
PRESSURE SUIT

SOURCE: Compendium...Vol. III (52), Hewes (86), Kuehnegger, et al (105), Webb (195) and Wortz and Prescott (212).

METABOLIC COST OF WORK - LUNAR GRAVITY

Effect of Gravity, Task, Suit and Simulator Variables

a. Change in Metabolic Rate for Classes of Tasks as a Function of Simulated Reduced Gravity (Shirtsleeves)

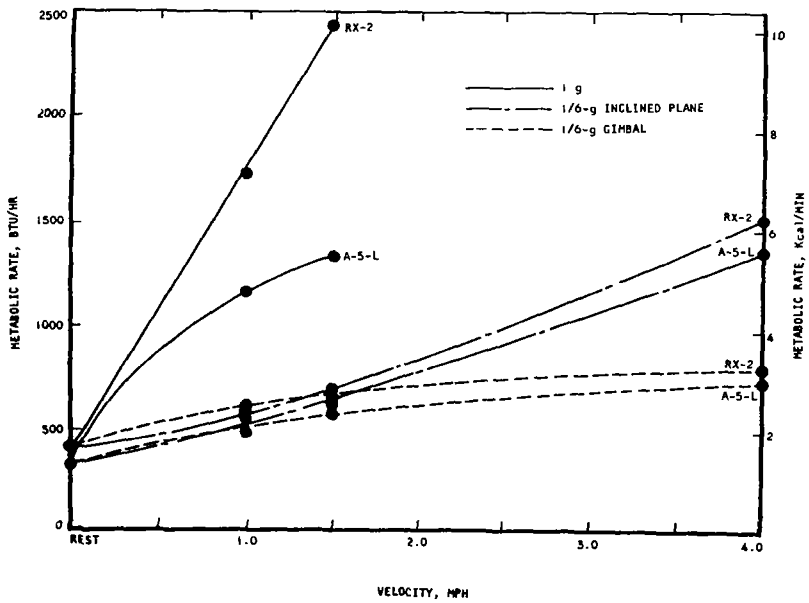


SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Wortz (209).

METABOLIC COST OF WORK - LUNAR GRAVITY

Figures b and c emphasize the effect of the different simulators and suits. Figure c illustrates these data in terms of the lunar weight of the subjects; the metabolic rate is plotted in terms of body weight for lunar gravity conditions.

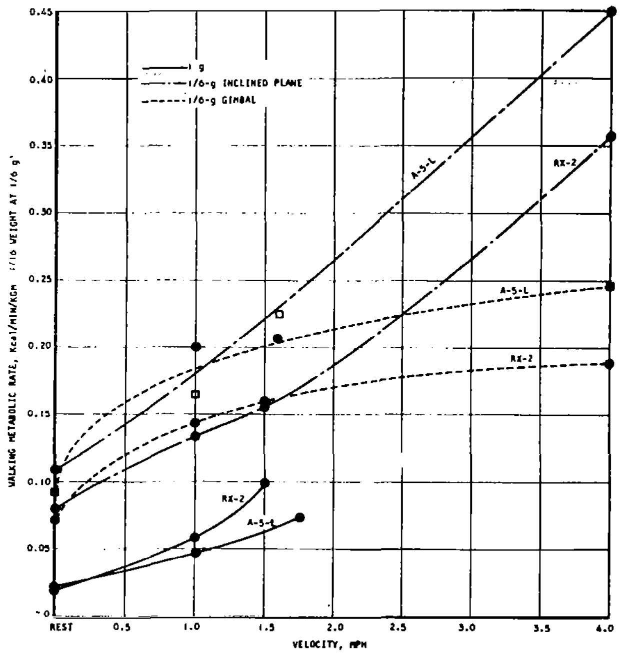
b. Metabolic Rates for Walking in Different Pressurized Suits on Different Simulators



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52), Wortz (209), Wortz and Robertson (211).

METABOLIC COST OF WORK - LUNAR GRAVITY

c. Metabolic Rates for Walking in Pressurized Suits on Different Simulators



Data are normalized for body weights; lunar weight is used for lunar gravity simulated conditions; suits refer to Apollo prototypes

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Wortz and Robertson (211).

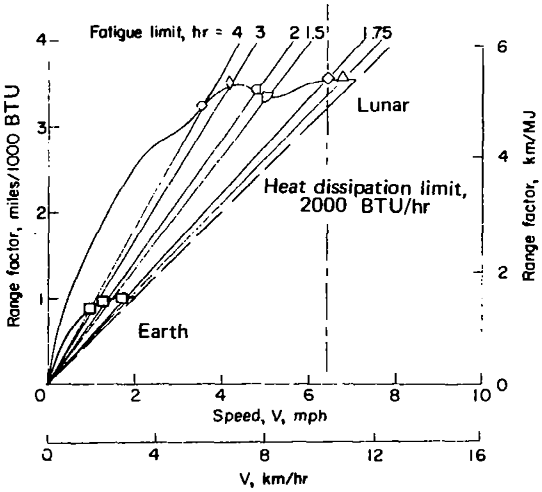
METABOLIC COST OF WORK - LUNAR GRAVITY

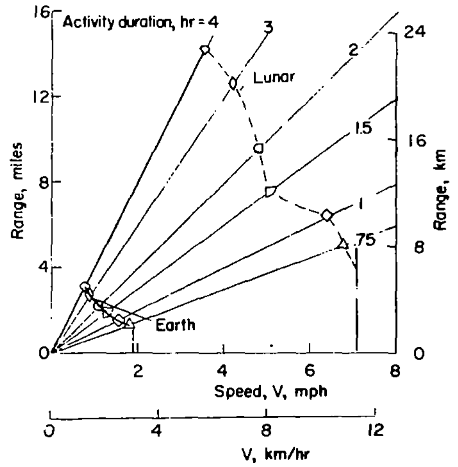
d. Effect of Subgravity Suit Pressurization on Human Locomotor Performance of Different Types

Energy Cost of Locomotion - Unpressurized BTU/hr			
	1/6 g	1 g	Ref.
2 mph level	560	810	266
4 mph level	740	1700	
	850	1980	266
4 mph 10° incline	1300	2800	137

Gravity	Suit pressure psi	Max. forward vel., fps	Vert. jump max. ht., ft	Broadjump horiz. dist., ft
1 g	0	11.3	1.7	5.4
	3.5	9.2	1.0	3.3
1/6 g	0	5.4	7.7	12.0
	3.5	4.0	4.6	7.0

e. Estimated Effects of Speed, Activity Duration, Fatigue, and Suit System Limits on Range Capability of Lunar Explorers on Lunar Surface and Earth

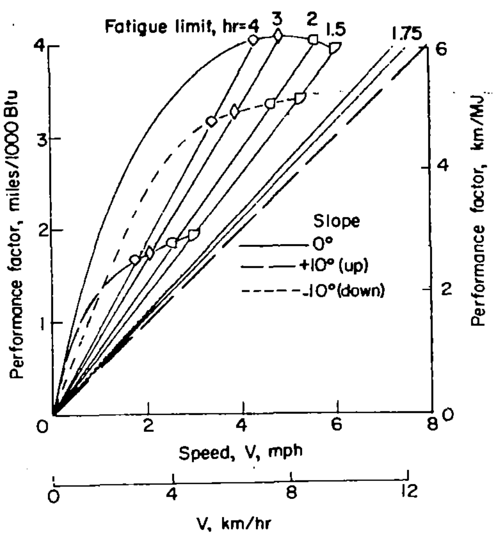


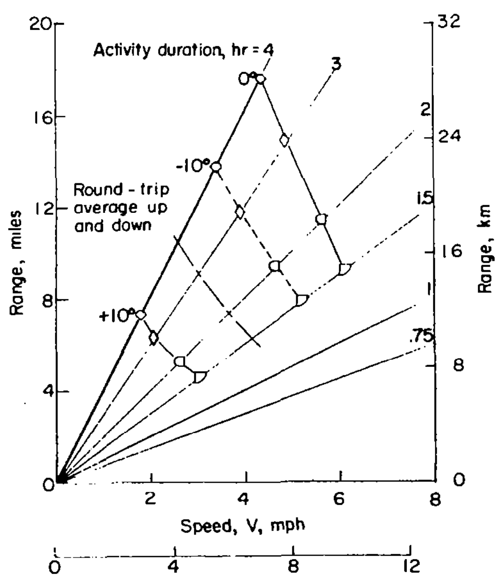


SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

METABOLIC COST OF WORK - LUNAR GRAVITY

f. Estimated Effect of Surface-Slope Variations on the Range Capability of Lunar Explorers (One Subject)

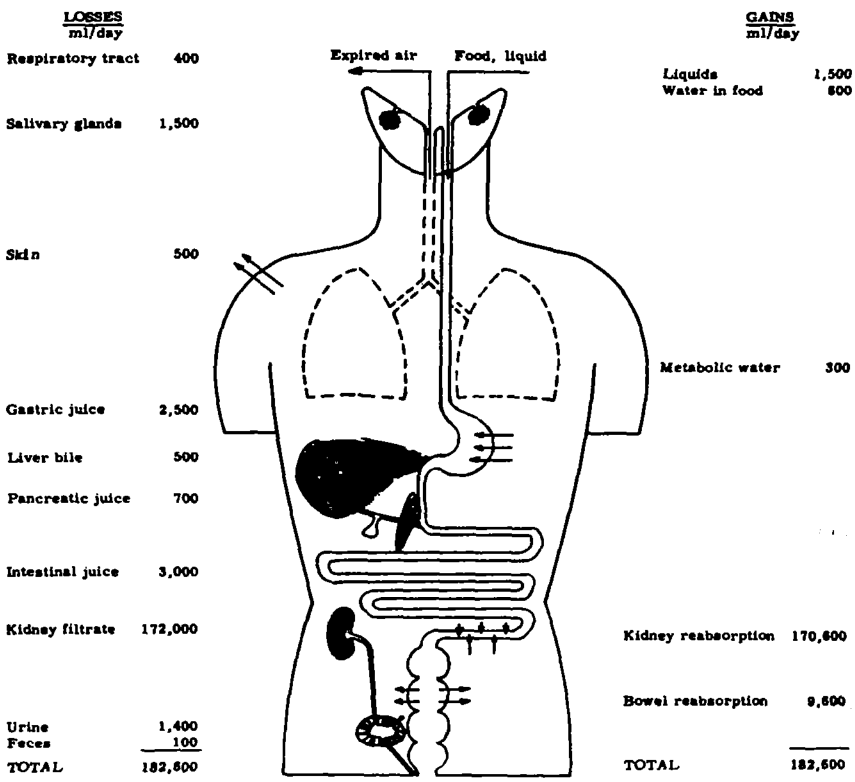




SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

WATER BALANCE

a. Water Exchanges Between Man and Environments



Water balance is defined as the difference between the input from all sources into the exchangeable water pool and the output from all sources.

Primary factors in the calculation of water balance in logistic analysis assumes that a male subject is at rest, quiet and comfortable and at a steady state so that such secondary factors as H_2O poly, H_2O nonexch, H_2O hydr, and H_2O assoc, H_2O milk or H_2O misc. may be eliminated and the following balance equation used:

$$H_2O_{balance} = (H_2O_{fluid} + H_2O_{food} + H_2O_{ox})$$

$$- (H_2O_{fecal} + H_2O_{pulm} + H_2O_{derm} + H_2O_{urine}$$

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Webb (196).

WATER BALANCE

Details on the extension of such an equation relating water balance to manifestations of metabolic activity as changes in body weight ($W_2 - W_1$), solids ingested (Sol_{ing}), solids excreted (Sol_{fecal}) and (Sol_{urine}), urinary nitrogen excretion (N_u) and respiratory activity such as oxygen uptake ($O_{2\ abs}$) and CO_2 expired ($CO_{2\ exp}$) are expressed in the modified Peters - Passmore equation:

$$H_2O_{balance} = (W_2 - W_1) + (1.3349\ CO_{2\ exp} - 0.9566\ O_{2,\ abs}$$

$$- 1.04\ N_u) + (Sol_{urine} + Sol_{fecal} - Sol_{ing})^*$$

* All values in grams.

b. Sources and Avenues of Input and Output for the Exchangeable Water Pool

Source or avenue	Input	Output
Gastrointestinal	Beverage (H_2O_{fluid}) Moisture in food (H_2O_{food})	Feces (H_2O_{fecal}) Vomitus or saliva
Pulmonary	Absorption of gaseous or fluid water (H_2O_{pulm})	Vaporization (H_2O_{pulm})
Dermal	Absorption of gaseous or fluid water (H_2O_{derm})	Transpiration (H_2O_{derm}) Sweat (H_2O_{sweat}) Milk (H_2O_{milk})
Renal		Urine (H_2O_{urine})
Circulatory	Infusion or injection (H_2O_{misc})	Hemorrhage (H_2O_{blood}) Exudation or transudation (H_2O_{misc})
Metabolic (H_2O_{met})	Oxidation (H_2O_{ox}) Condensation or polymerization (H_2O_{poly}) Release of nonexchangeable water of hydration ($H_2O_{nonexch}$)	Hydrolytic reactions (H_2O_{hydr}) Water associated with protein, fat, or glycogen (H_2O_{assoc})

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Johnson (95).

WATER BALANCE

c. Estimates of Metabolic Rate, Thermal Balance, and Water Requirements for Apollo Crew Members

	PER MAN		COMMAND MODULE ROUTINE FLIGHT PER DAY	COMMAND MODULE EMERGENCY DECOMPRESSION PER DAY	LEM ** ROUTINE FLIGHT PER HOUR	LEM ** ROUTINE FLIGHT PER DAY	LEM *** EMERGENCY DECOMPRESSION PER HOUR	LUNAR SURFACE EXTRAVEHICULAR (LCG OPERATION)* PER HOUR
Metabolic Rate Data	Heat Output	BTU	11,200	12,000	520	12,400	800	1,600
	Oxygen	lb	1.84	1.97	.085	2.04	.13	0.26
	Carbon Dioxide	lb	2.12	2.27	.098	2.40	.15	0.13
Thermal Data	Heat due to insensible water loss (Lungs, Skin)	BTU	2,600	2,700	115	2,750	150	250
	Latent Heat (Sweat)	BTU	1,370	7,430	170	3,990	572	230
	Sensible Heat to gas steam	BTU	7,230	1.870	235	5,660	78	0
	Sensible Heat to water	BTU	- - - -	- - - -	- -	- - - -	- -	1,120
Water Requirements Data	Urinary Loss	g	1,200	1,200	50	1,200	50	50
	Sweat Loss	g	597	3,240	74	1,740	250	100 max.
	Lung Loss	g	1,130	1,180	50	1,200	65	109
	Total Water Requirement	g	2,930	5,620	174	4,140	365	259
	Total Water Requirement	lb	6.5	12.4	.38	9.1	.80	.57

* LCG = Liquid Cooled Garment
** Both men are likely to be on duty most of the time
*** Work output per man will be higher than Command Module Emergency Decompression Phase

SOURCE: Billingham (25) and Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

EFFECTS OF DEHYDRATION

a. Spectrum of Dehydration

DEHYDRATION WEIGHT LOSS - % initial weight

0 (NORMAL WEIGHT)

Thirst

2 — Stronger thirst, vague discomfort and sense of oppression, loss of appetite.

Increasing hemoconcentration.

4 — Economy of movement.

Lagging pace, flushed skin, impatience; in some, weariness and sleepiness, apathy; nausea, emotional instability.

6 — Tingling in arms, hands, and feet; heat oppression, stumbling, headache; fit men suffer heat exhaustion; increases in body temperature, pulse rate and respiratory rate.

Labored breathing, dizziness, cyanosis.

8 — Indistinct speech.

Increasing weakness, mental confusion.

10 — Spastic muscles; positive Romberg sign (inability to balance with eyes closed); general incapacity.

Delirium and wakefulness; swollen tongue.

Circulatory insufficiency; marked hemoconcentration and decreased blood volume; failing renal function.

Shriveled skin; inability to swallow.

15 — Dim vision.

Sunken eyes; painful urination.

Deafness; numb skin; shriveled tongue.

Stiffened eyelids.

Cracked skin; cessation of urine formation.

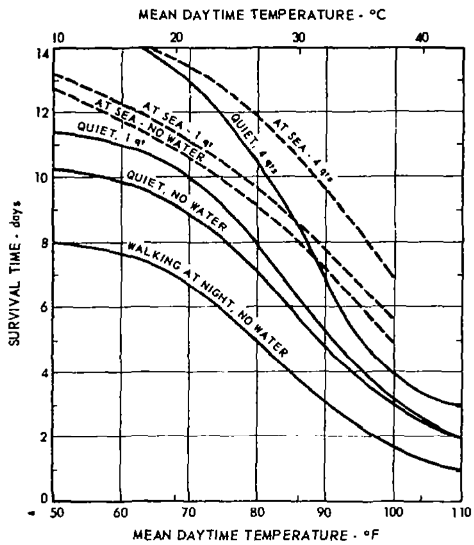
20 — Bare survival limit

Death

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Webb (195).

EFFECTS OF DEHYDRATION

b. Effects of Water Deprivation on the Survival Time in Different Thermal Environments on Earth

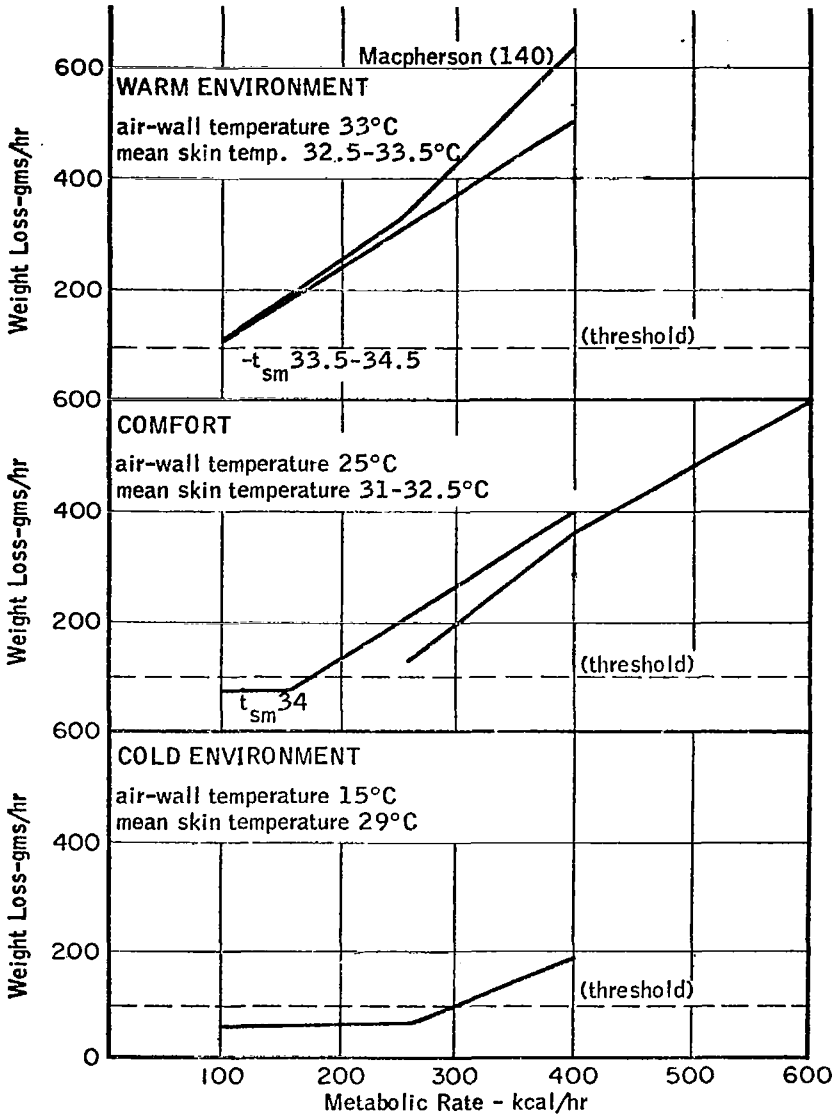


Predicted survival times on land and sea are shown when men have no water, or 1 quart per man, or 4 quarts per man, total supply. The man on land is expected to rest, and not to try to walk out of the situation, but to stay in whatever shade he can muster. The effect of walking only at night is shown in the lowest curve. The survival time is set by dehydration.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Webb (195).

WATER LOSS AS A FUNCTION OF AIR TEMPERATURE/METABOLIC RATES

a. Sweat Rates as Functions of Metabolic Rate in Warm, Comfortable and Cold Environments for Men in Shorts*



* The threshold for sweating is taken to be a rate of weight loss of 100 gm/hr.

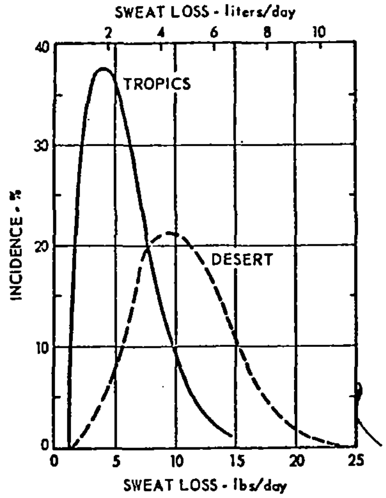
SOURCE: Blockley (27), Compendium...Vol. I (50), MacPherson (122), Robinson, et al (151) and Webb (196).

PHYSIOLOGICAL STANDARDS AND TOLERANCES

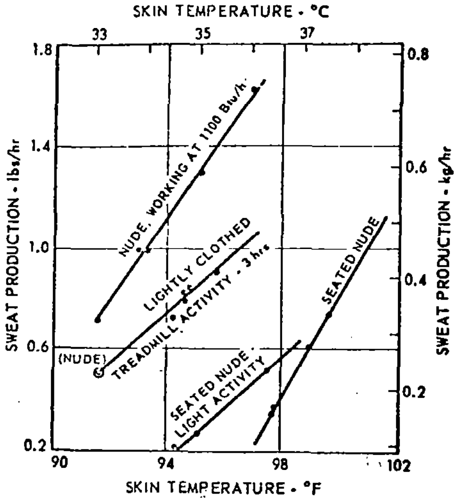
METABOLISM

WATER LOSS BY SWEATING UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

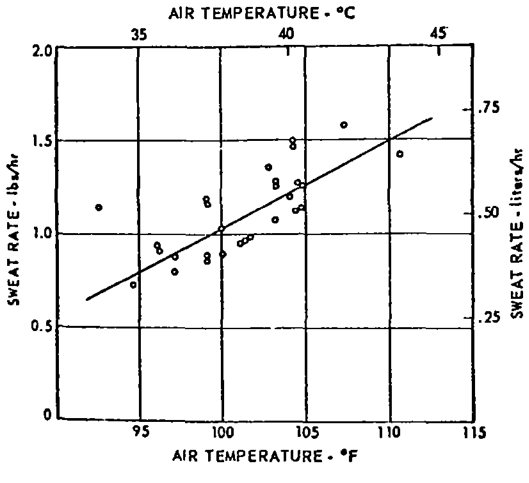
a. Frequency Distribution of Daily Sweat Production for 26 Men in Tropics and 57 Men in the Desert



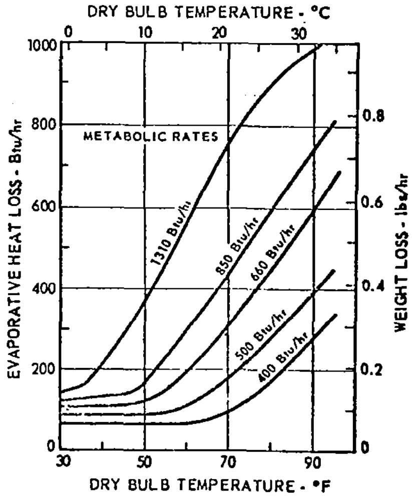
b. Sweat Rates During Various Laboratory Procedures as a Function of Skin Temperature



c. Air Temperature Influence of Sweating in Men Sitting Still in Desert Sun



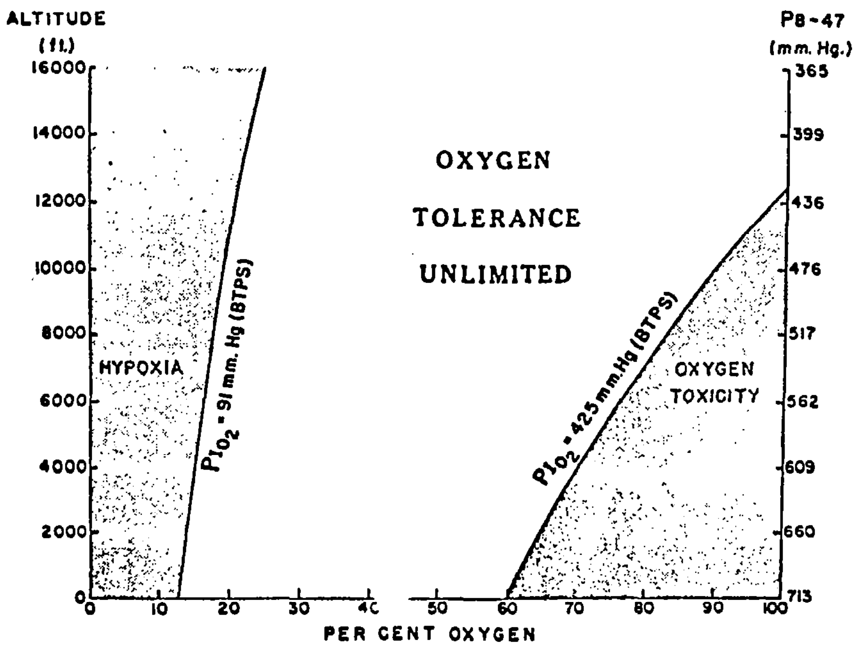
d. Sweating and Evaporative Heat Loss as a Function of Air Temperature and Activity Level



SOURCE: Adolph, et al (3), MacPherson (122), Taylor and Buettner (183), Webb (195) and Thompson (189).

ALTITUDE EFFECT

a. Oxygen Tolerance in Man



SOURCE: Air Force Manual AFM 160-5 (4) and Roth (155).

RESPIRATORY ATMOSPHERIC REQUIREMENTS

ALTITUDE EFFECT

b. Pressure and Temperature Values in the Atmosphere

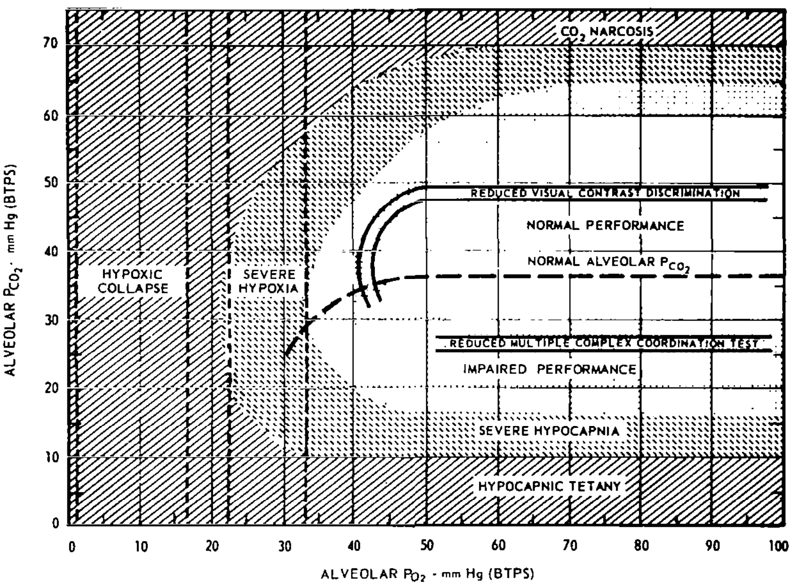
Altitude	Pressure		Temperature	
Feet	Mm of Hg	Lb per sq in	°C	°F
0	760.0	14.69	15.0	59.0
2000	706.6	13.67	11.0	51.9
4000	656.3	12.69	7.1	44.7
6000	609.0	11.78	3.1	37.6
8000	564.4	10.91	− 0.8	30.5
10000	522.6	10.11	− 4.8	23.3
12000	483.3	9.35	− 8.8	16.2
14000	446.4	8.63	−12.7	9.1
16000	411.8	7.96	−16.7	1.9
18000	379.4	7.34	−20.7	− 5.3
20000	349.1	6.75	−24.6	−12.3
22000	320.8	6.20	−28.6	−19.5
24000	294.4	5.69	−32.5	−26.6
26000	269.8	5.22	−36.5	−33.7
28000	246.9	4.77	−40.5	−40.9
30000	225.6	4.36	−44.4	−48.0
32000	205.8	3.98	−48.4	−55.1
34000	187.4	3.62	−52.4	−62.3
35332	175.9	3.41	−55.0	−67.0
36000	170.4	3.30	−55.0	−67.0
38000	154.9	3.00	−55.0	−67.0
40000	140.7	2.72	−55.0	−67.0
42000	127.9	2.47	−55.0	−67.0
44000	116.3	2.25	−55.0	−67.0
46000	105.7	2.04	−55.0	−67.0
48000	96.05	1.86	−55.0	−67.0
50000	87.30	1.69	−55.0	−67.0
52000	79.34	1.53	−55.0	−67.0
54000	72.12	1.39	−55.0	−67.0
56000	65.55	1.27	−55.0	−67.0
58000	59.58	1.15	−55.0	−67.0
60000	54.15	1.05	−55.0	−67.0
62000	49.2	.951	−55.0	−67.0
64000	44.7	.864	−55.0	−67.0
		Lb per sq ft		
66000	40.6	113.2	−55.0	−67.0
68000	36.9	102.9	−55.0	−67.0
70000	33.6	93.52	−55.0	−67.0
72000	30.4	85.01	−55.0	−67.0
74000	27.7	77.26	−55.0	−67.0
76000	25.2	70.22	−55.0	−67.0
78000	22.9	63.8	−55.0	−67.0
80000	20.8	58.01	−55.0	−67.0
82000	18.9	52.72	−55.0	−67.0
84000	17.2	47.91	−55.0	−67.0
86000	15.6	43.55	−55.0	−67.0
88000	14.2	39.59	−55.0	−67.0
90000	12.9	35.95	−55.0	−67.0
92000	11.7	32.1	−55.0	−67.0
94000	10.7	29.7	−55.0	−67.0
96000	9.7	27.02	−55.0	−67.0
98000	8.8	24.55	−55.0	−67.0
100000	8.0	22.31	−55.0	−67.0

(Note: Conversion Factor—to obtain PSI, multiply pressure in MM Hg by .0193)

SOURCE: Air Force Manual AFM 160-5 (4) and Roth (155).

ALTITUDE EFFECT

c. Performance Versus Alveolar O_2 and CO_2 Composition



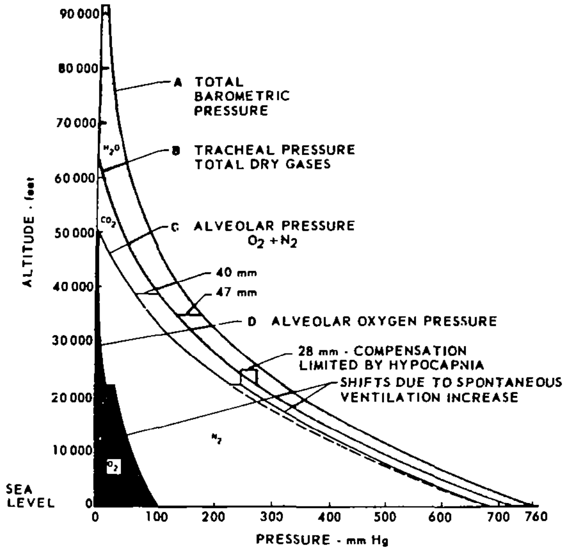
The relationship of alveolar O_2 and CO_2 composition to performance is shown in C. The scales are partial pressures of the two gases, at body temperature and pressure, saturated with water (BTPS). Above the dashed line labeled "normal alveolar CO_2" are zones of increasing hypercapnia, limited by the zone of CO_2 narcosis. Below the dashed line, marked as zones of increasing hypocapnia, are lower levels of alveolar CO_2, which are commonly the result of excessive respiratory ventilation. The left side of the graph shows low levels of alveolar P_{O_2}, labeled zones of "severe hypoxia" and "hypoxic collapse," and these hypoxic zones combine with hyper- or hypocapnia to affect performance as shown.

Normal performance is seen when the gas tensions fall in the clear area; impaired performance in a hand-steadiness test is shown by shading, and the results of two other performance tests are plotted also to indicate the variation to be expected when "performance" is variously measured.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Webb (195).

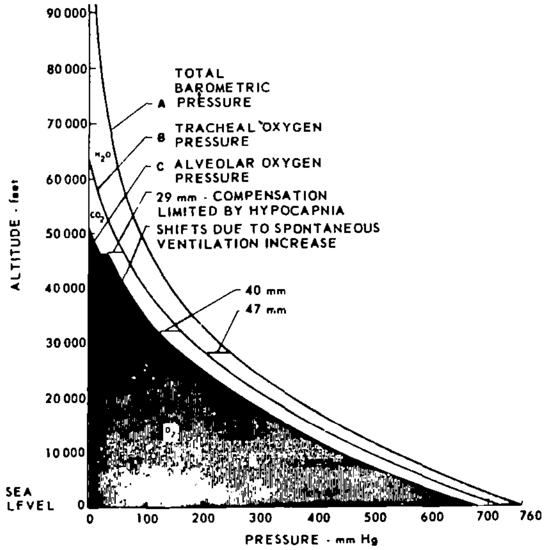
ALTITUDE EFFECTS

d. Breathing Air



Altitude (feet)	Total Pressure (mm Hg)	N_2 Percentage	H_2O Percentage	CO_2 Percentage	O_2 Percentage	O_2 Pressure (mm Hg)
AMBIENT DRY ATMOSPHERE						
0	760.0	79.02	0	0.03	20.95	159 2
5000	632.3	79.02	0	0.03	20.95	132 5
10000	522.6	79.02	0	0.03	20.95	109.5
15000	428 8	79.02	0	0.03	20.95	89 8
20000	349.1	79.02	0	0.03	20.95	73.1
22000	320.8	79.02	0	0.03	20.95	67.2
TRACHEAL GAS						
0	760.0	74.13	6.18	0.03	19.66	149.4
5000	632.3	73.14	7.43	0.03	19.39	122.6
10000	522.6	71.91	8.99	0.03	19.06	99.6
15000	428.8	70.31	10.96	0.03	18.66	80.0
20000	349.1	68.38	13.46	0.03	18.13	63.3
22000	320.8	67.46	14.65	0.03	17.85	57.4
ALVEOLAR GAS						
0	760.0	75.00	6.18	5.26	13.55	103
5000	632.3	74.06	7.43	6.01	12.49	79
10000	522.6	72.45	8.99	6.89	11.67	61
15000	428.8	70.62	10.96	7.70	10.73	46
20000	349.1	68.49	13.46	8.59	9.45	33
22000	320.8	67.27	14.65	8.73	9.35	30

e. Breathing 100 Percent O_2

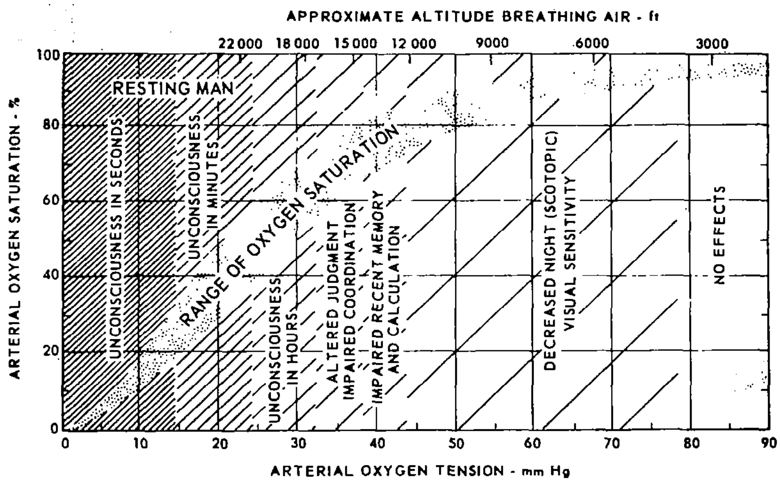


Altitude (feet)	Total Pressure (mm Hg)	N_2 Percentage	H_2O Percentage	CO_2 Percentage	O_2 Percentage	O_2 Pressure (mm Hg)
AMBIENT DRY OXYGEN						
33000	196 3	0	0	0	100	196 3
36000	170 3	0	0	0	100	170 3
39000	147 5	0	0	0	100	145 5
42000	127 9	0	0	0	100	127 9
45000	110 9	0	0	0	100	110 9
46000	105 6	0	0	0	100	105 6
TRACHEAL GAS						
33000	196 3	0	23 94	0	76 06	149 3
36000	170 3	0	27 60	0	72 40	123 3
39000	147 5	0	31 96	0	68 04	100 4
42000	127 9	0	36 75	0	63.25	80 9
45000	110 9	0	42 38	0	57 62	63 9
46000	105.6	0	44 51	0	55 49	58 6
ALVEOLAR GAS						
33000	196 3	0	23 94	20 38	55 68	109 3
36000	170.3	0	27 60	22 31	50 09	85 3
39000	147 5	0	31 96	24 41	43 63	64 4
42000	127 9	0	36 75	25 80	37 45	47 9
45000	110.9	0	42 38	27 05	30 57	33 9
46000	105 6	0	44 51	27 46	28 03	29 6

SOURCE: Webb (195).

ALTITUDE EFFECTS

f. Performance Versus Arterial Oxygen Status

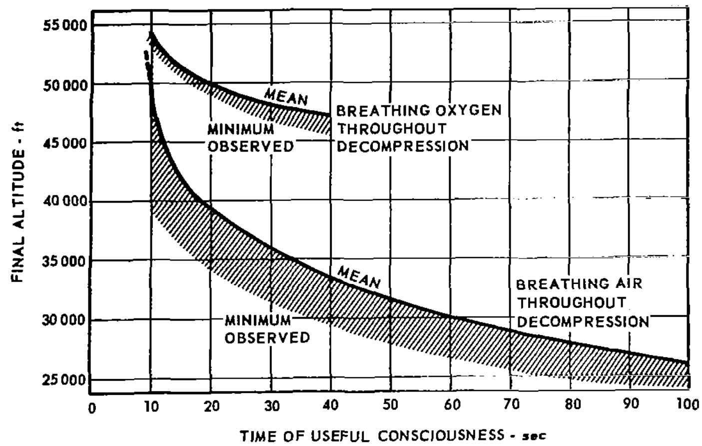


As arterial oxygen tension falls, progressive impairment occurs in the central nervous system, as indicated on the chart by zones of increasing density. These changes occur in resting men who are not fatigued or otherwise stressed. The oxygen saturation of arterial blood for resting men is also shown as a function of oxygen tension (the hemoglobin dissociation curve). A range of saturations for each value of tension is shown, because temperature and pH influence the saturation values also. Individual variability and time dependency are characteristic of these data.

SOURCE: Blockley and Hamfan (28), Compendium...Vol. III (52), McFarland (121), United States Air Force (190) and Webb (195).

ALTITUDE EFFECTS

g. Duration of Effective Consciousness (Decompression Hypoxia)

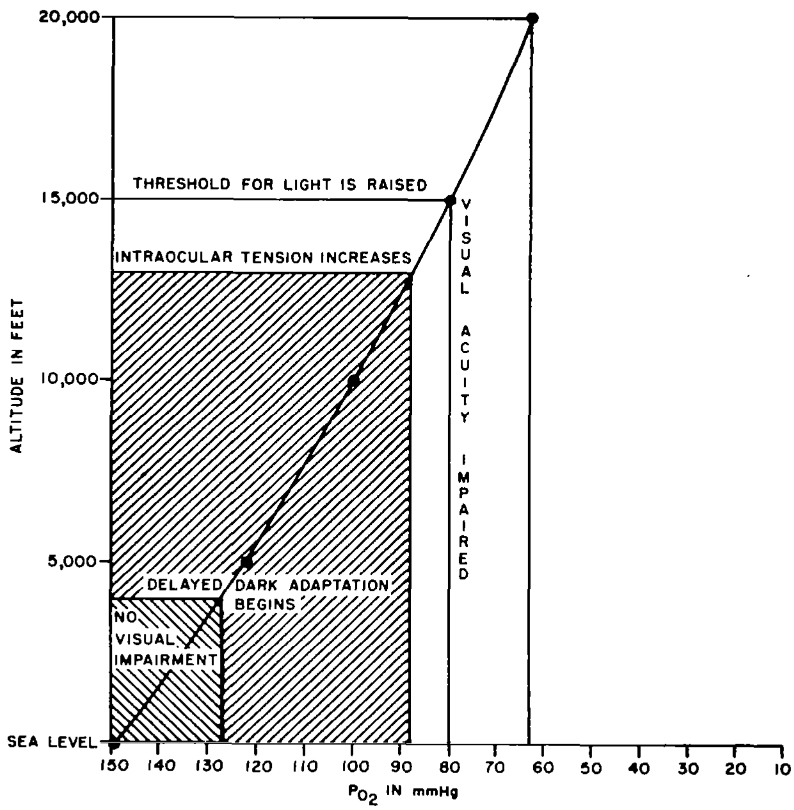


This figure indicates minimum and average duration of effective consciousness in human subjects following rapid decompression breathing air (lower curve) and oxygen (upper curve). At altitudes above 20,000 to 23,000 feet, unacclimatized subjects breathing air will lose consciousness after a variable period of time. Individual susceptibility varies widely except at the highest altitudes.

SOURCE: Blockley and Hamfan (28), Compendium...Vol. III(52) and Webb (195).

ALTITUDE EFFECTS

h. Impairment of Visual Functions Produced by Hypoxia

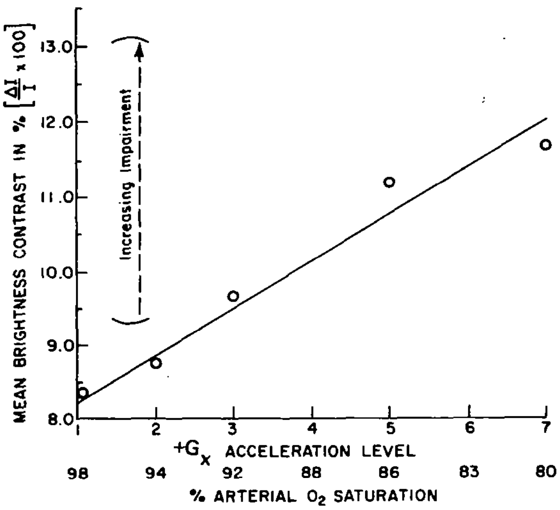


Impairment of the following functions: Judgment of Distance
Range of Visual Fields
Accommodation
Convergence
Retinal Sensitivity

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

ALTITUDE EFFECTS

i. Brightness Contrast Discrimination at Given Arterial Oxygen-Saturation Level or G_X Level

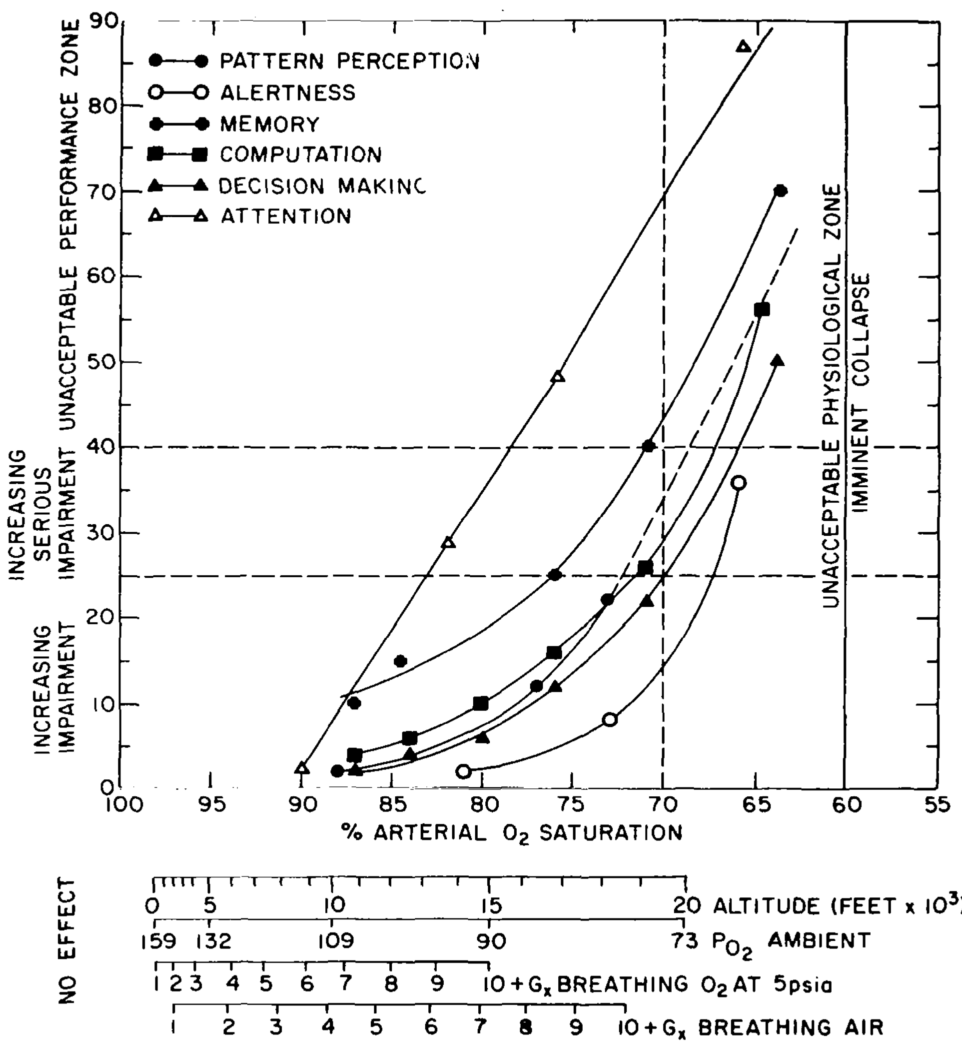


DATA FROM EXPOSURES OF 90 SECONDS AT PEAK G

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

ALTITUDE EFFECTS

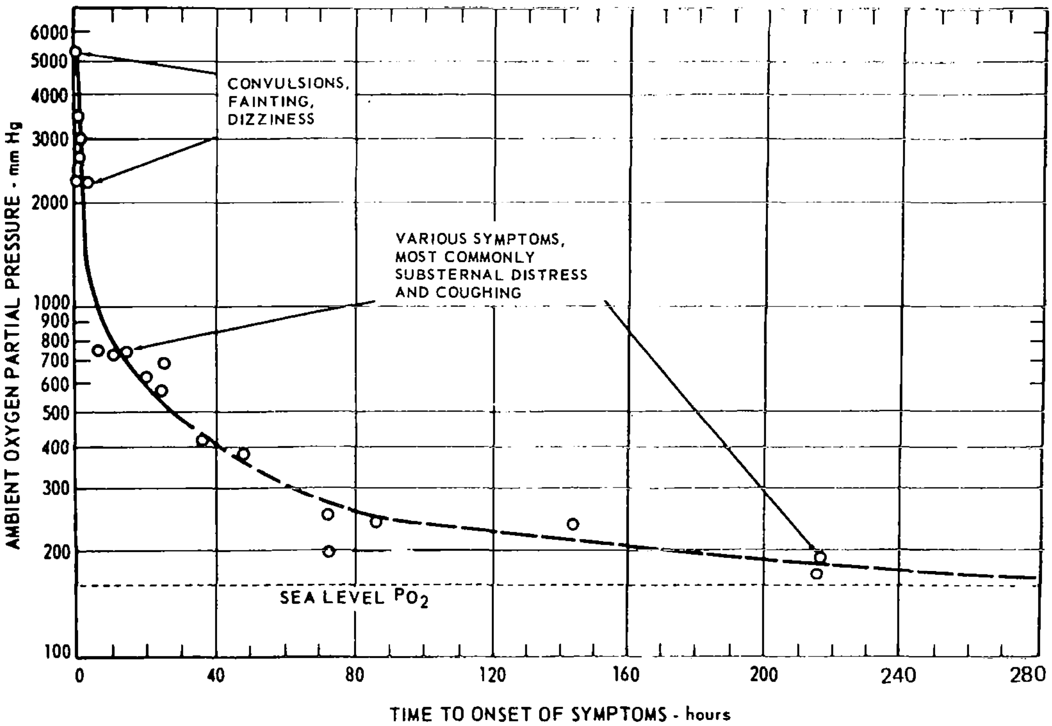
j. Effects of Hypoxemia on Some Intervening Mental Processes



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

ALTITUDE EFFECTS

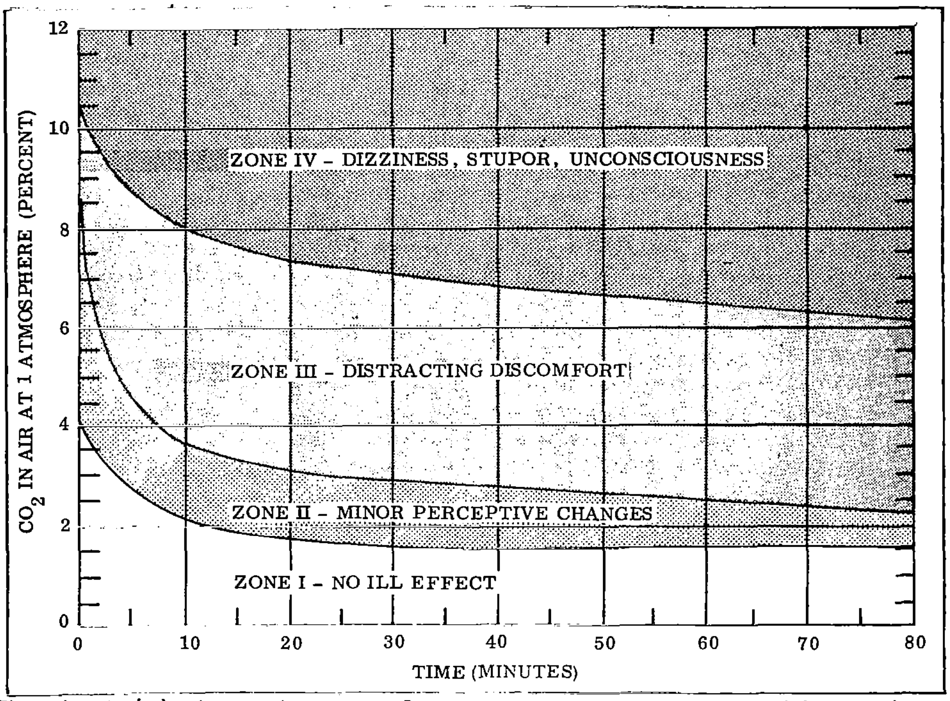
k. Times to First Symptoms of Oxygen Toxicity



SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

CARBON DIOXIDE EFFECTS

a. Symptoms for Short Time Exposure to Various CO_2 Concentrations

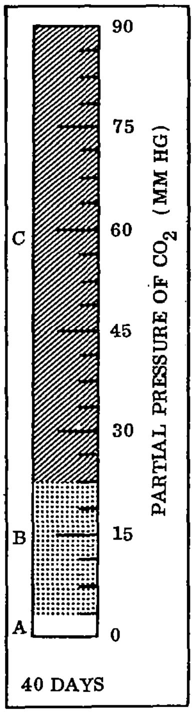


The chart (a) shows the general symptoms common to most subjects when exposed for the times indicated to mixtures of carbon dioxide in air at a total pressure of 1 atmosphere. In Zone I, no psychophysiological performance degradation, or any other consistent effect, is noted. In Zone II, small threshold hearing losses have been found and there is a perceptible doubling in depth of respiration. In Zone III, the zone of distracting discomfort, the symptoms are mental depression, headache, dizziness, nausea, "air hunger," and decrease in visual discrimination. Zone IV represents marked deterioration leading to dizziness and stupor, with inability to take steps for self-preservation. The final state is unconsciousness.

SOURCE: Comepndium...Vol. III (52), King (103), Nevison (138) and Schaefer (161).

CARBON DIOXIDE EFFECTS

b. Prolonged (40-Day) Exposure



The bar graph (b) shows that for prolonged exposures of 40 days, concentrations of CO_2 in air of less than 0.5 percent (Zone A) cause no biochemical or other effects, concentrations between 0.5 and 3.0 percent (Zone B) cause adaptive biochemical changes, which may be considered a mild physiological strain; and concentrations above 3.0 percent (Zone C) cause pathological changes in basic physiological functions.

SOURCE: Compendium...Vol. III (52), King (103), Nevison (138) and Schaefer (161).

CARBON DIOXIDE EFFECTS

c. Symptoms Occurring in 39 Resting Subjects Who Inhaled CO_2 for 15 Minutes*

	3.3% CO_2	5.4% CO_2	7.5% CO_2
Dyspnea	2	4	24
Headache	0	0	15
Stomach ache	0	0	1
Dizziness	0	0	6
Sweating	1	1	5
Salivation	0	0	1
Numbness of extremities	0	0	5
Cold sensations	1	1	3
Warmth sensations	1	1	4
Increased motor activity	0	0	10
Restlessness	0	0	10
Loss of control over limbs (overactivity)	0	0	4
Loss of balance (spatial disorientation)	0	0	7
Color distortion	0	0	2
Visual distortion	0	0	6
Irritability	0	0	4
Mental disorientation	0	0	2

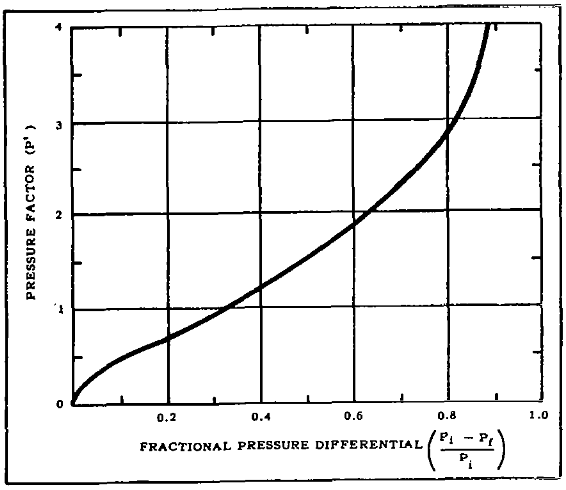
* Symptom frequency noted.

From numerous other studies, a more detailed CO_2 response spectrum can be described. During the first day of their exposure to 3 percent CO_2, several individuals remained mentally keen in spite of exhibiting general excitement and increased activity. Four percent CO_2 was found to be the upper limit toleranced by sleeping individuals and has been shown to increase the auditory threshold significantly.

SOURCE: Schaefer, Cornish, et al (162).

MECHANICAL EFFECTS OF RAPID DECOMPRESSION

a. Pressure Factor (P') as a Function of Initial Pressure (Pi) and Final Pressure (Pf)



The physical damage that may occur in the lungs is generally considered to be the critical limiting factor in human tolerance for very rapid decompressions.

Haber and Clamann have defined pressure transients during rapid decompression in terms of two principal parameters. The time characteristic, t_c, has the general form:

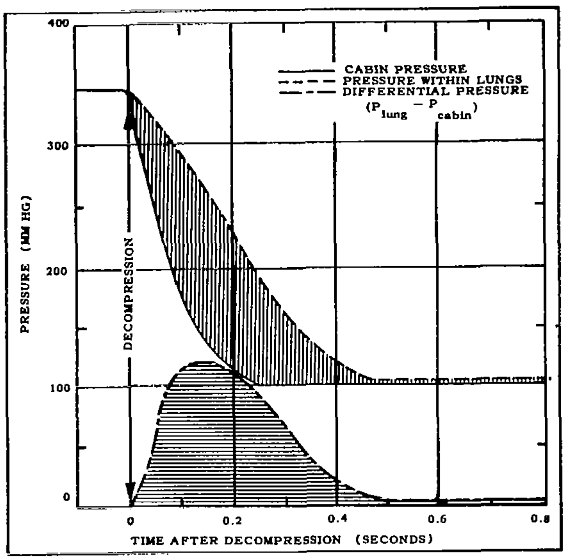
$$t_c = \frac{V}{A \cdot C}$$

where V is the volume of the container being decompressed, A is the effective area of the orifice (A is always somewhat smaller than the geometric orifice, for aerodynamic reasions), and C is the velocity of sound.

SOURCE: Haber and Clamann (77), Luft (114) and Webb (195).

MECHANICAL EFFECTS OF RAPID DECOMPRESSION

b. Transient Differential Pressure Buildup



The pressure factor, P', is a function of the initial pressure, P_i, and the final pressure, P_f in the container (see a):

$$P' = f\frac{[P_i - P_f]}{P_i}$$

The total decompression time, or duration of the transient, t_d, is the product of the time characteristic of the system t_c, and the pressure factor, P':

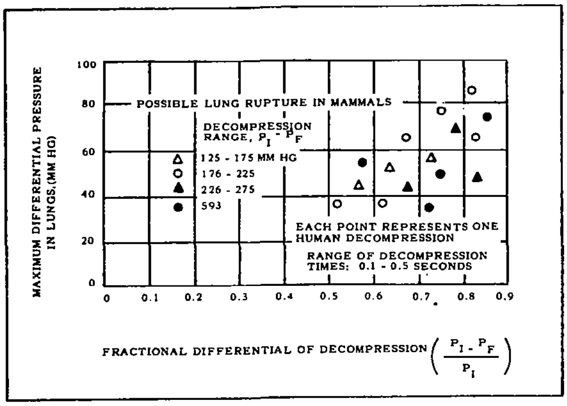
$$t_d = t_c \cdot P'$$

If the time characteristic of the human lungs and airways is greater than the time characteristic of the pressure suit or cabin in which a subject is confined during a decompression, a transient differential pressure buildup must occur within the lungs, This is illustrated diagrammatically in b., redrawn after Luft.

SOURCE: Haber and Clamann (77), Luft (114) and Webb (195).

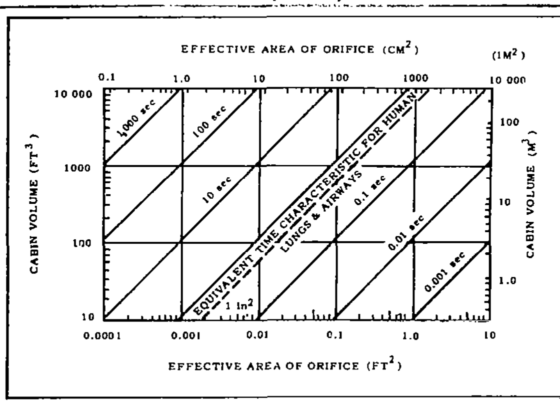
MECHANICAL EFFECTS OF RAPID DECOMPRESSION

c. Differential Pressure



Experimental data demonstrating the differential pressures observed during various decompressions is shown in c. Points have been derived from the data of Luft and Bancroft and Luft, Bancroft, and Carter. It has been shown by Adams and Polak that the mammalian lung may rupture when distended by a differential pressure above 80 mm Hg. The subjects whose data are shown were apparently uninjured.

d. Decompression Characteristics (Time) as a Function of Orifice Size

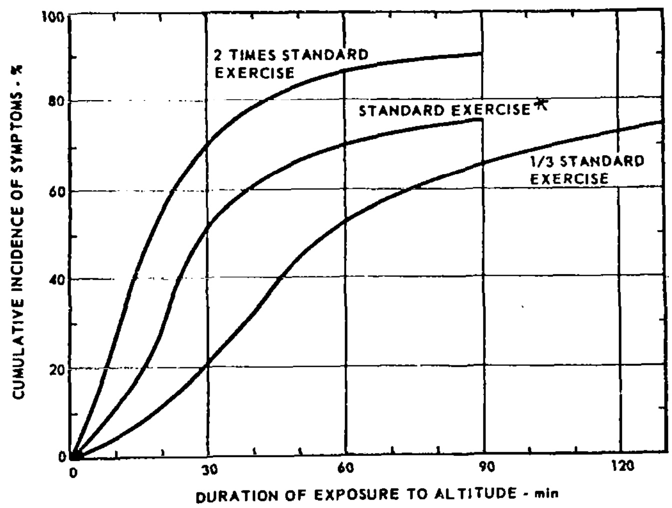


The time characteristic after Luft and Bancroft, is shown in d. as a function of container volume, V, and effective orifice area, A. The time characteristic for one of the subjects whose data are plotted in c. is shown. Since the volume of the lung varies with respiration, it is obvious that the time characteristic of the lungs may vary considerably, depending on the phase of respiration during which a rapid decompression occurs.

SOURCE: Adams and Polak (1), Luft and Bancroft (116), Luft and Bancroft, et al, (117) and Webb (195).

DECOMPRESSION SICKNESS

a. Effect of Physical Activity on Appearance of Clinical Manifestation, of Decompression Sickness at 38,000 Feet



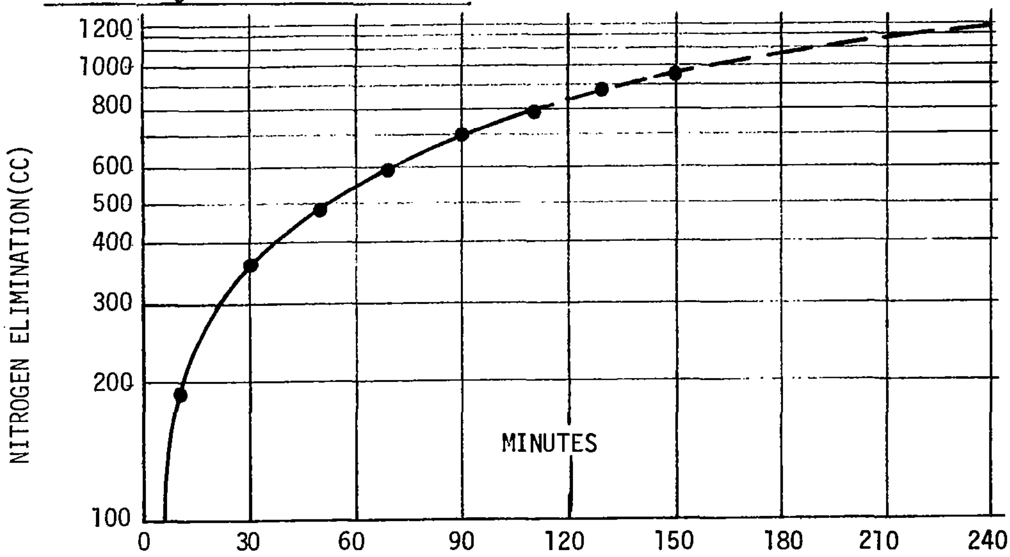
* Standard exercise was 10 step-ups onto a nine-inch stool in 30 seconds, repeated every five minutes.

The marked influence which physical activity has on the rate of appearance of clinical manifestations of decompression sickness deserves emphasis here, especially in the light of the fact that extravehicular operations in space will be associated with strenuous physical activity. This relationship was studied intensively by Henry who published data presented graphically in a.

SOURCE: Henry (83) and Webb (195).

DECOMPRESSION SICKNESS

b. Nitrogen Elimination Curve



Adequate protection can be established against decompression sickness both in actual flight at altitude and in routine altitude chamber operations. This is accomplished by two methods. By breathing pure oxygen for a period of time before exposure to low barometric pressure -- a process known as denitrogenation and by the use of pressurized cabins. The former is used routinely before altitude chamber flights and the latter is used routinely during aircraft flights.

The process of denitrogenation is very effective in eliminating a great amount of nitrogen from the body. The flow of body nitrogen from the tissues to the blood and into the alveoli occurs when the alveolar nitrogen pressure is reduced. This set of conditions can be created at ground level without reducing the total barometric pressure. When 100% oxygen is breathed by means of a mask or other appropriate oxygen equipment, no atmospheric nitrogen can enter the lungs. This creates an alveolar nitrogen pressure of zero. A very marked pressure differential then exist between the body tissues and the alveoli, in fact, the differential is 573 to 0. Nitrogen rapidly diffuses from the tissues to the blood to the alveoli and is exhaled. The amount of nitrogen lost is dependent upon time. The amount of nitrogen "washed out" of the body be denitrogenation per given period of time is shown in b. Assuming that the average male body contains ap roximately 1200 cc of dissolved nitrogen, slightly more than 350 cc could be eliminated by prebreathing 100% oxygen for 30 minutes. Denitrogenation for at least 30 minutes prior to a standard Type II altitude chamber flight to 43,000 feet will reduce the incidence of decompression sickness to an almost negligible figure.

SOURCE: Air Force Manual AFM 160-5 (4).

CRITERIA FOR SELECTION OF SPACE-CABIN ATMOSPHERE

a. Physiological Factors

FACTOR	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION
	1) 3.5 PSIA O_2 3.5 PSIA N_2	2) 3.5 PSIA O_2 3.5 PSIA He	3) 3.5 PSIA O_2 1.5 PSIA N_2	4) 3.5 PSIA O_2 1.5 PSIA He	5) 5 PSIA O_2	ORDER*
1. Aural atelectasis	No Problem	No Problem	No Problem	No Problem	Does occur in lab	(1 2 3 4) 5
2. Pulmonary atelectasis	No Problem	No Problem	No Problem	No Problem	Does occur in lab	(1 2 3 4) 5
3. Vital Capacity reduction	No Problem	No Problem	No Problem	No Problem	Does occur in lab	(1 2 3 4) 5
4. Hemolytic anemia	No Problem	No Problem	No Problem	No Problem	Has occurred in lab; ? significance	(1 2 3 4) 5
5. Urinary abnormalities	No Problem	No Problem	No Problem	No Problem	Has occurred in lab ? significance	(1 2 3 4) 5
6. Radiation Sensitivity	No Change	No Change	No Change	No Change	Nc change at this pressure	(1 2 3 4 5)
7. Voice Pitch Change	Insignificant	Minimal	Insignificant	Minimal	Insignificant	1 (3 5) (4 2)
8. Decompression time prior to symptoms of hypoxia	Longest available	Intermediate	Next to shortest	Shortest available	Intermediate	1 (5 2) 3 4
9. Alteration of trace contaminant effects	None expected	None expected	None expected	None expected	Has occurred in lab	1 2 3 4 5
10. Abdominal gaseous distress	Least, same as 2	Least, same as 1	Most, same as 4 and 5	Most, same as 3 and 5	Most, same as 3 and 4	(1 2) (3 4 5)
11. Decompression Sickness						
a) Bends	Rare but most susceptible	Same as 1	Very rare intermediate susceptibility	Same as 3	Probably will not occur when fully denitrogenated	5 (4 3) (1 2)
b) Neurocirculatory collapse	Extremely rare; most susceptible	Extremely rare; Intermediate susceptibility	Very extremely rare	Insignificantly low possibility	Probably will not occur when fully denitrogenated	5 4 3 2 1
c) Ebullism survival time	Least time	Intermediate time	Intermediate time	More time	Most time	5 4 (2 3) 1
12. Explosive Decompression	Extremely rare; most susceptible	Extremely rare; low susceptibility	Extremely rare; Intermediate susceptibility	Extremely rare; lowest susceptibility	Extremely rare; Intermediate susceptibility	4 2 (3 5) 1

* Mixtures are presented in descending order of desirability, those within parentheses are equally desirable.

SOURCE: Compendium of Human Response to the Aerospace Environment, Vol. III, (52) and Roth (157).

CRITERIA FOR SELECTION OF SPACE-CABIN ATMOSPHERE

a. Physiological Factors (Cont.)

FACTOR	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION
	1) 3.5 PSIA O_2 3.5 PSIA N_2	2) 3.5 PSIA O_2 3.5 PSIA He	3) 3.5 PSIA O_2 1.5 PSIA N_2	4) 3.5 PSIA O_2 1.5 PSIA He	5) 5 PSIA O_2	ORDER *
13. Blast overpressure	Intermediate lung damage; worst gas emboli	More favorable than 1	More lung damage; less dangerous emboli than 1	More lung damage; less dangerous emboli than 2	Same lung damage; less dangerous emboli than 3.	(2 4) 5 3 1
14. Flash blindness from meteoroid penetration.	Least dangerous	Same as 1	Intermediate	Intermediate	Most dangerous	(1·2) (3 4) 5
15. Possible metabolic side effects	Least	Slightly more than 4	Slightly greater than 1	Slightly less than 2	Most likely	1 3 4 2 5
16. Tolerance of high air temperature	Least	Most	Slightly more than 1	Next to 2	Same as 3	2 4 (3 5) 1
17. Changes in bacterial flora of skin and mouth	Least	Same as 1	Much less expected than in 5	Much less expected than in 5	Does occur in lab	(1 2) (3 4) 5

* Mixtures are presented in descending order of desirability, those within parentheses are equally desirable.

SOURCE: Compendium of Human Response to the Aerospace Environment, Vol. III, (52) and Roth (157).

CRITERIA FOR SELECTION OF SPACE-CABIN ATMOSPHERE

b. Fire and Blast Hazards

FACTOR	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION
	1) 3.5 PSIA O_2 3.5 PSIA N_2	2) 3.5 PSIA O_2 3.5 PSIA He	3) 3.5 PSIA O_2 1.5 PSIA N_2	4) 3.5 PSIA O_2 1.5 PSIA He	5) 5 PSIA O_2	ORDER*
1. Burning rate of fabrics and plastics	Slowest rate	Greater than 1 but hardest to ignite by contact with hot solid	Slightly greater rate than 2	Greater than 3 but harder to ignite by contact with hot solid	Fastest burning rate	(2 1) (4 3) 5
2. Flame temperature of burning hydro-carbon vapor.	Lowest	Probably same as 1	Slightly higher than 1	Probably same as 3	Highest	(2 1) (4 3) 5
3. Decompression time to extinguish flame.	Longest	Intermediate	Next to shortest	Shortest	Intermediate	4 3 (2 5) 1
4. Selectivity of cabin materials	Least restrictive	Same as 1	Intermediate	Same as 3	Most restrictive	(2 1) (4 3) 5
5. Flash oxidation from meteorite penetration	Least dangerous	Slightly more dangerous than 1	Slightly more dangerous than 1	Slightly more dangerous than 3	Most dangerous	1 2 3 4 5
6. Reduction of fire hazard by zero-gravity	Slightly more reduced than 3	Probably most reduced; most diffusible inertant at flame front.	Slightly less than 4	Slightly less than 2	Markedly reduced but least susceptible to zero-gravity effects	2 4 1 3 5
7. Toxicity of oxida-tion products of atmosphere.	Most toxic; oxides of nitrogen	Least toxic	Slightly less than 4	Least toxic	Same as 4	(2 4 5) (3 1)
8. Overall fire hazard	Least severe	Same as 1	Intermediate	Intermediate	Most severe	(1 2) (3 4) 5

* Mixtures are presented in descending order of desirability; those within parentheses are equally desirable.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Roth (157).

CRITERIA FOR SELECTION OF SPACE-CABIN ATMOSPHERE

c. Engineering Factors for 30-Day, 2-Man Mission **

FACTOR	MIXED 7 PSIA		MIXED 5 PSIA		SINGLE 5 PSIA	SELECTION
	1) 3.5 PSIA O_2 3.5 PSIA N_2	2) 3.5 PSIA O_2 3.5 PSIA He	3) 3.5 PSIA O_2 1.5 PSIA N_2	4) 3.5 PSIA O_2 1.5 PSIA He	5) 5 PSIA O_2	ORDER*
1. Gas Storage						
Overall tankage weight penalty	Less than 2)	Greatest	More than 5)	Less than 1)	Least	5 3 4 1 2
Weight of diluent gas used	Most	Slightly more than 4)	Slightly less than 1	Least used	None	5 4 2 3 1
Total gas storage weight.	Most	Intermediate	Intermediate	Least	Slightly more than 4)	4 5 (2 3) 1
2. Fan Power Weight						
Atmosphere control	Most	Slightly more than 4	Intermediate	Least	Intermediate	4 2 (3 5) 1
Ventilation and heat transfer	Most (same as 3 and 5)	Least	Most (same as 1 and 5)	More than 2	Most (same as 1 and 3)	2 3 (5 4 1)
3. Controls, weight and complication	More complicated than 5	Same as 1	Same as 1	Same as 1	Least weight and complication	5 (1 2 3 4)
4. Total ECS weight penalty	Most	Intermediate	Intermediate	Least	Intermediate	4 5 (2 3) 1
5. *Development time and cost*	*Intermediate*	*High*	Intermediate	Slightly more than 2 (if small diluent tankage)	Least	5 (1 3) (2 4)
6. Reliability of hardware	Less than 5	Less than 1	Same as 1	Less than 3	Most	5 (1 3) (2 4)
7. Compatability with current re-entry modules	Least	Same as 1	Intermediate	Intermediate	Most	5 (3 4) (1 2)
8. Sensitivity to extension of active missions to 90 days	Little	Some increase in storage efficiency less than 4	Little	Value does gain slightly because of increased storage efficiency.	Little	4 2 (1 3 5)
9. Sensitivity to stand-by operations	Gaseous storage insensitive, cryogenic is same as 3 and 5	*Sensitive due to* greater heat sink of cryogenic helium; gaseous may leak at high pressure.	*Same as 1*	*Slightly greater* than 2 due to greater heat leak; gaseous may leak at high pressure.	Same as 1	(1 3 5) 2 4

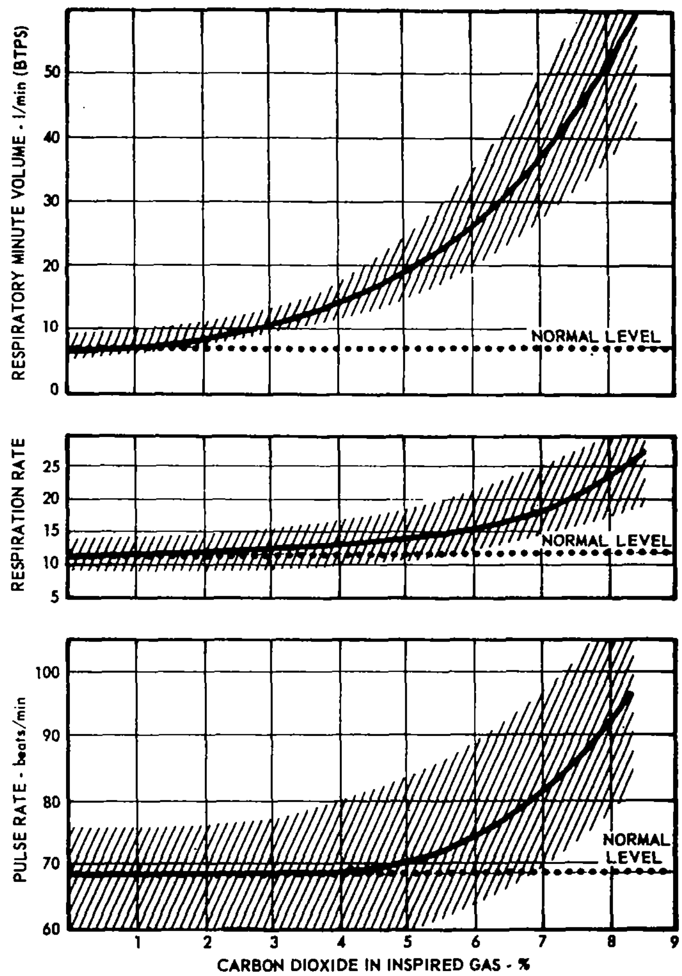
* Mixtures are presented in descending order of desirability; those within parentheses are equally desirable.

** Other missions may have other factors.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Roth (157).

CARDIORESPIRATORY RESPONSE TO CARBON DIOXIDE

a. Ranges of Response of Normal Population to Acute Elevation of CO_2

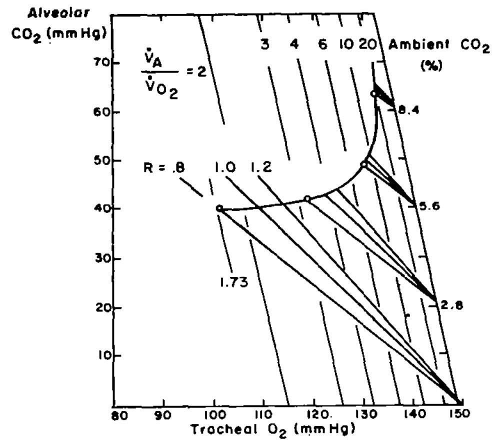


The immediate effects of increased CO_2 on pulse rate, respiration rate, and respiratory minute volume are shown for subjects at rest. The hatched areas represent one standard deviation on each side of the mean. To convert percentage of CO_2 to partial pressure, multiply fraction of CO_2 by 760 mm Hg.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Webb (195).

CARDIORESPIRATORY RESPONSE TO CARBON DIOXIDE

b. Effect of Inspiring Various CO_2 - Air Mixtures Upon the Steady State Alveolar Gas Composition of Normal Man at Rest



The ratio V_A/V_{O2} represents liters (BTPS) per minute of alveolar ventilation for every 100 ml (STPD) of oxygen consumed per minute. R represents the respiratory exchange ratio (volume of CO_2 output for volume of O_2 intake) and would be equal to the respiratory quotient (RQ) under steady state conditions at sea level.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52) and Fenn (65).

SECTION 2

CHARACTERISTICS OF SPACE ENVIRONMENT

INTRAVEHICULAR

DYNAMICS

INTRAVEHICULAR

DYNAMICS

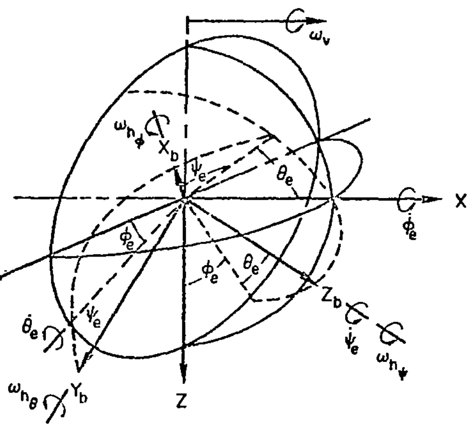
VESTIBULAR RESPONSES TO ROTATION

<u>Rotating Space Vehicles</u>

Vestibular Responses

In view of some uncertainty regarding the effect of zero gravity on body systems and housekeeping functions, the rotation of vehicles has been suggested as a possible method of supplying an artificial gravity. The movement of the head and body in a rotating space vehicle imposes angular acceleration of the semicircular canals of crewman which are considered in the following material.

a. <u>Vectorial Representation of Head Orientation and Angular Motion In A Rotating Space Vehicle</u>



a_{G_θ} cross-coupled nodding acceleration
ω_{G_ψ} cross-coupled turning acceleration
a_{G_ϕ} cross-coupled rolling acceleration
$\omega_{G_\theta} = \int a_{G_\theta}\, dt$
$\omega_{G_\psi} = \int a_{G_\psi}\, dt$
$\omega_{G_\phi} = \int a_{G_\phi}\, dt$

θ_n nodding displacement
ψ_n turning displacement
ϕ_n rolling displacement
θ_e, ψ_e, ϕ_e Euler angular displacement using the order of rotation
t time
$\theta_G = \iint a_{G_\theta}\, dt^2$
$\psi_G = \iint a_{G_\psi}\, dt^2$
$\phi_G = \iint a_{G_\phi}\, dt^2$

θ_{sc} backward tilt of semicircular canals from X_bY_b plane
ψ_{sc} rotation of semicircular canals from X_bZ_b plane
X, Y, Z inertial space axes
X_b, Y_b, Z_b body axes

ω_V vehicle rotational velocity
ω_{h_x} total angular velocity of head about rolling axis
ω_{h_y} total angular velocity of head about nodding axis
ω_{h_z} total angular velocity of head about turning axis

ω_{h_θ} nodding velocity — a fore and aft motion of the head at the neck or from the whole body
ω_{h_ψ} turning velocity — a motion about the neck or long-body axis
ω_{h_ϕ} rolling velocity — a sideways motion of the head or from the body

These are angular head motions and may be from motions at the neck and shoulders or from body bending, etc.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Stone and Letko (177).

INTRAVEHICULAR

DYNAMICS

VESTIBULAR RESPONSES TO ROTATION

The general expression for the angular accelerations that will be experienced while moving the head in a rotating space vehicle having constant velocity. There results the following expressions:

$$\dot{\omega}_{h_x} = \dot{\omega}_{h_\phi} - \omega_V\left(\omega_{h_\theta} \sin\theta_e + \omega_{h_\psi} \cos\theta_e \sin\psi_e\right)$$

$$\dot{\omega}_{h_y} = \dot{\omega}_{h_\theta} - \omega_V\left(\omega_{h_\psi} \cos\theta_e \cos\psi_e - \omega_{h_\phi} \sin\theta_e\right)$$

$$\dot{\omega}_{h_z} = \dot{\omega}_{h_\psi} + \omega_V\left(\omega_{h_\theta} \cos\theta_e \cos\psi_e + \omega_{h_\phi} \cos\theta_e \sin\psi_e\right)$$

The following accelerations are those sensed by the semicircular canals and are the cause of the disquieting effects experienced in rotating devices particularly when the vision is restricted to the rotating frame of reference.

$$\alpha_{G_\phi} = -\omega_V\left(\omega_{h_\theta} \sin\theta_e + \omega_{h_\psi} \cos\theta_e \sin\psi_e\right)$$

$$\alpha_{G_\theta} = \omega_V\left(\omega_{h_\phi} \sin\theta_e - \omega_{h_\psi} \cos\theta_e \cos\psi_e\right)$$

$$\alpha_{G_\psi} = \omega_V\left(\omega_{h_\theta} \cos\theta_e \cos\psi_e + \omega_{h_\phi} \cos\theta_e \sin\psi_e\right)$$

b. Canal Stimulation for Various Orientations of Canals in the Head

(Assume $\psi_e = \phi_e = \theta_e = 0$ with the head moving steadily through these values for consideration of this table)

Canal acceleration	$\theta_{sc} = 15^\circ$		$\theta_{sc} = 30^\circ$	
	ψ_{sc}		ψ_{sc}	
	35°	65°	35°	65°
Head nodding				
$\dot{\omega}_{sc_{tr}}$	$0.9659\omega_V\omega_{h_\theta}$	$0.9659\omega_V\omega_{h_\theta}$	$0.8660\omega_V\omega_{h_\theta}$	$0.8660\omega_V\omega_{h_\theta}$
$\dot{\omega}_{sc_{ar}}$	$0.1484\omega_V\omega_{h_\theta}$	$0.2346\omega_V\omega_{h_\theta}$	$0.2882\omega_V\omega_{h_\theta}$	$0.4532\omega_V\omega_{h_\theta}$
$\dot{\omega}_{sc_{pr}}$	$-0.2120\omega_V\omega_{h_\theta}$	$-0.1094\omega_V\omega_{h_\theta}$	$0.4096\omega_V\omega_{h_\theta}$	$0.2113\omega_V\omega_{h_\theta}$
Head turning				
$\dot{\omega}_{sc_{tr}}$	0	0	0	0
$\dot{\omega}_{sc_{ar}}$	$-0.8192\omega_V\omega_{h_\psi}$	$-0.4226\omega_V\omega_{h_\psi}$	$-0.8192\omega_V\omega_{h_\psi}$	$-0.4226\omega_V\omega_{h_\psi}$
$\dot{\omega}_{sc_{pr}}$	$-0.5736\omega_V\omega_{h_\psi}$	$-0.9063\omega_V\omega_{h_\psi}$	$-0.5736\omega_V\omega_{h_\psi}$	$-0.9063\omega_V\omega_{h_\psi}$

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Stone and Letko (177).

VESTIBULAR RESPONSES TO ROTATION

c. Angular Accelerations of Various Orientations of Subjects in a Rotating Space Vehicle

(a) $\psi_e = \phi_e = 0^\circ$

θ_e (a)	0°	-45°	-90°
$\dot{\omega}_{h_x} = \dot{\omega}_{h_\phi} - \omega_V$	0	$-0.7071\omega_{h_\theta}$	$-\omega_{h_\theta}$
$\dot{\omega}_{h_y} = \dot{\omega}_{h_\theta} - \omega_V$	ω_{h_ψ}	$0.7071(\omega_{h_\phi} - \omega_{h_\psi})$	ω_{h_ϕ}
$\dot{\omega}_{h_z} = \dot{\omega}_{h_\psi} + \omega_V$	ω_{h_θ}	$0.7071\omega_{h_\theta}$	0

(b) $\psi_e = 90^\circ$; $\phi_e = 0^\circ$

θ_e (a)	0°	-45°	-90°
$\dot{\omega}_{h_x} = \dot{\omega}_{h_\phi} - \omega_V$	ω_{h_ψ}	$0.7071(\omega_{h_\psi} - \omega_{h_\theta})$	$-\omega_{h_\theta}$
$\dot{\omega}_{h_y} = \dot{\omega}_{h_\theta} - \omega_V$	0	$0.7071\omega_{h_\phi}$	ω_{h_ϕ}
$\dot{\omega}_{h_z} = \dot{\omega}_{h_\psi} + \omega_V$	ω_{h_ϕ}	$0.7071\omega_{h_\phi}$	0

[a] The total angular accelerations are obtained by multiplying ω_V by the specific column of concern and adding the result to $\dot{\omega}_{h_\phi}$, $\dot{\omega}_{h_\theta}$, and $\dot{\omega}_{h_\psi}$ as noted.

Operating Limits for Rotating Space Stations

A choice of G from 1/5 to 1 appears suitable. The limits for Coriolis/gravity ratio are as yet not clear. In orbital flight, the force acting upon any particle inside can be described by the expression:

$$F = m(a + w^2 r + 2wv \sin\theta)$$

where
- F = total force on the particle
- m = mass of the particle
- a = linear acceleration of the particle with respect to the vehicle
- w = angular velocity of the vehicle
- r = radial distance from the axis of rotation to the particle
- v = linear velocity of the particle with respect to the vehicle
- θ = angle between axis of rotation and direction of "v"

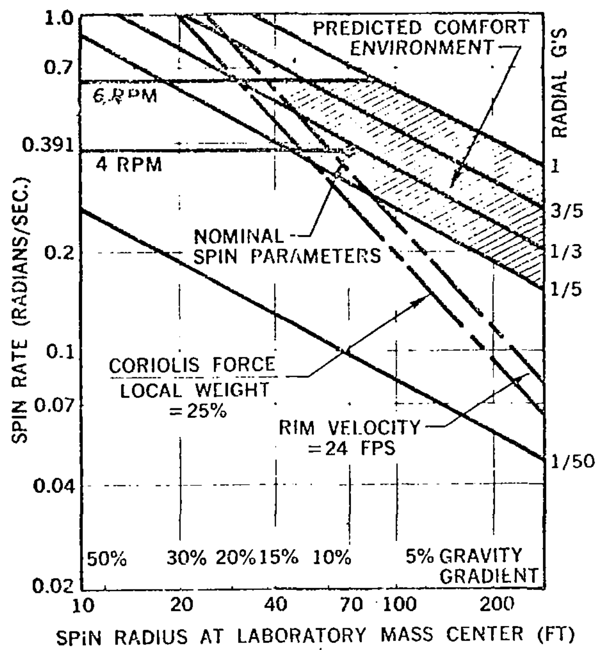
SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Stone and Letko (177).

INTRAVEHICULAR

DYNAMICS

VESTIBULAR RESPONSES TO ROTATION

d. Tentative Rotational Limits in Space Vehicle Design



In addition to spin envelope, the general principles that should be observed in a rotating space station design can be summarized as:

1. Radial traffic should be kept to a minimum.

2. Transport across the spin axis and human activity at the spin axis should be prohibited unless the hub is nonrotating.

3. The living-working compartment should be located as far as possible from the axis of rotation.

4. The compartment should be oriented so that the direction of traffic -- i.e., the major dimension of the compartment -- is parallel to the vehicle spin axis.

5. Crew duty-station positions should be oriented so that, during normal activity, the lateral axis through the crew member's ears is parallel to the spin axis. In conjunction with this requirement, the work-console instruments and controls should be designed so that left-right head rotations and up-down arm motions are minimized.

SOURCE: Compendium...Vol. II (51), Stone & Letko (177) and Stone & Pilanel(178).

VESTIBULAR RESPONSES TO ROTATION

6. Sleeping bunks should be oriented with their long axes parallel to the vehicle spin axis.

7. The presence of confusing visual stimuli should be minimized. For example, the apparent convergence of the vertical from any two points separated tangentially should be played down by proper interior decoration and, except for necessary observation ports, which should be covered when not in use, the living-working compartment should probably be windowless.

A factor often overlooked is the high rpm desired for vehicle stability. Disturbances, such as docking impacts and active or of structural and force-field oscillations, most of which could be significantly detrimental to crew function. The stimuli to the labyrinth due to vehicle instability can complement those due to the crewman's active head movements. The wobble or spin axis precession and precession of the vehicular angular momentum vector, more easily generated in vehicles of low mass and spin rate, may present the crewman with illusions of complex and ever-varying tilting of the floor as his body perceives the resultant of the linear acceleration oscillating along his longitudinal body axis and the linear acceleration normal to this axis. Simultaneous dynamic mass unbalances along both transverse axes would increase the complexity of the vector pattern and the resulting disturbances.

SOURCE: Compendium...Vol. II (51), Stone & Letko (177) and Stone & Pilanel(178).

VESTIBULAR RESPONSES TO ROTATION

e. Man's Rotary Stimulation of the Semicircular Canal

Abbreviations and Symbols: K = constant; α = angular acceleration; t = duration of α; T = time constant; SE = standard error; ~ = approximately.

	Stimulus			Response		
	Characteristics of Rotation	Head Orientation (Principal Organ Stimulated)	Factors Affecting Response Intensity	Motion Sensation [1]	Eye Movement [1]	Motion Sickness
1	Brief angular acceleration to constant rotation (10 rpm) around earth-vertical axis; head at center of rotation	Horizontal plane of skull in plane of rotation (Lateral semicircular canals)	$K\alpha(1-e^{-t/T})$[2]; mental alertness; visual stimulation; habituation	Spinning around earth-vertical axis. T of response, 10.2 ± 0.9 sec (SE)[3]. Stopping produces spinning sensation in opposite direction but with similar characteristics.	Nystagmus in horizontal plane, around earth-vertical axis. T of response, 15.6 ± 0.6 sec (SE)[3]. Stopping produces similar response but reversed in direction.	Negligible in absence of visual conflict.
2		Sagittal plane of skull in plane of rotation (Superior and posterior semicircular canals)	$K\alpha(1-e^{-t/T})$[2]; mental alertness; visual stimulation; habituation	Spinning around earth-vertical axis. T of response, 5.3 ± 0.35 sec (SE)[3,4]. Stopping produces spinning sensation in opposite direction but with similar characteristics.	Nystagmus in sagittal plane, around earth-vertical axis. T of response, 6.6 ± 0.35 sec (SE)[3,4]. Stopping produces similar response but reversed in direction.	Negligible in absence of visual conflict
3		Frontal plane of skull in plane of rotation (Superior and posterior semicircular canals)	$K\alpha(1-e^{-t/T})$[2]; mental alertness; visual stimulations; habituation	Spinning around earth-vertical axis. T of response, 6.1 ± 0.6 sec (SE)[3,4]. Stopping produces spinning sensation in opposite direction but with similar characteristics.	Nystagmus in frontal plane, around earth-vertical axis. T of response, 4.0 ± 0.2 sec (SE)[3,4].	Negligible in absence of visual conflict
4	Brief angular acceleration to constant rotation (10 rpm) around earth-horizontal axis; head at center of rotation	Horizontal plane of skull in plane of rotation (Lateral canals; otoliths and other gravity-sensitive structures)	Same as for entry 3, but complicated by continual reorientation of gravity-sensitive structures	Rotation around earth-horizontal axis. T indeterminate. Response persists throughout rotation. Stopping produces very short reversed responses or none at all.	Nystagmus in horizontal plane, around earth-horizontal axis. Response persists throughout rotation. Stopping produces short reversed response. T undetermined during rotation. After rotation, T = 6.8 sec	Nausea in ~50% of men tested during 5-min exposure. Associated effects with longer exposure: sweating, pallor, vomiting, antidiuresis.
5		Sagittal plane of skull in plane of rotation (Superior and posterior canals; otoliths and other gravity-sensitive structures)	Same as for entry 3, but complicated by continual reorientation of gravity-sensitive structures	Same as for entry 4	Nystagmus in sagittal plane, around earth-horizontal axis. Time characteristics same as for entry 4.	Same as for entry 4
6	Constant rotation (15 rpm) about one axis (ω-axis), plus head rotation about an orthogonal axis	Changing relative to plane of rotation (Semicircular canals and otoliths)	Angular displacement: head-tilt axis; angular velocity: head-tilt axis and ω-axis	Rotation about a 3rd axis approximately orthogonal to head-tilt axis and ω-axis	Nystagmus about a 3rd axis approximately orthogonal to head-tilt axis and ω-axis	Nausea in ~50% of men tested after 6 head movements during 4-min exposure. Associated effects: sweating, pallor, vomiting, antidiuresis

1 Recorded with subject in dark. 2 During normal head movements, nystagmus slow-phase velocity is opposite in direction and directly related in magnitude to the angular velocity of the skull 3 Time constants from estimates made by G. Melvill Jones 4 Time constant does not apply to a single canal or pair of canals because no single pair was in the plane of rotation.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51) and Guedry (74).

INTRAVEHICULAR

ATMOSPHERE CONTROL

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines

Toxic Hazard Rating

1. SLIGHT: readily reversible effects
2. MODERATE: not severe enough to cause death or permanent injury
3. HIGH: may cause death or permanent injury after very short exposure to small quantities

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments	Toxic Effects**
Acetaldehyde		200	General narcotic action on the CNS. Irritating to the eyes. High concentrations cause headache and stupefaction.	4, 12
Acetic Acid		10	Irritating to the eyes and mucous membranes. Penetrates the skin easily and can cause dermatitis and ulcers.	9, 12
Acetone		2000 for 24 hrs. 300 for 90 days	Narcotic in high concentrations	4, 9
Acetylene	Systemic 1-2	2500 for 24 hrs. 2500 for 90 days	When mixed with oxygen, in proportions of 40% or more, a narcotic. A simple asphyxiant.	4, 9, 13
Acrolein		0.1	Particularly affects the membranes of the eyes and respiratory tract.	9, 10, 12
Acrylic Acid	Acute Local: 3		Irritant by ingestion and inhalation	
Adipic Acid			Details unknown; toxicity probably slight.	
Alkyl Nitrate			No physiological information available.	
Alkyl Siloxanes			No specific physiological information available. Generally siloxanes are eye irritants.	
Allyl Alcohol		2	Irritation of skin, eyes and mucous membranes. Systemic poisoning is possible.	
Alumino Silicates		N	No physiological information available.	
Ammonia		400 for 1 hr. 50 for 24 hrs. 25 for 90 days		5, 9, 12

*Unless otherwise specified as provisional limits under normoxic conditions by the NAS-NRC(136) the limits are given as TLV (Earth equivalent), covering exposures for 8 hrs/day, 5 days per week at standard temperatures and pressures.

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

INTRAVEHICULAR

ATMOSPHERE CONTROL

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments	Toxic Effects**
Ammonia, Anhydrous		50	Irritating to eyes and mucous membranes of respiratory tract. Irritation of the skin may occur, especially if it is moist.	
Amyl Alcohol	Local:1 Systemic: 2-3		Vapor may be irritating to the eyes and upper respiratory tract.	3, 4, 9, 12
Benzene		100 for 24 hrs. 1 for 90 days	Exposure to high concentrations (3,000 ppm) may result in acute poisoning; narcotic action on the CNS. A definite cumulative action on bone marrow from 100 ppm exposures.	3, 4, 7, 9, 12
Bisphenol A		5	As phenol.	
1-3 Butadiene		1000	Vapors are irritating to eyes and mucous membranes. Inhalation of high concentrations can cause unconsciousness and death. If spilled on skin or clothing, it may cause burns or frostbite.	
Butane	Systemic: 1-2		Simple asphyxiant. Produces drowsiness.	4, 13
2 Butanone		100 for 60 min. 20 for 90 days 20 for 1000 days	Irritation of mucous membranes	
Butene-1	Systemic: 2		An anesthetic and asphyxiant.	4, 13
CIS-Butene-2			Details unknown. May act as a simple asphyxiant.	4, 13
Trans-Butene-2			Toxicity unknown.	4, 13
(N.-) Butyl Alcohol		100 (TLV) 10 for 90 days 10 for 1000 days	Irritation of the eyes with corneal inflammation, slight headache, slight irritation of the nose and throat and dermatitis of the fingers. Keratitis has also been reported.	4, 8, 9, 10, 12
Butyraldehyde	Local:1-2 Systemic: 2		Local: Irritant; Ingestion, Inhalation. Systemic: Ingestion, Inhalation.	9, 12
Butyric Acid	Local:1 Systemic: 1		Local: Irritant; Ingestion, Inhalation. Systemic: Ingestion, Inhalation.	9

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M³	Comments	Toxic Effects**
Caprylic Acid			Details unknown. Irritating vapors can cause coughing. Experimental data suggest low toxicity.	
Carbon Dioxide		25,000 for 1 hr. 10,000 for 24 hrs. 5,000 for 90 days	Inhalation. (See Oxygen-CO_2-Energy, No. 10.)	4, 13
Carbon Disulfide		20	Narcotic and anesthetic effect in acute poisoning, with death following from respiratory failure. Sensory symptoms precede motor involvement. Liver, kidney and heart may be damaged.	5, 6, 11
Carbon Monoxide		50 200 for 1 hr. 200 for 24 hrs. 5 for 90 days 15 for 1000 days	Effect is predominantly one of asphyxia, due to formation of irreversible carboxyhemoglobin in blood. 1,000 to 2,000 ppm for 1 hr. is dangerous, 4,000 ppm is fatal in less than 1 hr.	2
Carbon Tetrachloride		10	Narcotic action. High concentrations produce unconsciousness, followed by death. After effects may include damage to kidneys, liver and lungs. 1,000 to 1,500 ppm for 3 hrs. may cause symptoms.	3, 4, 8, 10
Carbonyl Fluoride		25 for 60 min.	Pulmonary irritation (animals)	
Chlorine		1 1 for 24 hrs. 0.1 for 90 days	Irritating to mucous membranes. If lung tissues are attacked, pulmonary edema may result.	9, 12
Chlorobenzene		75	Slight irritant. May cause kidney and liver damage upon prolonged exposure.	
Chloroform		5 for 90 days 1 for 1000 days	Fatty infiltration of liver at toxicological threshold.	
Chloroprene		25	Asphyxiant. Vapor is a central system depressant. Lowers blood pressure. In animals causes severe degenerative changes in the vital organs, especially kidneys and liver.	

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments	Toxic Effects**
Chloropropane			No physiological information available, but should have toxic properties similar to ethyl chloride.	
Cupric Oxide	Local: 1 Systemic: 1-2		As the sublimed oxide, copper may be responsible for one form of metal fume fever.	
Cyanamide	Systemic: 1-2		Causes an increase in respiration and pulse rate, lowered blood pressure and dizziness. There may be a flushed appearance of the face. Does not contain free cyanide.	
Cyclohexane		300	May act as a simple asphyxiant.	4, 8, 10
Cyclohexanol		50	Local: irritant; ingestion, inhalation. Systemic: ingestion, inhalation, skin absorption.	
Dichloromethane		25 for 90 days 5 for 1000 days	Reduction of voluntary activity at threshold (in animals).	
2, 2 Dimethylbutane			Toxicity: details unknown.	4
1, 1 Dimethylcyclohexane			No physiological information available.	
Trans-1, 2 Dimethylcyclohexane			No physiological information available.	
Dimethyl Hydrazine		0.5	Can be absorbed through intact skin. May result in convulsive siezures, pulmonary edema and hemorrhage.	
Dimethyl Sulphide			Toxicity: details unknown. Probably highly toxic.	
1-4 Dioxane		100 10 for 90 days 2 for 1000 days	Repeated exposure has resulted in human fatalities, the affected organs being the liver and kidneys. Death results from acute hemorrhagic nephritis. Brains and lungs show edema.	
Epichlorohydrin		5	In acute poisoning, death is the result of respiratory paralysis. Chronic poisoning is the result of kidney damage.	

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M^3	Comments	Toxic Effects**
Ethyl Acetate		400 40 for 90 days 40 for 1000 days	Irritating to mucous surfaces. Prolonged or repeated exposures cause conjunctival irritation and corneal clouding. High concentrations are narcotic and can cause congestion of the liver and kidneys.	4, 9, 12
Ethyl Alcohol		500 for 24 hrs. 100 for 90 days	No cumulative effect. Irritating to eyes and mucous membranes of upper respiratory tract. Narcotic properties.	
Trans-1, ME-3 Ethylcyclohexane			No physiological information available.	
Ethylene	Acute Systemic: 2		High concentrations cause anesthesia. A simple asphyxiant.	4
Ethylene Dichloride		50	Irritating to eyes and upper respiratory passages. Vapor causes a clouding of the cornea which may progress to endothelial necrosis. Strong narcotic action. Edema of the lungs in animals.	4, 8, 10, 12
Ethylene Glycol	Local: 0-1 Systemic:	0.2 100 for 60 min.	If ingested, it causes initial central nervous system stimulation, followed by depression. Later, it causes kidney damage which may terminate fatally.	10, 12
Ethyl Sulfide			Details unknown, but probably moderately toxic.	6, 9
Fluoro Ethylenes			No specific physiological information available. Generally fluorinated compounds are potentially toxic because they yield fluorine, hydrofluoric acid, etc. after ingestion, which are toxic.	
Formaldehyde		5 0.1 for 90 days. 0.1 for 1000 days	Toxic effects are mainly irritation. If swallowed it causes violent vomiting and diarrhea which can lead to collapse, increased airway resistance (animals) at threshold.	9, 12
Fluorotrichloromethane R-11		30,000 for 1 hr. 20,000 for 24 hrs. 1,000 for 90 days		

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments	Toxic Effects**
F_2ClC-$C\ ClF_2$ R-114		30,000 for 1 hr. 20,000 for 24 hrs. 1,000 for 90 days		
Freons		1000	High concentrations cause narcosis and anesthesia.	4, 9, 13
Hexachlorophene	Local: 1		Strong concentrations may be irritating.	
Hexamethylcyclotrisiloxane			No physiological information available. Generally siloxanes cause eye irritation.	9, 12, 13
Hexamethylene Diamine	Acute Local: 2		Local: irritant; ingestion, inhalation-all present.	
N-Hexane		500	Local: irritant; ingestion, inhalation. Systemic: inhalation, ingestion.	9, 12, 13
Hexene-1	Acute Local: 2 Acute Systemic: 2		Local: irritant; ingestion, inhalation. Systemic: inhalation	4, 9
Hydrocyanic Acid		10	Can be absorbed via intact skin. A true protoplasmic poison, combining in the tissues with the enzymes associated with cellular oxidation and rendering the oxygen unavailable to the tissues.	
Hydrogen	Acute Systemic: 1	3,000 for 24 hrs. 3,000 for 90 days	Inhalation	13
Hydrogen Chloride		10 for 1 hr. 4 for 24 hrs. 1 for 90 days	Irritating to the mucous membranes	9, 12
Hydrogen Fluoride		8 for 1 hr. 1 for 24 hrs. 0.1 for 90 days	Inhalation may cause ulcers of the upper respiratory tract. Produces severe skin burns, slow in healing.	6, 8, 9, 10, 12
Hydrogen Sulfide		50 for 1 hr.	An irritant and an asphyxiant. The effect on the nervous system is one of depression with small amounts, stimulation with larger ones. Asphyxia is due to paralysis of the respiratory system.	6, 9, 12

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M^3	Comments	Toxic Effects**
Indole			No physiological information available. May be considered an emetic after long exposure.	2, 9
Isobutyl Alcohol	Acute Local:3 Acute Systemic: 2	100	Local: irritant; ingestion, inhalation. Systemic: ingestion, inhalation.	
Isobutylene			Toxicity: details unknown. May have asphyxiant or narcotizing action.	
Isoprene	Acute Local:2 Acute Systemic: 2		Concentrations of 5% are fatal.	4, 9
Isopropyl Alcohol		400	Can cause corneal burns and eye damage. Acts as a local irritant and in high concentrations as a narcotic.	
Lithium Hydroxide	Local:1 Systemic: 1-2		Large doses of lithium compounds have caused dizziness and prostration, particularly on a low sodium intake.	
Maleic Acid	Acute Local:2		Irritant, ingestion, inhalation.	
Manganese Oxide	Systemic: 2-3	5 mg per cubic meter of air	The central nervous system is the chief site of damage, usually after 1 to 3 years of exposure to heavy concentrations of dust or fumes.	4, 8, 12
Mercaptans	Acute Local:3 Systemic: 2-3	0.5	Local: irritant; inhalation Systemic: inhalation.	
Mercury		0.1 mg per cubic meter of air	Chronic low grade exposure affects CNS and kidneys; may sensitize to oxygen toxicity and radiation.	3, 5, 8, 9
Methane	Systemic: 1	5,000 for 24 hrs. 5,000 for 90 days	Inhalation	4, 13
Methyl Acrylate		10	Chronic exposure has produced injury to lungs, liver and kidneys in experimental animals.	

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M^3	Comments	Toxic Effects **
Methyl Alcohol		200 for 24 hrs. 10 for 90 days	Distinct narcotic properties. Slight irritant to the mucous membranes. Main toxic effect is on the nervous system, particularly the optic nerves. Once absorbed, it is only very slowly eliminated; coma may last 2-4 days. A cumulative poison.	
2-Methylbutanone		20 for 90 days 20 for 1000 days	Irritation of mucous membranes in man at threshold.	
Methyl Chloride		100	Repeated exposure to low concentrations causes damage to the CNS, and less frequently to the liver, kidneys, bone marrow and cardiovascular system. Exposure to high concentrations may result in delirium, coma and death.	9, 12
Methyl Chloroform		1,000 for 1 hr. 500 for 24 hrs. 200 for 90 days	Local: irritant by ingestion, inhalation Systemic: toxic by ingestion, inhalation	3, 4, 8, 9
Methylene Chloride		500	Very dangerous to the eyes. Strong narcotic powers.	4, 9
Methylethyl Ketone		200	Local irritation and narcosis.	4, 9, 12
Methyl Isopropyl Ketone		200	No physiological information available. In general it should have same irritant properties as low molecular weight ketones; i.e., eye, skin and respiratory tract irritant.	
Methyl Methacrylate	Acute Local:1 Systemic: 1		Local: irritant by ingestion, inhalation. Systemic: toxic by ingestion, inhalation.	4, 9
Methyl Nitrate	Systemic:2		Ingestion, inhalation	
3-Methyl-Pentane			Details unknown; may have narcotic or anesthetic properties.	4, 9
Methyl Salicylate	Local:1-2 Acute Systemic:3		Acute accident poisoning is not uncommon. Kidney irritation, vomiting and convulsions occur.	

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments	Toxic Effects**
Monoethanolamine		50 for 1 hr. 3 for 24 hrs. 0.5 for 90 days	A skin irritant and necrotizer; a central nervous system stimulant in low doses; a depressant at high doses.	8, 9, 10, 12
Monomethylhydrazine		0.2	A respiratory irritant and convulsant at low doses.	
Nitric Oxide		5	60-150-ppm -immediate irritation of throat and nose. Shortness of breath, restless, loss of consciousness and - death may follow. 100-150 ppm for 30-60 minutes is dangerous.	4, 9, 12
Nitrogen Dioxide		10 for 1 hr. 1 for 24 hrs. 0.5 for 90 days	Highly toxic.	9, 12
Nitrous Oxide	Acute Systemic: 2		Inhalation	
Olefins			Prolonged exposure to high concentrations has led to liver damage and hyperplasia of the marrow in animals; no corresponding effects have been found in humans. Relatively innocuous.	
Ozone		1.0 for 1 hr. 0.1 for 24 hrs. 0.02 for 90 days	Strong irritant action on the upper respiratory system.	6, 9, 12
N-Pentane	Acute Systemic: 1		Inhalation. Narcotic in high concentrations.	4
Phenol		5	Can be absorbed through intact skin. Main effect is on the CNS in acute poisoning. Death may result within 30 minutes to several hours of spilling on the skin.	2, 3, 8, 10
Phosgene		1.0 for 1 hr. 0.1 for 24 hrs. 0.05 for 90 days	Irritating to eyes and throat. The main fatal effect is pulmonary edema.	12
Potassium Dichromate		0.1	A corrosive action on the skin and mucous membranes. Characteristic lesion is a deep ulcer, slow in healing. Chromate salts have been associated with cancer of the lungs.	

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

Agent	Toxic Code	Recommended Limits* ppm or mM per 25M³	Comments	Toxic Effects**
Propane	Acute Systemic: 1	1000	Inhalation	4, 13
N-Propylacetate		200	Causes narcosis and is somewhat irritating. Definite evidence of habituation - not likely to cause chronic poisoning.	
Propylene	Acute Systemic: 2		Inhalation. A simple asphyxiant.	4, 13
Silicic Acid			Toxicity slight, but dangerous in weightless conditions as it may form powders if not well confined.	
Skatole			No specific physiological information available. May be considered an emetic after lengthy exposures.	12
Sulfur Dioxide		10 for 1 hr. 5.0 for 24 hrs. 1.0 for 90 days	Irritating to nose and throat. MAC for 30-60 minutes exposure is 50-100 ppm. 400-500 ppm immediately dangerous to life.	9, 12
Terepthalic Acid			No specific physiological information available. A mild irritant with low acute oral toxicity.	
Tetrachloroethylene		100	Toxic by inhalation, prolonged or repeated contact with the skin, or mucous membranes or when ingested. Liquid can cause injuries to the eyes, irritation of the nose and throat.	
Tetrafluoroethylene Inhibited			Toxicity: can act as an asphyxiant and may have other toxic properties.	
Toluene		100 for 24 hrs.	Impairment of coordination and reaction time. Few cases of acute toluene poisoning.	4, 8, 9, 10
Toluene 2,4 di-isocyanate		0.02	Severe dermatitis and bronchial spasm. Particularly irritating to the eyes.	
Tri-aryl phosphates		5.0	As cresol. Ingestion, inhalation skin absorption.	11

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

Toxic Hazard Rating

1. SLIGHT: readily reversible effects
2. MODERATE: not severe enough to cause death or permanent injury
3. HIGH: may cause death or permanent injury after very short exposure to small quantities

Agent	Toxic Code	Recommended Limits* ppm or mM per $25M^3$	Comments	Toxic Effects**
1, 1, 1-Trichloroethane		1,000 for 1 hr. 500 for 24 hrs. 200 for 90 days	Narcotic at low levels. High levels may affect liver and lungs.	
Trichloroethylene		100 10 for 90 days 2 for 1000 days	Inhalation of high concentrations causes narcosis and anesthesia. A form of addiction has been observed. Death from cardiac failure due to ventricular fibrillation has been reported.	8, 9, 10, 12
1, 1, 2-Trichloro, 1, 2, 2-Trifluoroethane (Freon 113) and congeners		30,000 for 60 min. 1,000 for 90 days 200 for 1000 days	CNS and cardiovascular effects at threshold in animals.	
1, 1, 3-Trimethylcyclohexane			No physiological information available. Suspect it should be a skin irritant (solvent action) and irritant of the respiratory tract.	
Urea			Toxicity: no importance as an industrial hazard. Slightly dangerous when heated.	
Valeric Acid			Toxicity: details unknown. Nauseating. See Butyric Acid.	
Vinyl Acetate	Local: 1 Acute Systemic: 1		Local: Irritant Systemic: Inhalation.	
Vinyl Chloride		500	In high concentrations it acts as an anesthetic. Causes skin burns by rapid evaporation and consequent freezing.	4, 8
Vinylidene Chloride		5 for 30 to 90 days	Details unknown. See Vinyl Chloride.	4, 9
Xylene		100 for 24 hrs.	Local: irritant. Systemic: inhalation, skin absorption.	8, 9, 12

*Unless otherwise specified as provisional limits under normoxic conditions by the NAS-NRC(136) *the limits are given as TLV (Earth equivalent)*, covering exposures for 8 hrs/day, 5 days per week at standard temperatures and pressures.

** See Table of Toxic Effects on Page 2-19.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

a. Recommended Limits for Contaminants Already Found and Anticipated in Space Cabins and Submarines (Cont.)

** Table of Toxic Effects: Classification of possible contaminants of the space capsule according to their toxic effects on different body systems are presented below:

1. Autonomic N.S.
2. Blood
3. Cardiovascular
4. CNS Depressant
5. CNS Stimulant
6. Enzyme Inhibitor
7. Hemopoetic Tissue
8. Hepato Agent
9. Mucous Membrane
10. Nephro Agent
11. Peripheral N.S.
12. Respiratory
13. Simple Asphyxiant

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III, (52).

TOXICS

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS								
																					SUBMARINE				DOUGLAS		
		Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Mesa I	Mesa II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ACGIH TLV'S	USSR Industrial	1 Hour	24 Hour	90 Day	Boeing Company	Continuous'	Alert	Abort
Acetaldehyde	44.05	X	X						X	X	X	X	X	X	X	X	X		200	3				50	5	20	200
Acetic Acid	60.05						X		X	X					X	X	X		10	2				2	4	1 6	10
Acetone	58.08	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		1000	[a] 85		2000	300	50	20	80	1000
Acetylene	26.04	X	X	X											X		X					2500	2500	2500	25,000		
Allene	40.07								X														[b]				
Allyl Alcohol	58.08								X	X	X								2								
Ammonia	17.03			X			X			X		X				X	X		50	30	400	50	25	25	25	100	100
Amyl Acetate	130.18									X	X								100	[a] 20				20			53
Amyl Alcohol	88.15									X										25				25			50
Acrylonitrile	53.06							X											20						0.4	1.6	20
Benzene	78.11	X		X	X		X		X	X	X			X	X	X	X		25	[a] 6		100	1	5			
Benzyl Ether	198.25								X	X																	
1-3 Butadiene	54.09				X		X		X										1000	45			[b]				
n-Butane	58.12	X	X	X	X		X		X			X	X		X		X						[b]	5000			
iso-Butane	58.12								X								X										
2-Butanone	72.06	X	X				X		X	X	X	X		X		X	X		200	70				100	4	16	200

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES: Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Mesa I	Mesa II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ATMOSPHERIC LIMITS: ACGIH TLV'S	USSR Industrial	SUBMARINE: 1 Hour	24 Hour	90 Day	Boeing Company	DOUGLAS: Continuous	Alert	Abort
1-Butene	56.10	X		X		X			X						X		X						b	4000			
2-Butene cistrans	56.10	X	X				X		X								X						b	4000			
Butyl Acetate	150.61								X		X								150	40[a]				50			
iso-Butyl Acetate	150.61																										
n-Butyl Alcohol	74.12	X	X						X		X			X	X	X			100	65				25			
iso-Butyl Alcohol	74.12		X				X		X	X	X					X								25			
sec-Butyl Acrylate	128.17						X																				
n-Butyl Benzene	134.21																X						b				
tert-Butyl Benzene	134.21									X							X						b				
iso-Butylene	56.10								X			X			X		X						b				
Butyraldehyde	72.10								X	X	X													100			
-Butyrolactone	86.09															X											
Butyric Acid	88.10																X							5			
Carbon Dioxide	44.01	X						X	X	X	X	X	X		X	X	X		5000		25,000	10,000	5000	5000	10,000	12,500	15,000
Carbon Disulfide	76.14		X		X					X						X			20					2			
Carbon Monoxide	28.01			X	X				X	X	X					X	X		50	17	200	200	25	25	25	100	100

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

TOXICS

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS									
																					SUBMARINE				DOUGLAS		
		Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Mesa I	Mesa II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ACGIH TLV'S	USSR Industrial	1 Hour	24 Hour	90 Day	Boeing Company	Continuous	Alert	Abort
Carbon Tetrachloride	153.82						X		X	X	X								10	3				2	.5	2	10
Carbonyl Sulfide	60.07											X				X								2			
Chlorine	70.91																X		1			1	0.1	.5	0.4	.16	1.0
Chlorobenzene	112.56								X	X	X								75	11							
1-Chlorobutane	92.57							X																			
Chlorofluoro Bromomethane	147.47							X																			
Chlorofluoro ethylene	80.5			X				X																			
Chloroform	119.38			X			X		X	X	X					X			50								
Chloromethane	50.49			X				X	X			X							100					200	2	8	100
Chloropropane	78.54		X																								
Cyclohexane	84.16	X	X	X	X		X	X	X	X	X							X	300				b	200			
Cyclohexene	82.14								X		X								300				b				
Cyclopentane	70.13			X	X				X	X													b				
Cyclopentene	68.11									X													b				
Cyclopropane	42.08								X														b				
Decalin (various isomers	138.25								X	X	X																

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS									
																					SUBMARINE				DOUGLAS		
		Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Mesa I	Mesa II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ACGIH TLV'S	USSR Industrial	1 Hour	24 Hour	90 Day	Boeing Company	Continuous	Alert	Abort
Decane	142.29									X																	
Dichloroacetylene	94.93											X															
Dichlorobenzene	147.01															X			75	3							
1-2, Dichloroethane	98.96	X					X		X	X	X			X					50	2.5				5			
Dichloroethene	96.95		X																								
1-1, Dichloroethylene	98.96	X					X	X	X	X		X												5			
1-2, Dichloroethylene	98.96				X																						
*Dichloromethane	84.93	X	X		X	X	X	X	X	X	X			X	X				500	14				100			
1-2, Dichloropropane	112.99							X											75								
1-3, Dichloropropane	112.99							X																			
Diethylbenzene	134.21									X													b				
1-4, Dimethoxy benzene	138.16								X																		
Dimethylamine	45.08									X									10					5			
2-2, Dimethylbutane	86.17	X	X	X			X		X	X	X												b	4000			
2-3, Dimethylbutane	86.17								X	X	X												b				
Dimethylcychlohexane	112.22								X	X	X												b				

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

TOXICS

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS									
																					SUBMARINE				DOUGLAS		
		Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Mesa I	Mesa II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ACGIH TLV's	USSR Industrial	1 Hour	24 Hour	90 Day	Boeing Company	Continuous	Alert	Abort
Dimethylcyclopentane	100.13								X	X													b				
1-3, Dimethyl-5 ethylbenzene	134.22																X						b	25			
Dimethyl Furan	96.13								X	X	X																
Dimethyl Naphthalene	156.22								X	X													b				
2,4-Dimethyl Pentane	100.21									X													b				
Dimethyl Propane	72.15									X													b				
Dimethyl Sulfide	62.14									X	X													5	4	16	20
Dimethyl Thiophene	112.19								X																		
1,4-Dioxane	88.11	X						X						X					100	3				10			
Dioxene	86.10	X	X	X	X																			10			
Ethane	30.07		X	X	X	X	X	X	X	X							X						b				
Ethanethiol	62.13		X		X						X								10					2			
2-Ethoxyethanol	90.12															X			200								
2-Ethoxyethyl Acetate	132.16															X			100								
Ethyl Acetate	88.10	X	X	X			X		X	X	X			X	X	X	X		400	a 55				50			
Ethyl Acetylene	54.09			X																							

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES: Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Meso I	Meso II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ATMOSPHERIC LIMITS: ACGIH TLV'S	USSR Industrial	SUBMARINE: 1 Hour	24 Hour	90 Day	Boeing Company	DOUGLAS: Continuous	Alert	Abort
Ethyl Acrylate	100.12							X											25								
Ethyl Alcohol	46.07	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		1000	530		500	100	200			
Ethylamine	45.08															X			10					1			
Ethyl benzene	106.16								X	X	X					X	X	X	100				b	20			
Ethyl Chloride	64.52											X							1000								
Ethyl Cyclohexane	112.22																X										
Ethylene	28.05	X	X				X		X	X	X			X	X		X						b	500			
Ethylene Oxide	44.05															X			50	016							
Ethyl Ether	74.12			X	X				X	X	X	X							400	100				100			
Ethyl Formate	74.08								X	X	X				X				100					20			
*p-Ethyl Toluene	120.19									X						X	X						b	20			
Formaldehyde	30.03	X	X												X	X	X		5	0.8				0.1	0.2	0.8	5
Fluoroethane	48.06							X																			
2-Fluroropropene	60.07							X																			
R-11. Fluorotrichloro-methane	137.38	X	X	X			X		X	X	X			X			X		1000		30,000	20,000	1000	500			
R-12 Dichlorodifluoromethane	121.00	X					X			X									1000		30,000	20,000	1000	500			

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

TOXICS

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS								
																					SUBMARINE				DOUGLAS		
		Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Meso I	Meso II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ACGIH TLV'S	USSR Industrial	1 Hour	24 Hour	90 Day	Boeing Company	Continuous	Alert	Abort
R-22, Chlorodifluoromethane	86.50	X	X	X					X	X	X													500			
R-23, Trifluoromethane	70.01	X	X																					500			
R-113, $FCl_2C\text{-}CClF_2$	187.39						X		X		X								1000					500			
R-114, $F_2ClC\text{-}CClF_2$	170.93	X	X						X	X	X			X			X		1000		30,000	20,000	1000	500			
*R-125, $F_2HC\text{-}CF_3$	121.03	X	X						X		X													500			
Furan	68.07				X				X	X	X													10			
Furfural	96.08									X									5								
Furfuryl Alcohol	98.10									X									50								
n-Heptane	100.20						X		X	X	X					X	X	X	500				b				
Heptene	98.18									X													b				
Hexafluorobenzene	186.00									X																	
Hexamethyl cyclotrisiloxane	166.00	X																						50			
n-Hexane	86.17	X	X	X				X	X	X	X					X	X	X	500				b	200			
Henxene	84.16	X								X													b				
Hexene-1	84.16		X																				b	1			
Hydrogen	1.01		X							X					X		X					3000	3000	3000	30,000		

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

TOXICS

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS								
																					SUBMARINE				DOUGLAS		
		Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Mesa I	Mesa II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ACGIH TLV'S	USSR Industrial	1 Hour	24 Hour	90 Day	Boeing Company	Continuous	Alert	Abort
Hydrogen Chloride	36.46																X		5		10	4	1	0.1	0.1	0.4	5
Hydrogen Fluoride	20.01								X								X		3		8	1	0.1	0.1	0.1	0.4	3
Hydrogen Sulfide	34.08			X					X								X		10	7[a]	50			2	4	16	20
Indene	116.15						X		X	X																	
Indole	117.14									X														0.5			
Isoprene	68.11						X		X	X	X				X									200			
Isopentane	72.15	X	X						X	X	X	X					X						b	1,000			
*Mesitylene	120.19								X	X							X						b				
Methane	16.04		X	X	X		X	X	X	X	X					X	X	X				5,000	5,000	2,500			
Methyl Acetate	74.08								X	X	X								200	35[a]				25			
Methyl Alcohol	32.04	X	X	X	X		X		X	X	X	X	X	X			X		200	40[a]		200	10	3	4	16	200
Methylamine	31.06								X										10					1			
2-Methylbutanone-3	86.13	X								X			X														
Methyl Chloride	50.49			X				X	X			X							100					200	2	8	100
Methyl Chloroform	133.42	X							X	X	X			X			X		350		1000	500	200	50			
Methyl Cyclohexene	96.17									X													b				

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

TOXICS

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS								
																					SUBMARINE				DOUGLAS		
		Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Mesa I	Mesa II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ACGIH TLV'S	USSR Industrial	1 Hour	24 Hour	90 Day	Boeing Company	Continuous	Alert	Abort
Methyl Cyclopentane	84.13									X								X					b				
*Methylene Chloride	84.89	X	X		X	X	X	X	X	X	X			X	X				500	14				100			
Methyl Cyclohexane									X	X	X						X	X	500				b				
Methylethyl benzene	120.19									X						X	X						b	20			
Methyl Ethyl Ketone	72.06	X	X				X		X	X	X	X		X		X	X		200	70				100	4	16	200
Methyl Ethyl Thiophene	126.18								X																		
Methyl Formate	60.05												X						100					10			
Methyl Furan	82.10								X	X	X									0.3				10			
Methyl iso Butyl Ketone	100.16								X	X	X					X	X		100					10			
Methyl iso Propyl Ketone	86.13	X									X			X													
Methanethiol	48.10						X		X	X									10					2	1	4	50
Methyl Methacrylate	100.11										X					X			100					10			
Methyl Naphthalene	142.19								X	X													b				
Methyl Butyrate	102.13								X	X	X																
2-Methyl Pentane	86.17	X								X	X					X							b				
3-Methyl Pentane	86.17	X	X																				b	1000			

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES: Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Meso I	Meso II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ATMOSPHERIC LIMITS: ACGIH TLV'S	USSR Industrial	SUBMARINE: 1 Hour	SUBMARINE: 24 Hour	SUBMARINE: 90 Day	Boeing Company	DOUGLAS: Continuous	DOUGLAS: Alert	DOUGLAS: Abort
4-Methyl-2 Pentanone	100.16						X																				
Methylsiloxane Polymers									X	X	X					X	X										
Methyl Thiophene	84.14						X		X																		
Monochloro Acetylene	60.48											X															
Monoethanolamine	75.11																X		3		50	3	0.5	1			
Napthalene	128.16								X	X	X								10								
Nitric Oxide	30.01								X								X							1	0.4	1.6	10
Nitrogen Dioxide	92.01												X				X		5		10	1	0.5	.5	0.2	0.8	5
Nitrous Oxide	44.01																X							5000			
n-Nonane	128.25																	X					b				
Octane	114.23										X						X		500				b				
*iso-Octane	114.23			X					X	X									200				b				
Ozone	48.00																X		0.1		1.0	0.1	0.02	0.05	0.004	0.016	0.1
Pentafluoroethane	121.03	X	X						X		X													500			
Pentane	72.15	X	X						X	X	X	X					X		1,000				b	1,000			
iso-Pentane	72.15	X	X						X	X	X	X					X						b	1,000			

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

TOXICS

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS								
																					SUBMARINE				DOUGLAS		
		Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Mesa I	Mesa II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ACGIH TLV'S	USSR Industrial	1 Hour	24 Hour	90 Day	Boeing Company	Continuous	Alert	Abort
1-Pentene	70.13								X			X											b				
Perchloroethylene	165.85		X						X	X	X				X				100								
Phenol	94.11															X			5	1.3				1.0	0.2	0.8	5.0
Phosgene	98.92											X							0.1		1.0	0.1	0.05	0.05	0.04	0.16	1.0
Propane	44.09	X		X	X		X	X	X	X							X		1,000				b	1000		1800	
Propene	42.08					X		X															b				
Propenenitrile	53.06							X											20						0.4	1.6	20
Propionaldehyde	58.08															X								50			
Propionic Acid	74.08								X	X					X		X							2			
Propyl Acetate	102.13								X	X	X								200	50							
n-Propyl Alcohol	60.09	X	X						X	X	X			X		X			200	80				100			
iso-Propyl Alcohol	60.09			X	X	X	X		X	X	X					X	X		400	80				100			
iso-Propyl Benzene	120.19																X		50					20			
n-Propyl Benzene	120.19									X							X						b				
* Propyl Chloride	78.54		X								X																
Propylene	42.08	X	X						X	X	X	X			X		X						b	1000			

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS								
																					SUBMARINE				DOUGLAS		
		Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Mesa I	Mesa II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ACGIH TLV'S	USSR Industrial	1 Hour	24 Hour	90 Day	Boeing Company	Continuous	Alert	Abort
*1, 1, 1-Trichloroethane	133.42	X							X	X	X			X			X		350		1000	500	200	50			
Trichloroethylene	131.40	X	X						X	X	X	X		X	X	X			100	9				20			
Trifluorobenzene	132.00									X																	
Trifluorochloroethane	104.5							X																			
*1, 3, 5-Trimethyl Benzene	120.19								X	X							X						b				
Trimethyl Hexane	128.24									X													b				
*Trimethyl Pentane	114.22			X					X	X									200				b				
Trimethylsilanol	80.00															X											
Valeric Acid	102.13								X	X																	
Vinyl Chloride	62.50	X	X						X		X			X			X		500	12				100	10	40	500
Xylene	106.16	X					X		X	X	X			X		X	X	X	100	12		100	b	50			
m-Xylene	106.16	X																									

Notations defined on Page 2-32.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

TOXICS

b. Contaminants Found in Sealed Cabins and Their Compartments and Past Attempts at Setting Atmospheric Limits (Cont.)

COMPOUND	MOL. WT.	REPORTED OCCURRENCES																	ATMOSPHERIC LIMITS								
																					SUBMARINE				DOUGLAS		
		Mercury	GT-3	GT-4	GT-5	GT-7	GT-10	GT-12	SAM I	SAM II	SAM III	Meso I	Meso II	Merc. Malfunction	Integrated L/S/S	Offgassing	Submarines	Sea Lab II	ACGIH TLV's	USSR Industrial	1 Hour	24 Hour	90 Day	Boeing Company	Continuous	Alert	Abort
iso-Propyl Ether	102.17								X	X	X								500								
Propanethiol	76.16								X	X	X																
iso-Propanethiol	76.16						X																				
Propyne	40.06								X										1000				b	1000			
Pseudocumene	120.19								X	X							X						b	20			
Silicone Oil																X											
Skatole	131.17								X															0.5			
Styrene	104.14								X	X									100	a 12			b				
Sulfur Dioxide	64.06		X									X					X		5		10	50	1.0	0.2	0.2	0.8	5
1, 2, 4, 5-Tetrachlorobenzene	215.90															X											
Tetrachloroethane	102.03									X																	
Tetrafluorobenzene	150.00									X																	
Tetrafluoroethylene	100.2		X																								
Tetrahydrofuran	72.10								X	X	X								200					20			
Tetramethylbenzene	134.21								X	X																	
Toluene	92.13	X	X	X	X		X		X	X	X			X	X	X	X	X	200	13		100	b	50			

* = Listed under two synonyms

a = USSR Community Levels available

b = Submarine Levels

Aliphatic Hydrocarbons	60 mg/m3
Aromatic Hydrocarbons (other than benzene)	10 mg/m3
Benzene	3 mg/m3

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

INTRAVEHICULAR

ATMOSPHERE CONTROL

TOXICS

Particulates and Aerosols

Many of the toxic materials covered above may be in particulate or aerosol form. Even nontoxic particulates may be a hazard in space operations because of the zero gravity aspect of the environment. In reviewing toxic hazards, one must be concerned with the fact that aerosols can act as condensing nuclei for toxic gases. This facilitates the entrance into the lower respiratory tract of such materials which, because of their high water solubility, are generally trapped in the upper respiratory tract. It also provides for local areas of extreme irritation due to the concentration of the toxic gas in a finite area.

The aerosols may be classified as shown in Table c. Generally, aerosols have a diameter of less than 50μ. The usual range is from 0.01μ to 10μ. Surface air on the Earth contains a considerable aerosol load. The problem, unique in the closed living space, is the tendency of these to increase in numbers and mean diameters. In submerged nuclear powered submarines the concentration reached a steady state concentration of about 0.4μg/L at approximately 100 hours. This compared unfavorably with the aerosol concentration in Los Angeles on a smoggy day where the concentration averaged 0.2μg/L. Also there was approximately 8 times the content of organic aerosols in the submarine.

c. Classification of Aerosols

Smokes:	Usually solid particles of carbon resulting from the burning of carbonaceous material. Carbon smoke is composed of particles about 0.01μ which tend to coagulate or agglomerate rapidly into long, irregular filaments several microns in length.
Dusts:	Solid particles ranging in size from 0.1μ or less, which produce a haze, to large particles found in a sandstorm which are likely to be the size range considered to be aerosols.
Fogs:	Liquid droplets generated by atomization or condensation of volatile substances on minute nuclei. The size of these particles is often quite large, ranging from 4 to 40μ, as in a natural water fog.
Fumes:	Solid particles generally produced by sublimation, combustion, or condensation, usually between 0.05 and 0.5μ. Fumes are produced by arcing at high temperature.

Theoretical considerations of the role of zero gravity in generation of aerosols imply that the amount of particle or droplet contaminant inhaled in orbit could be increased over the amount inhaled in a similar situation under one-gravity environment. The predicted characteristics of particle and droplet deposition in the respiratory passages for the weightless environment show

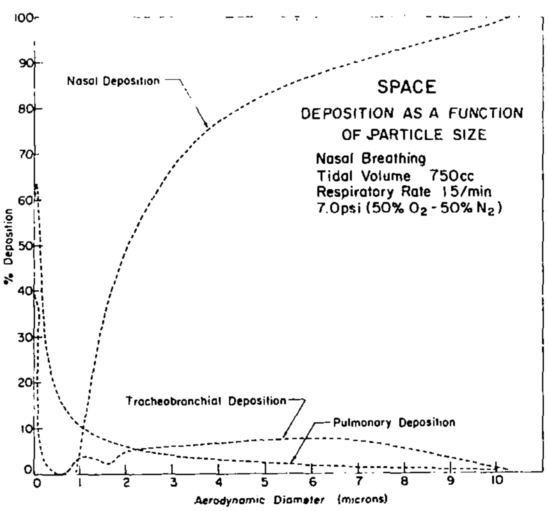
SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. III (52) and Punte (147).

that in space, as on Earth, the nose or mouth should continue to operate as highly efficient filters, protecting the lower respiratory passages from all particles and droplets above about 10 microns in diameter. Fortunately, this size is considerably less than that of particles and droplets of most contaminants which may be introduced into the spacecraft cabin atmosphere. In this respect, it should be pointed out that the use of powdered chemicals of particle sizes greater than 10 microns in space would be an important safety measure.

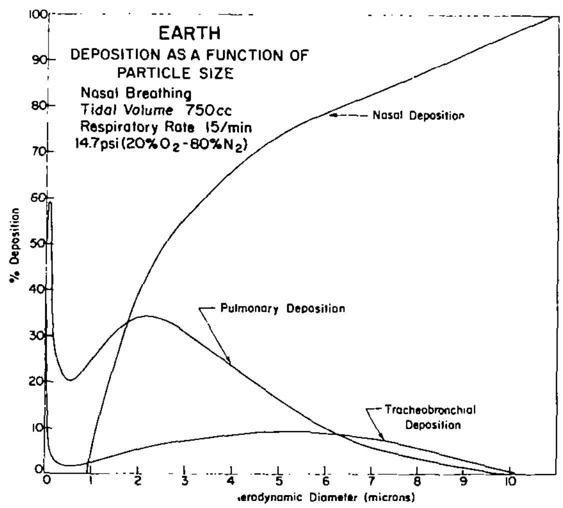
It is possible for an astronaut to be exposed to aerosols and droplets (i.e., liquid ejected as a fine spray) less than about 10 microns in diameter. The "deposition curves" predict that fewer inhaled particles and droplets between about 0.5 and about 10 microns in diameter will be deposited in the lower respiratory passages, especially in the pulmonary region, (Figure d versus Figure e) in the weightless as compared to the one-gravity environment. This implies that weightlessness might offer some protection to an astronaut from certain contaminants which, if inhaled in a similar concentration in a unit gravity environment, would be irritating to or damage alveoli.

The lack of gravity will probably have an effect on the site of deposition of aerosols. Figure d represents calculation for respiratory deposition sites for particles of different aerodynamic diameter in space cabins at zero g. Figure e shows similar calculations for the Earth environment. Figure f compares total deposition in orbiting spacecraft versus Earth environment.

d. Space Cabin Atmosphere in a Weightless Environment



e. Air at One Atmosphere in a 1-G Environment



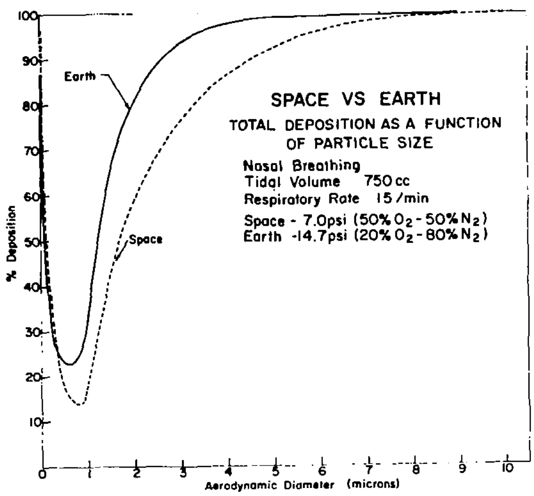
SOURCE: Busby and Mercer (41) and Compendium of Human Responses to the Aerospace Environment, Vol. III (52).

INTRAVEHICULAR

ATMOSPHERE CONTROL

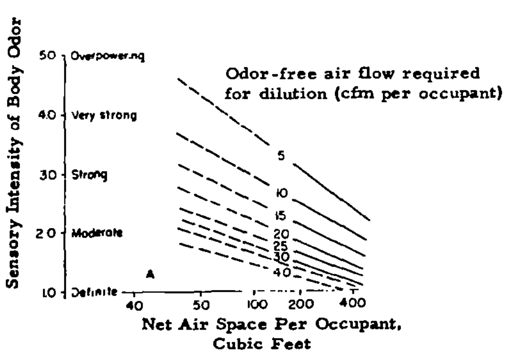
TOXICS

f. Comparison of Total Deposition



Comparison of theoretical deposition of aerosols in space cabin atmospheres at zero gravity and in air at Earth gravity as a function of particle or droplet size.

g. Ventilation Requirements in Relation to Net Air Space and Body Odor

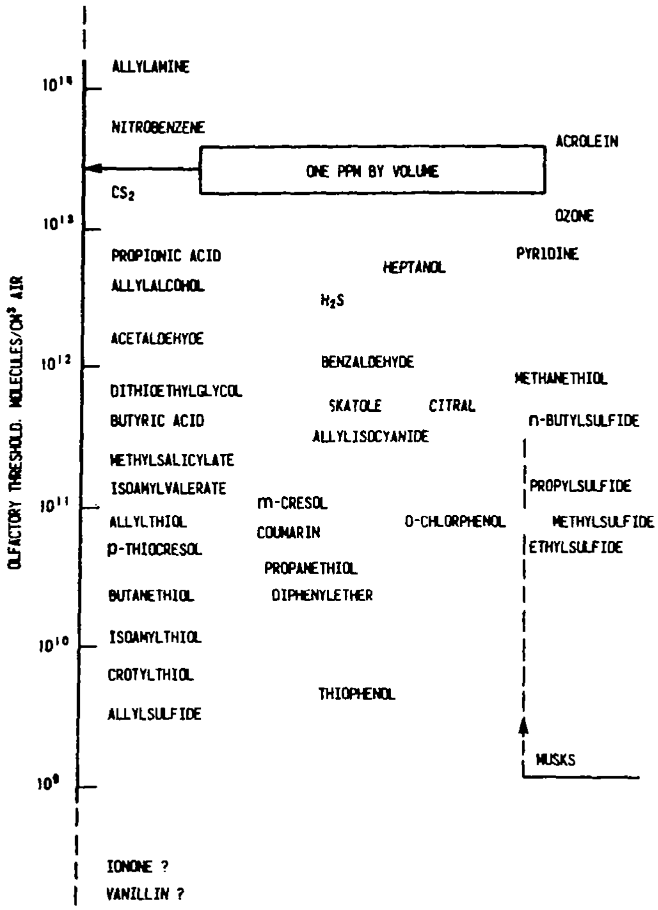


The graph shows that the intensity of body odors in a given area depend on the rate of flow of odor-free air. The solid portions of the curves are based on experimental data; the broken parts are extrapolations to the conditions found on aircraft.

SOURCE: Busby and Mercer (41), Compendium of Human Responses to the Aerospace Environment, Vol. III (52), Dravnieks (57) and Yaglow (214).

TOXICS

h. Olfactory Threshold



SOURCE: Busby and Mercer (41), Compendium of Human Responses to the Aerospace Environment, Vol. III (52), Dravnieks (57) and Yaglow (214).

INTRAVEHICULAR

ILLUMINATION

TASK RELATED ILLUMINATION REQUIREMENTS

Visual efficiency is directly dependent on illumination. Human performance is also dependent on illumination to the extent that vision is a requirement. While insufficient illumination may be an obvious contributor to performance degradation, too much light in the form of glare or an adequate amount of illumination which is applied improperly, may also have the same effect.

a. Recommended Illumination Levels

MAINTENANCE TASK OR AREA DESCRIPTION	ILLUMINATION*- FOOT CANDLES
Drilling, Riveting, and Screw Fastening,	70
Welding: General	50
Supplementary	1,000
Assembly:	
Rough (easy seeing)	30
Rough (difficult seeing)	50
Fine	500
Extra Fine	1,000
Repairs	
Inspection:	
Ordinary	50
Difficult	100
Highly difficult	200
Very difficult	500
Most difficult	1,000
Reading vernier calipers:	
Non-etched	631**
Reading new micrometers	7.4**
Reading old micrometer	
Specular on numbers	282**
Specular on divisions	7.6**

* It is generally assumed that brightness of the peripheral field is uniform and equal to the immediate background of objects to be seen with central vision. All laboratory data are based on this condition, where gross departures from this are indicated, new values must be determined.

** Foot Lamberts

SOURCE: Human Engineering Design Criteria (88) and Lighting Handbook (111).

TASK RELATED ILLUMINATION REQUIREMENTS

a. Recommended Illumination Levels (Cont.)

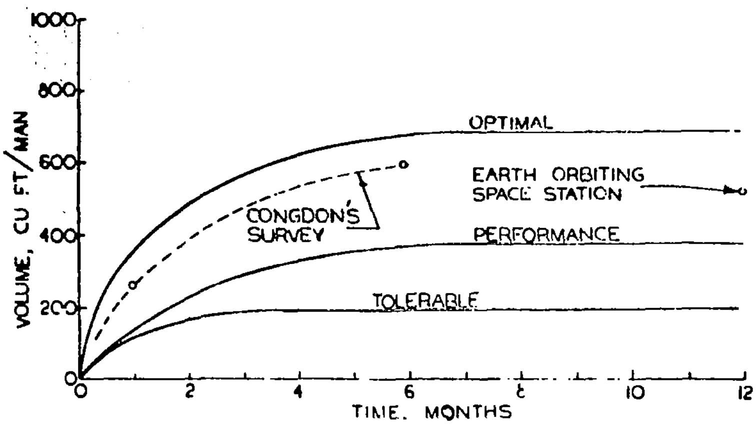
TASK CONDITIONS	FOOT-CANDLES AT WORK POINT
Rough Seeing Tasks Inactive storage, hallways, large objects	1 to 5
Casual Seeing Tasks Active storage, service areas, stairways	5 to 10
Visual Tasks Comparable to Reading 10 or 11 Point Print on Good Quality Paper (I.E., Good Legibility	10 to 15
Visual Tasks Comparable to Reading Newsprint	15 to 20
Ordinary Seeing Tasks Involving Moderately Fine Detail with Normal Contrasts Reading, handwriting, ordinary bench and assembly work	20 to 30
Visual Tasks Requiring Very Fine Discrimination, Small detail, fine finishing, fine assembly	30 to 50*
Difficult Visual Tasks with Poor Control and Precision Requirements Extra fine finishing or assembly under low brightness contrast conditions	50 to 100*

* It is generally assumed that brightness of the peripheral field is uniform and equal to the immediate background of objects to be seen with central vision. All laboratory data are based on this condition, where gross departures from this are indicated, new values must be determined.

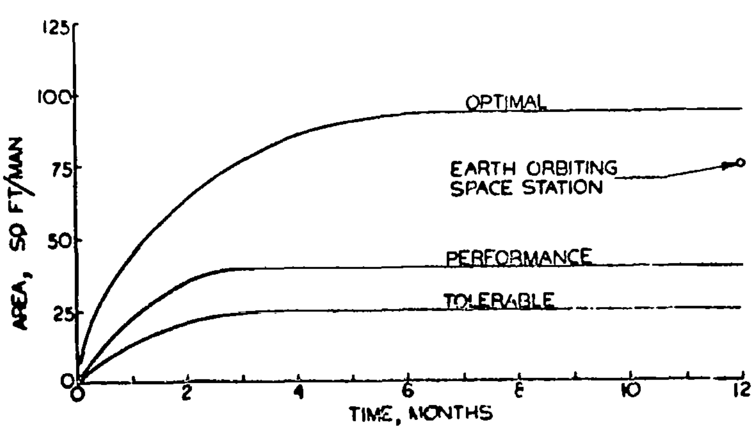
SOURCE: Human Engineering Design Criteria (88) and Lighting Handbook (111).

HABITAT LIVING AREA REQUIREMENTS

a. Living Space Per Man (Volume)



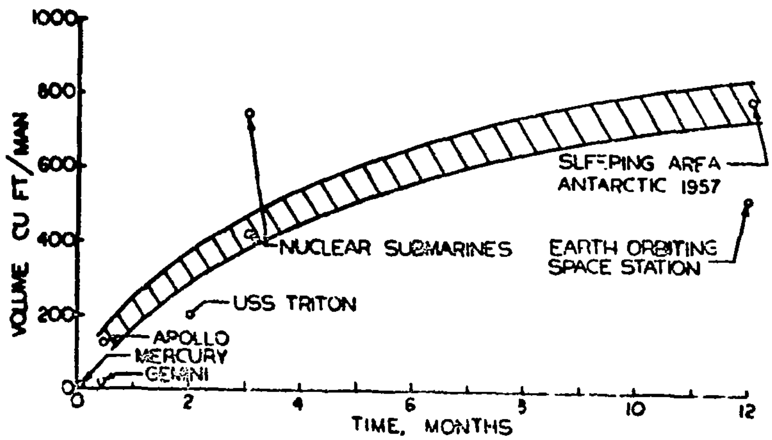
b. Living Space Per Man (Area)



SOURCE: Amorelli, Celentano, et al (9) and Congdon, et al (53).

HABITAT LIVING AREA REQUIREMENTS

c. Total Habitable Living Volume



SOURCE: Amorelli, Celentano, et al (9) and Congdon, et al (53).

EXTRAVEHICULAR ENVIRONMENT

HAZARDS

SUMMARY OF HAZARDS DURING EXTRAVEHICULAR ACTIVITY

CONDITION	METHOD OF HAZARD REDUCTION	EMERGENCY PROCEDURE
Environmental		
Solar radiation	Use of visor and shielding afforded by structures	Wait for blindness to pass or wait for rescue
Particle radiation	Avoid regions of high flux density	Withdrawal to craft
Micrometeorite flux	Use of shielding afforded by structures	Return to craft
Vacuum	Suit maintenance and checkout	Use of emergency oxygen system and-or crew rescue bag
Spacecraft discharge	Avoid attitude changes or jettisoning waste during EVA	Remove particles from face plate
Electrical potential	Provide electrical path among structures touched by astronaut Danger from this source has not been determined	(unknown)
Garment/Life Support		
Tears	Maintenance and checkout, short missions, avoid sharp objects, avoid narrow passages	Rescue if trapped, self-release to be avoided
Condensation on face plate	Short missions, frequent rest	Rest, wait for plate to clear, return to craft
Loss of communication	Check out communications frequently	Return to craft
Crew Morphology/Health		
Vertigo	*Avoid sudden movements, training*	*Rest or rescue*
Rapture	Selection and training	Rest, communication
Dissociation	Training	Activity, communication
Fatigue	Training, frequent rest	Rest, return to craft
Fear	Training, communication bio-monitoring, return if fear increases with time	Perform familiar activity, return to craft, communicate
Bends	Denitrogenation procedure, slow change in pressure	Increase pressure, then reduce pressure slowly
Heat exhaustion	Monitor physiological variables, short missions, rest	Rest
Nausea	Selection and training, diet control, avoidance of fatigue	Reschedule EVA so man not required (return to craft at first sympton)
Operating Procedures		
Tangle umbilical	Training, monitoring of procedure by standby astronaut	Stop movement, allow standby to free lines
Caught between moving structures	Communications with other crewmen, training, improve design to avoid EVA near moving structures	Rescue

SOURCE: Air Force Systems Command Design Handbook 1-G (5) and Compendium of Human Responses to the Aerospace Environment, Vol. II (51).

EXTRAVEHICULAR ENVIRONMENT

WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

The Experimental Study of Dynamic Effects of Crew Motion in a Manned Orbital Research Laboratory (MORL) was conducted by Douglas Aircraft Company, Inc., Missile and Space Systems Division, for the NASA Langley Research Center.

The four general categories of crew motion investigated were: (1) body segment motion, (2) exercise, (3) translation, and (4) console operation. The maximum, nominal, and minimum disturbance levels which could be achieved by the test subjects were recorded during the locomotion and console tasks. Only the nominal disturbance level was recorded during simulation of the various exercises and body segment motions. The body segment motions investigated included single pendulum arm motion, double pendulum arm motion, head motion, waist bending, and leg motion. The exercises simulated included trunk bending, neck bending, rowing, pedal ergometer, oscillating acceleration, trunk rotation, and full-length body exercise. Translation involved the investigation of free soaring, guided soaring, velcro walking, and compression walking. Console operation was limited to torquing, sliding, and push-pull operations.

The zero-g simulation technique used consisted of a counterbalanced pendulous support of the test subject. The suspended subject performs the selected crew motions while in contact with an instrumented platform. The crew motions performed on the platform produce forces and moments which are transmitted through the platform to a six-component force balance. This force balance transforms the three orthogonal forces and three orthogonal moments induced by the subject into electrical signals. These signals are transmitted to the data reduction system which transforms the electrical signals into tabulated data, plotted data, and an analytical expression defining the best fit curve to the plotted data.

After the simulation scheme was selected, the simulation hardware was designed and fabricated. This hardware consists of a velcro walk strip, velcro shoes, foot restraint, hand rails, full-length body exercise machine, pedal ergometer, compression walking simulator, waist restraint, and a control console.

The experimental test program was initiated following fabrication of the simulation equipment. Two subjects were selected to perform the crew motions. Each crew motion was performed three times by each subject.

SOURCE: Fuhrmeister and Fawler (68).

EXTRAVEHICULAR ENVIRONMENT

WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

The following symbols and subscripts are used in association with the graphs contained in this section (Weightlessness).

SUBSCRIPTS		SYMBOLS	
i	along i axis	F	force, pounds
x	along x axis	I	moment of inertia, slug-ft^2
y	along y axis	L	pendulum arm length, ft.
z	along z axis	M	moment, lb-ft
n_i	hinge axis parallel to the i axis	t	time, seconds
		W	weight, pounds
n_x	hinge axis parallel to the x axis	x, y, z	rectangular Cartesian coordinates
n_y	hinge axis parallel to the y axis	δ	pendulum displacement, ft
n_z	hinge axis parallel to the z axis	θ	angular displacement x-y plate, radians
LAL	left arm, lower	ϕ	angular displacement y-z plane, radians
LAU	left arm, upper		
LLL	left leg, lower	$\dot{\theta}$	angular rate x-y plane, radians per second
LLU	left leg, upper	$\ddot{\theta}$	angular acceleration x-y plane, radians per second^2
T	trunk		
RAL	right arm, lower		
RAU	right arm, upper		
RLL	right leg, lower		
RLU	right leg, upper		

SOURCE: Fuhrmeister and Fawler (68).

EXTRAVEHICULAR ENVIRONMENT

WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

a. Crew Motion Range of Disturbances

MOTION	STANDING SURFACE PEAK DISTURBANCE RANGE (LB.)
Single Pendulum Arm Motion	2.6 to 3
Double Pendulum Arm Motion	3.2 to 4
Leg Motion	4 to 7.6
Bending at Waist	8 to 9
Console Operation	3 to 13
Guided Locomotion	6 to 50
Velcro Walking	10 to 50
Compression Walking	10 to 74
Free Soaring	30 to 350
Pedal Ergometer Exercise	19 to 20
Trunk Bending Exercise	13 to 33
Full Length Body Exercise	40 to 62
Oscillating Acceleration Exercise	98 to 110

The test results indicate that for MORL fine pointing requirements, the crew member may have to be isolated from the spacecraft. THis would be accomplished with vibration isolators between the astronaut and the spacecraft to reduce the disturbance transmitted to the spacecraft.

Similar crew motion tests should be conducted for the subject wearing a space suit. This study would simulate the extravehicular activity (EVA) and would be valuable for use in the orbital astronaomy support facility program.

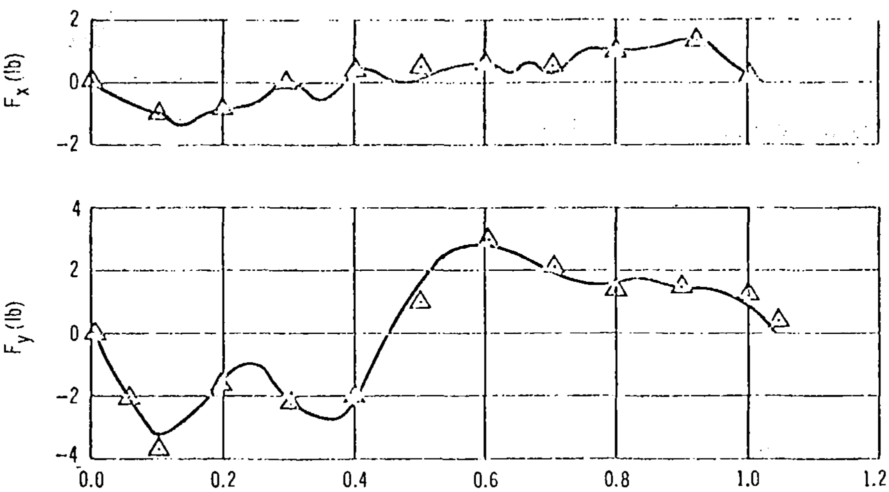
SOURCE: Fuhrmeister and Fawler (68).

EXTRAVEHICULAR ENVIRONMENT

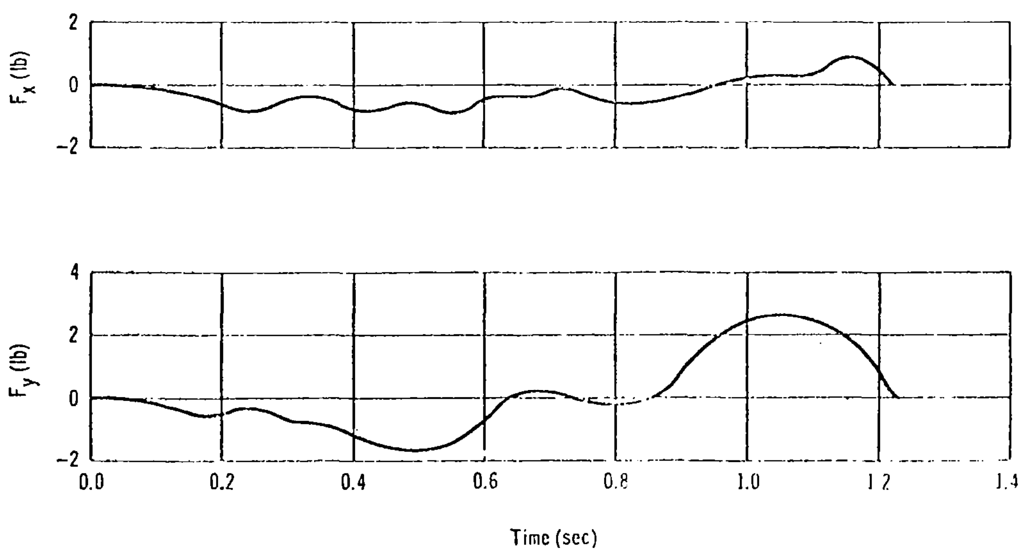
WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

b. Single Pendulum Arm Motion Disturbance Profile - Subject A



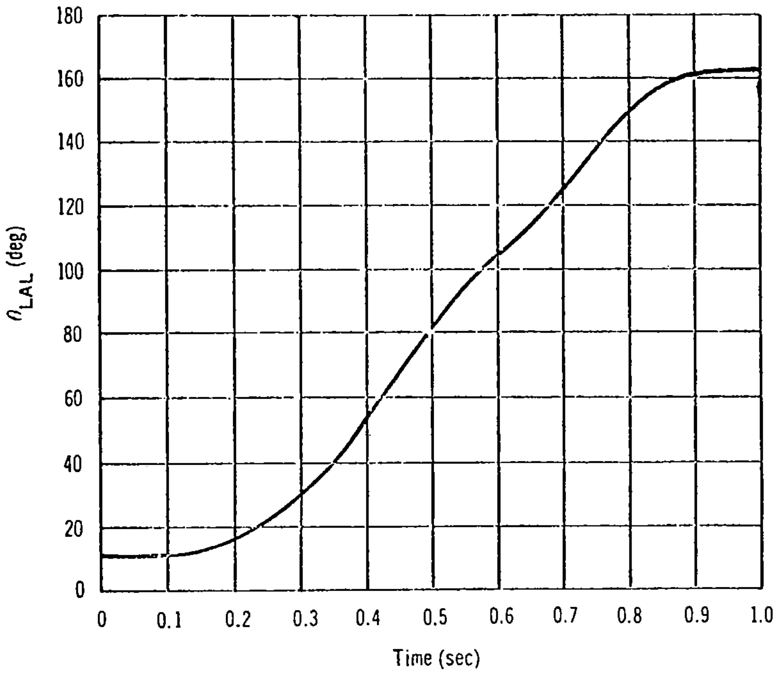
c. Single Pendulum Arm Motion Disturbance Profile - Subject B



SOURCE: Fuhrmeister and Fawler (68).

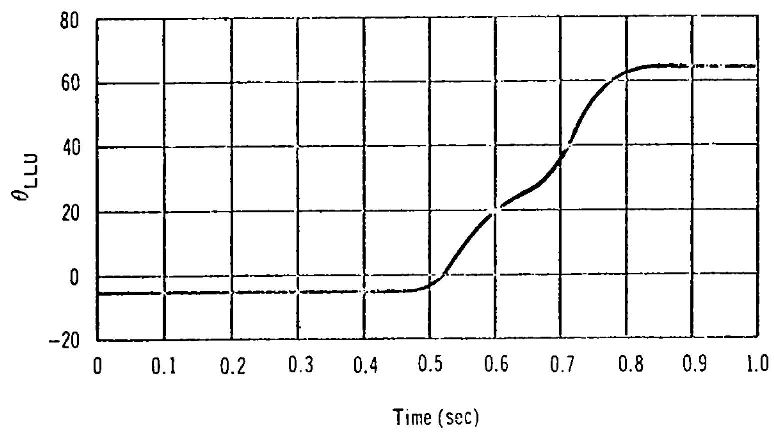
EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

d. Double Pendulum Arm Motion Euler Angles



CONSTANT ANGLES

$\theta_T = 174°$
$\theta_{LLU} = 4°$
$\theta_{LLL} = 4°$
$\theta_{RAU} = 0°$
$\theta_{RAL} = 4°$
$\theta_{RLU} = 4°$
$\theta_{RLL} = 4°$



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

The following rate profiles of the upper and lower arm are obtained from Figure d above.

(1) Lower Arm

$\theta_{LAL} = 10°$ for $t = 0$

$\ddot{\theta}_{LAL} = 20.6$ rad/sec^2 for $0.12 \leq t \leq 0.32$ sec

$\dot{\theta}_{LAL} = 4.14$ rad/sec for $0.32 < t \leq 0.8$ sec

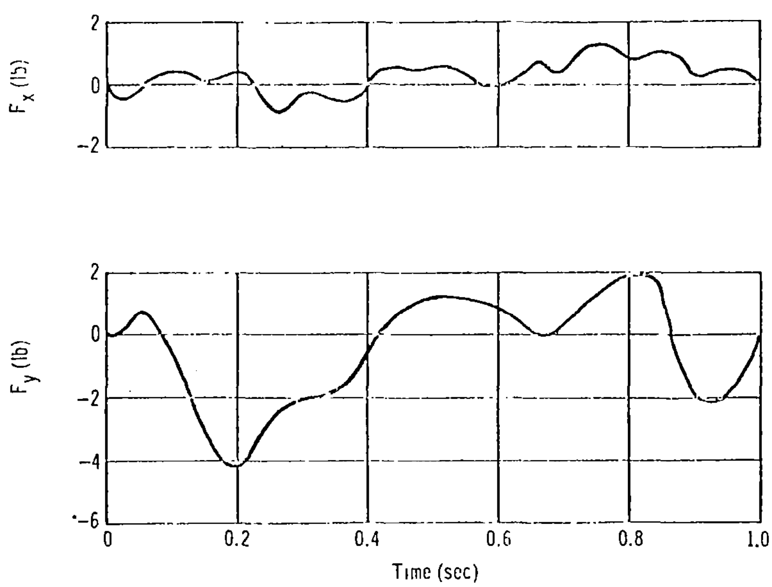
$\ddot{\theta}_{LAL} = -34.3$ rad/sec^2 for $0.8 < t \leq 0.92$ sec

(2) Upper Arm

$\theta_{LAU} = -6°$ for $t = 0$

$\ddot{\theta}_{LAU} = 50$ rad/sec^2 for $0.45 \leq t \leq 0.53$ sec

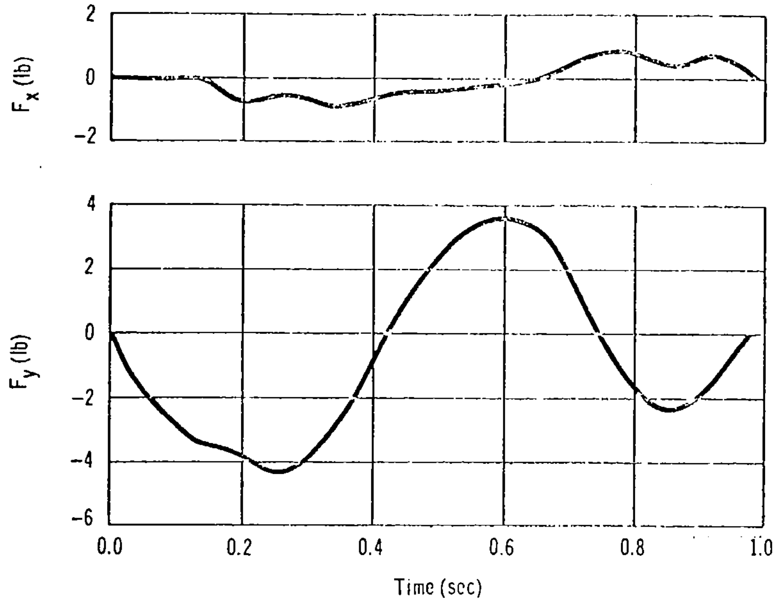
e. Double Pendulum Arm Motion Disturbance Profile - Subject A



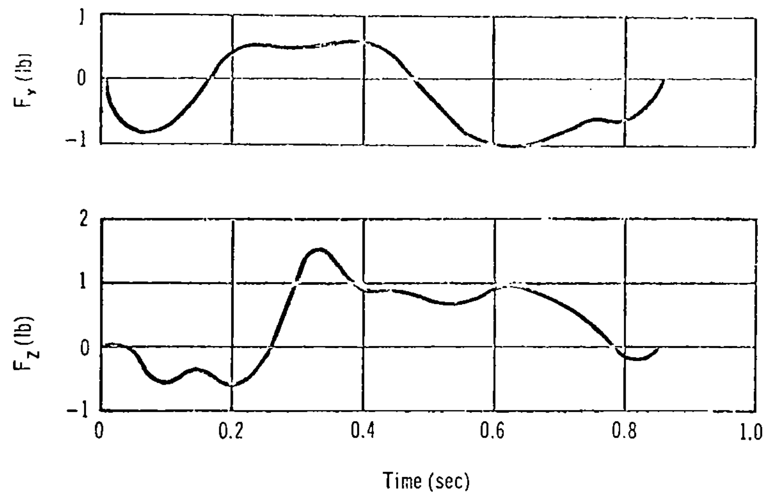
SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

f. Double Pendulum Arm Motion Disturbance Profile - Subject B



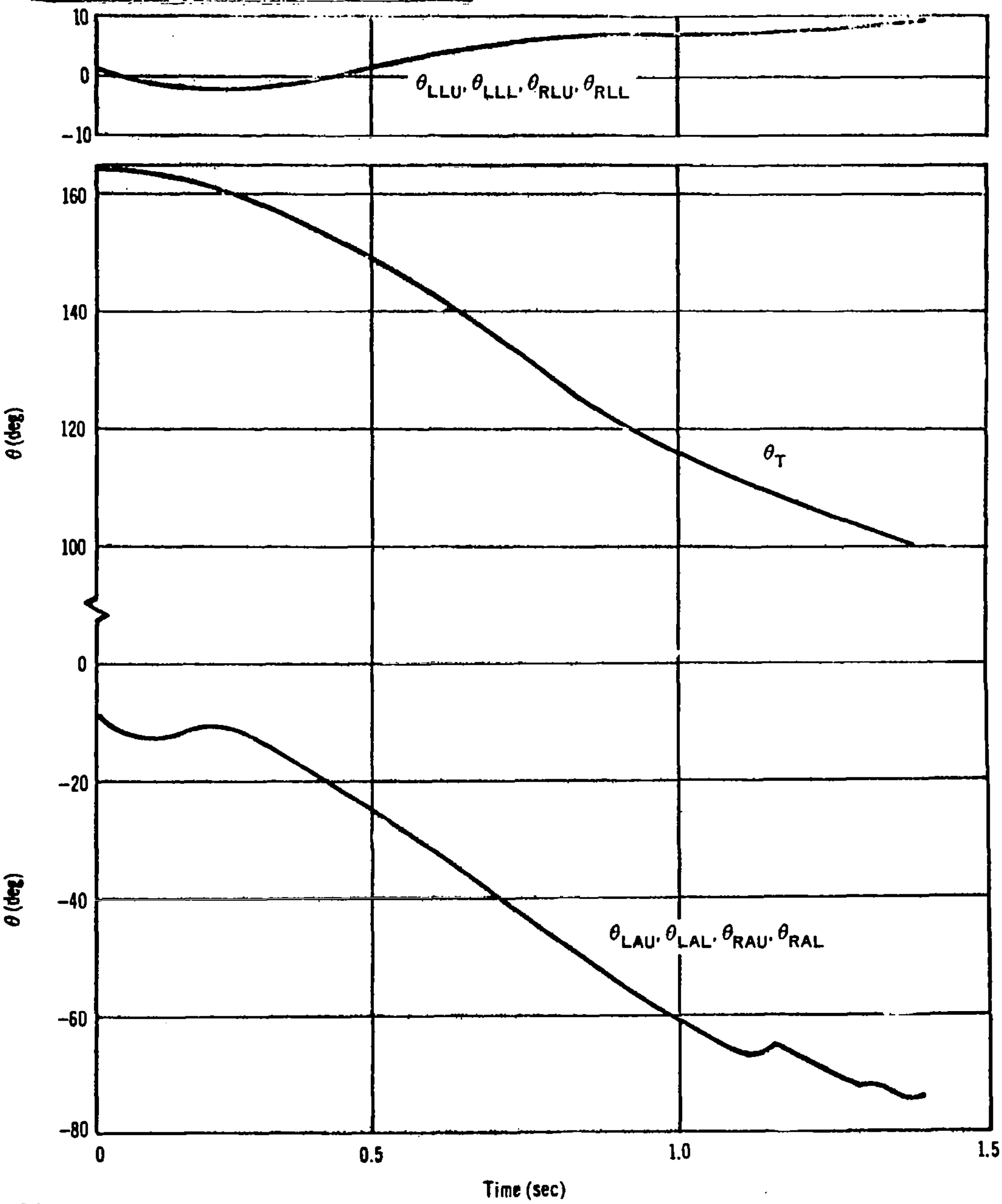
g. Head Motion Disturbance Profiles



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

h. Bending at Waist Euler Angles



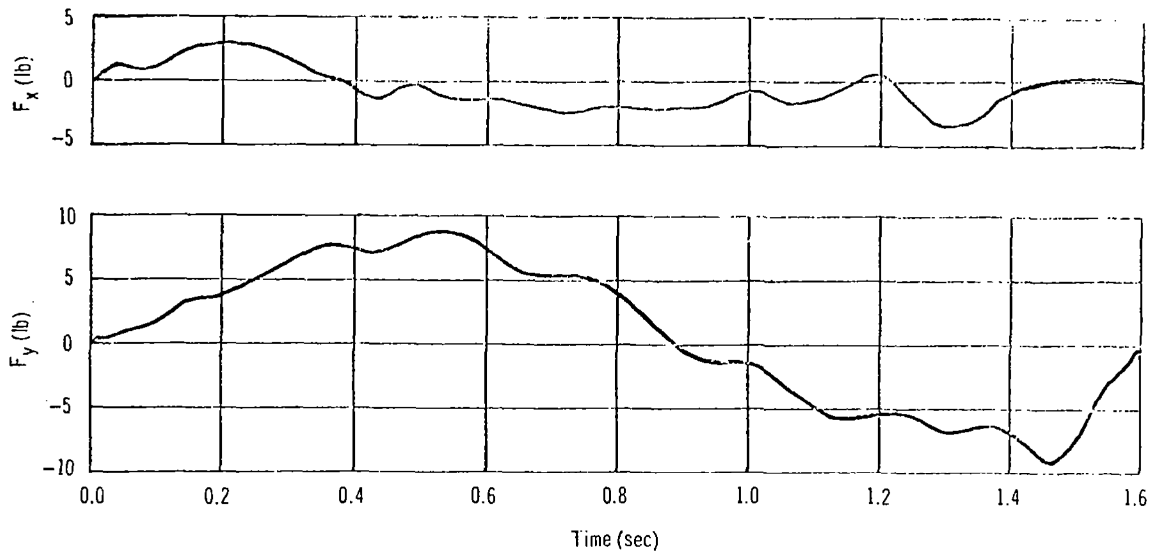
SOURCE: Fuhrmeister and Fawler (68).

EXTRAVEHICULAR ENVIRONMENT

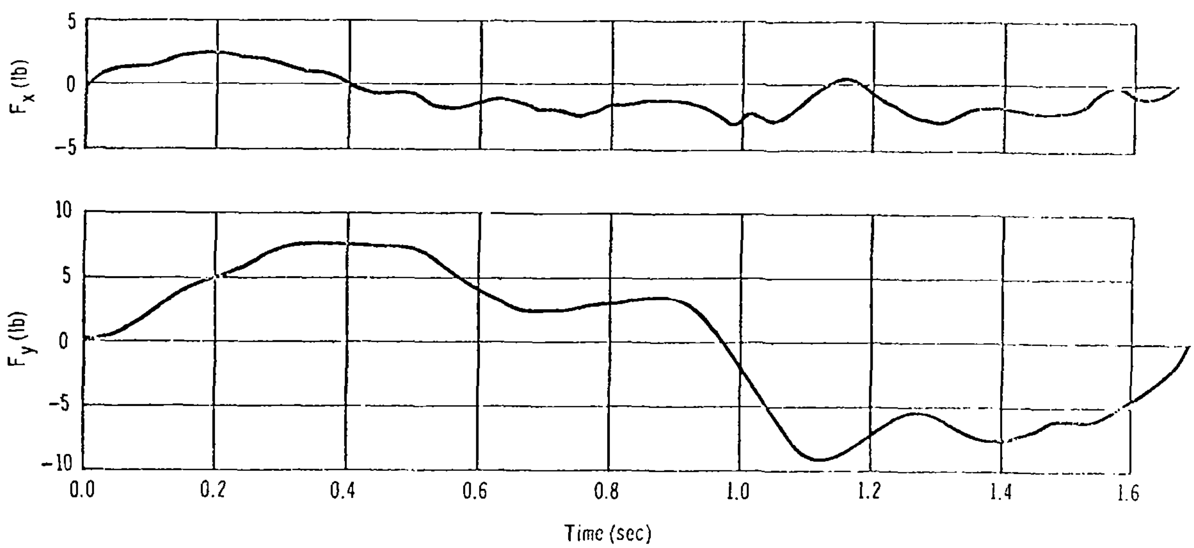
WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

i. Bending at Waist Disturbance Profiles - Subject A



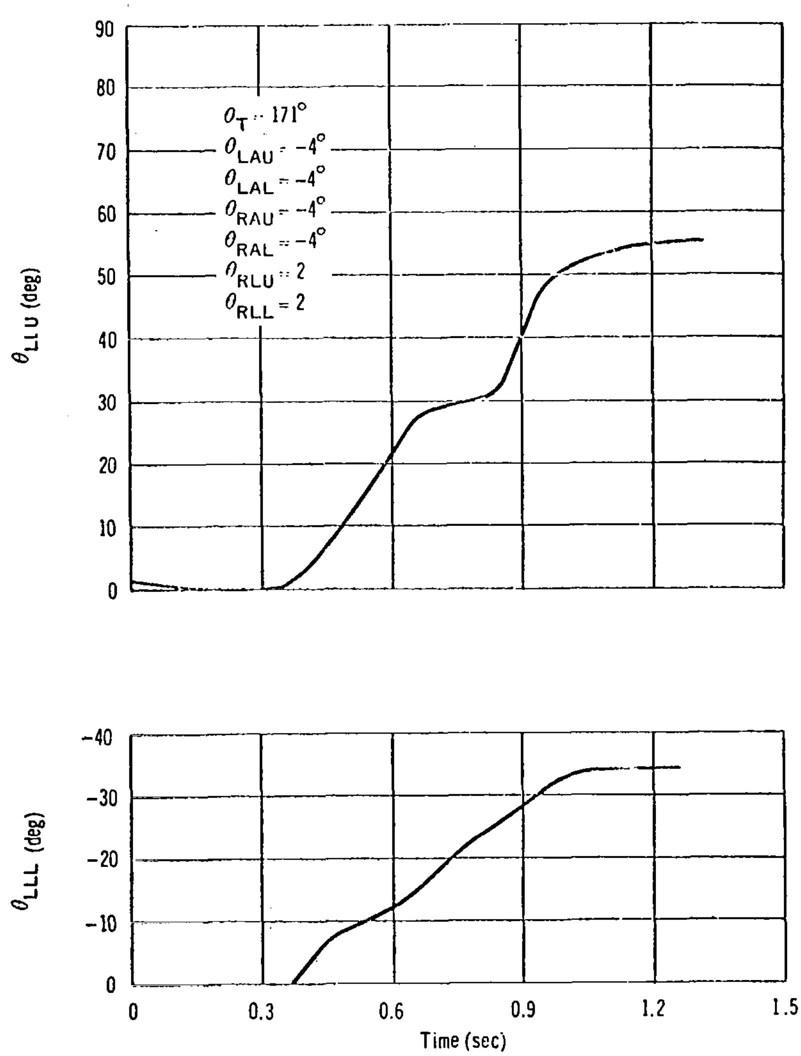
j. Bending at Waist Disturbance Profiles - Subject B



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

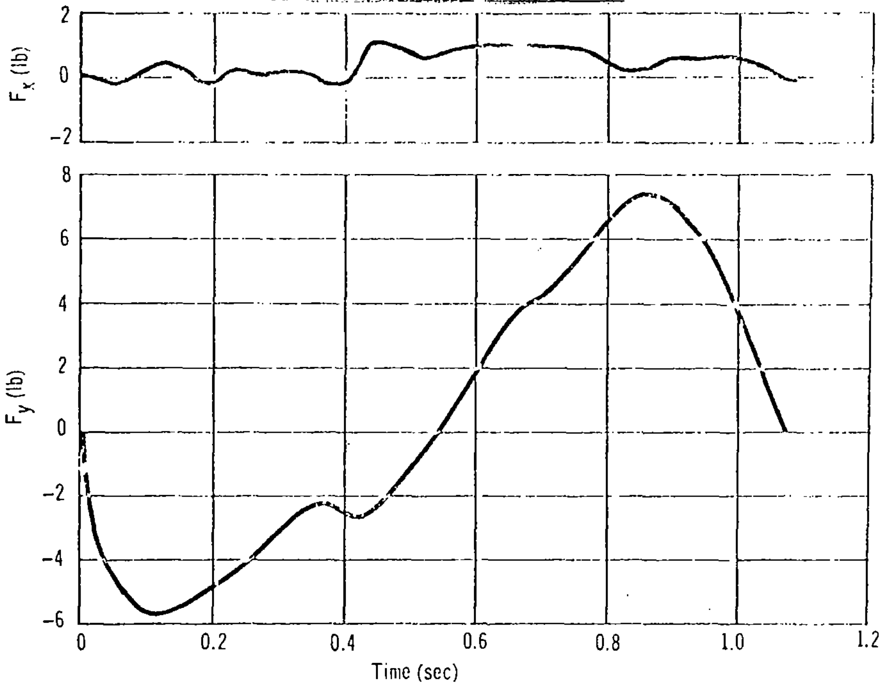
k. Leg Motion Euler Angles



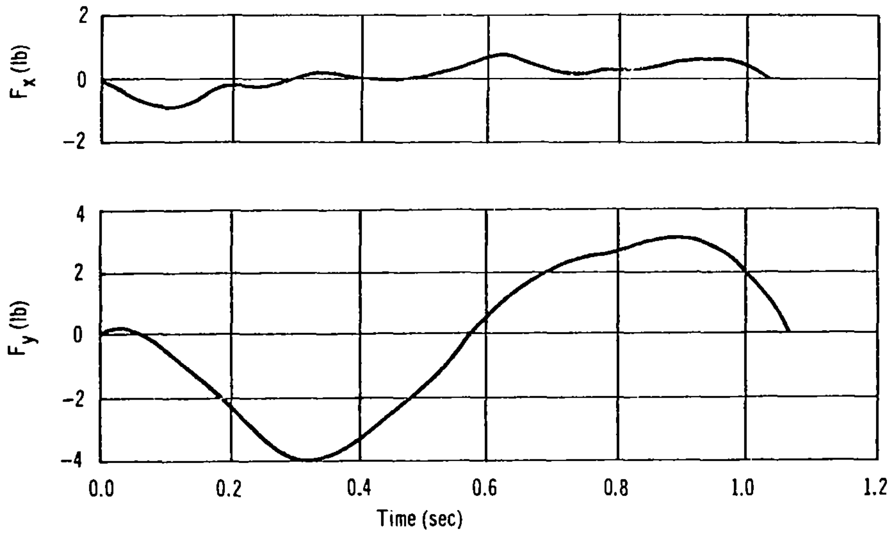
SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

l. Leg Motion Disturbance Profiles - Subject A



m. Leg Motion Disturbance Profiles - Subject B

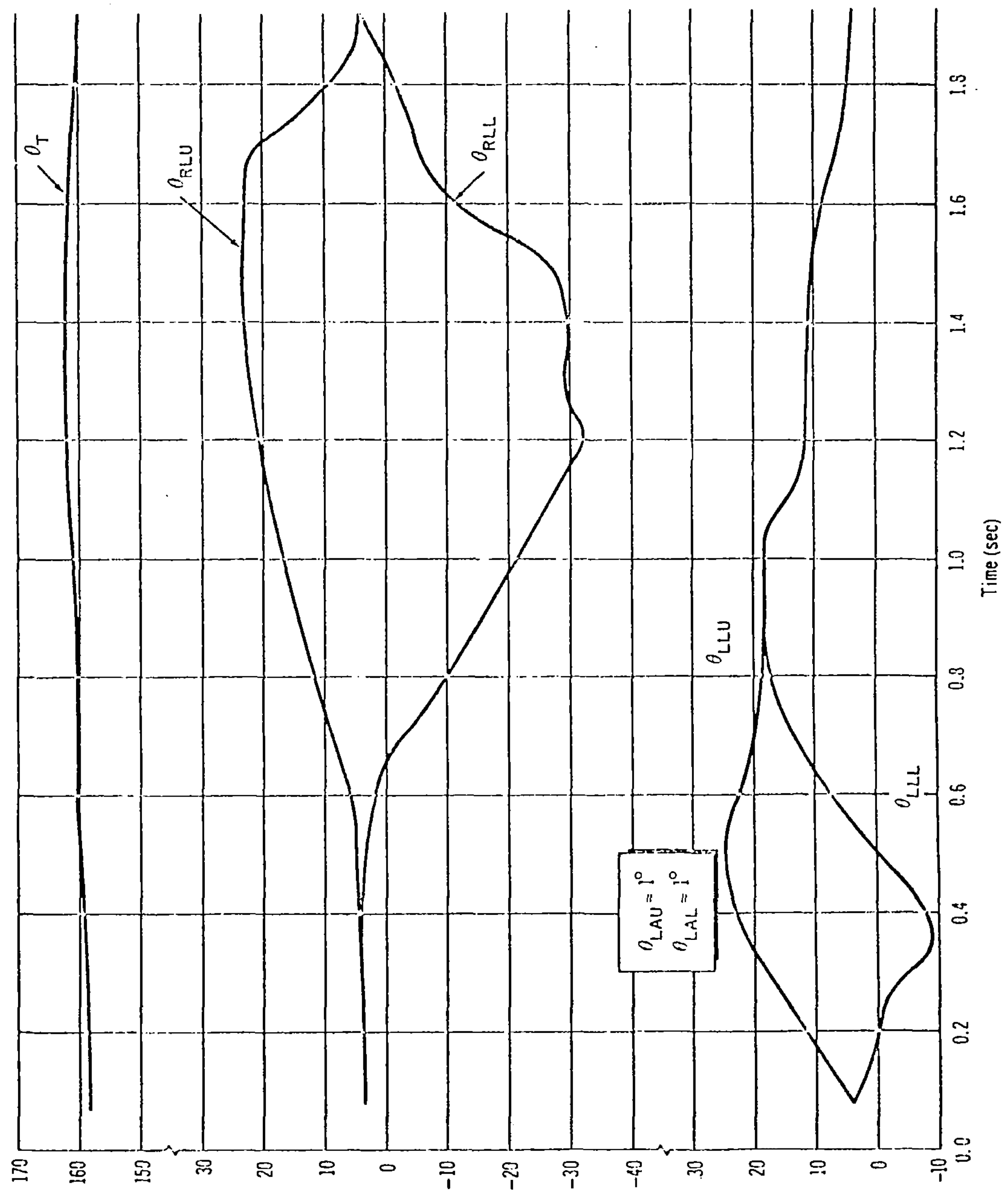


SOURCE: Fuhrmeister and Fawler (68).

EXTRAVEHICULAR ENVIRONMENT

WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

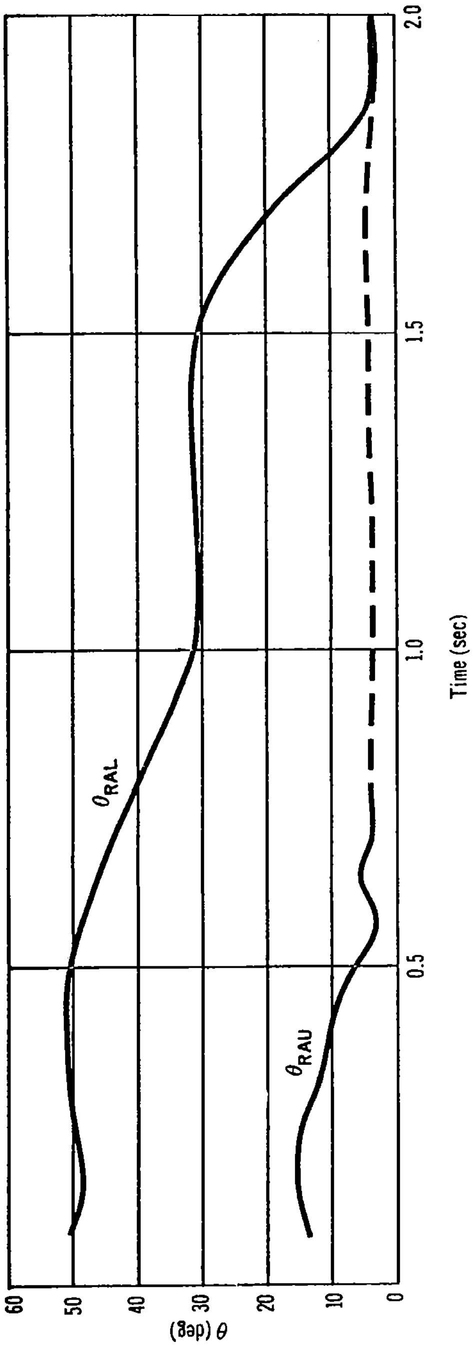


n. Velcro Walking Euler Angles

SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

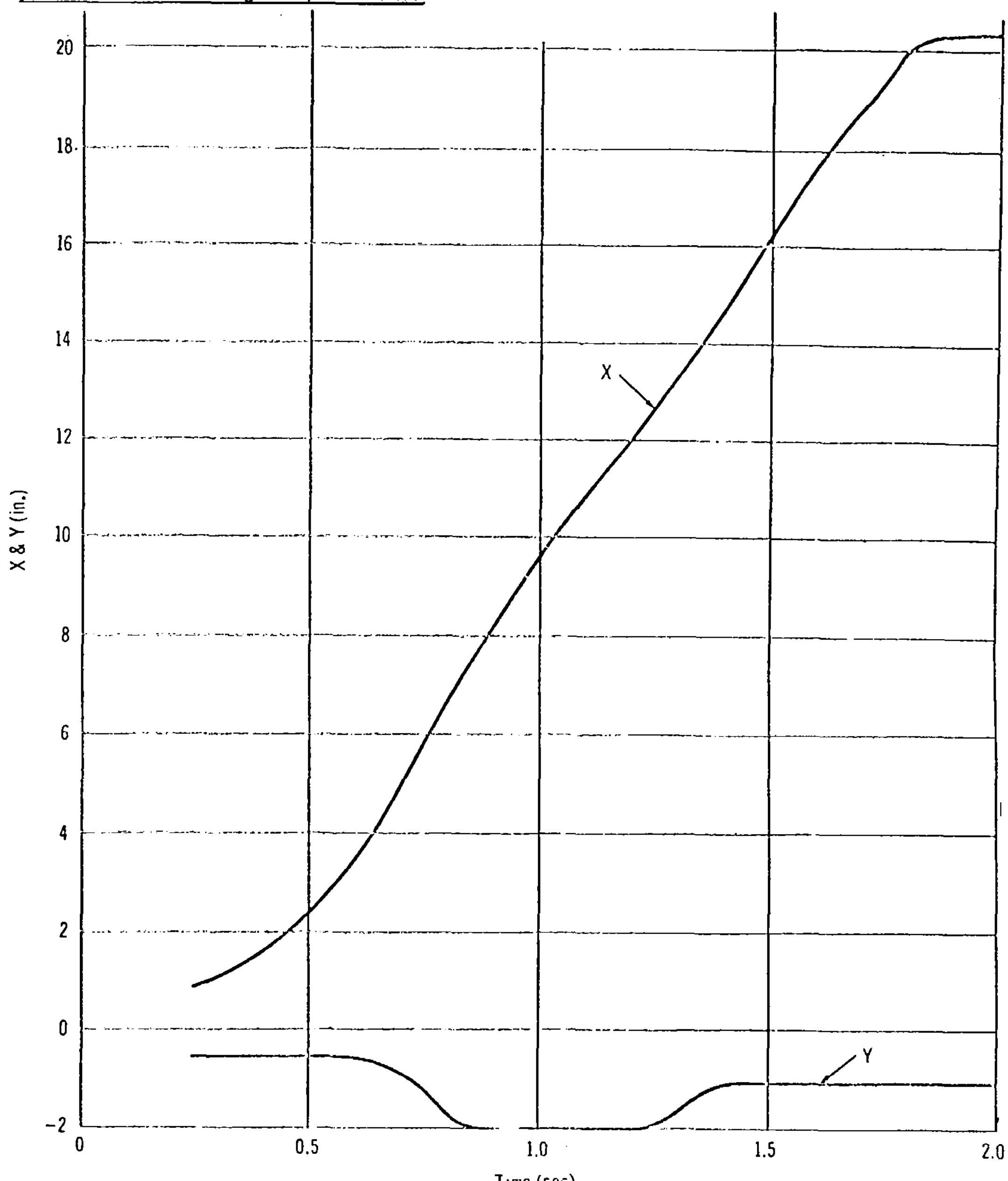
o. Velcro Walking Euler Angles



SOURCE: Fuhrmeister and Fawler (68).

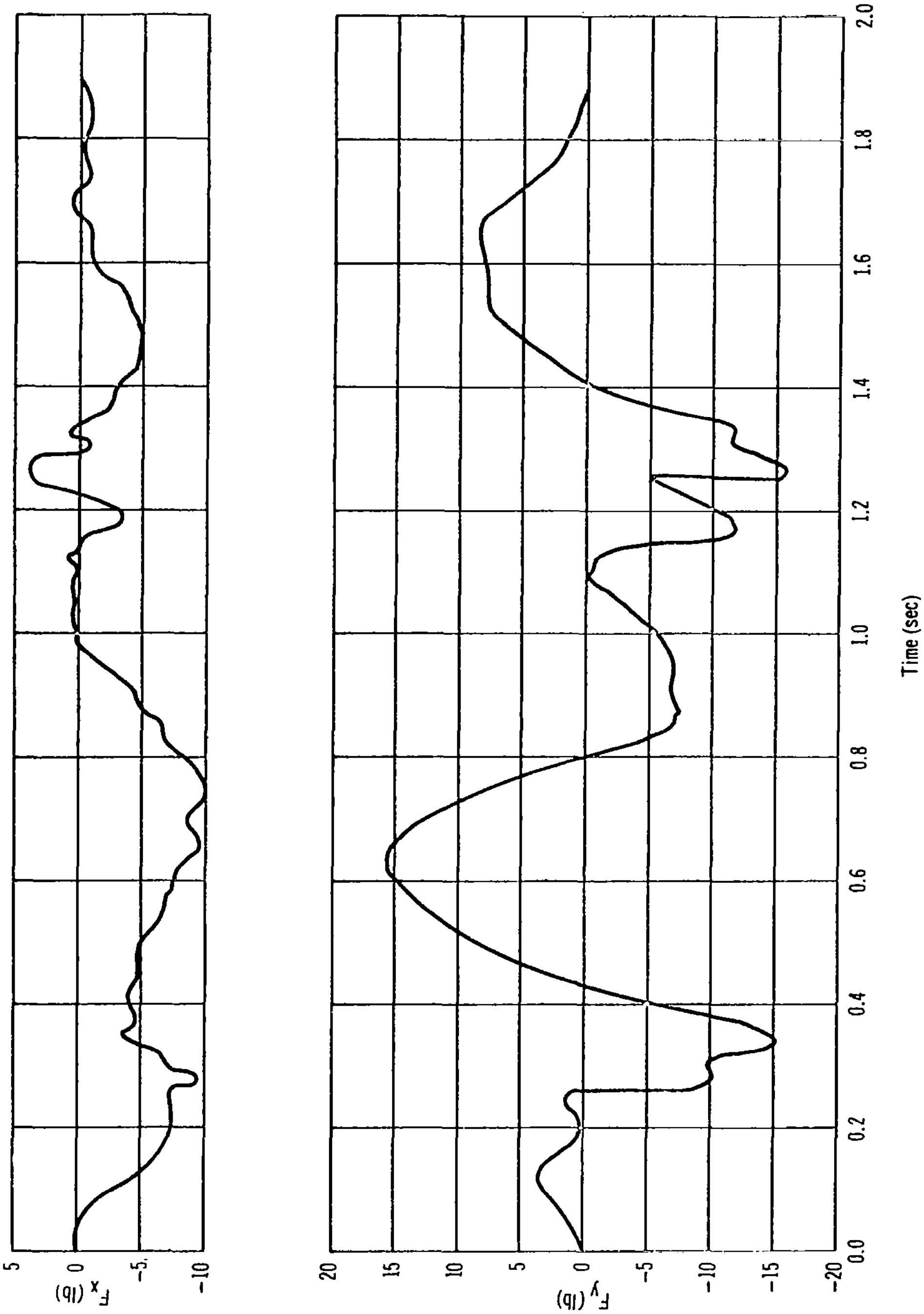
EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

p. Velcro Walking Displacement



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

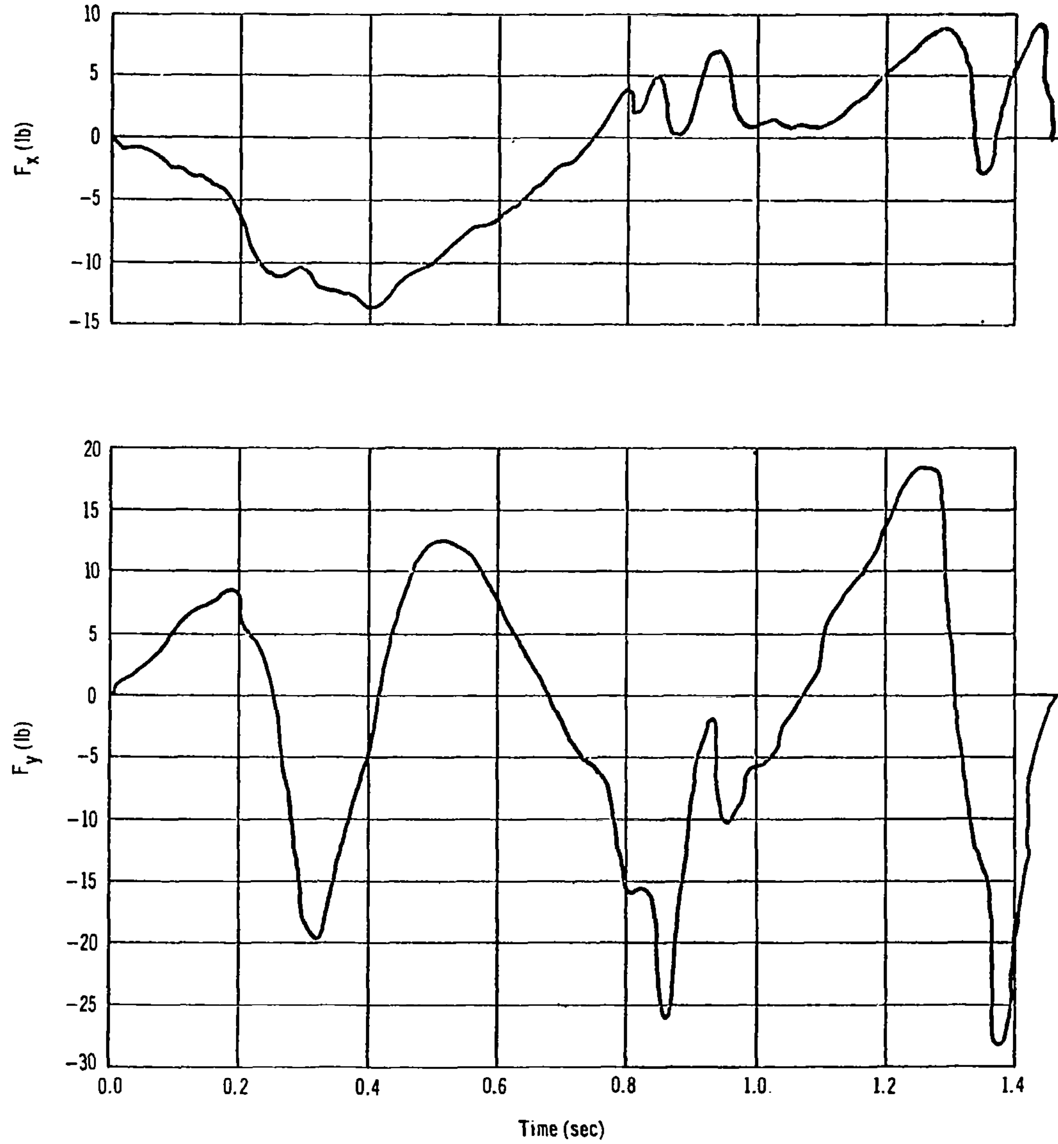


g. Velcro Walking Nominal Disturbance Profile - Subject A

SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

r. Velcro Walking Nominal Disturbance Profile - Subject B

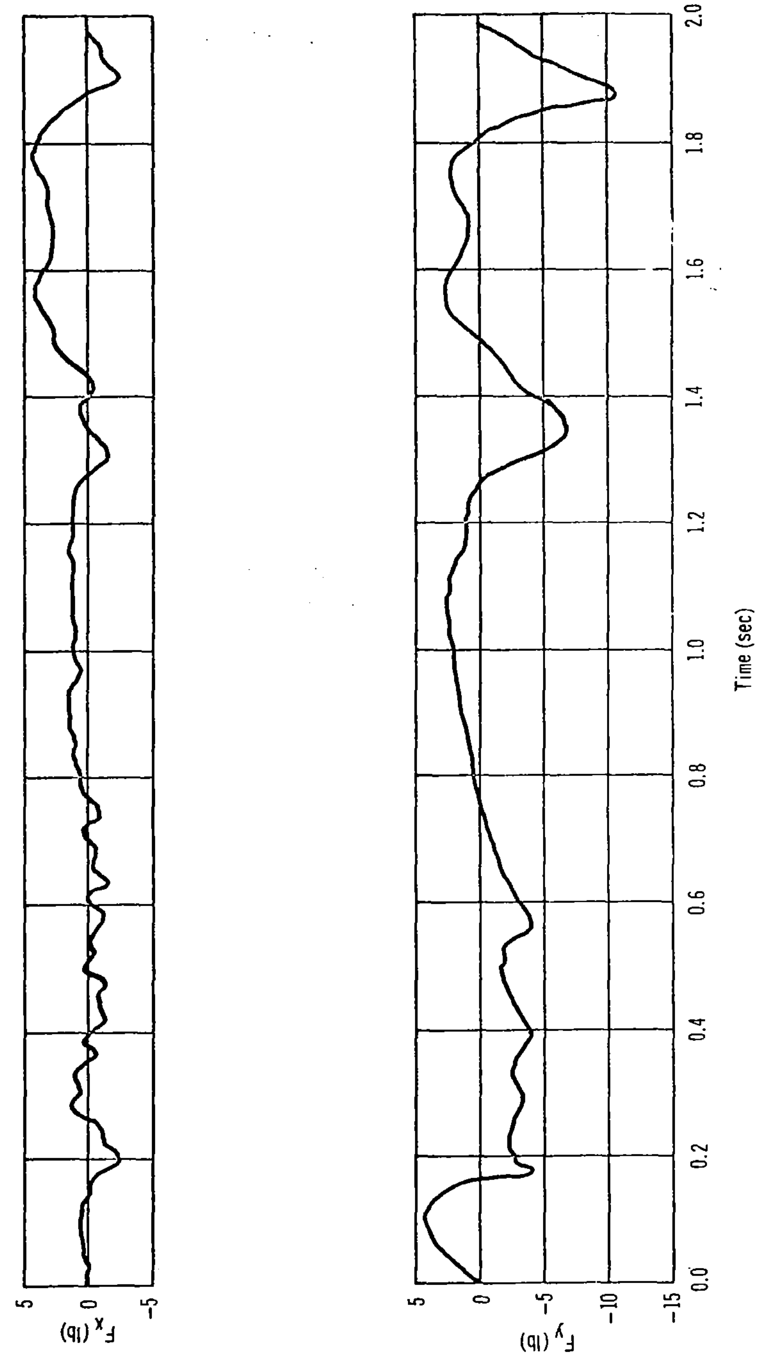


SOURCE: Fuhrmeister and Fawler (68).

EXTRAVEHICULAR ENVIRONMENT

WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT



s. Velcro Walking Minimum Disturbance Profile - Subject A

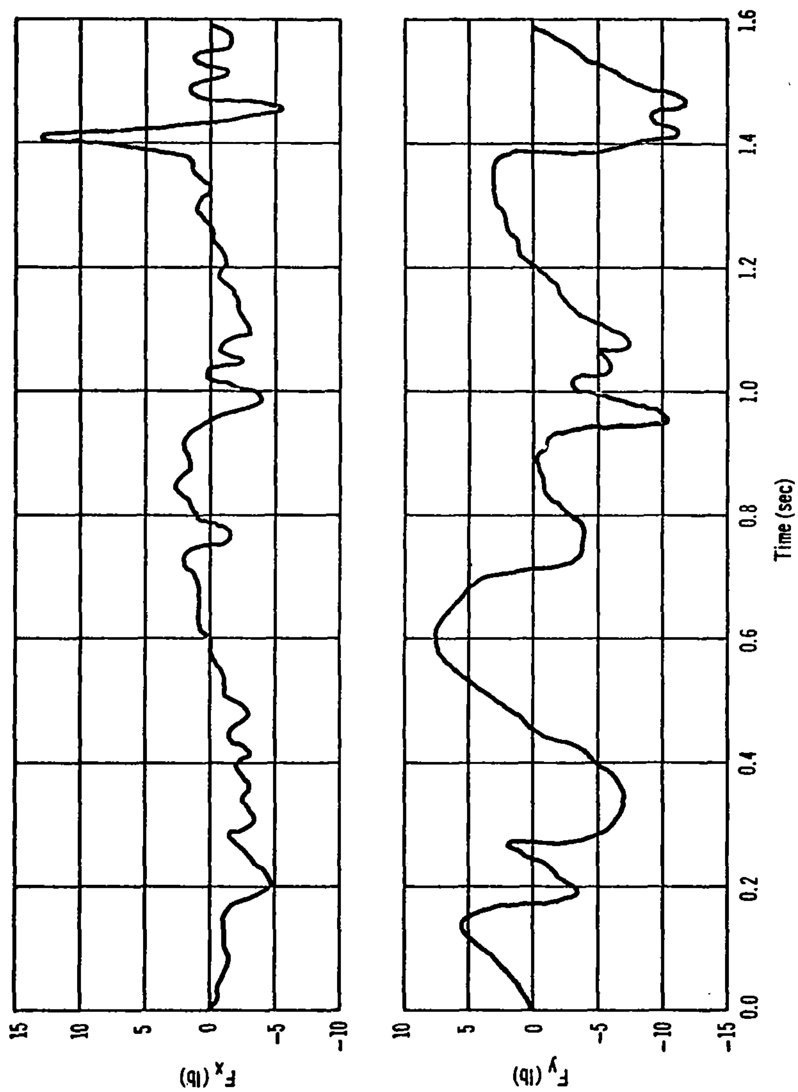
SOURCE: Fuhrmeister and Fawler (68).

EXTRAVEHICULAR ENVIRONMENT

WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

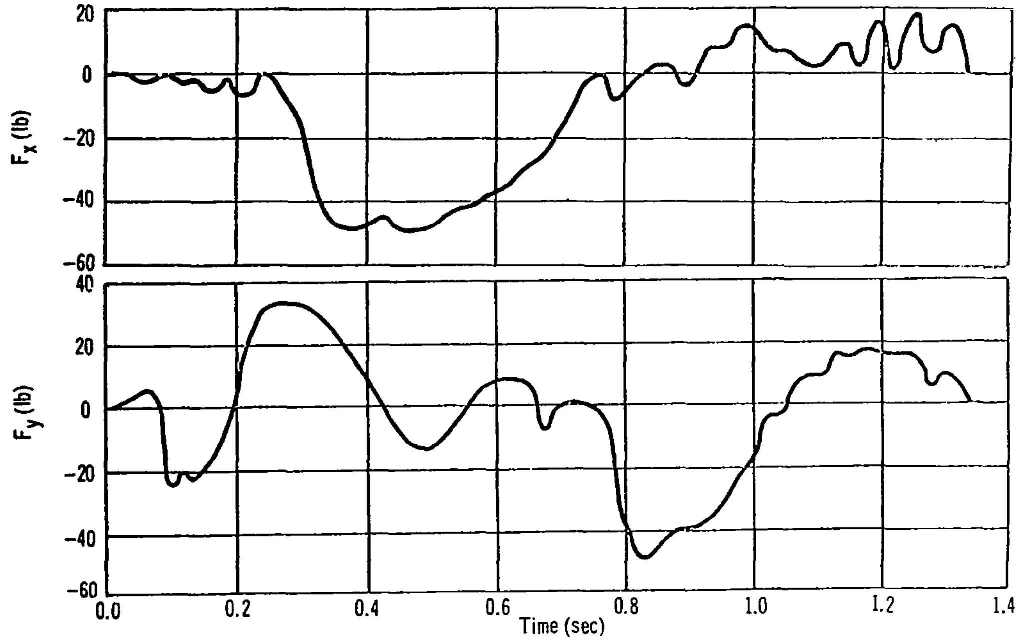
t. Velcro Walking Minimum Disturbance Profile - Subject B



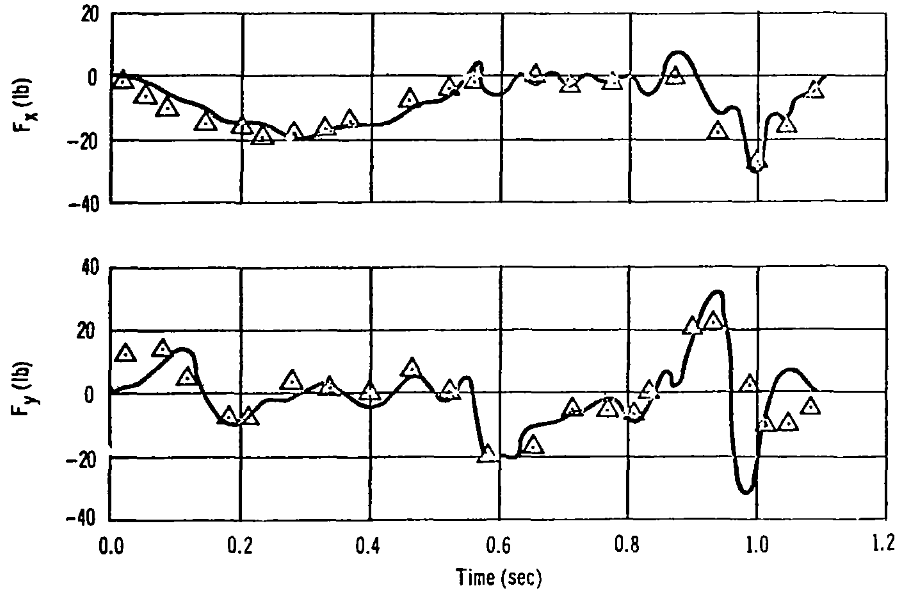
SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

u. Velcro Walking Maximum Disturbance Profile - Subject A



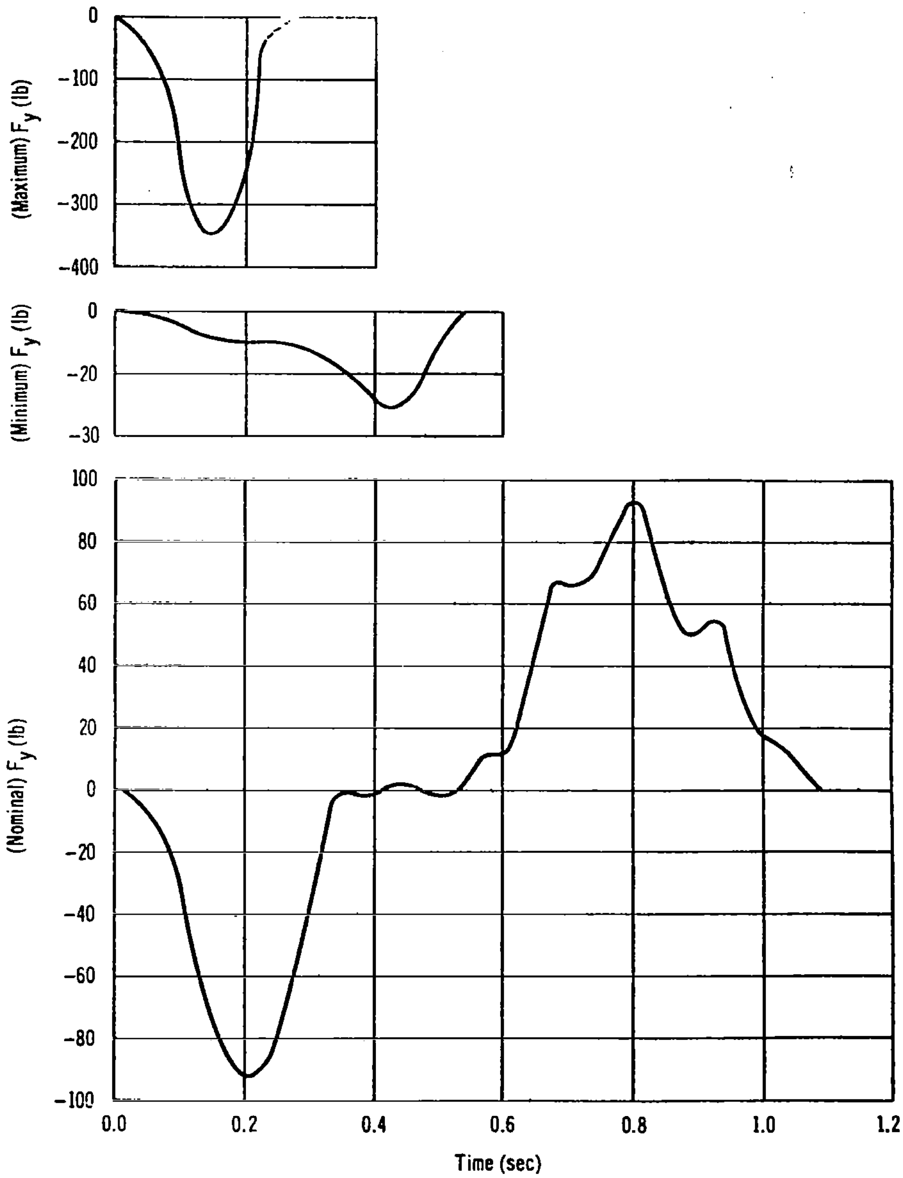
v. Velcro Walking Maximum Disturbance Profile - Subject B



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

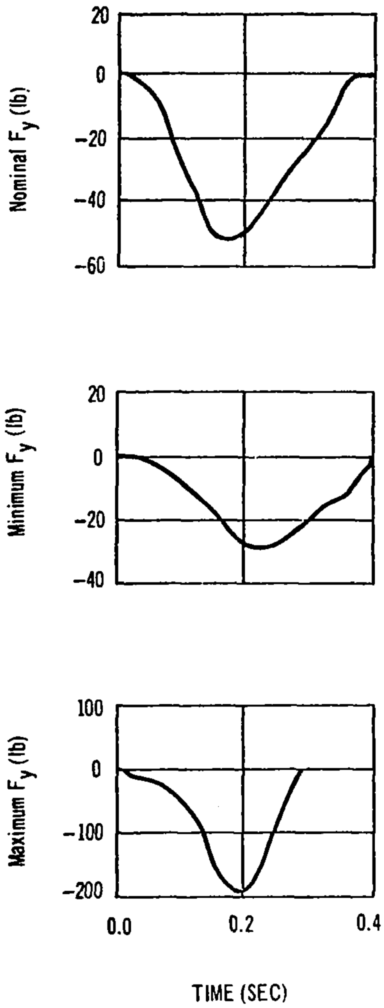
w. Free-Soaring Disturbance Profiles - Subject A



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

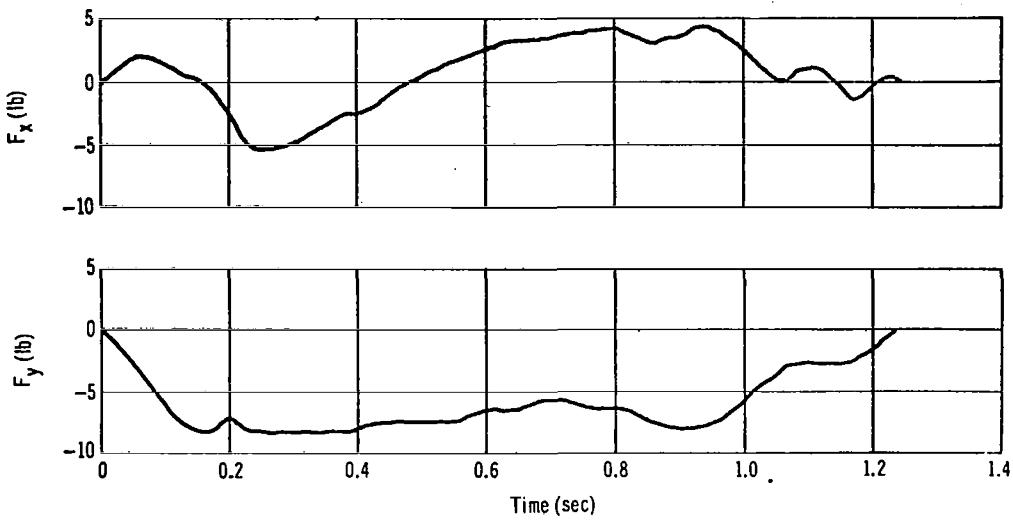
x. Free-Soaring Disturbance Profiles - Subject B



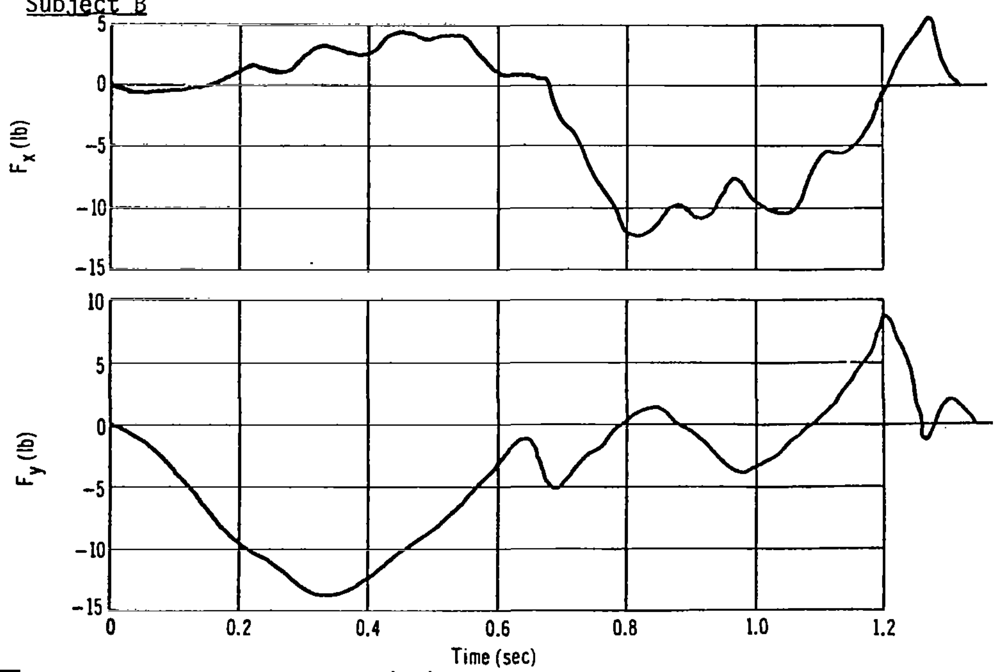
SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

y. Guided Locomotion Normal to Force Table Nominal Disturbance Profile - Subject A

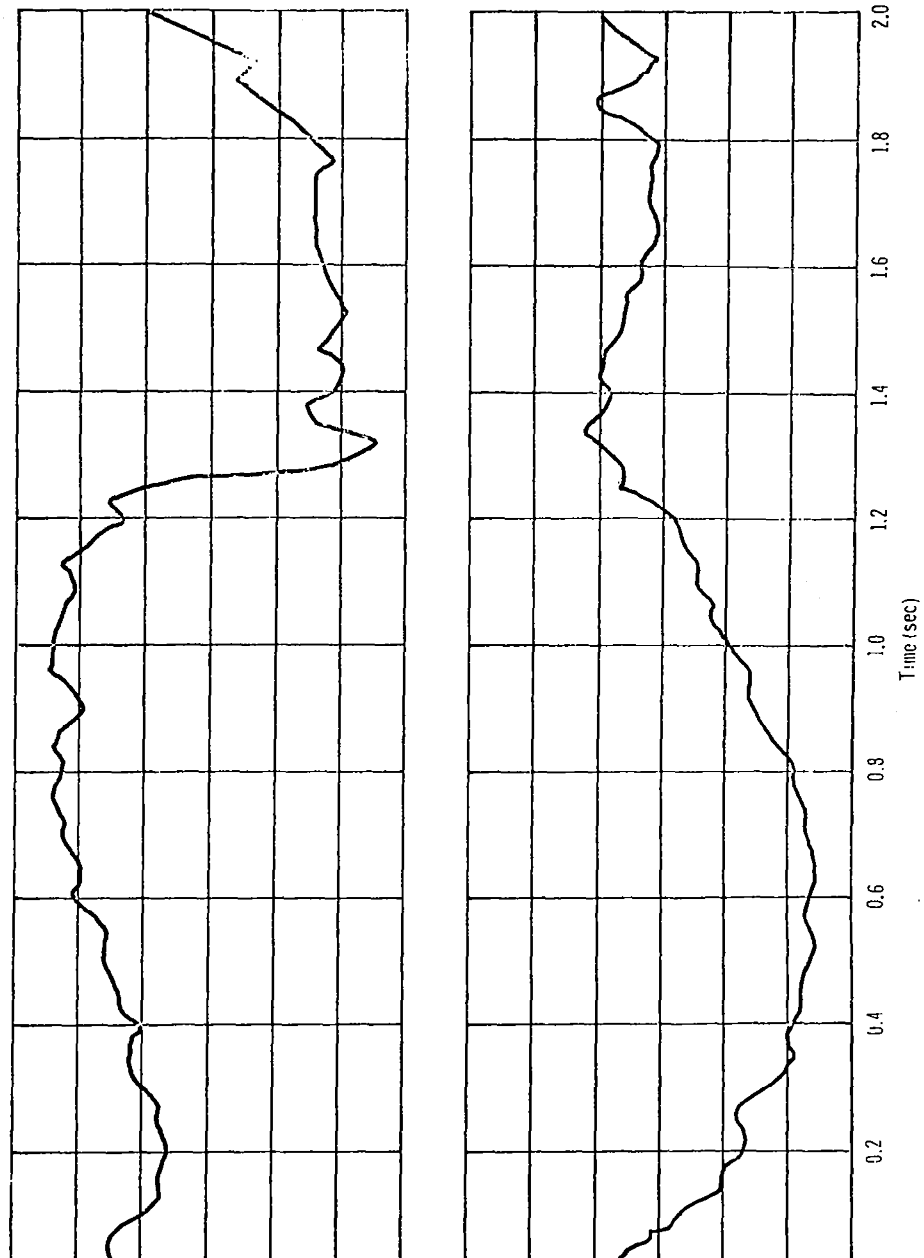


z. Guided Locomotion Normal to Force Table Nominal Disturbance Profile - Subject B



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

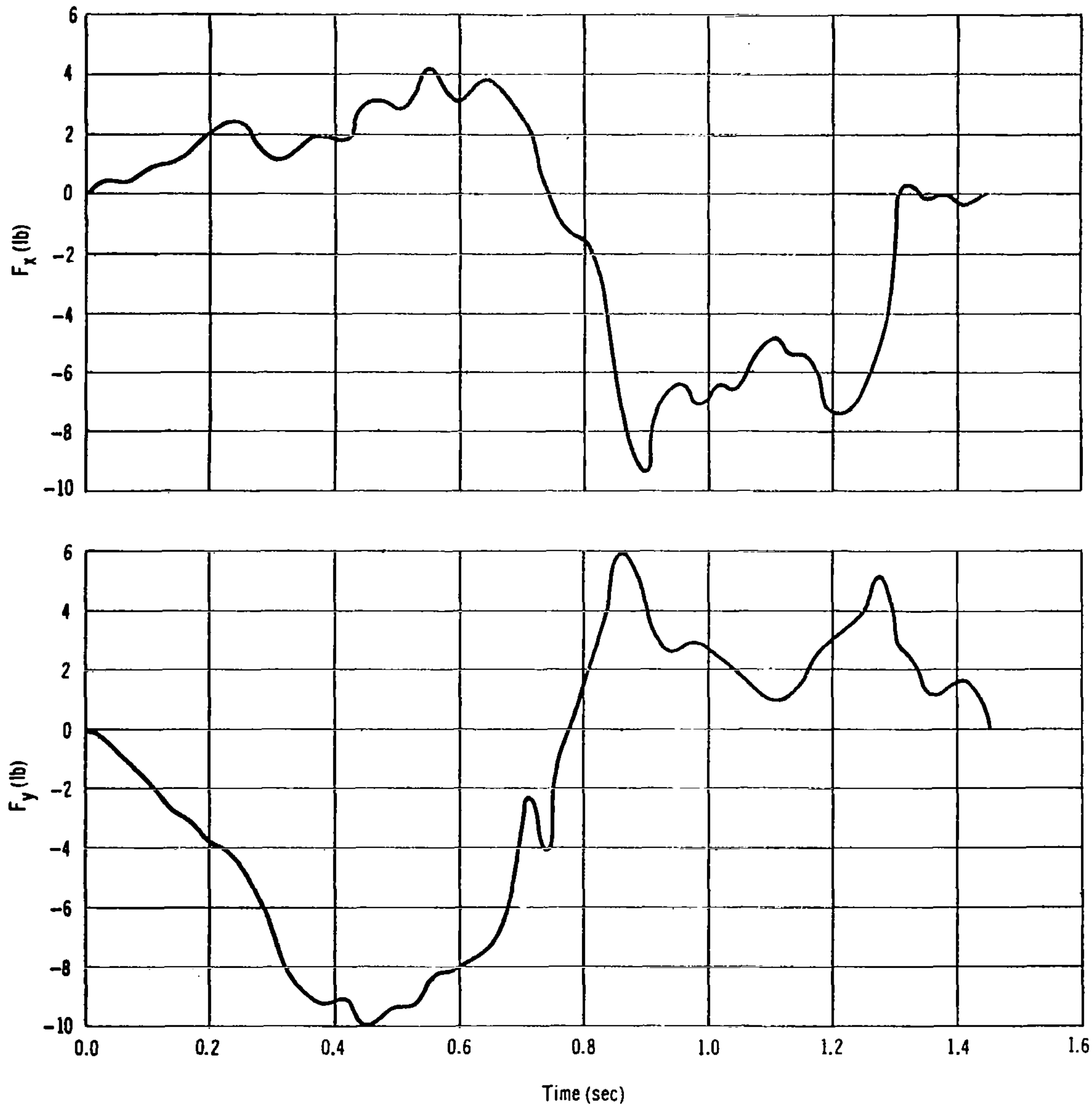


aa. Locomotion Normal to Force Table Minimum Disturbance Profile - Subject A

SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

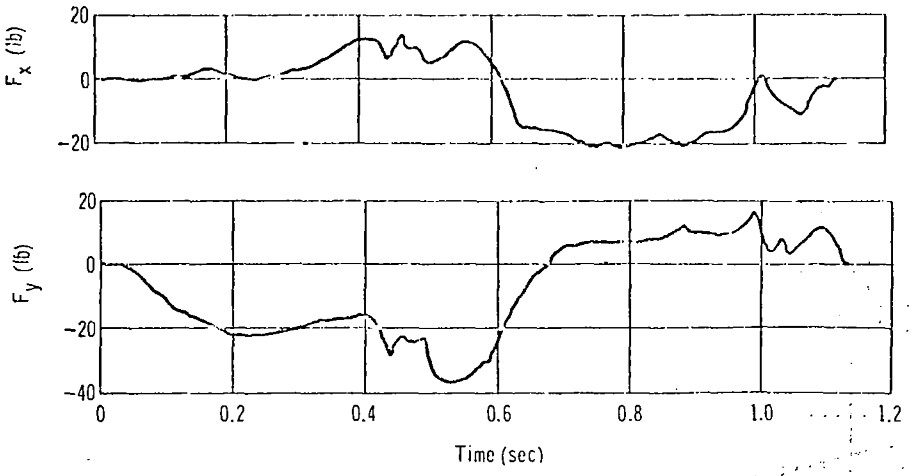
ab. Locomotion Normal to Force Table Minimum Disturbance Profile - Subject B



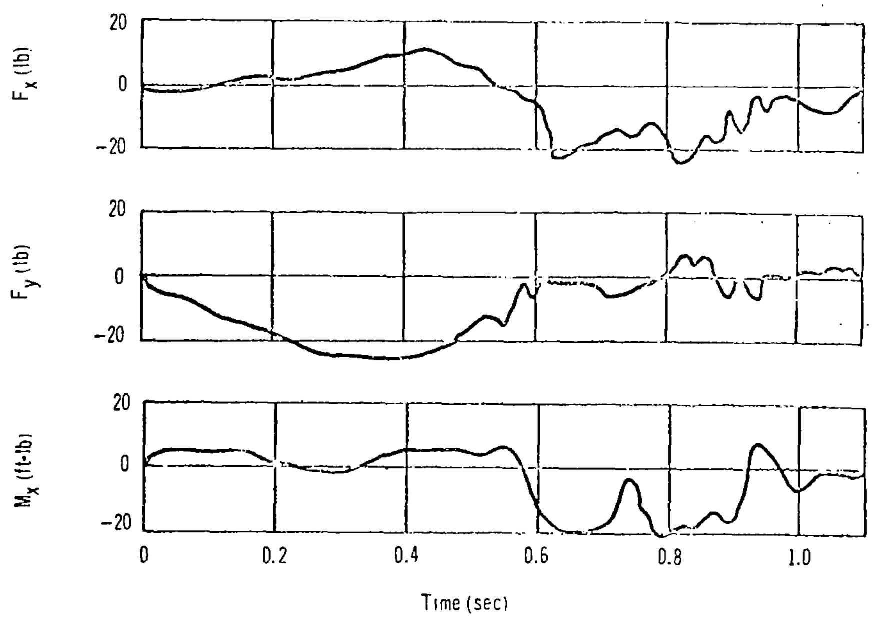
SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

ac. Guided Locomotion Normal to Force Table Maximum Disturbance Profile - Subject A



ad. Guided Locomotion Normal to Force Table Maximum Disturbance Profile - Subject B



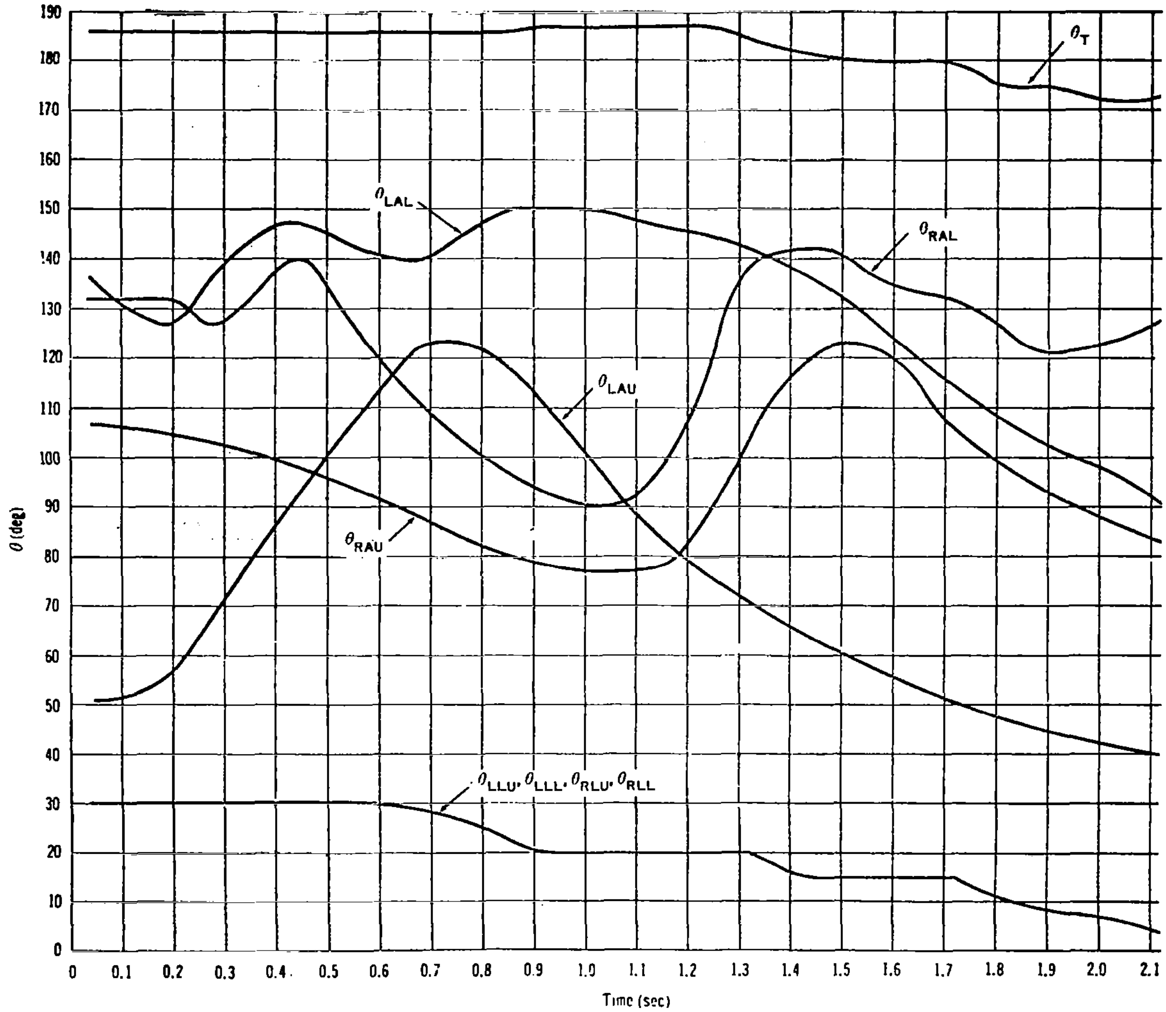
SOURCE: Fuhrmeister and Fawler (68).

EXTRAVEHICULAR ENVIRONMENT

WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

ae. Guided Locomotion Parallel to Force Table Euler Angles



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

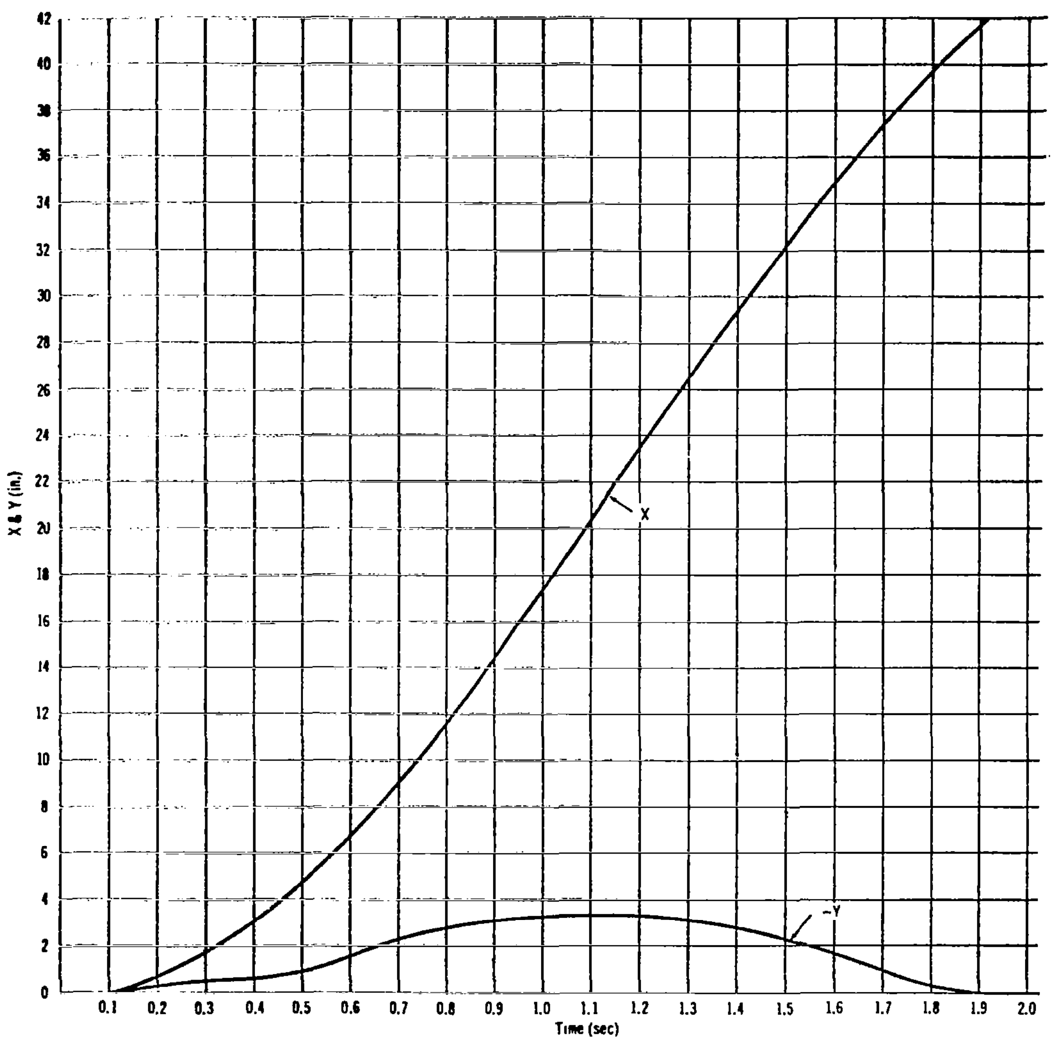
Figure af is the time history of the linear displacement of the subject for this locomotion. The subject translated nearly 4 ft. parallel to the platform, keeping his head at a nearly constant distance away from it. The velocity of the motion is obtained by computing the slope of the x displacement, which is found to be approximately 2.5 ft/sec and is fairly constant throughout most of the test. The subject here performs a smooth motion for this locomotion test.

The nominal level of intensity is shown in figs. ag and ah for Subjects A and B, respectively. In this locomotion test, as in velcro walking, the x component of force contains the gravity component of the pendulum support. It was pointed out previously that for equal deflections about the static position of the pendulum support, the component of force resulting from gravity can be eliminated by superimposing the curve of W sin σ/L for the line of zero force of the x component of force. In both figures, the peak x components of force occur within 0.3 sec of the initial movement. Because the subject's velocity is approximately 2.5 ft/sec, as obtained from fig. af, the total movement during 0.3 sec is 0.75 ft. For the pendulum support length of 54 ft, this 0.75-ft deflection produces a 2.3-lb error in the x component of force. Noting fig. ag, this amounts to an error of approximately 11% for the peak x component of force. Hence, the maximum amplitudes of the x component of force, which is the acceleration force, is reasonably close, but its' profile needs modifying to remove gravity effects.

SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

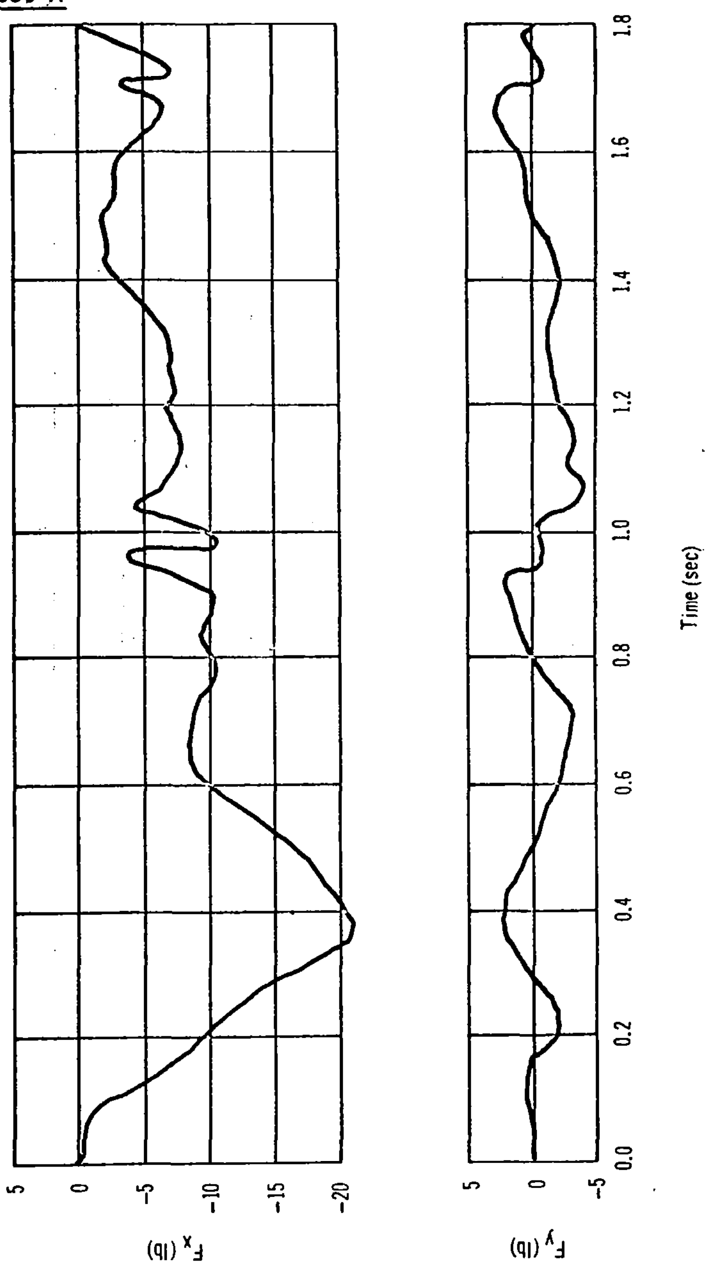
af. Guided Locomotion Parallel to Force Table Displacement



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

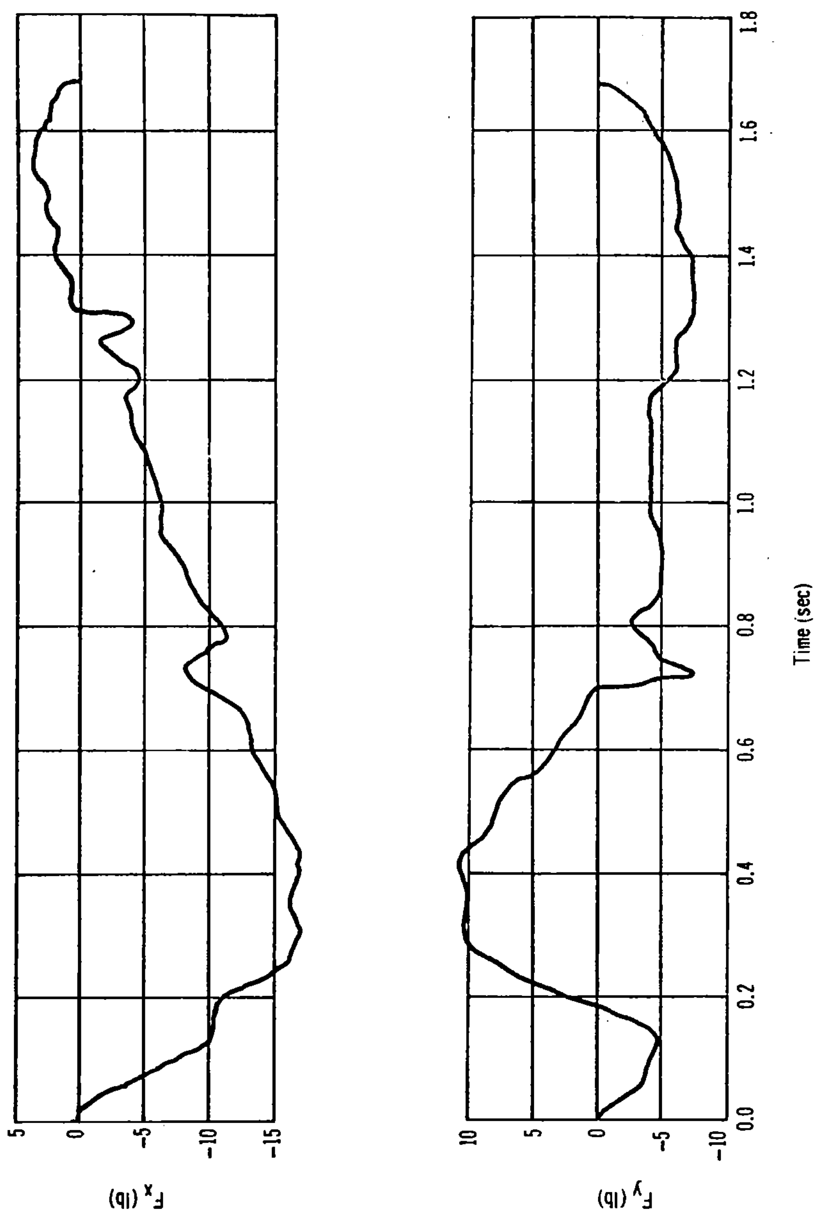
aq. Guided Locomotion Parallel to Force Table Nominal Disturbance Profile - Subject A



SOURCE: Fuhrmeister and Fawler (68).

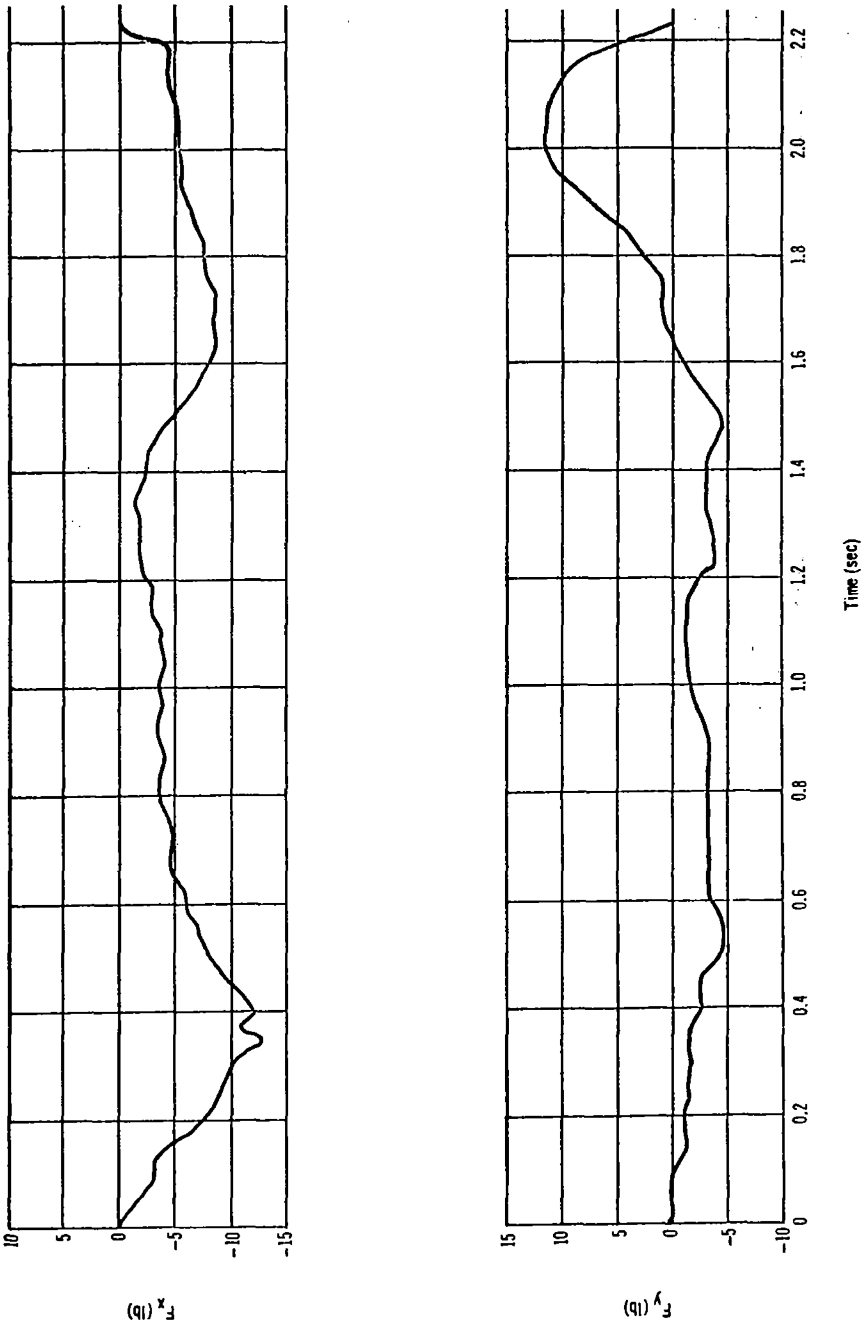
EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

ah. Guided Locomotion Parallel to Force Table Nominal Disturbance Profile-Subject B



SOURCE: Fuhrmeister and Fawler (68).

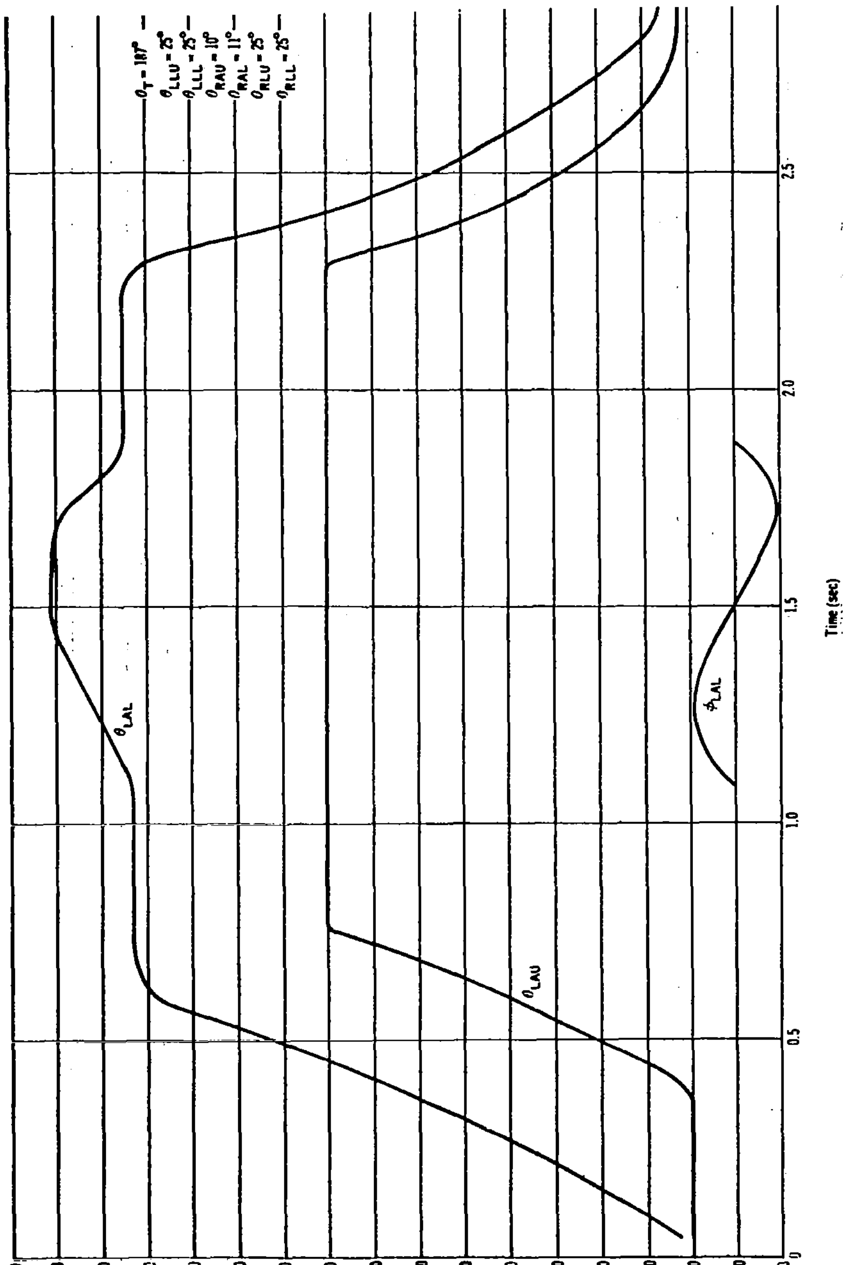
EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT



ai. Guided Locomotion Parallel to Force Table Minimum Disturbance Profile

SOURCE: Fuhrmeister and Fawler (68).

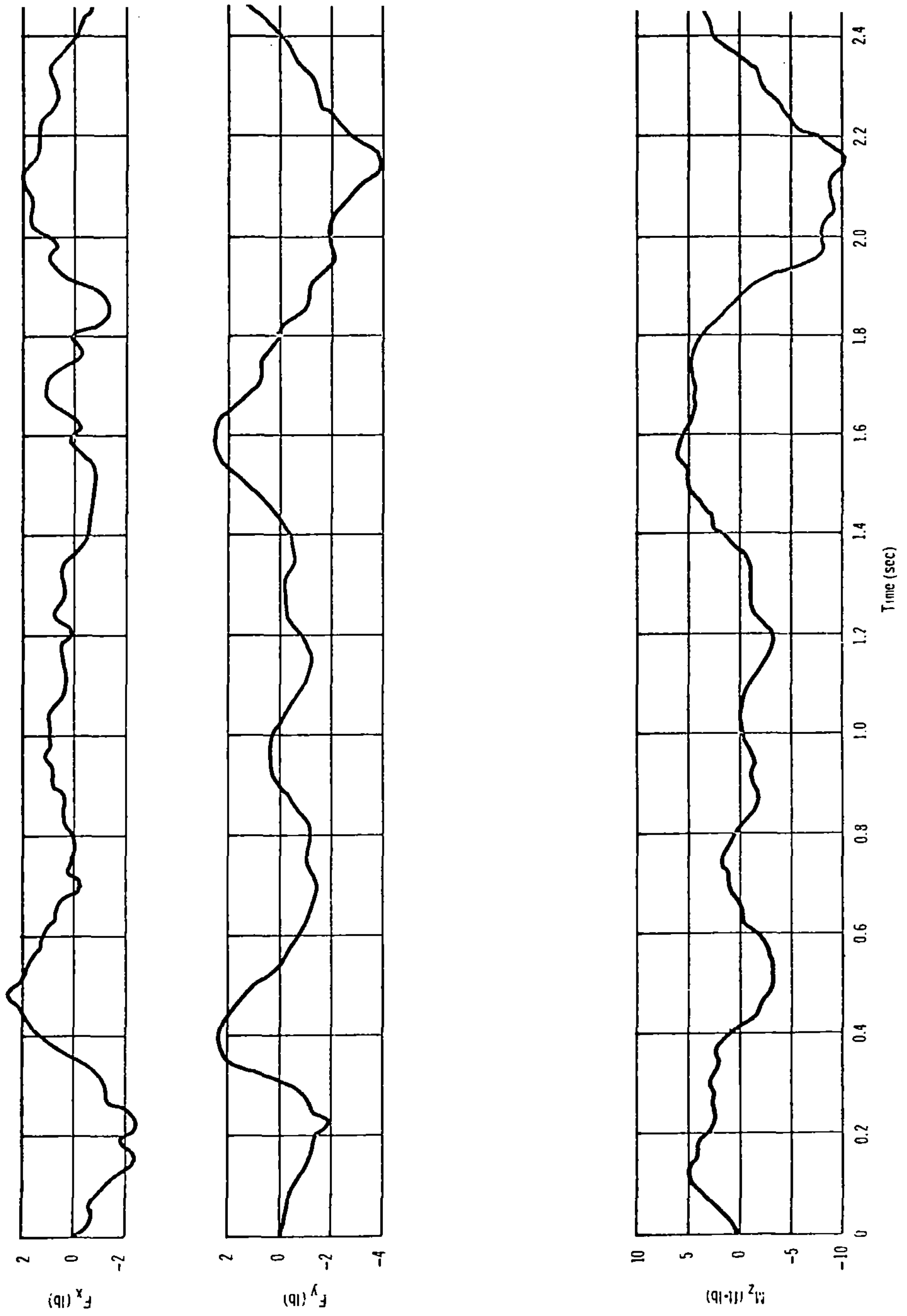
EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT



aj. Console and Operation Torquing Euler Angles

SOURCE: Fuhrmeister and Fawler (68).

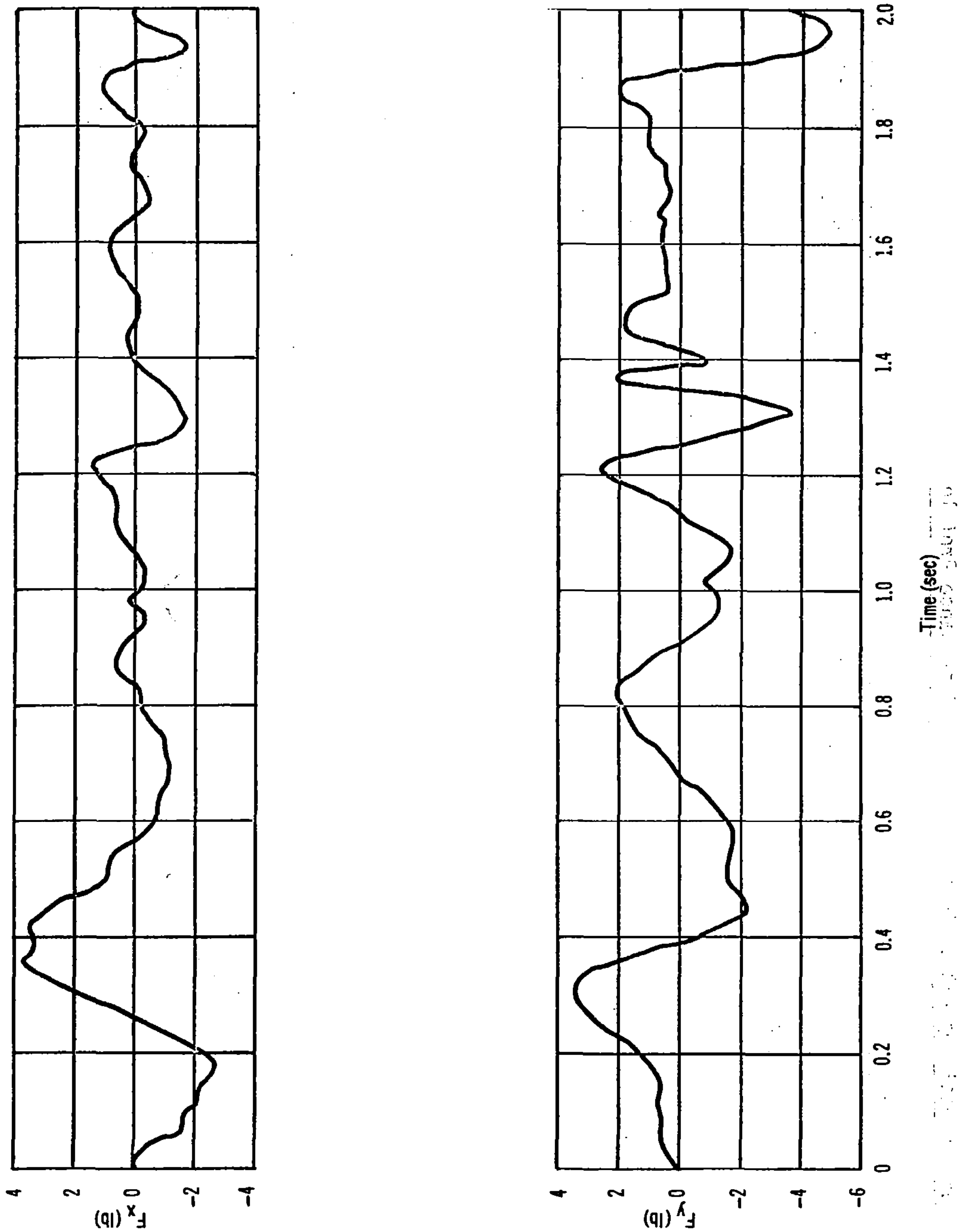
EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT



ak. Console Operation Torquing Nominal Disturbance Profiles

SOURCE: Fuhrmeister and Fawler (68).

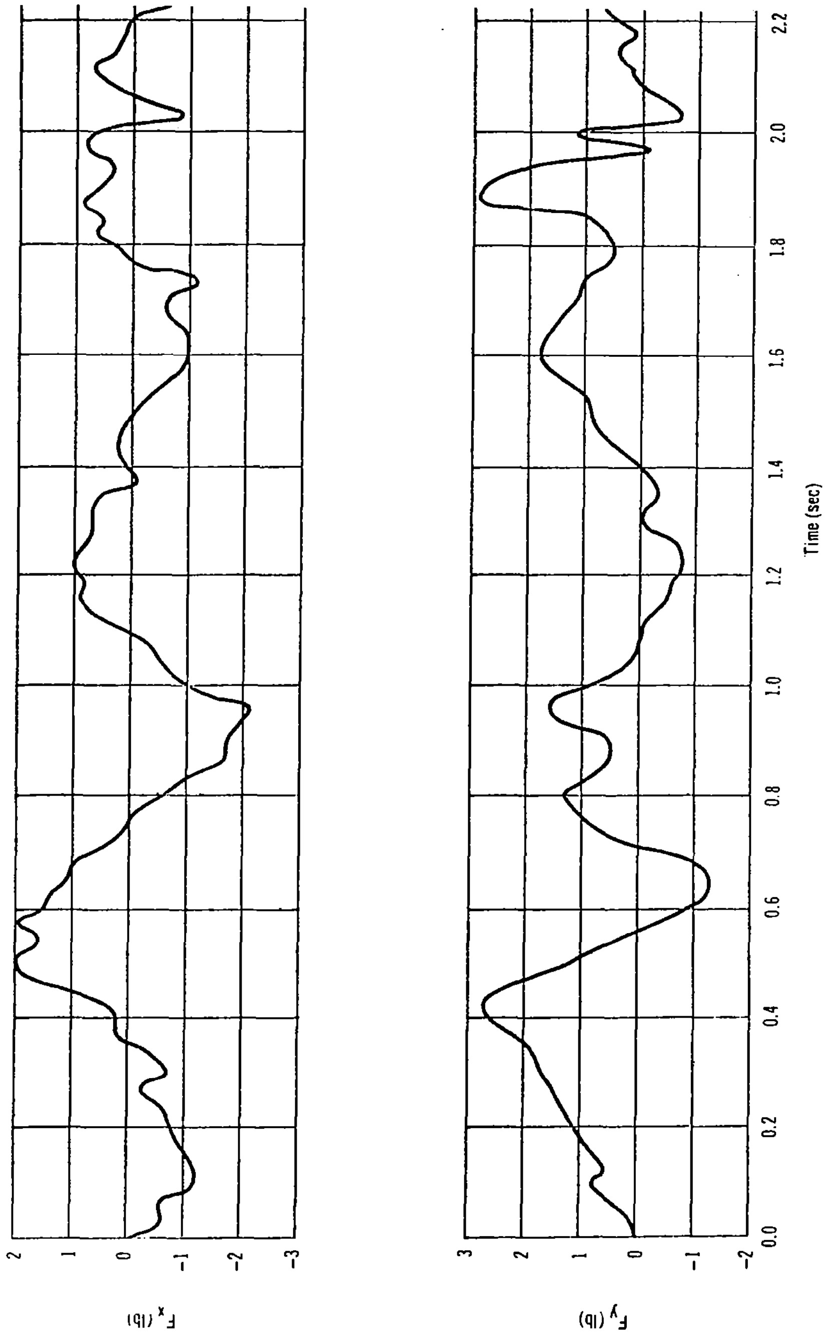
EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT



a1. Console Operation Push-Pull Nominal Disturbance Profile

SOURCE: Fuhrmeister and Fawler (68).

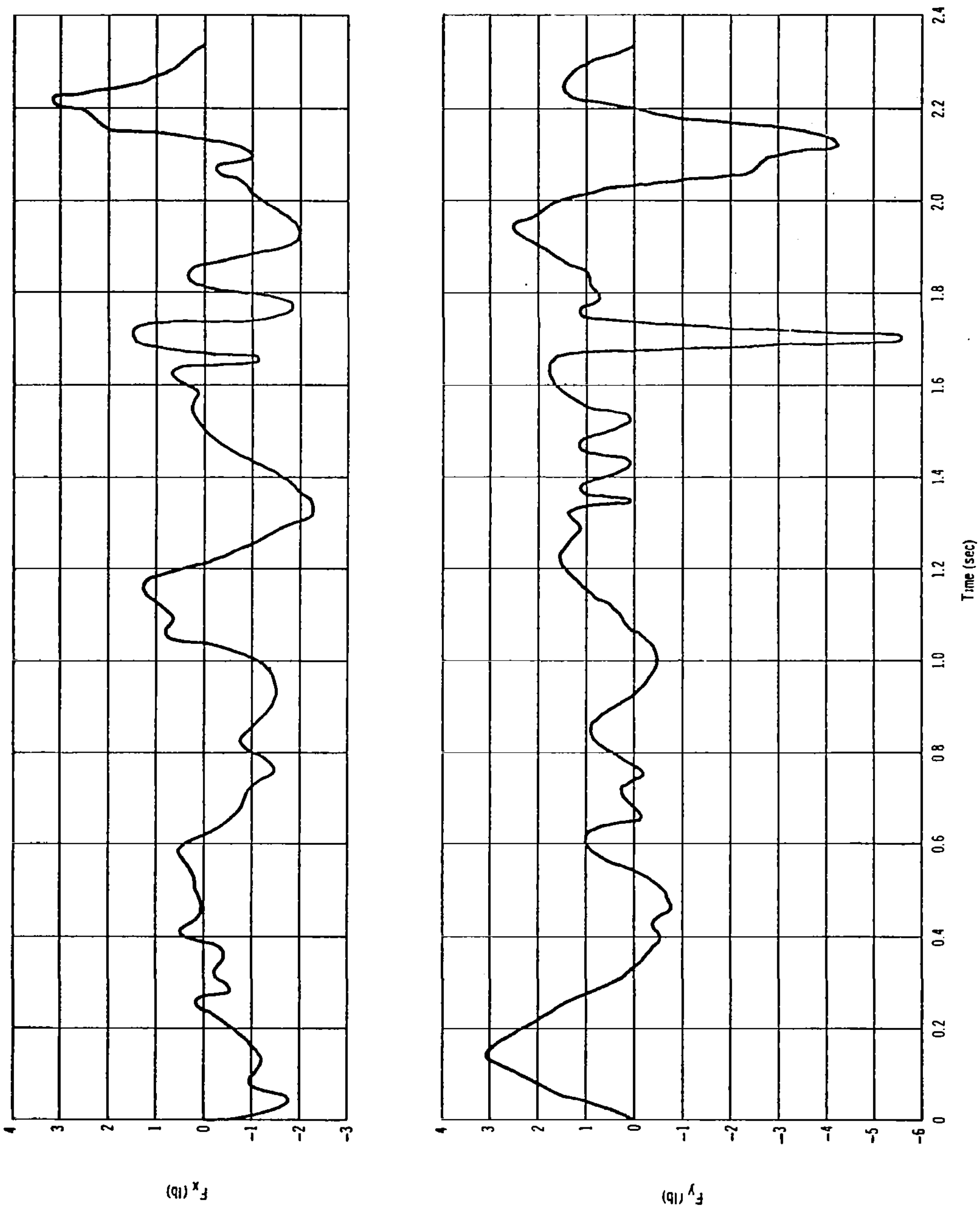
EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT



am. Console Operation Push-Pull Minimum Disturbance Profile - Subject A

SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

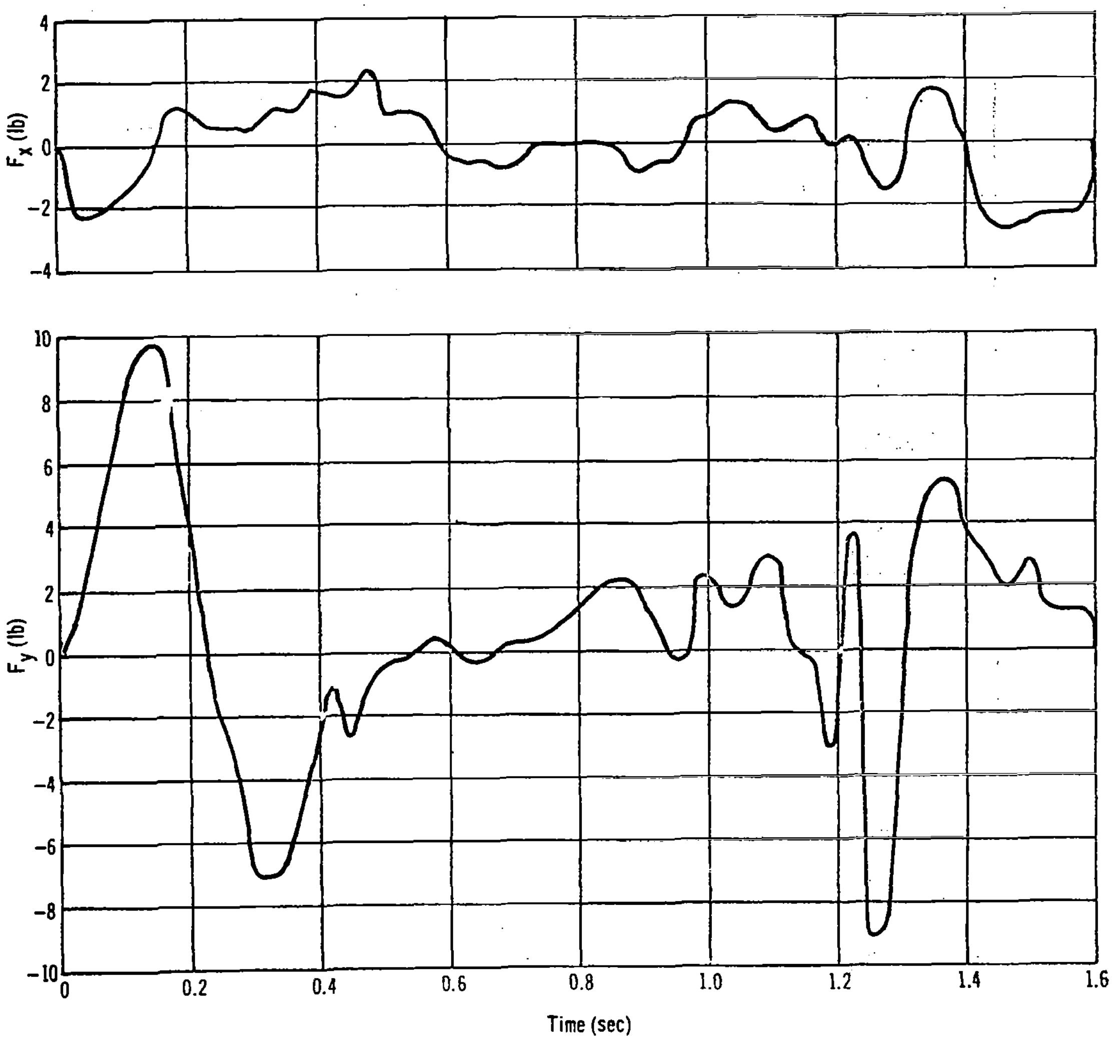


an. Console Operation Push-Pull Minimum Disturbance Profile - Subject B

SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

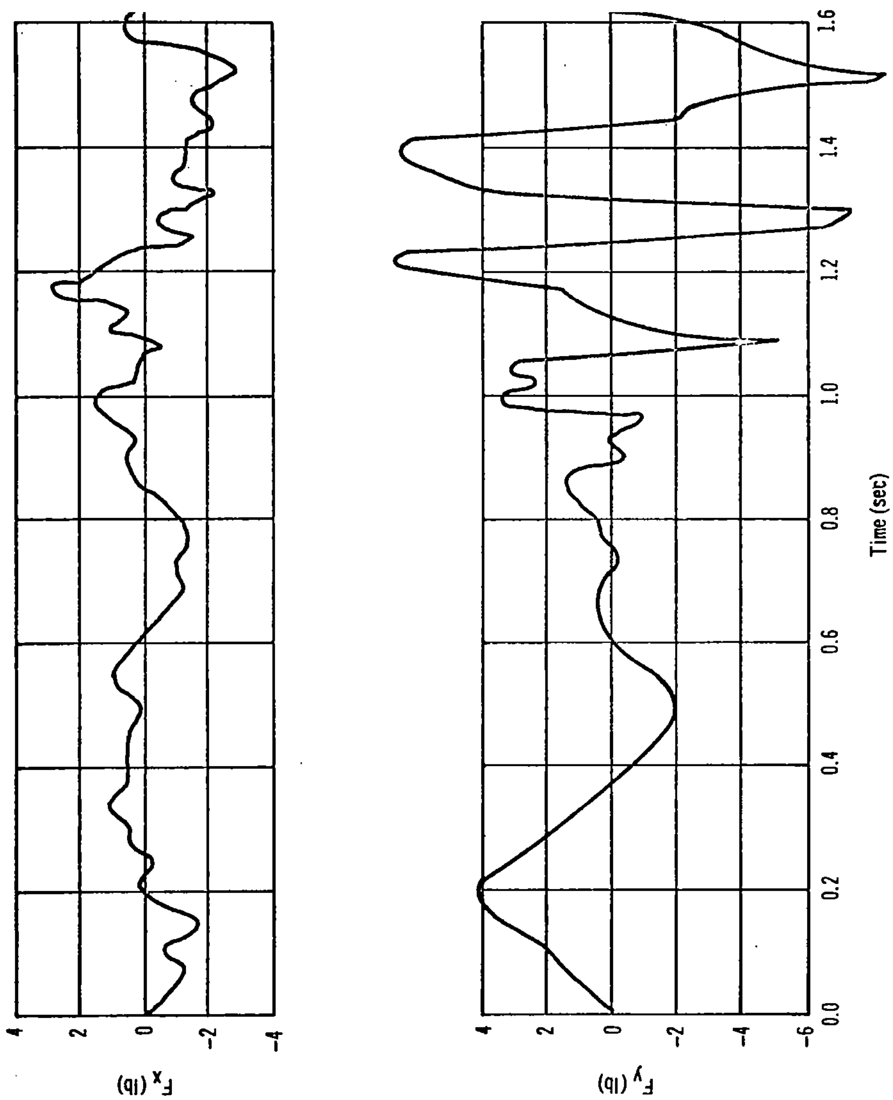
ao. Console Operation Push-Pull Maximum Disturbance Profile - Subject A



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

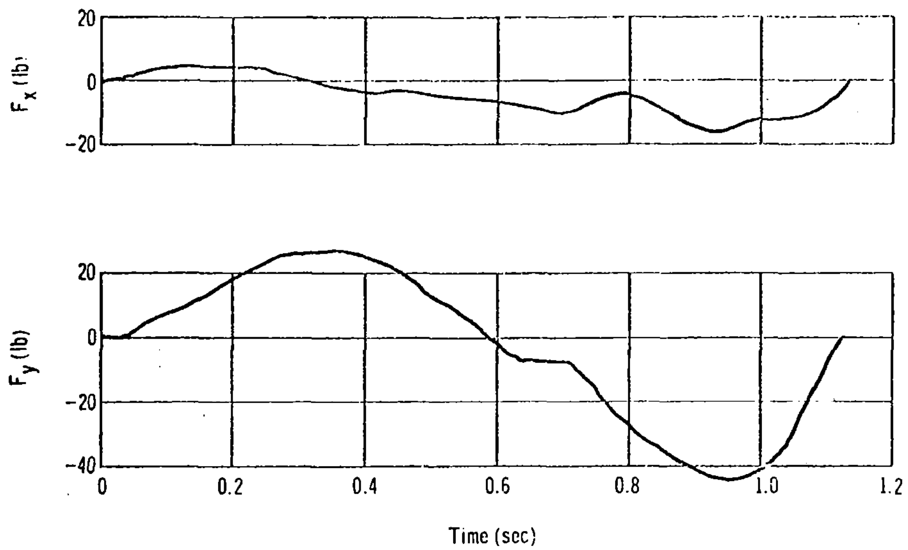
ap. Console Operation Push-Pull Maximum Disturbance Profile - Subject B



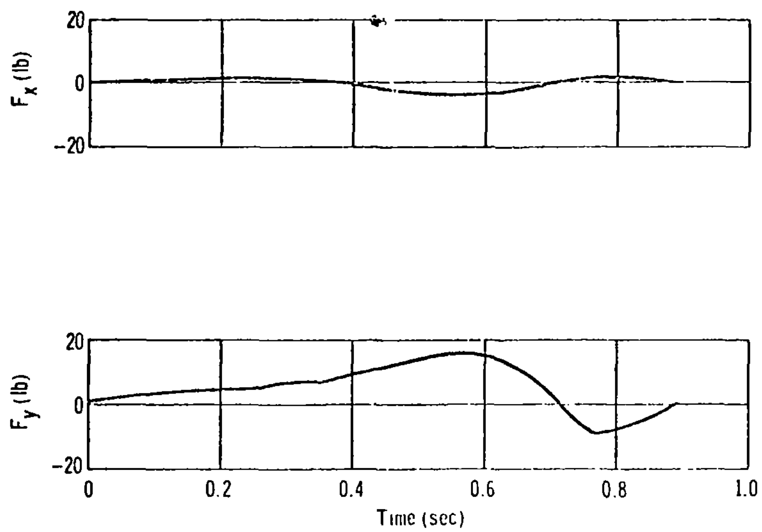
SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

aq. Trunk Bending Exercise Disturbance Profile - Subject A



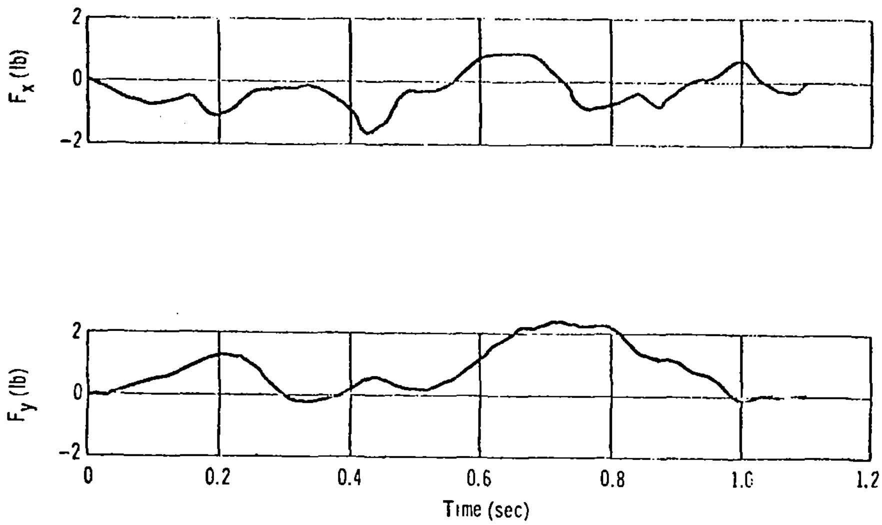
ar. Trunk Bending Exercise Disturbance Profile - Subject B



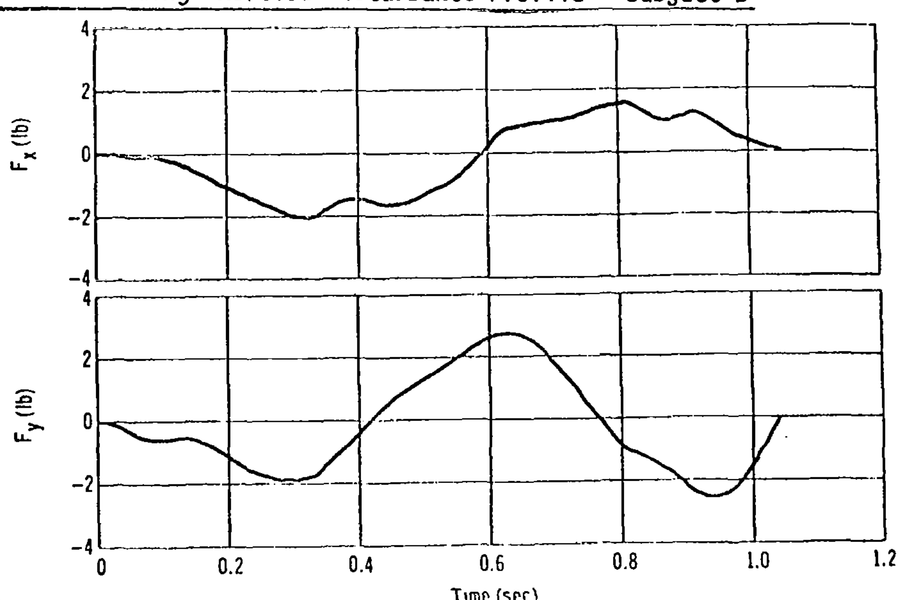
SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

as. Neck Bending Exercise Disturbance Profile - Subject A



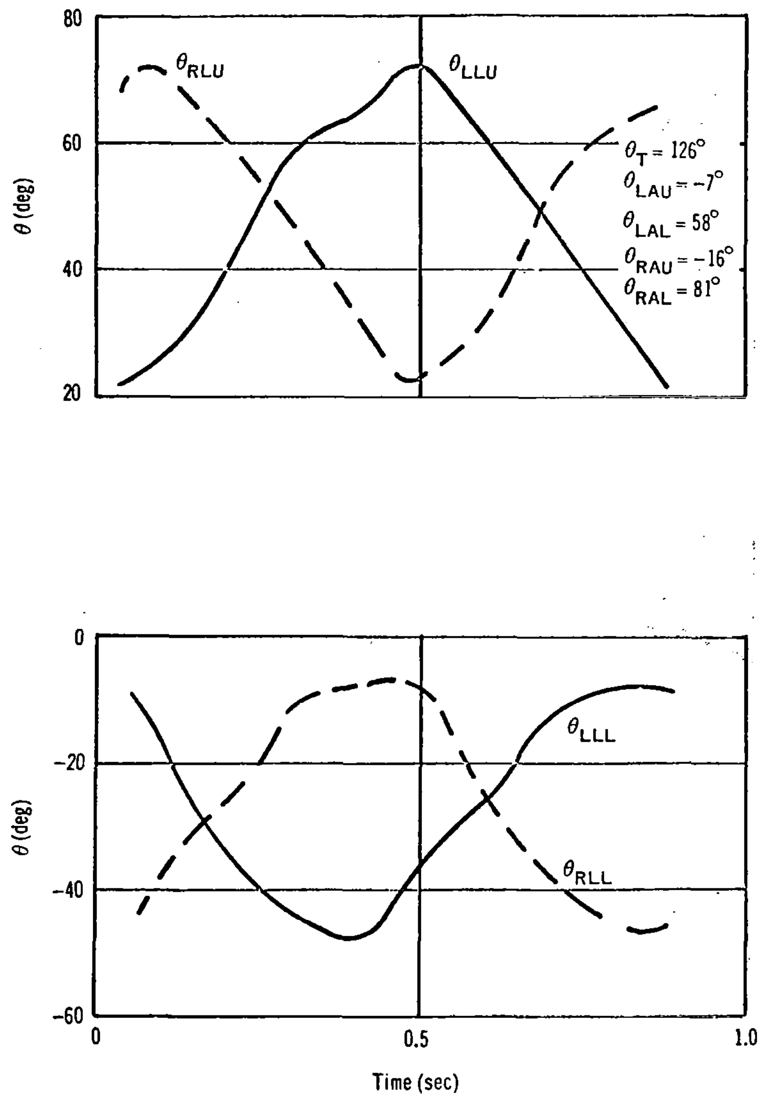
at. Neck Bending Exercise Disturbance Profile - Subject B



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

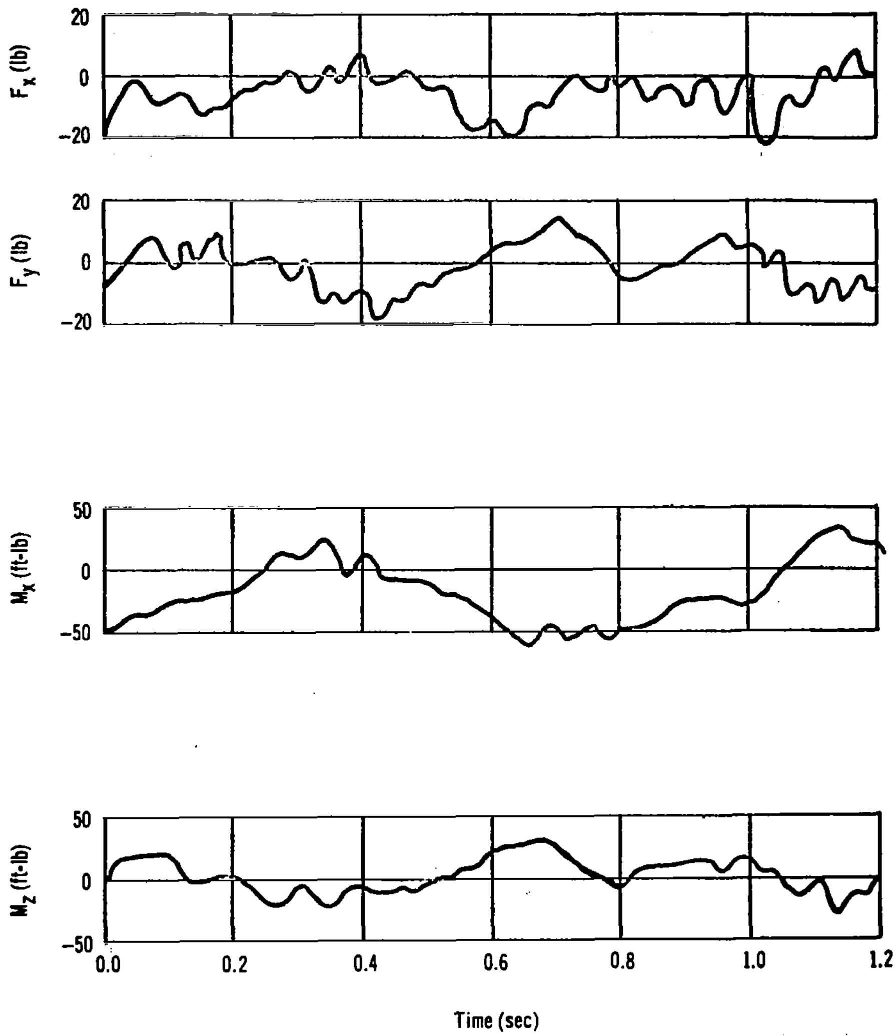
au. Pedal Ergometer Endurance Exercise Euler Angles



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

av. Pedal Ergometer Endurance Exercise Disturbance Profile

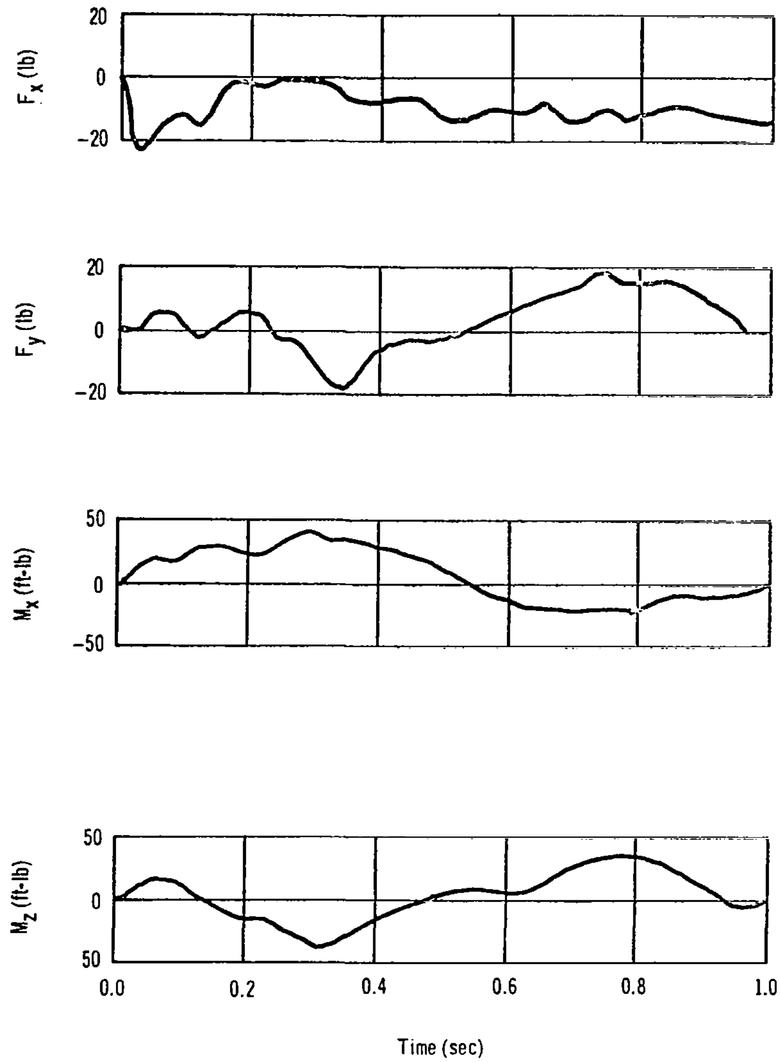


SUBJECT A

SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

av. Pedal Ergometer Endurance Exercise Disturbance Profile (Cont.)

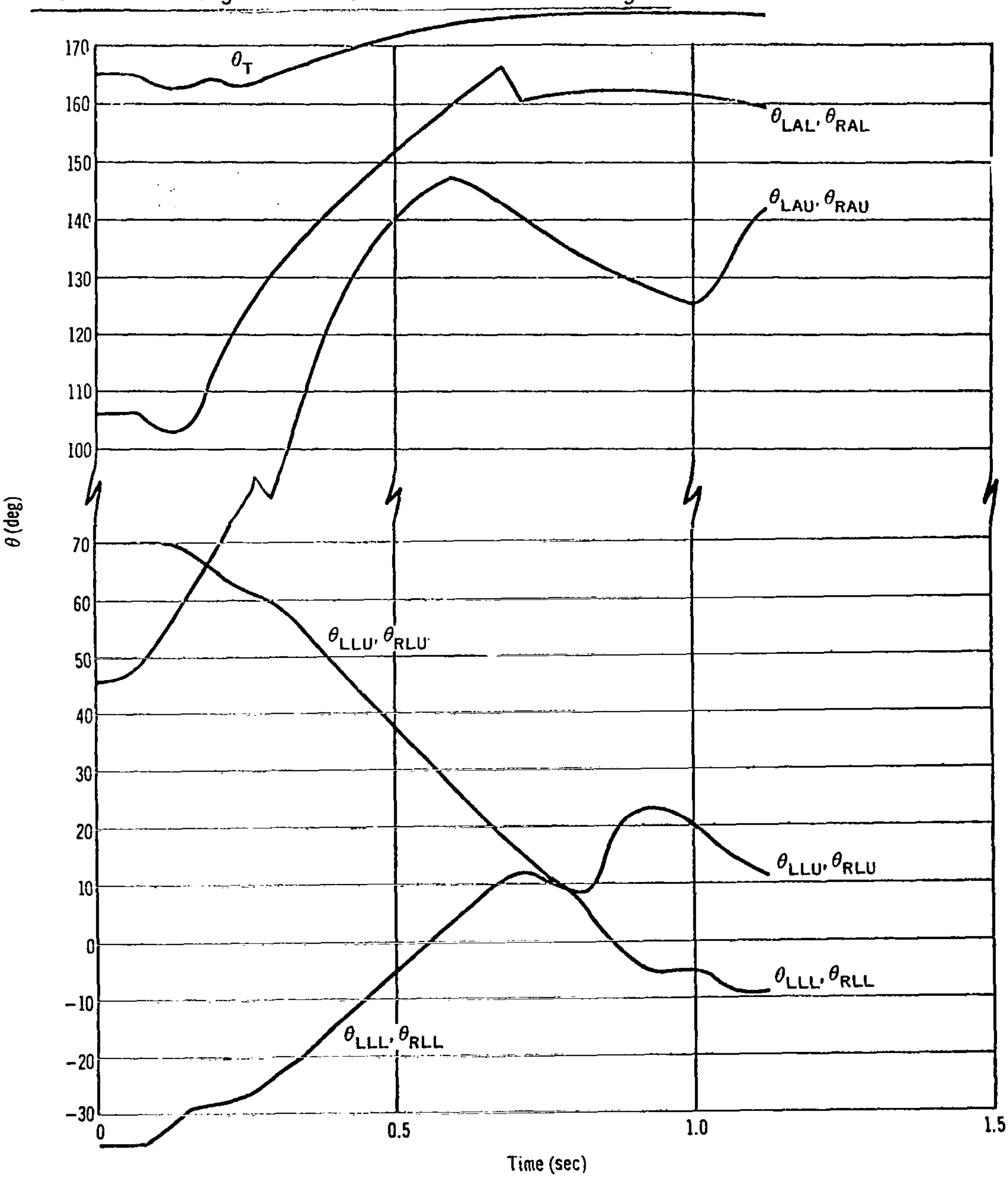


SUBJECT B

SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

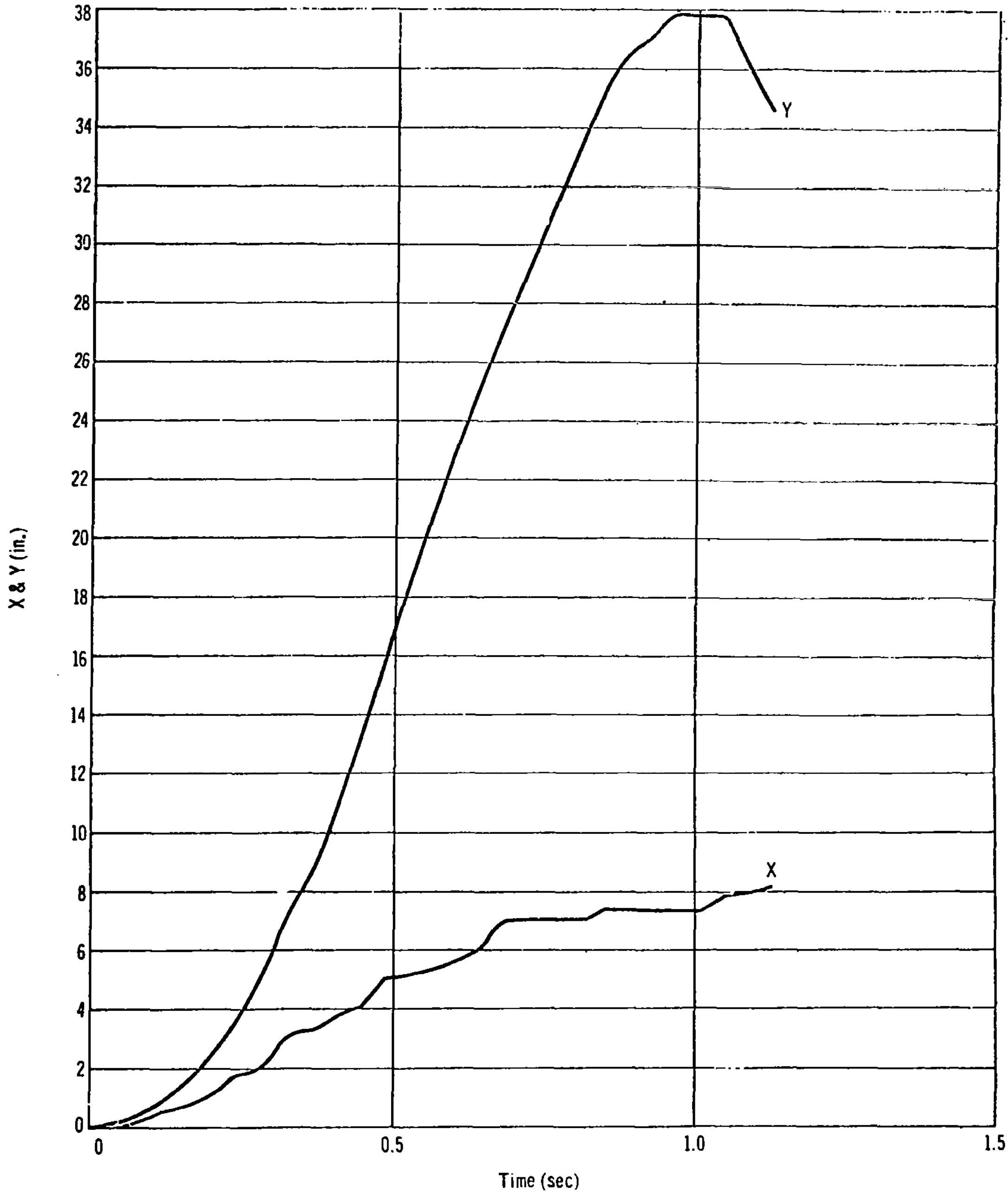
aw. Oscillating Acceleration Exercise Euler Angles



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

ax. Oscillating Acceleration Exercise Displacement

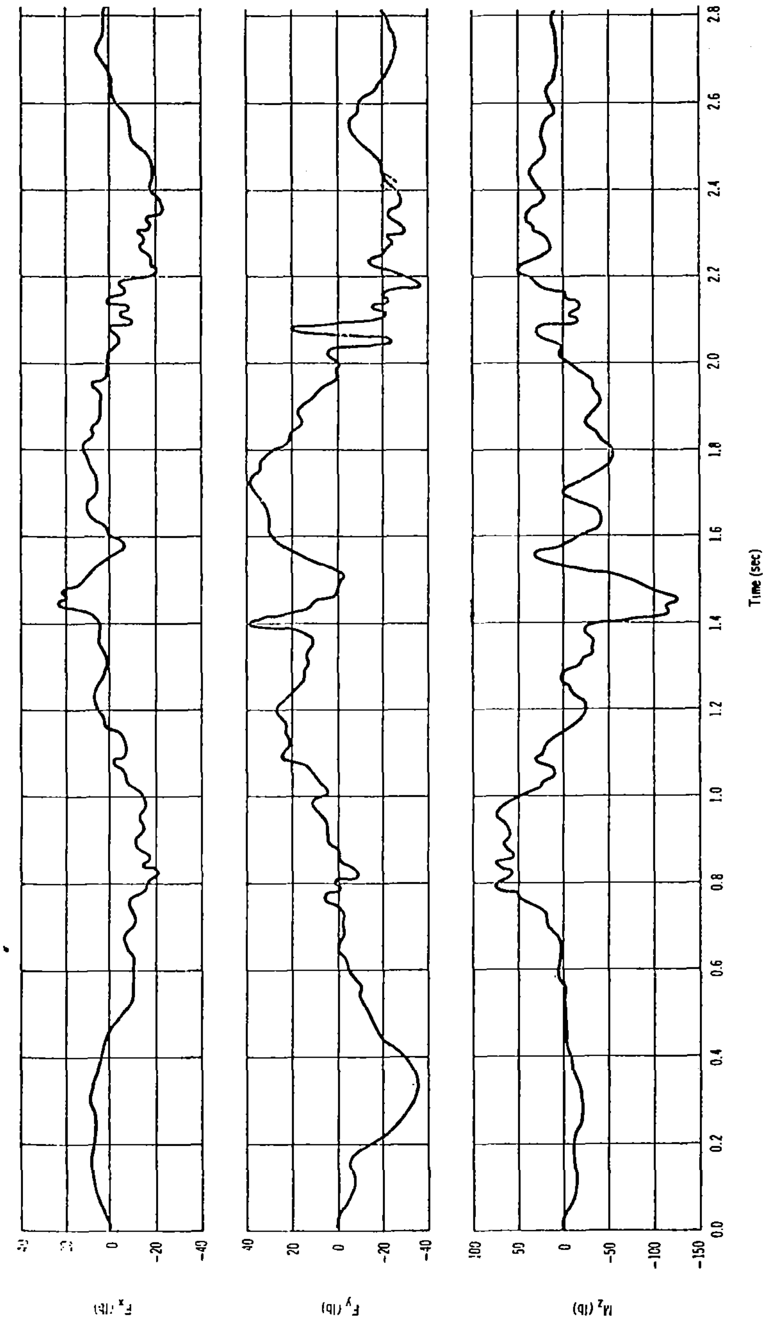


SOURCE: Fuhrmeister and Fawler (68).

EXTRAVEHICULAR ENVIRONMENT

WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT



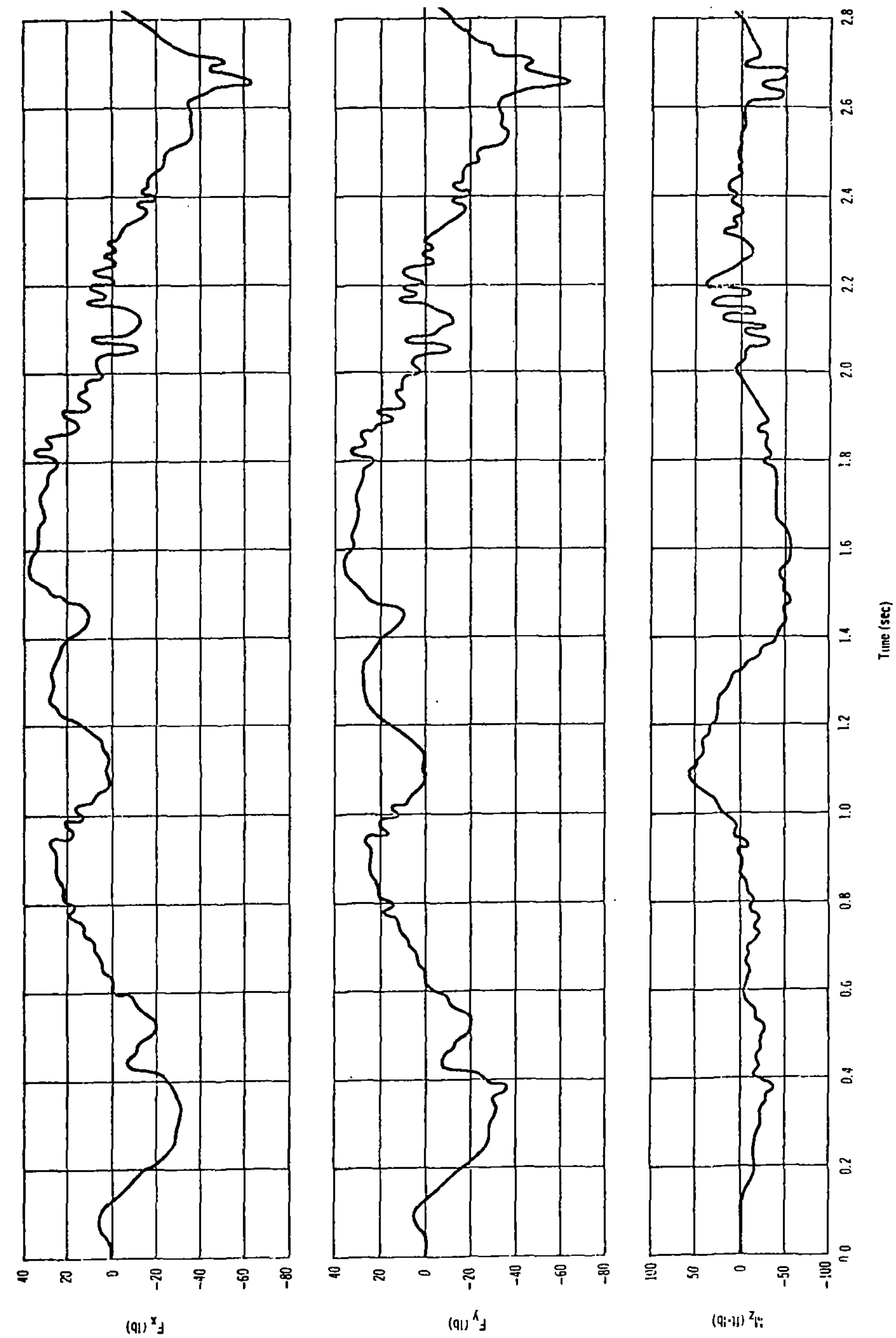
ay. Full-Length Body Exercise Disturbance Profile - Subject A

SOURCE: Fuhrmeister and Fawler (68).

EXTRAVEHICULAR ENVIRONMENT

WEIGHTLESSNESS

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

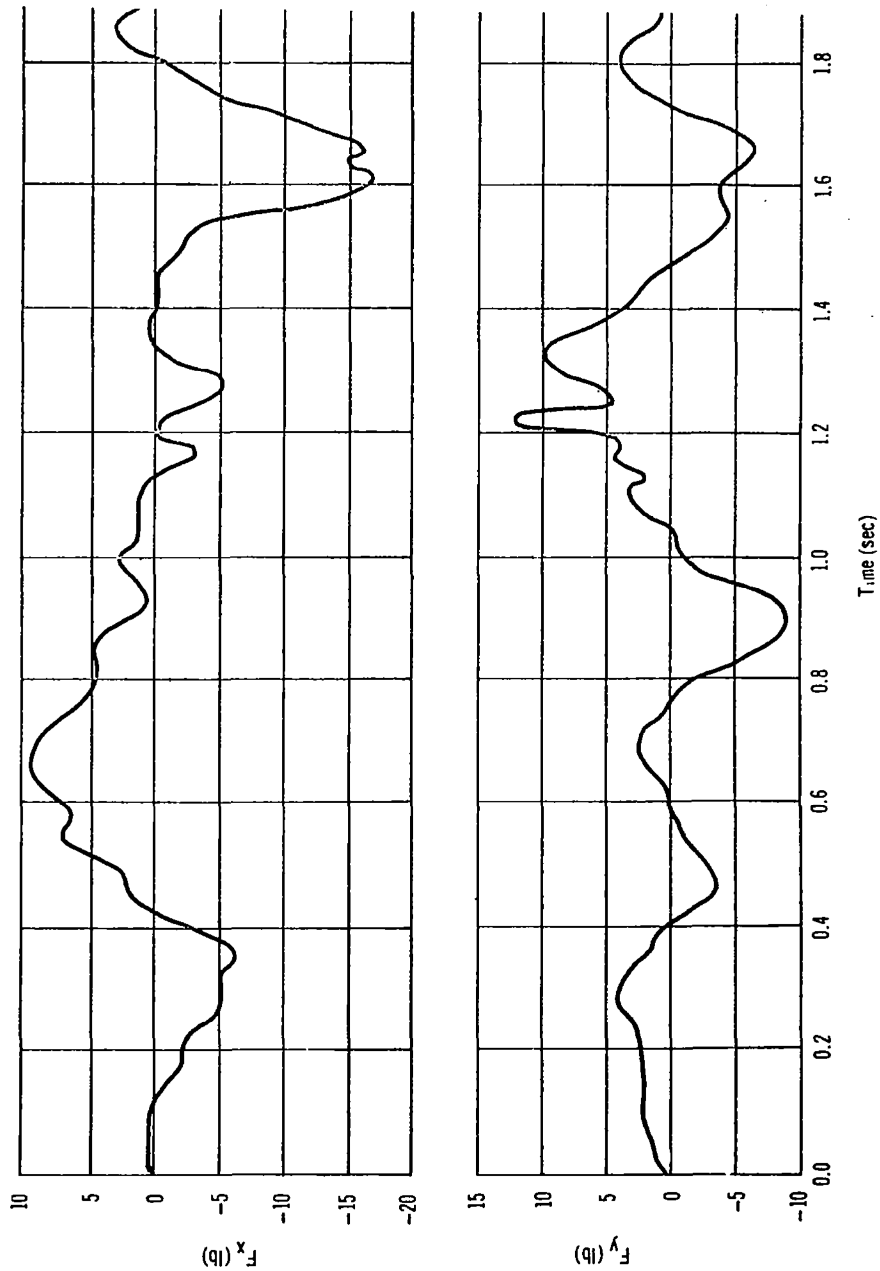


az. Full-Length Body Exercise Disturbance Profile - Subject B

SOURCE: Fuhrmeister and Fawler (68).

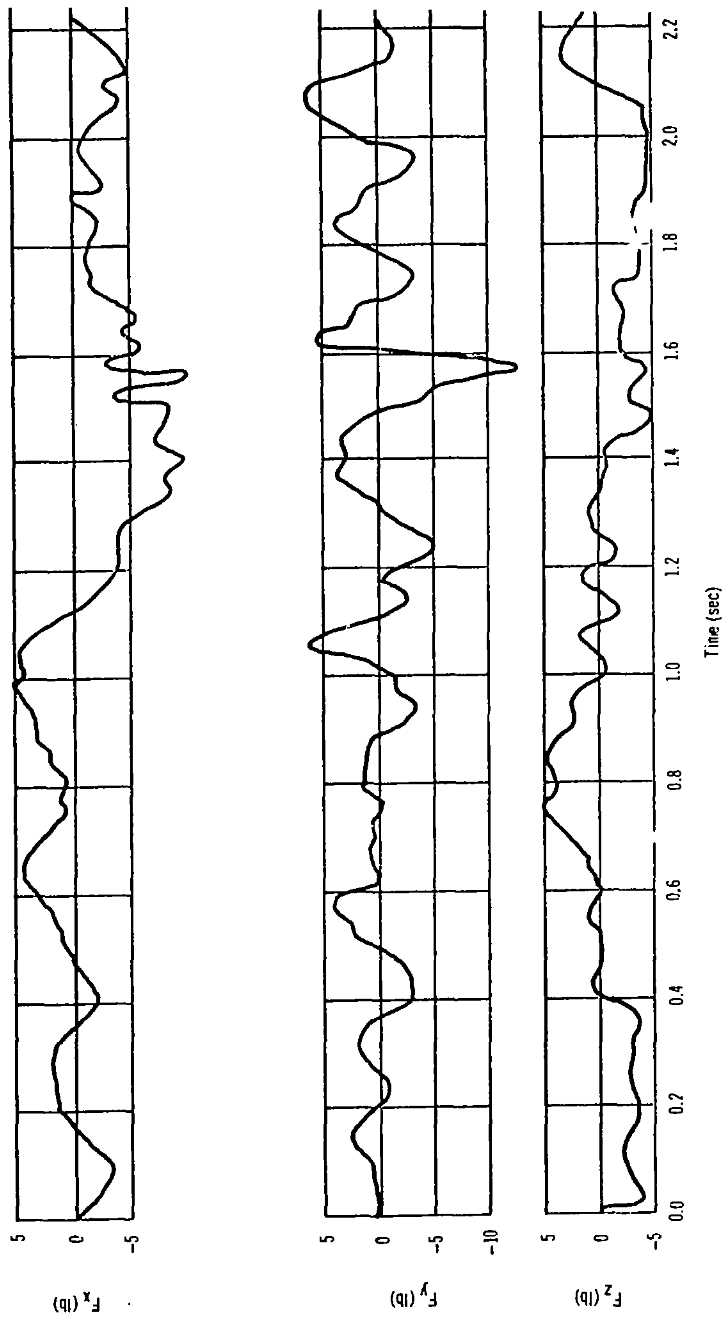
EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

ba. Trunk Rotation Exercise Disturbance Profile - Subject A



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

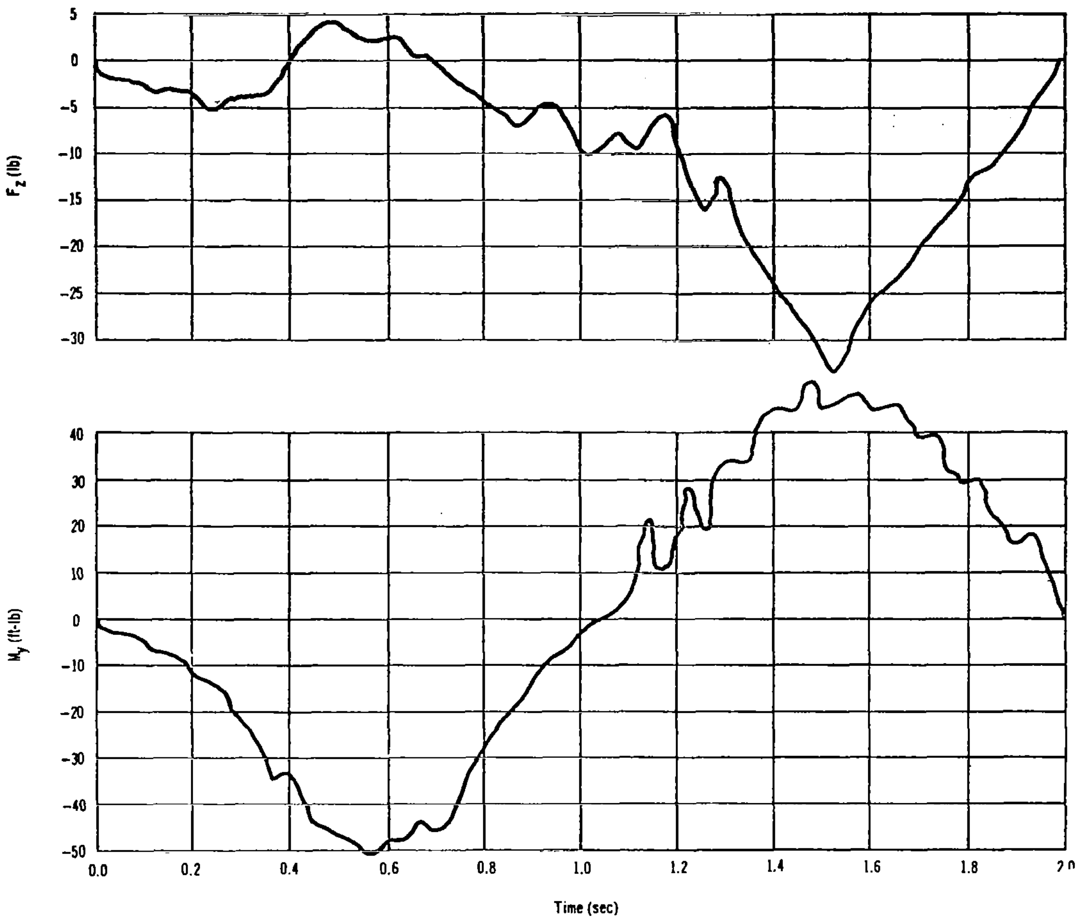


bb. Trunk Rotation Exercise Disturbance Profile - Subject B

SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

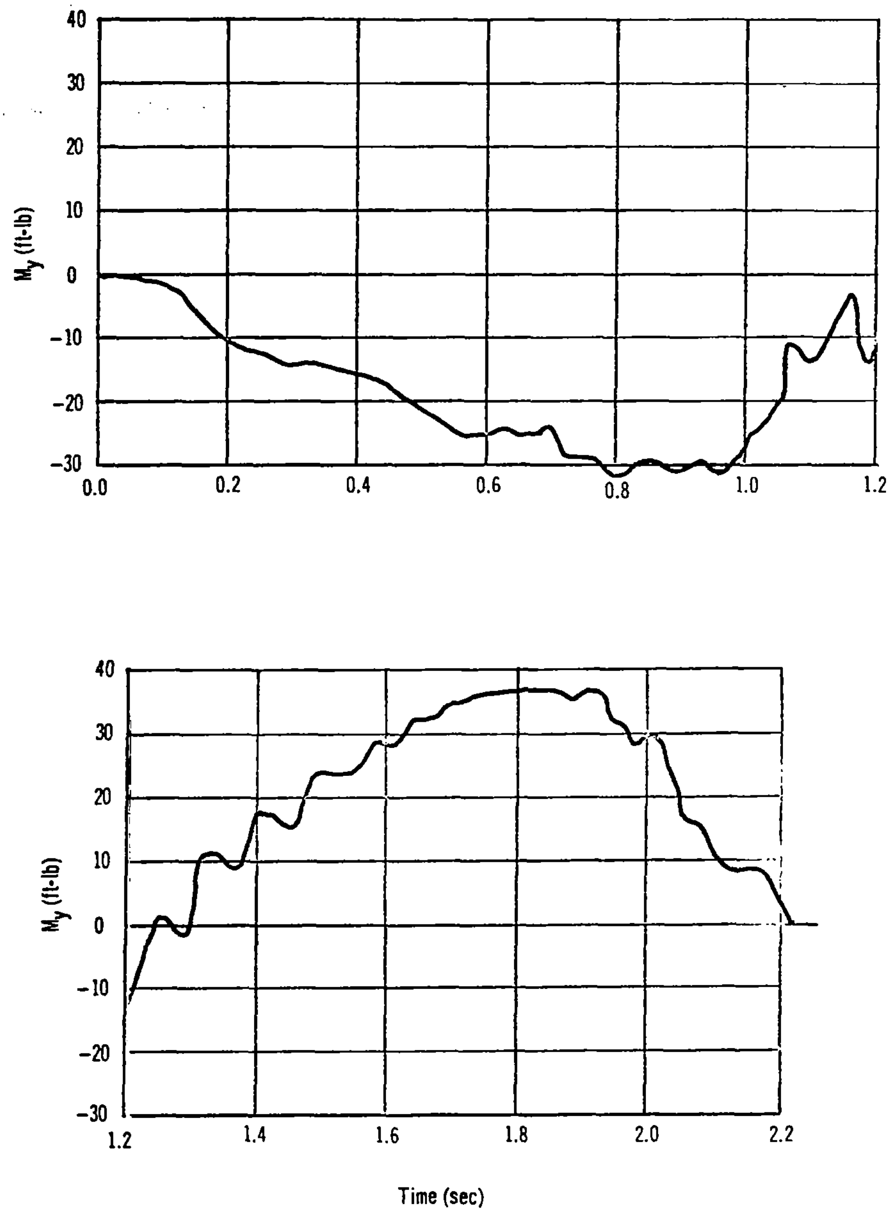
bc. Trunk Rotation Exercise Disturbance Profile - Subject A



SOURCE: Fuhrmeister and Fawler (68).

EFFECT OF CREW MOTION ON A SPACE VEHICLE IN WEIGHTLESS ENVIRONMENT

bd. Trunk Rotation Exercise Disturbance Profile - Subject B



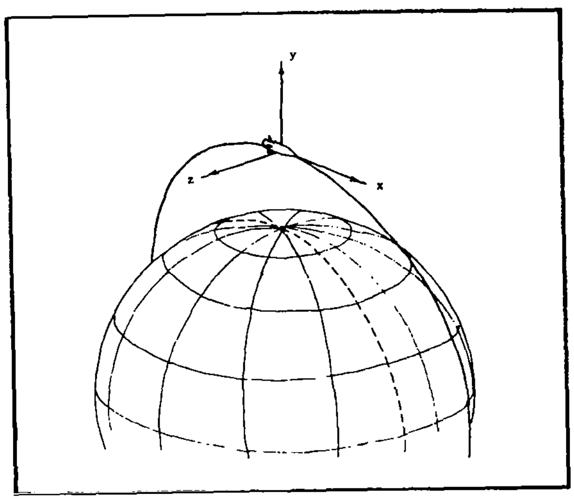
SOURCE: Fuhrmeister and Fawler (68).

AN ANALYSIS OF THE BEHAVIOR OF LONG TETHERLINES IN SPACE

EQUATIONS OF MOTION

In describing the problem, a rotating xyz-coordinate frame attached to an orbiting vehicle in a circular or near-circular orbit around the earth, moon, or another planet is assumed. As shown in figure be below, the y-axis lies along the local vertical in the orbital plane and the x-axis lies along the local horizontal in the direction of orbital motion. The z-axis is perpendicular to the orbital plane and in a direction consistent with a right-handed coordinate frame.

a. Coordinate Reference Frame



The linearized equations which describe the motion of a mass in this coordinate frame have been derived and discussed in detail by many authors.

$$\ddot{x} = -2\omega\dot{y} + f_x \quad (1)$$

$$\ddot{y} = 2\omega\dot{x} + 3\omega^2 y + f_y \quad (2)$$

$$\ddot{z} = -\omega^2 z + f_z \quad (3)$$

where ω is the angular velocity of the coordinate frame with respect to inertial space about the z-axis and f_x, f_y, and f_z are the x, y, and z components of external force per unit mass acting on the mass in question. In this paper, the only external forces assumed to act are due to the tetherline. We also assume that the mass of the parent vehicle is considerably larger than the mass at the end of the tetherline so that the orbit of the parent vehicle remains unchanged while the orbit of the smaller mass changes in response to tetherline forces.

SOURCE: Mueller (137).

AN ANALYSIS OF THE BEHAVIOR OF LONG TETHERLINES IN SPACE

This is not so serious a limitation as one might suppose since it can be shown that, even when the two masses at the opposite ends of the line are equal, the relative motion between them is the same as that described below.

Only coplanar motions will be considered in this paper, so we need concern ourselves only with equations 1 and 2.

IMPULSIVE JERKS ON A SLACK TETHERLINE

In considering the technique to be employed in retrieving a man on the end of a long tetherline, it is obvious that so long as tension is maintained on the line the man will be accelerated. Since accelerating the man continuously to higher and higher closure velocities would be undesirable, it is instructive to see what happens if the line is impulsively jerked so as to give the man a small initial closure velocity toward the parent vehicle and then to allow the man to coast in toward the vehicle while the line remains slack.

The coasting trajectory of the man will be determined by solving equations 1 and 2 with f_x and f_y equal to zero. If the line becomes taut, however, a rebound will occur which will cause the radial component of velocity to reverse while the tangential component remains constant. The coasting trajectory subsequent to such a bounce will be determined by the same equations with appropriately altered initial conditions.

As a numerical example, we will consider the vehicle to be in a 200-nautical-mile earth orbit (ω= 0.00114 radian per second) with the man initially positioned horizontally ahead of the vehicle in the orbital plane and at rest relative to it in the xyz-coordinate frame.

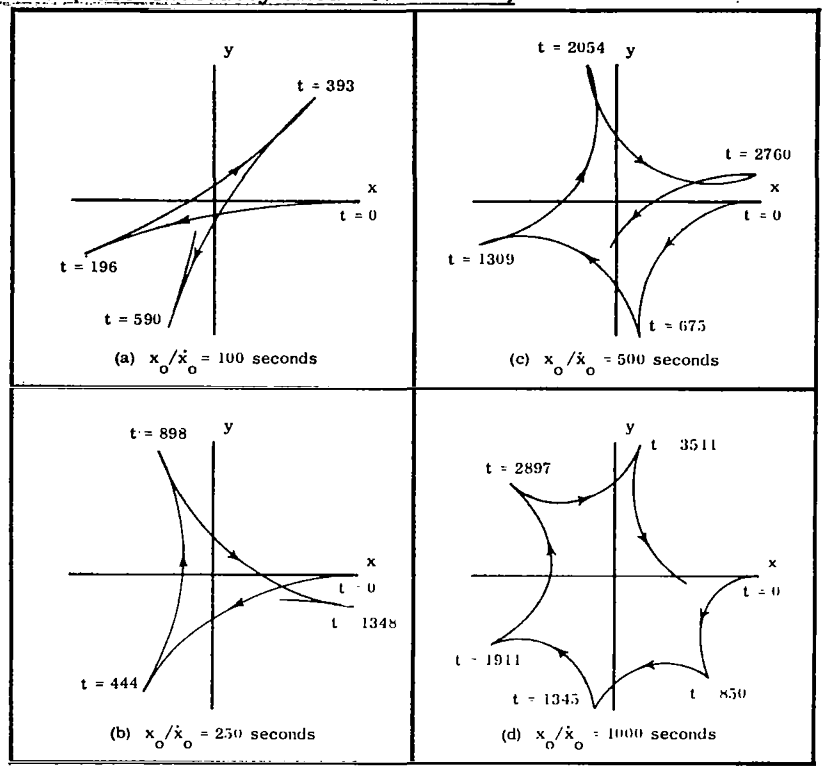
The motion which ensues depends only on the ratio of the initial distance, x_0, to the initial velocity, $\dot{x}_0$. Figure bf shows the trajectories which result for four different values of $x_0/\dot{x}_0$. If, for example, we assume that the man is initially 500 feet ahead of the vehicle, figure b (a) would represent the case in which the line is jerked so as to give the man an initial coasting velocity of 5 feet per second. Figure b (b) would then represent an initial coasting velocity of 2 feet per second; figure b (c), a velocity of 1 foot per second; and figure b (d), a velocity of 1/2 foot per second. The time in seconds at which each rebound occurs is labeled in figure b.

The consequence of giving the man a small closure velocity toward the vehicle is to reduce the orbital velocity of the man by this same amount. As a result, the man, in addition to coasting toward the vehicle, drops to a lower orbital altitude as shown. When the line is stretched to its original length, it becomes taut again, and, assuming that the line has a high modulus of elasticity, the man is jerked sharply toward the vehicle. As a result of orbital forces, the

SOURCE: Mueller (137).

man again describes a curved path terminating in a similar rebound, repeating the process indefinitely.

b. Path of a Mass on the End of a Slack Tetherline After an Initial Impulse (Mass Initially Ahead of Vehicle)



There is evidence (see figure b (c) above) that the trajectory approaches the vehicle after many bounces, but the long times involved would seem to preclude this technique as a method for retrieving a disabled astronaut.

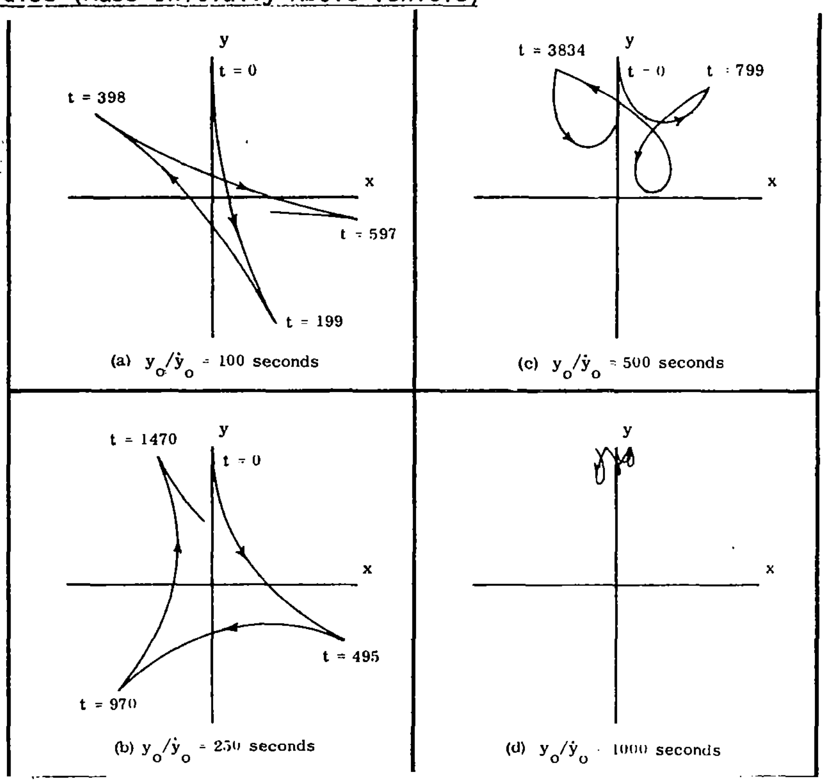
Several alternatives are, however, still open to us. We could, for example, reel in the slack line up to the point of closest approach at which time the line would become taut. If nothing else were done the man would circle endlessly about the vehicle. By now we can see the real nature of the problem: the initial velocity of the man which was originally radial has been transformed into a tangential velocity with a corresponding build-up of angular momentum about the

SOURCE: Mueller (137).

vehicle. Since we are assuming that the man has lost his means of propulsion, there is nothing that we can do by pulling radially on the line that will remove this tangential velocity. Furthermore, the tendency for angular momentum to be conserved means that, if the line length is decreased to zero, the tangential velocity will tend toward infinity.

If the man started from some other initial position, the situation would be similar. Figure c shows the trajectories which result if the man is initially positioned directly above the orbiting vehicle and at rest relative to it*. Note in figures c (c) and c (d) that the gravity gradient effect (which tends to keep a dumbbell-shaped satellite oriented along the local vertical) causes the path of the man to be more sharply curved and tends to keep him above the vehicle's altitude.

c. Path of a Mass on the End of a Slack Tetherline After an Initial Impulse (Mass Initially Above Vehicle)



*Trajectories for starting positions behind or below the parent vehicle are identical in shape to those shown in figures bf and bg and may be visualized by rotating these figures 180 degrees.

SOURCE: Mueller (137).

AN ANALYSIS OF THE BEHAVIOR OF LONG TETHERLINES IN SPACE

In figure c (c), the path is so sharply curved that, by the time the first bounce occurs at 799 seconds, the man has acquired a counterclockwise component of tangential velocity. Any time a counterclockwise component exists, it is possible to add to it a radial component by means of the tetherline which will cause the man to impact the vehicle. In the particular case of figure c (c), a small pull on the line after the first bounce could have straightened the path so as to intersect the vehicle.

In all cases, the successful retrieval of an object on the end of a tetherline involves the generation of a favorable component of tangential velocity followed by the addition of a radial component, by means of the line, which will cause impact with the vehicle. Unfortunately, the generation of a favorable component of tangential velocity where none exists initially can take hundreds of seconds, and is feasible only when relatively long times are available for the recovery of the object at the end of the tetherline.

CONSTANT LINE TENSION

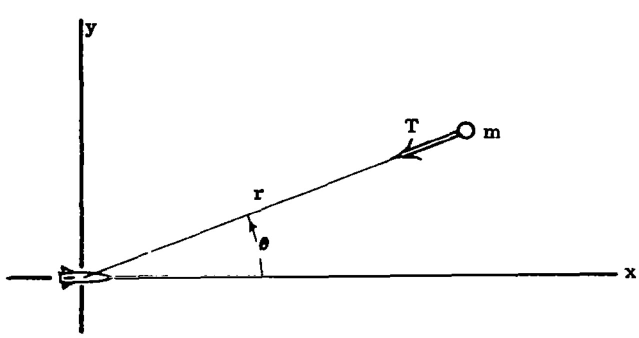
An alternative to jerking the line and then leaving it slack would be to maintain a constant tension on the tetherline. This would produce a constant acceleration toward the parent vehicle at all times. The forces per unit mass acting on the mass in this case would be:

$$f_x = -T/m \cos \theta \qquad (4)$$

$$f_y = -T/m \sin \theta \qquad (5)$$

where T is the line tension, m is the mass at the end of the tetherline, and is the angle defined in figure bh.

d. Line Tension Force Acting on Mass



SOURCE: Mueller (137).

AN ANALYSIS OF THE BEHAVIOR OF LONG TETHERLINES IN SPACE

If we again take as a numerical example a mass 500 feet horizontally ahead of a vehicle in a 200-nautical-mile earth orbit, and assume that T/m is equal to 0.01 foot per second^2, the result is similar in many respects to the previous examples.

Figure e illustrates the effect of reducing the line tension. Note the greater loss in altitude and more gradual turn-around as the value of T/m is decreased. The trajectory for T/m = 0.005 foot per second^2 is particularly interesting since it indicates that the path intersects the vehicle. The impact occurs after 1450 seconds at a speed of 2 feet per second.

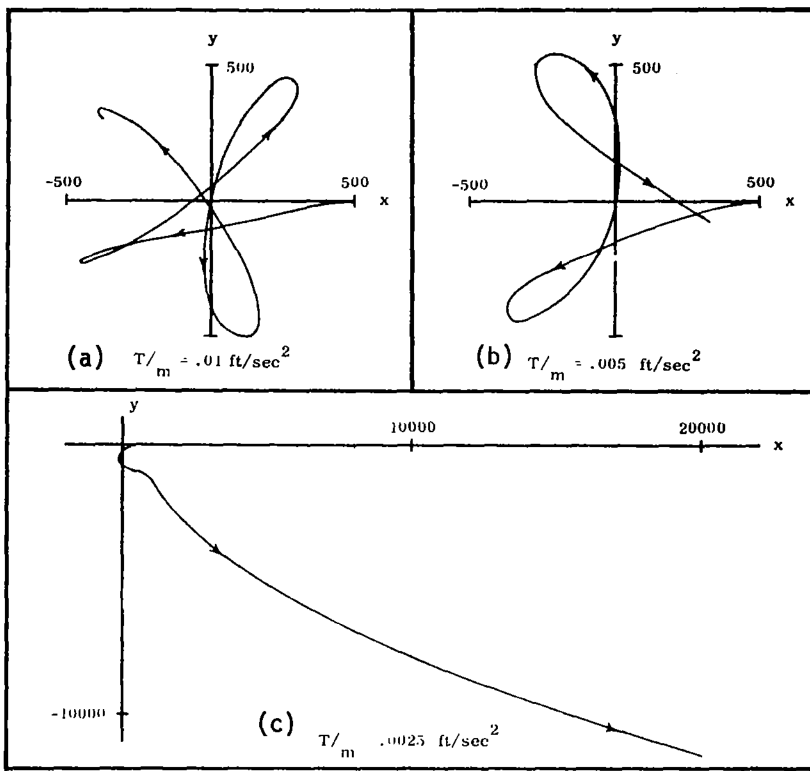
Clearly, then, an object on the end of a tetherline can be retrieved by exerting a constant line tension; but, where no initial tangential velocity exists, the process is time consuming.

Figure e (c) also illustrates a curious phenomenon which occurs if the value of T/m is reduced to 0.0025 foot per second^2. The mass turns around and proceeds ahead of the vehicle, losing altitude steadily. At the end of 5800 seconds the mass is 30,888 feet ahead of the vehicle and 14,321 feet below it with a velocity of 30 feet per second relative to the vehicle. Because the line is continuously reducing the orbital velocity of the mass, the mass is constantly forced into a lower orbit with a shorter period. This behavior is similar to the decay of a satellite orbit due to atmospheric drag. While this particular case is of no interest to us if we are seeking to retrieve the mass, it does suggest that a re-entry from a low earth orbit can be initiated by means of a very long cable without the expenditure of energy. The principle behind such a re-entry is very simple. If we consider the parent vehicle and an escape capsule as a system, we can say that the system possesses a certain total energy by virtue of the fact that it is in orbit. It is impossible to change the total energy of the system without applying an external force and thereby expending energy. But it is possible, by means of an internal force (the line tension in this case), to transfer energy from one part of the system (the escape capsule) to the other (the parent vehicle), thereby causing the escape capsule to re-enter the earth's atmosphere while the parent vehicle rises to a slightly higher orbit. The very low tensions required in such a scheme may make it entirely feasible to carry several hundred miles* of lightweight line as an emergency re-entry system in the event of retro-rocket failure. For the example given above, a line tension of less than 1 pound would be sufficient to cause a 1000-pound capsule to re-enter.

*Two hundred nautical miles of 15-pound test nylon line, 0.013 inch in diameter and 100 pounds in weight, can be wrapped on a spool 1 foot in diameter and 1 foot wide.

SOURCE: Mueller (137).

e. Path of a Mass on the End of a Tetherline if Line Tension is Kept Constant



CONSTANT REEL-IN SPEED

So far we have seen that a mass at the end of a long tetherline can be retrieved by impulsive jerks or by a constant line tension, but only with the expenditure of considerable time. Another quicker and more direct method is available: simply to reel in the line at a constant speed. Thus, if the mass is initially 500 feet from the vehicle and we reel in the line at 1 foot per second, the mass will arrive at the vehicle at the end of 500 seconds, regardless of the path it follows. The equations of motion which describe this situation are:

SOURCE: Mueller (137).

AN ANALYSIS OF THE BEHAVIOR OF LONG TETHERLINES IN SPACE

$$\ddot{x} = -2\omega\dot{y} - (T/m) \quad (6)$$

$$\ddot{y} = 2\omega\dot{x} + 3\omega^2 y - (T/M)\frac{y}{r} \quad (7)$$

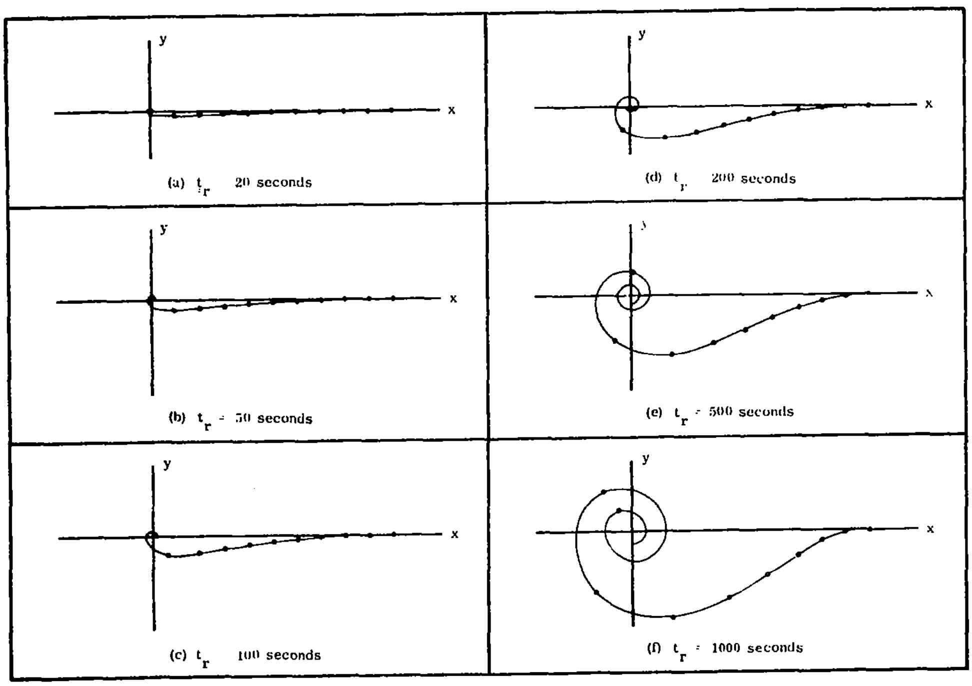
$$(T/m) = \frac{(x\dot{y} - y\dot{x})^2}{r^3} + \frac{y}{r}(2\omega\dot{x} + 3\omega^2 y) - \frac{x}{r}(2\omega\dot{y}) \quad (8)$$

where the symbols are as defined by figure d.

If we again look at the case where the mass is initially horizontally ahead of the vehicle and at rest relative to it, we find that the shape of the resulting trajectory depends only on the time required to reel in the line. The reel-in time, t_r, is simply the initial length of the tetherline divided by the rate at which the line is reeled in.

Figure f shows the trajectories which result for several different values of reel-in-time. Note that angular momentum is built up and that the mass follows a spiral path in toward the vehicle.

f. Path of a Mass on the End of a Tetherline if Line is Reeled in at Constant Speed



SOURCE: Mueller (137).

AN ANALYSIS OF THE BEHAVIOR OF LONG TETHERLINES IN SPACE

The reason for the build-up in angular momentum is that initially the mass, although it is at rest in the rotating xyz-coordinate frame, has angular momentum around the vehicle (with respect to inertial space) equal to $m\omega x_0^2$. In the absence of gravity gradient forces this angular momentum would be conserved and the mass would possess angular momentum per unit mass as measured in the xyz frame given by the expression:

$$h = \omega(r_0^2 - r^2) \qquad (9)$$

where r_0 is the initial line length and r is the instantaneous line length.

The effect of the gravity gradient term $(3\omega^2 y)$ in equation 7 is to modify the angular momentum slightly from the values predicted by equation 9. The digital computer data indicated that the deviation from equation 9 increases with reel-in time, approaching 10 percent for reel-in times of 1000 seconds. The actual values of angular momentum were slightly grater than predicted by equation 9 for the case where the mass was initially ahead of or behind the vehicle and slightly less than predicted by equation 9 for the case where the mass was initially above or below the vehicle.

Since tangential velocity, v_t, is related to angular momentum and instantaneous line length by the expression, $h = v_t r$, the build-up in angular momentum consequently causes the tangential velocity to tend toward infinity as the line length approaches zero. At the same time the centripetal acceleration acting on the mass and the tension in the tetherline also tend toward infinity as the line length is reduced to zero. The centripetal acceleration is related to angular momentum and line length by equation 10:

$$a_r = h^2/r^3 \qquad (10)$$

where a_r is the centripetal acceleration, and h is the angular momentum per unit mass.

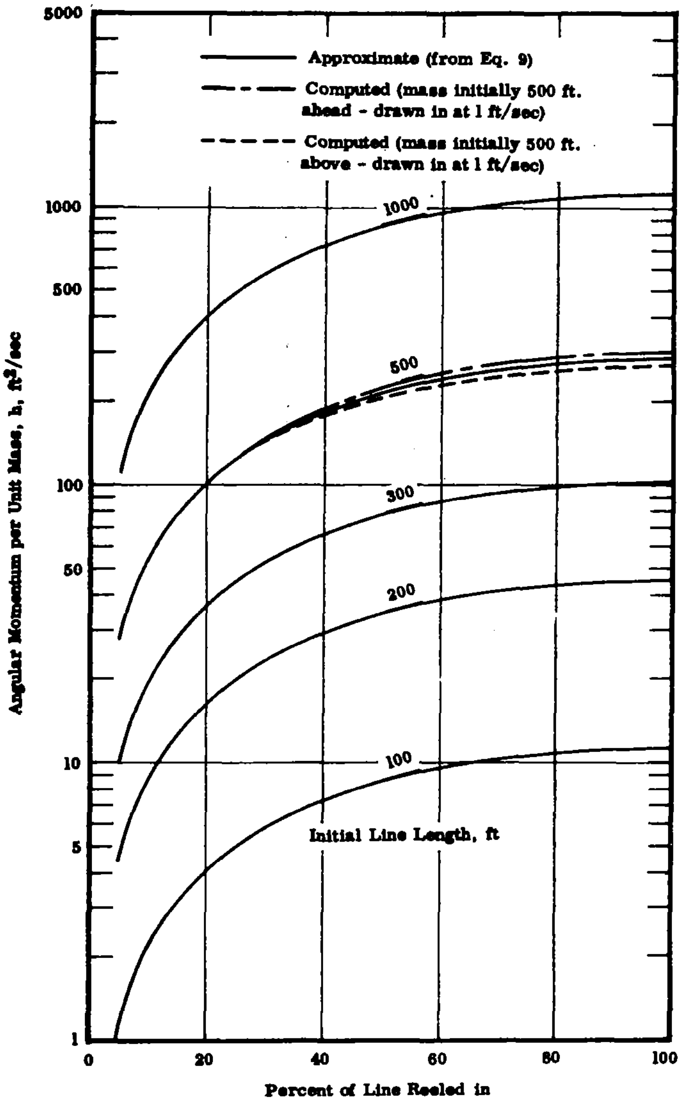
The relationship of tangential velocity and centripetal acceleration to angular momentum and instantaneous line length is plotted in figures h and i.

We may now apply the results of equations 9 and 10 to the specific problem of reeling in an astronaut who has lost his means of propulsion. If we assume that the man is initially 100 feet ahead of the vehicle and at rest relative to it, and that we reel the tetherline in at the rate of 1 foot per second, the reel-in time will be 100 seconds and the trajectory will be as shown in figure f (c). From equation 9 we know that the angular momentum per unit mass will approach a maximum of ωr_0^2 or, in this case, 11.40 feet^2 per second as the line. length approaches zero. We may, however, consider the man as retrieved when he comes within arm's reach or about 4 feet of the vehicle. At this distance the angular momentum per unit mass would be 11.38 feet^2 per second. The man would be

SOURCE: Mueller (137).

rotating around the vehicle at the rate of 0.70 radian per second or about 6.8 rpm, and he would be experiencing a centripetal acceleration of approximately 1/16 of a G.

g. Build-Up of Angular Momentum in XYZ Frame Due to Conservation of Angular Momentum in Inertial Space

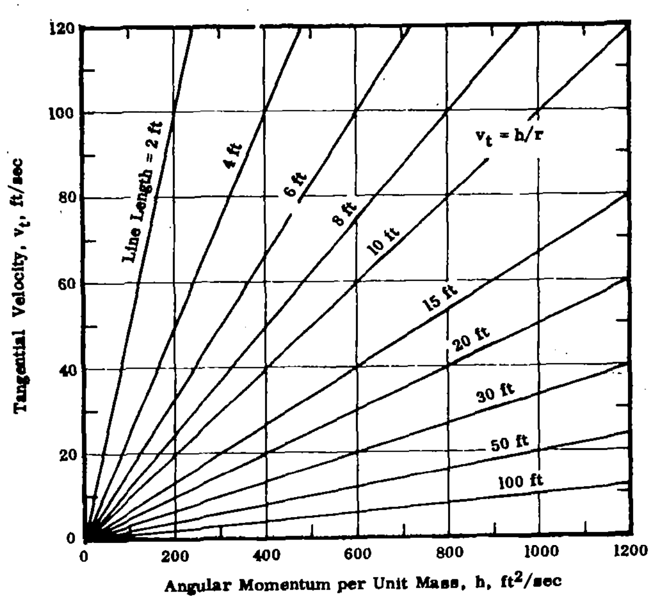


SOURCE: Mueller (137).

Figure g shows a plot of angular momentum as measured in the rotating xyz frame versus instantaneous line length as predicted by equation 9 for several values of initial line length. The dashed lines in figure g show the actual computed values of angular momentum for the case where the mass is initially 500 feet above and also for the case where the mass starts 500 feet ahead of the vehicle. The discrepancy between actual values and those predicted by equation 9 is small and illustrates how nearly angular momentum as measured in a nonrotating frame is conserved.

AN ANALYSIS OF THE BEHAVIOR OF LONG TETHERLINES IN SPACE

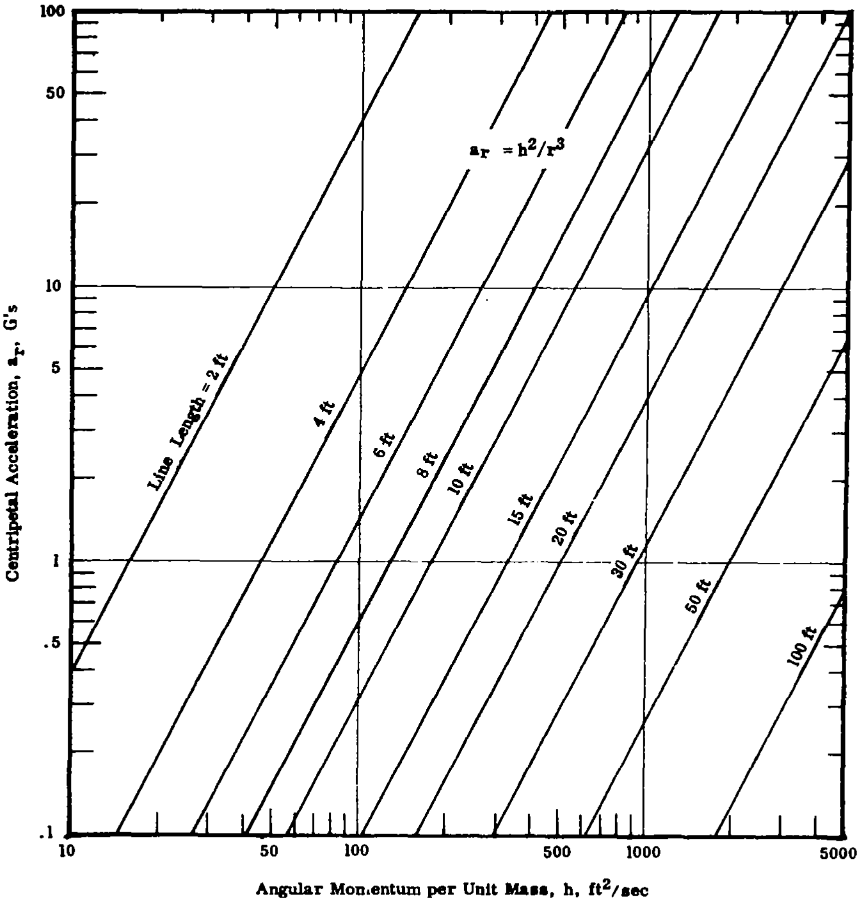
h. Relationship of Tangential Velocity and Line Length for Different Values



SOURCE: Mueller (137).

AN ANALYSIS OF THE VEHAVIOR OF LONG TETHERLINES IN SPACE

i. Relationship of Centripetal Acceleration and Line Length for Different Values of Angular Momentum



If, however, the man were initially 500 feet ahead of the vehicle instead of 100 feet, the angular momentum per unit mass would built to a maximum of 285 feet^2 per second. By the time the line was reeled in to 4 feet the man would be traveling at 72 feet per second and rotating around the vehicle at 170 rpm. He would, if still alive, be experiencing a centripetal acceleration of nearly 40 G's.

It is interesting to note that the speed at which the line is reeled in does not affect the maximum value of angular momentum. The maximum value of h depends

SOURCE: Mueller (137).

AN ANALYSIS OF THE BEHAVIOR OF LONG TETHERLINES IN SPACE

only on the initial length of the line. Changing the reel-in speed does change the time required to get the man in and, hence, affects the shape of the trajectory as seen in figure f. But the angular velocity and centripetal acceleration are a function only of the instantaneous line length and the original line length.

The results given above are for the case where the man is initially at rest with respect to the vehicle. If the man has any tangential component of velocity initially, the situation could be better or worse, depending on the direction of the tangential component. If, for example, the man had a counterclockwise component of exactly r_0, he would have exactly zero angular momentum with respect to inertial space and would not spiral around the vehicle as he was drawn in. The difficulty of retrieving a man by means of a tetherline, therefore, depends on both the initial line length and the initial component of tangential velocity. Or, more simply, the initial angular momentum as measured in a nonrotating coordinate frame is very nearly conserved and its magnitude determines the difficulty of retrieving an object by this method. Since, in an emergency retrieval of an astronaut, one cannot count on having a low value of angular momentum, the forces generated by reeling him in may be intolerable, particularly if the line is very long.

SUMMARY AND CONCLUSIONS

Three methods for retrieving an inert mass on the end of a long tetherline have been investigated in this paper. The first, in which the line is jerked to start the mass coasting in toward the vehicle while the line is left slack, results in a series of bounces as the mass coasts in along a curved path and is jerked back toward the vehicle each time the line becomes taut. The second method, in which a constant line tension is maintained as the line is reeled in or out, results in a complex, looping path which can be made to intersect the vehicle only after a fairly long time. Both of these methods require accurate control over the line tension or the impulse imparted to the mass and neither seems attractive as a means of retrieving an astronaut whose self-maneuvering unit has failed.

The third method, which involves reeling in the line at a constant rate, has the advantage of being direct and uncomplicated. However, it results in a spiral path which could wrap the line around the vehicle and which causes a rapid buildup of tangential velocity and centripetal acceleration.

The problem of retrieving a mass on the end of a tetherline reduces to one of conservation of angular momentum in inertial space. The only way in which the mass can be reeled in safely is to reduce this angular momentum to zero. Since we are assuming that the mass is inert (without propulsion), one way to accomplish this is to maneuver the vehicle to kill the apparent drift of the mass against the star background. If the line of sight between the vehicle and

SOURCE: Mueller (137).

the mass is not rotating with respect to inertial space (as defined by the stars), the problems associated with all three methods of retrieval are minimized.

In view of the dubious safety value which a long lifeline offers to an astronaut operating outside his vehicle, the astronaut would probably be better off without the encumbrance of such a tetherline. If his self-maneuvering unit fails, it would be simpler for the vehicle to maneuver toward the drifting astronaut.

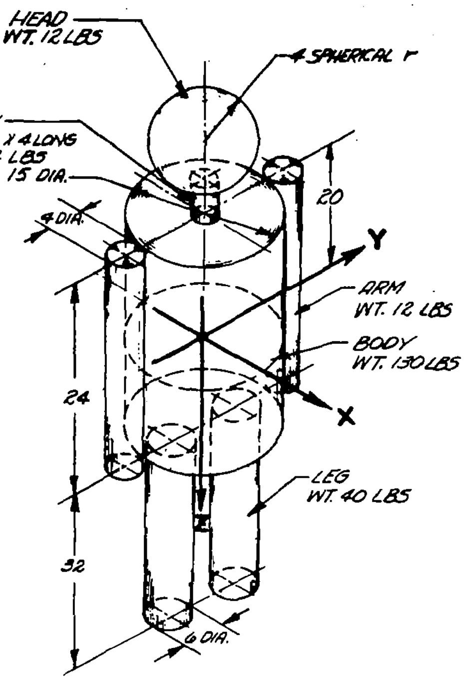
Schemes for using tetherlines as an aid in the orbital docking of two vehicles must take into account the problems associated with the conservation of angular momentum. This should present no great problem since one or both of the vehicles would have propulsion.

The possibility of using long tetherlines as a means of effecting re-entry from low earth orbits has also been presented in this paper. Further study to determine the feasibility of such a scheme is required.

SOURCE: Mueller (137).

SELF-MANEUVERING

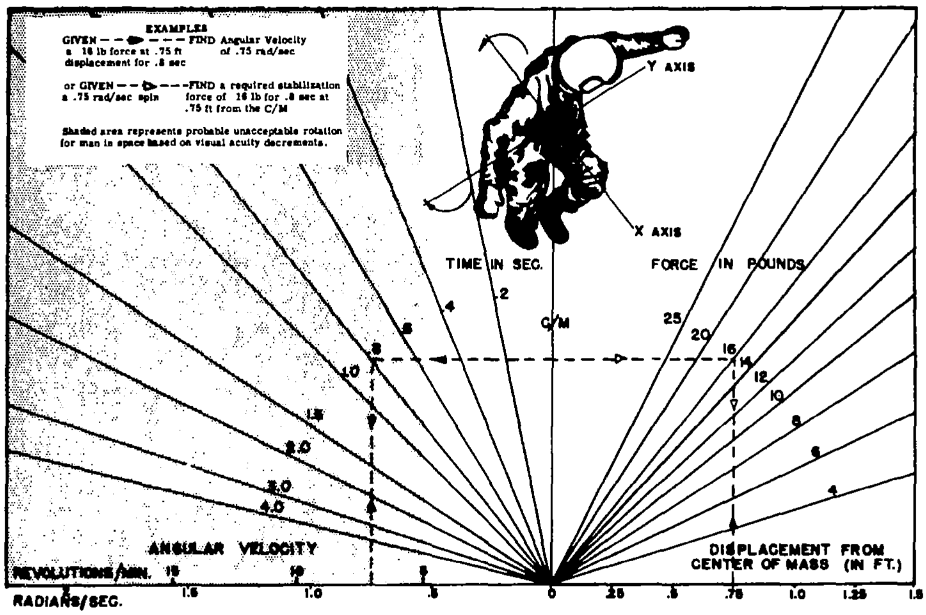
a. Rigid Man Model



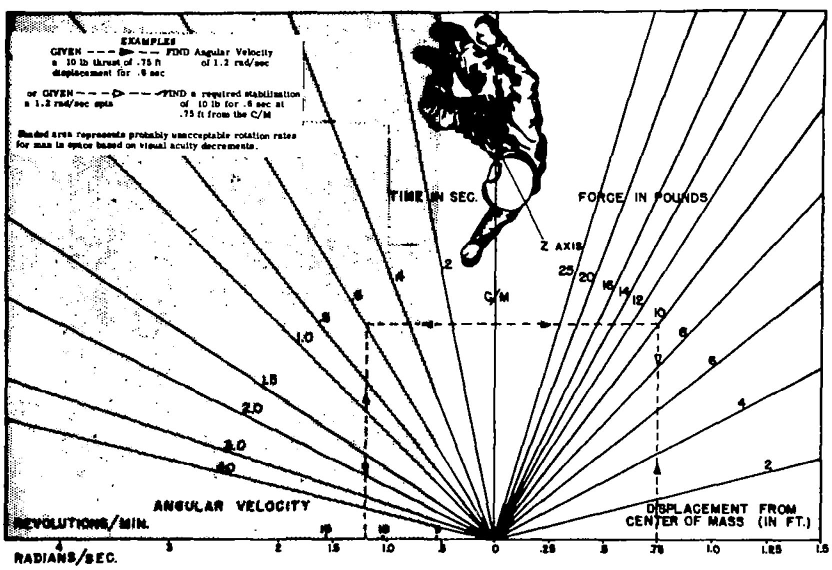
SOURCE: Simons and Gardner (169).

SELF-MANEUVERING

b. <u>Angular Acceleration and Thrust Misalignment About the X and Y Axes</u>



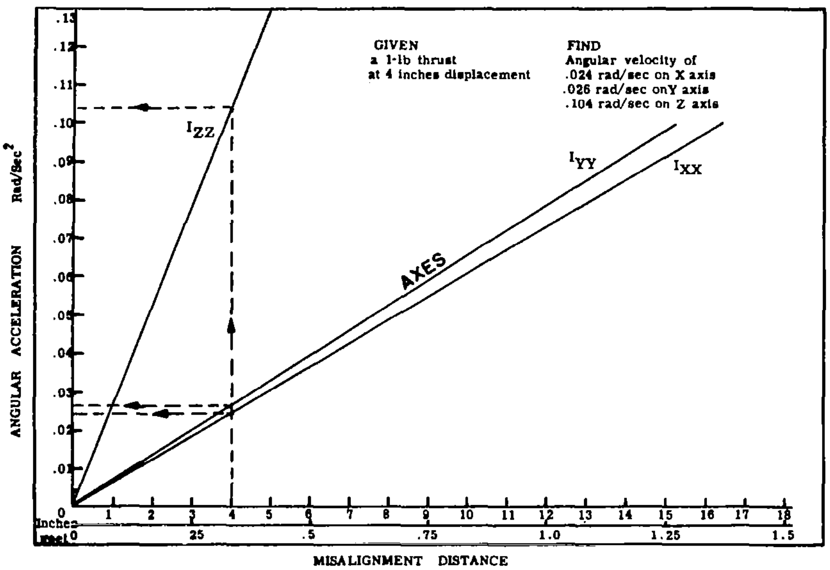
c. <u>Angular Acceleration and Thrust Misalignment About the Z Axis</u>



<u>SOURCE</u>: Simons and Gardner (169).

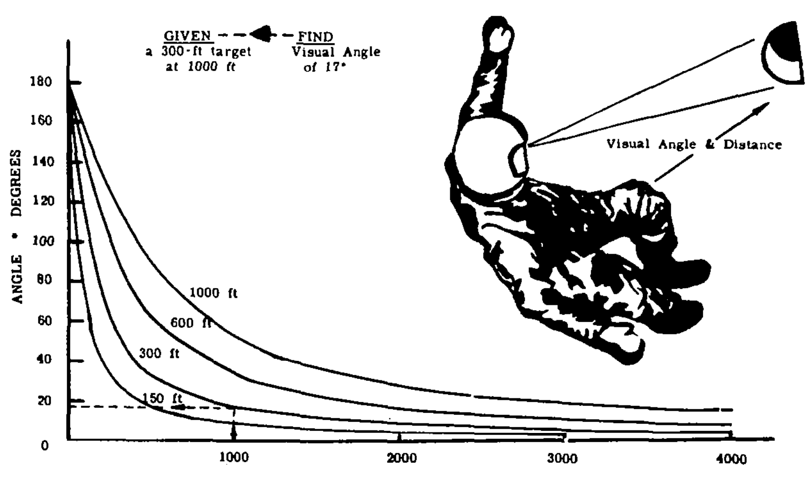
SELF-MANEUVERING

d. Angular Acceleration and One-Pound Thrust Misalignment About the Three Axis



e. Visual Angle and Distance

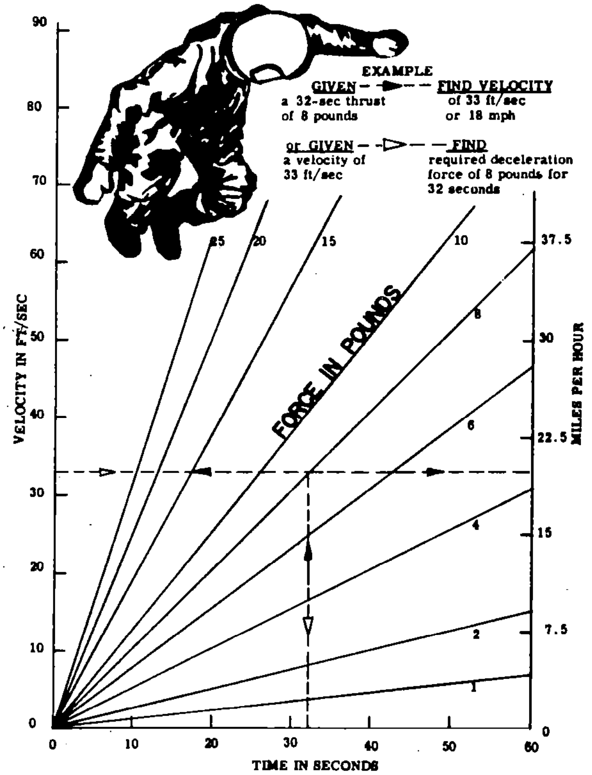
SUBTENDED ANGLE CHANGE VS DISTANCE TO GO FOR FOUR DIAMETERS



SOURCE: Simons and Gardner (169).

SELF-MANEUVERING

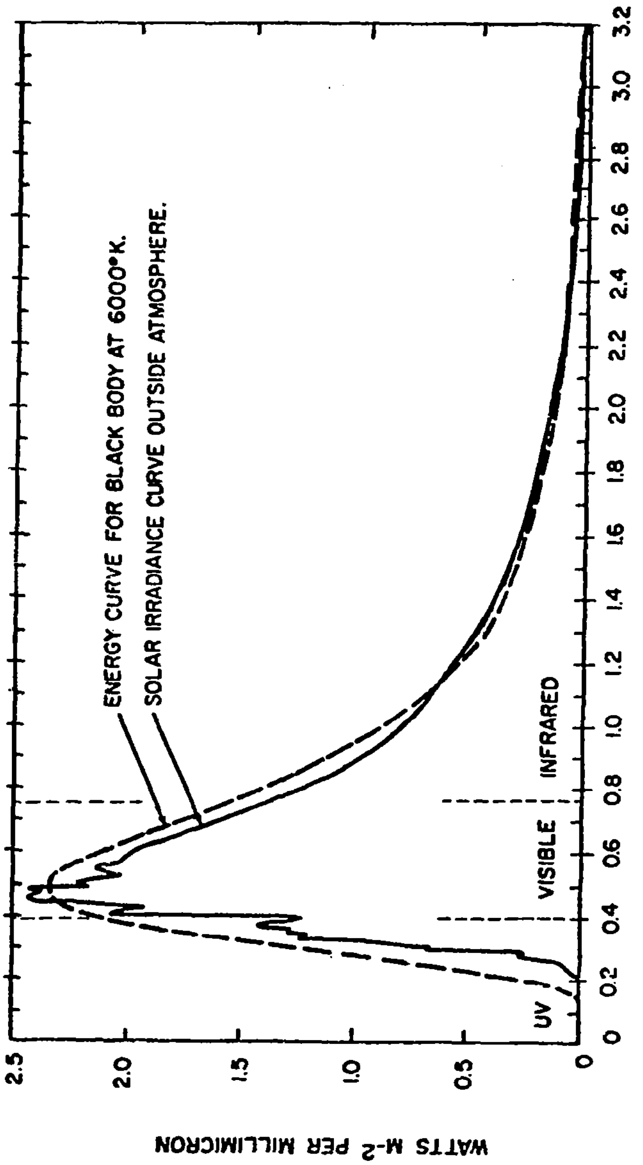
f. Translation Velocity, Time and Force



SOURCE: Simons and Gardner (169).

SOLAR RADIATION

a. Spectral Energy Curve of Solar Radiation



SOURCE: Saylor, et al (159).

SOLAR RADIATION

b. Energy Distribution of Solar Electromagnetic Radiation

Type	Wavelengtn Interval in Angstroms	Approximate Percentage of Radiant Energy
x-ray and ultraviolet	1 to 2,000	0.2
ultraviolet	2,000 to 3,800	7.8
visible	3,800 to 77,000	41
infrared	7,000 to 10,000	22
infrared	10,000 to 20,000	23
infrared	20,000 to 100,000	6

c. Solar Radiation Temperatures

Wavelength, A	Temperature, °K
3500	5500
2900	5500
2600	5000
2200	4900
2000	4500
1500	4500
1200	6000

SOURCE: Saylor, et al (159).

EXTRAVEHICULAR ENVIRONMENT

RADIATION

SOLAR RADIATION

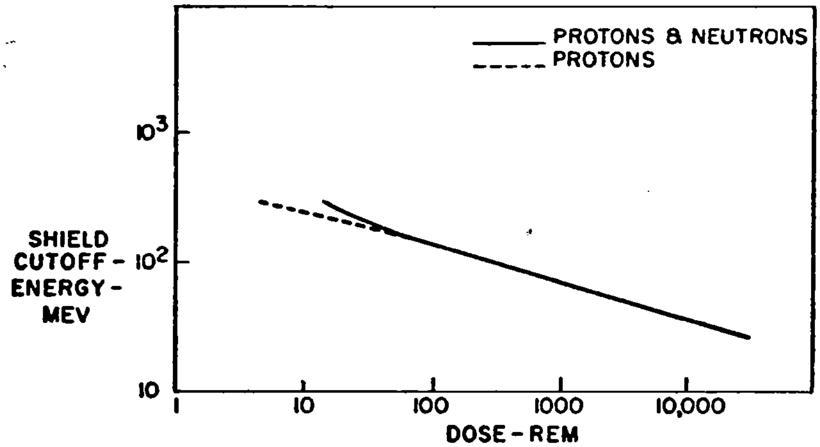
d. Distinctions Between Galactic Cosmic Rays and Flare Produced High Energy Solar Particles

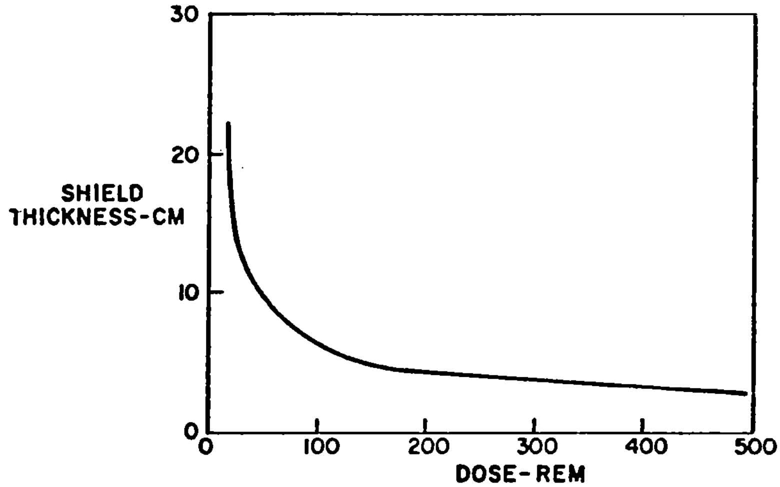
CRITERION	COSMIC RAYS	SOLAR CORPUSCLES
Spatial distribution	Isotropic beyond terrestrial influence (no preferred direction of arrival)	Nonisotropic at onset, later becoming diffused through solar system
Composition	Approximately 75-80% proton, 15-19% helium nuclei, remainder nuclei of heavier elements to atomic numbers 26 or 27	Almost all protons, some alpha particles, no evidence for heavy nuclei
Temporal variations	Permanent phenomenon, practically constant with time	Transient radiation, greatly variable with time
Energy	Extending to at least 10^{17} ev in some cases (much greater maximum than solar particles)	About 10^{10} ev highest recorded
Origin	Theories only; perhaps supernovae explosions in the galaxy	Active regions of flares on the sun
Intensity	Relatively low: about 2 particles/cm^3/sec of all energies	Very high: may be as high as 10^6 particles/cm^2/sec
Biological effects	Primarily chronic; perhaps some vital cell destruction	Primarily acute damage; possible sudden illness; incapacitation, or death

SOURCE: Saylor, et al (159).

SOLAR RADIATION

e. Shield Cutoff Energy and Shield Thickness as a Function of Dose

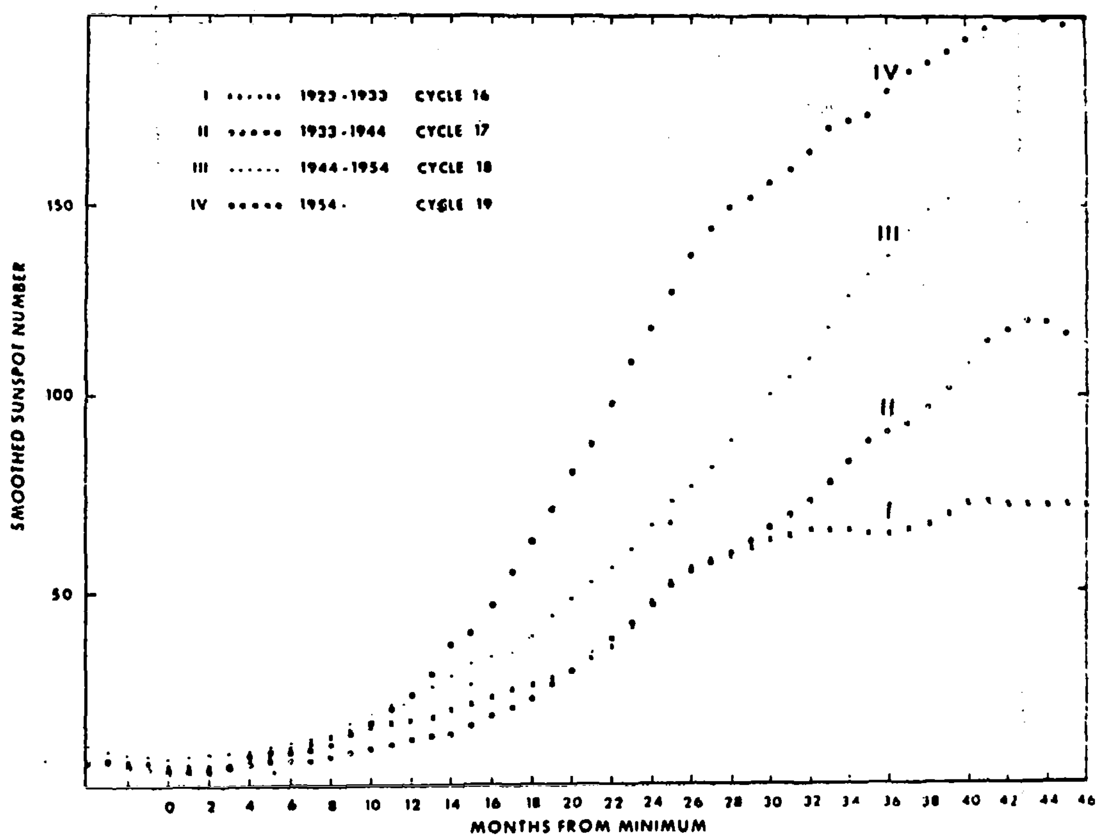




SOURCE: Saylor, et al (159).

SOLAR RADIATION

f. Four Recent Solar Cycles

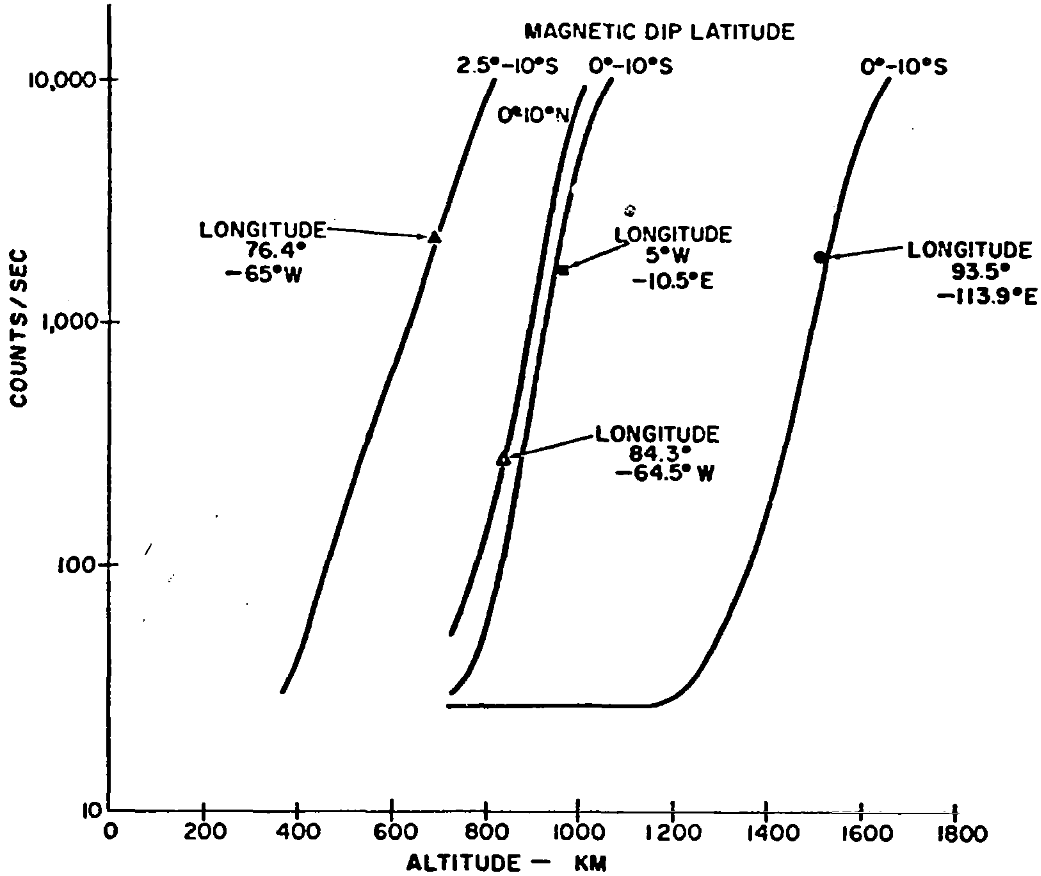


NOTE: Sunspot number at 18 months is thought to show tendency towards a high or low peak.

SOURCE: Saylor, et al (159).

SOLAR RADIATION

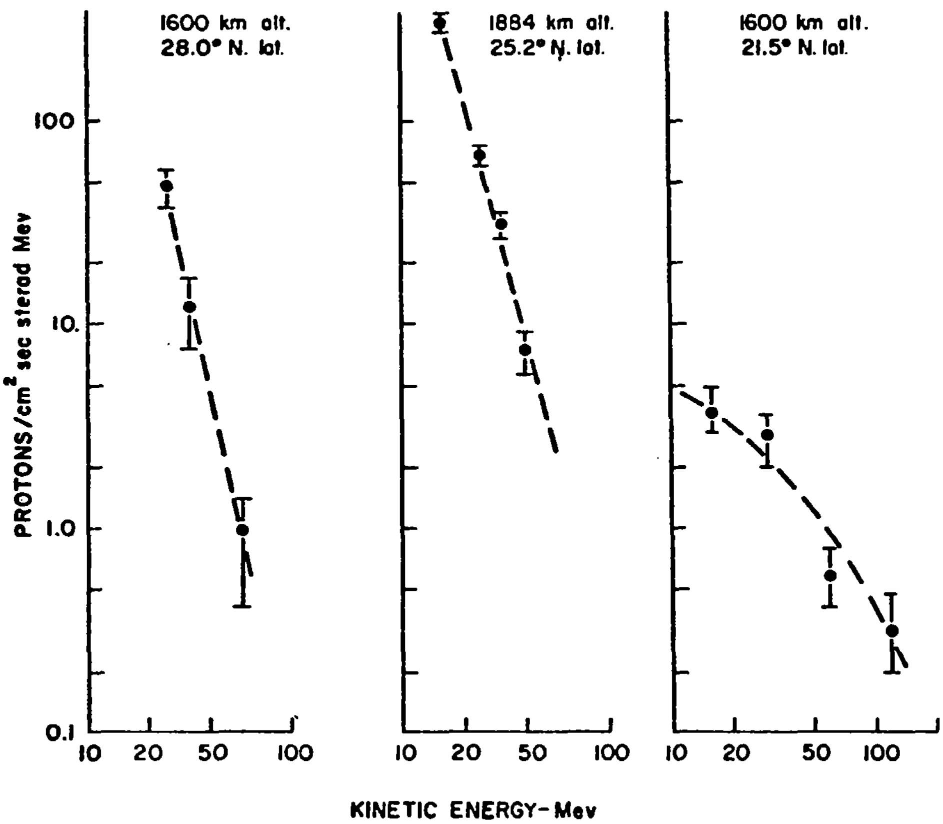
g. Variation of Radiation Intensity with Longitude



SOURCE: Saylor, et al (159).

SOLAR RADIATION

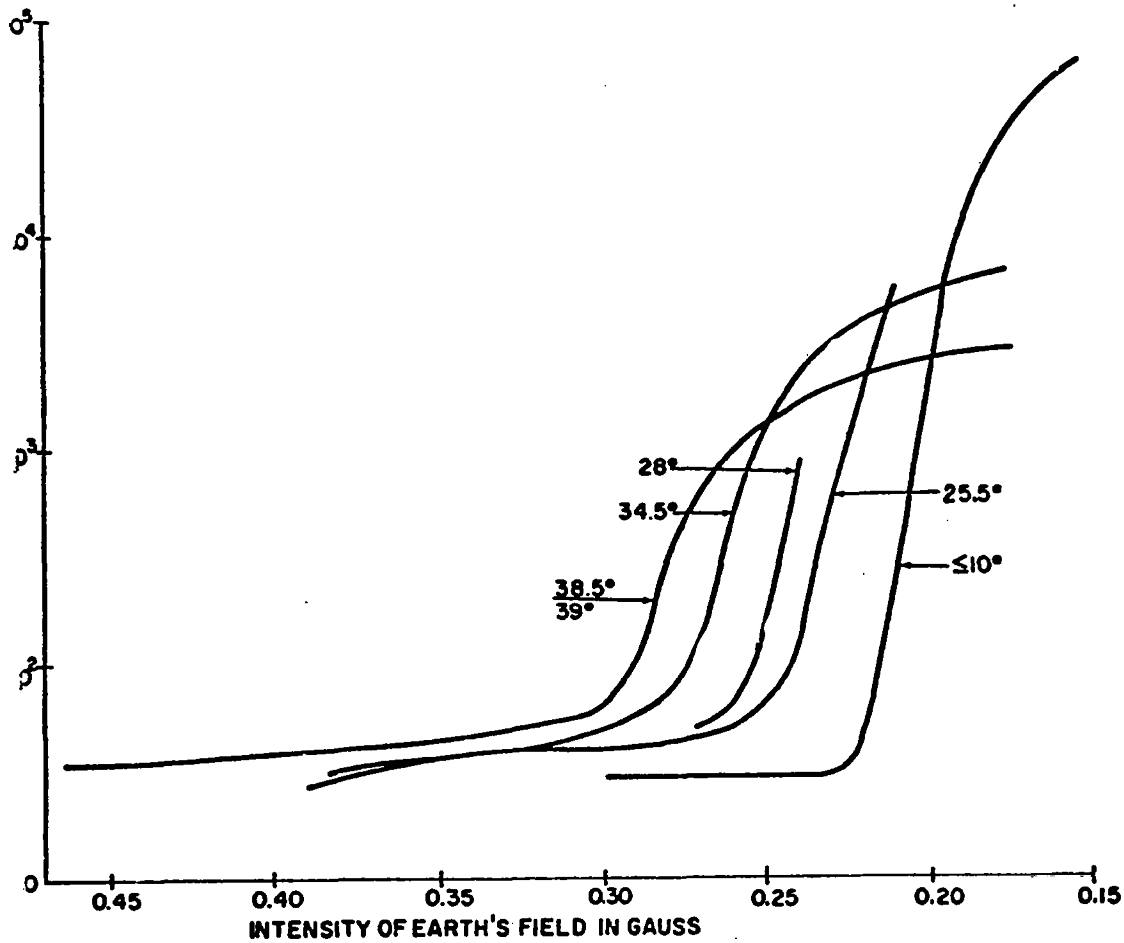
h. Differential Energy Spectra of Protons in the Inner Van Allen Belt Showing Variation With Latitude



SOURCE: Saylor, et al (159).

SOLAR RADIATION

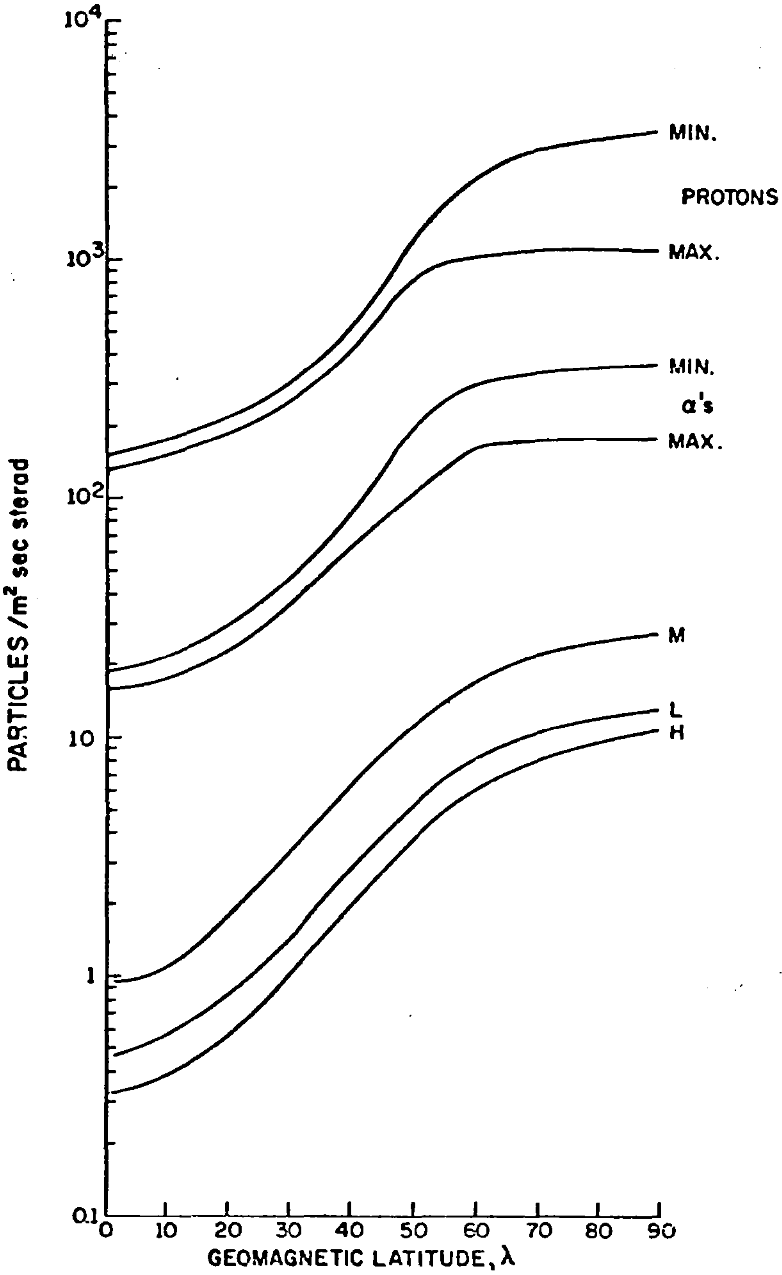
i. Variation of Radiation Intensity with Geomagnetic Latitude



SOURCE: Saylor, et al (159).

SOLAR RADIATION

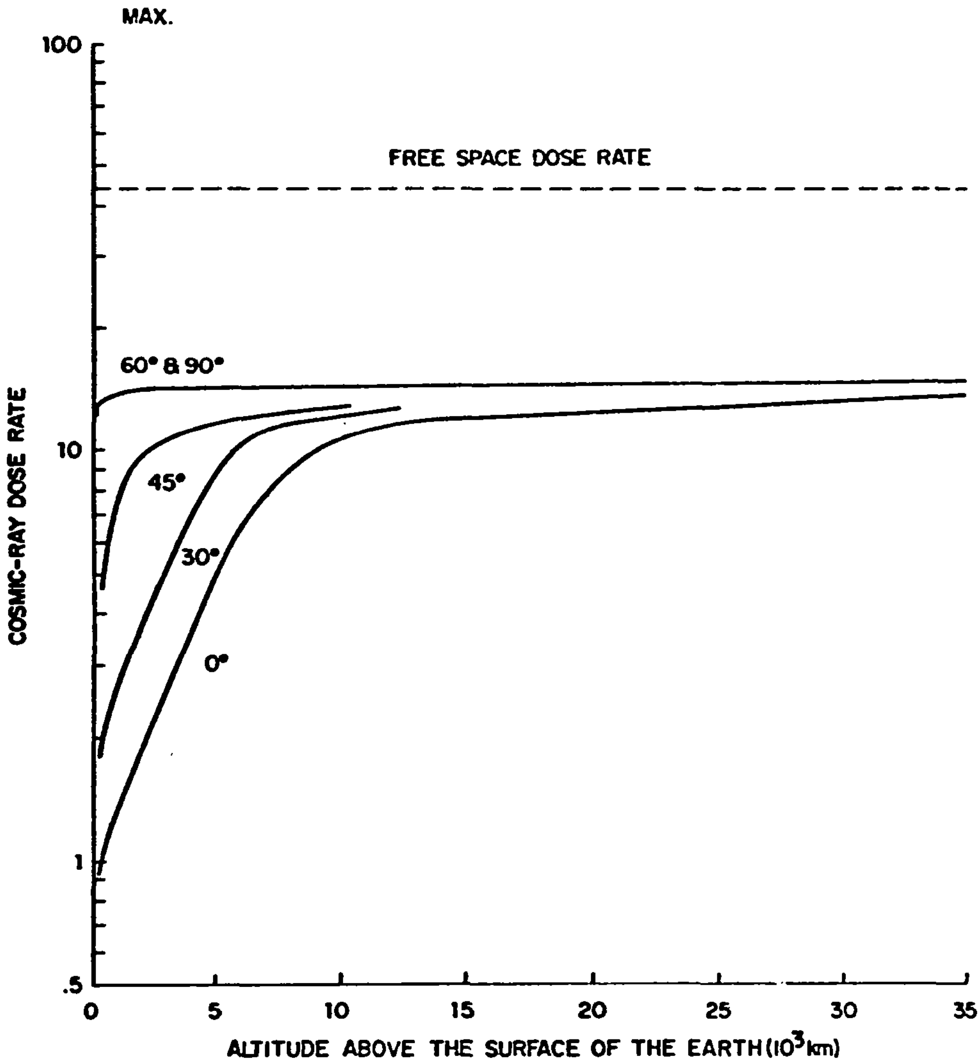
j. Intensity of the Various Primary Components of the Galactic Cosmic Radiation as a Function of Geomagnetic Latitude



SOURCE: Syalor, et al (159).

SOLAR RADIATION

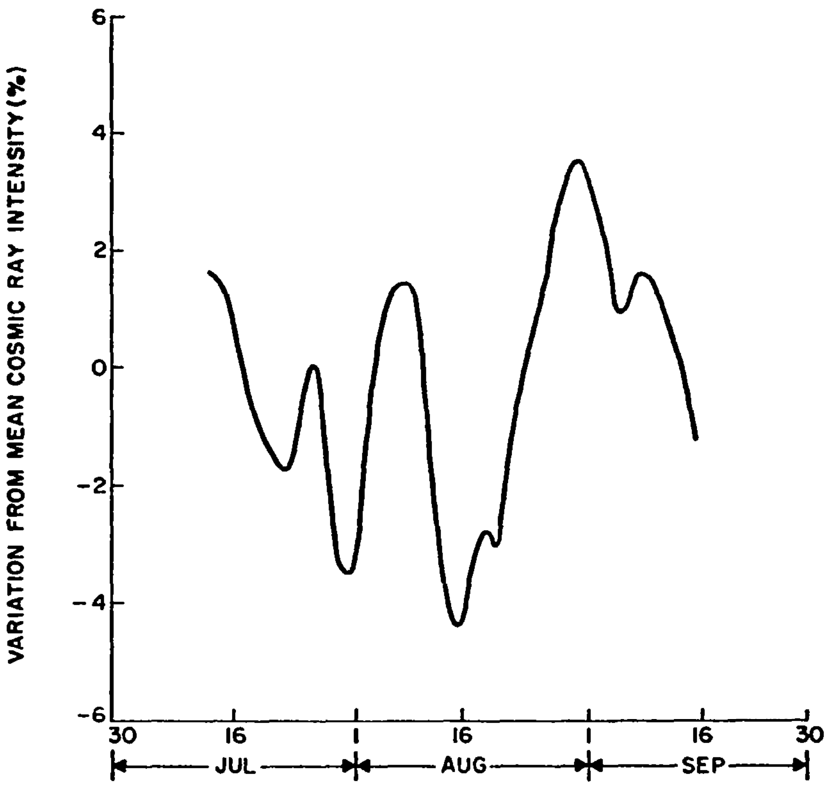
k. Cosmic Radiation Dose Rate as a Function of Geomagnetic Latitude for High Altitudes During the Period of Solar Activity Maximum



SOURCE: Saylor, et al (159).

SOLAR RADIATION

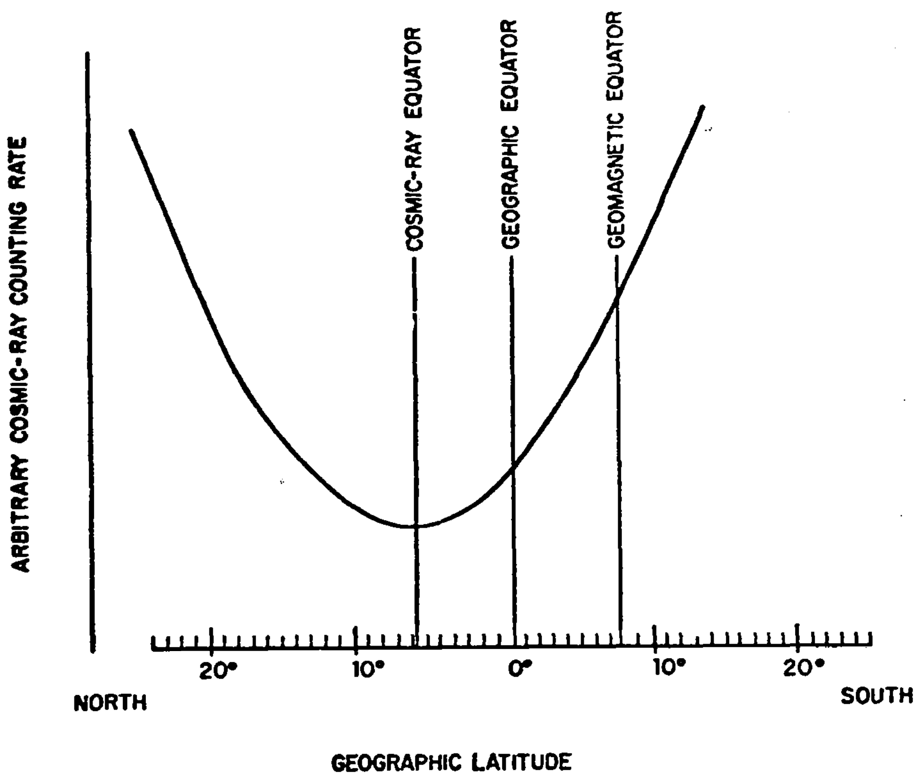
1. Typical 27-Day Cosmic Ray Intensity Variation



SOURCE: Saylor, et al (159).

SOLAR RADIATION

m. Position of the Geographic, Geomagnetic, and Cosmic Ray Equations



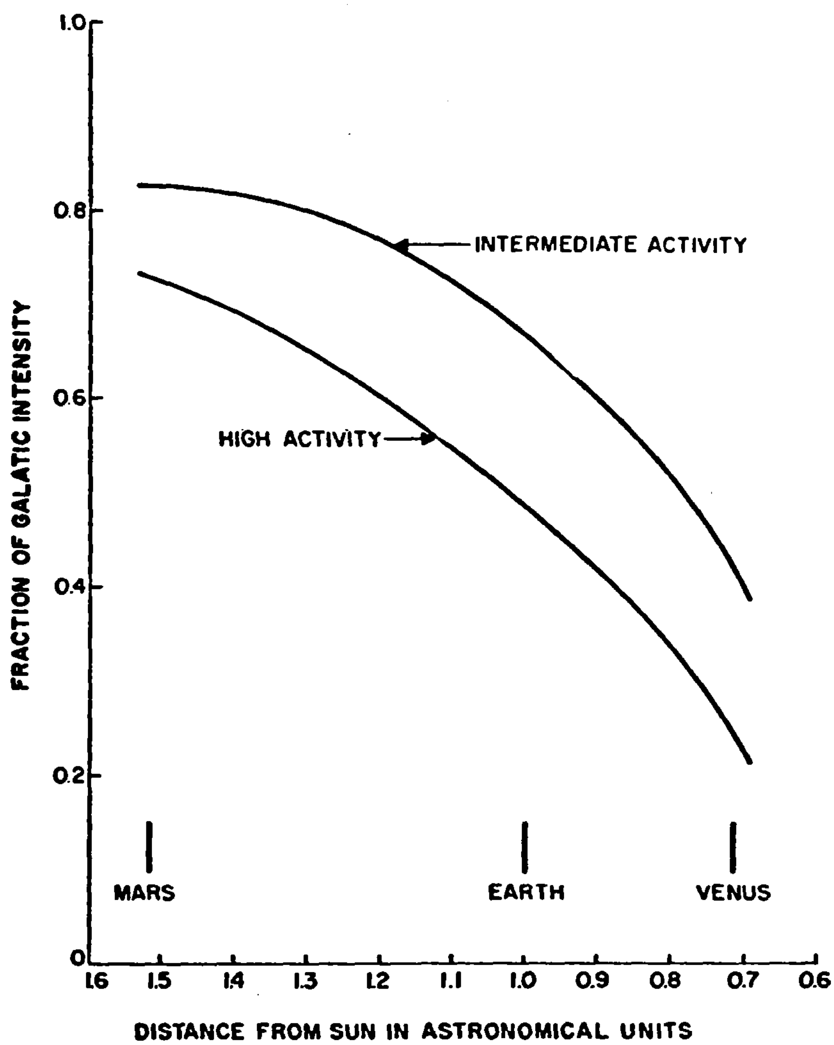
SOURCE: Saylor, et al (159).

EXTRAVEHICULAR ENVIRONMENT

RADIATION

SOLAR RADIATION

n. Theoretical Solar Modulation of Cosmic Ray Intensity Interplanetary Space



SOURCE: Saylor, et al (159).

EXTRAVEHICULAR ENVIRONMENT

RADIATION

VAN ALLEN BELTS

The knowledge of the immense radiation field, temporarily trapped in the geomagnetic field is demonstrated by results obtained by the Explorer XII Energetic Particle Satellite. This satellite, launched into a highly elliptical orbit (perigee 300 km, apogee 77,250 km) completed 102 orbits in 112 days lifetime and transmitted back to earth findings that can be summarized as follows:

1. The existence of high energy protons of the order of several ten million ev in the heart of the Inner Van Allen Belt was confirmed at approximately 1.5 earth radii. (Measured from the center of the earth). However, the altitude range of protons extends much larger than previously assumed; i.e. they are trapped to an altitude of at least 8 earth radii. At 3 earth radii, the average proton energy is a fraction of one Mev but their flux density rises to a maximum and equals that of the electrons present ($10^8/cm^2$ - sec.). Their average energy ranges from 100 Kev to 400 Kev. The proton flux density now appears to decrease slowly with distance from the earth.

2. Also the altitude range of electrons extends farther than previously measured with Explorer I, III, IV, and Pioneer III and confirmed by Sputnik III and Mechta. Soft electrons with energies of several ten-thousand ev were found from 6 earth radii to the outer edge of the magnetosphere. (The outer edge varies daily from 8 to 12 earth radii).

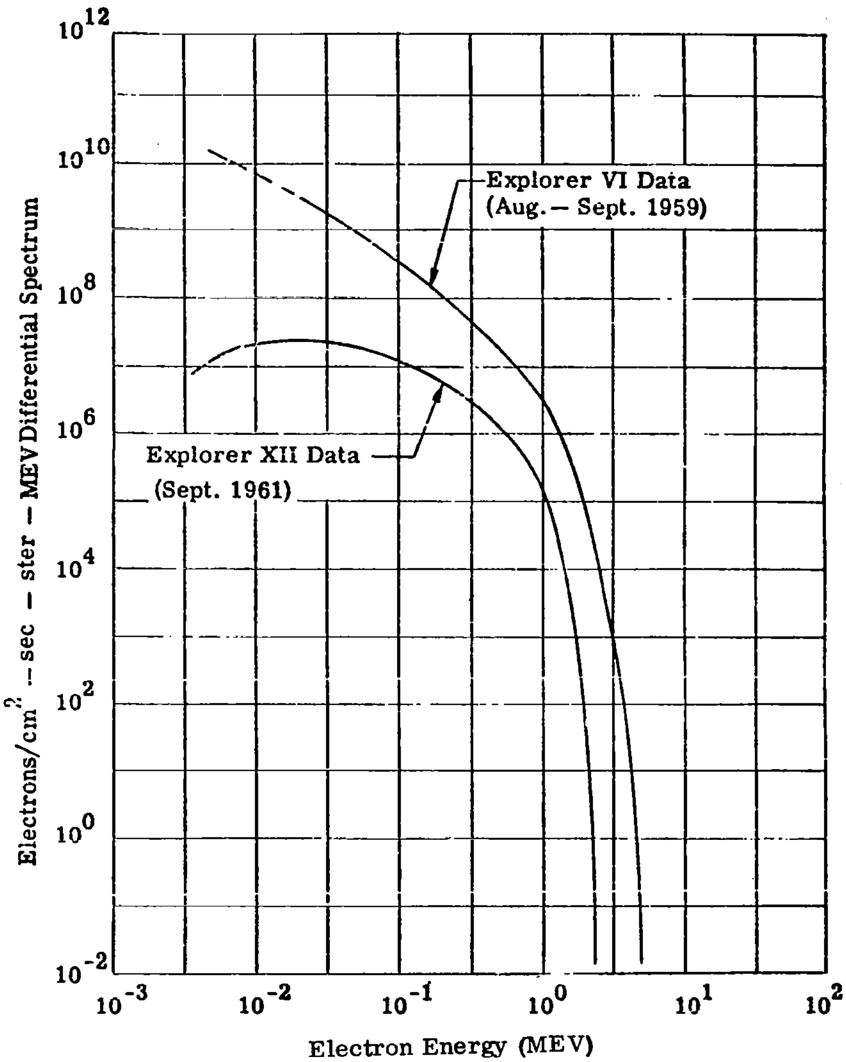
3. The flux density of electrons in the heart of the outer Van Allen Belt is about 1000 times lower than the previous estimate of $10^{11}/cm^2$ - sec. In other words the highest flux density of electrons with energies about 40 Kev does not exceed $10^8/cm^2$ - sec. Figure a presents a summary of these data.

4. The outer edge of the trapped particle region exhibits an abrupt discontinuity; the low energy electron radiation falls to the free space radiation described in the foregoing section.

SOURCE: Study of Space Maintenance Techniques (182).

VAN ALLEN BELTS

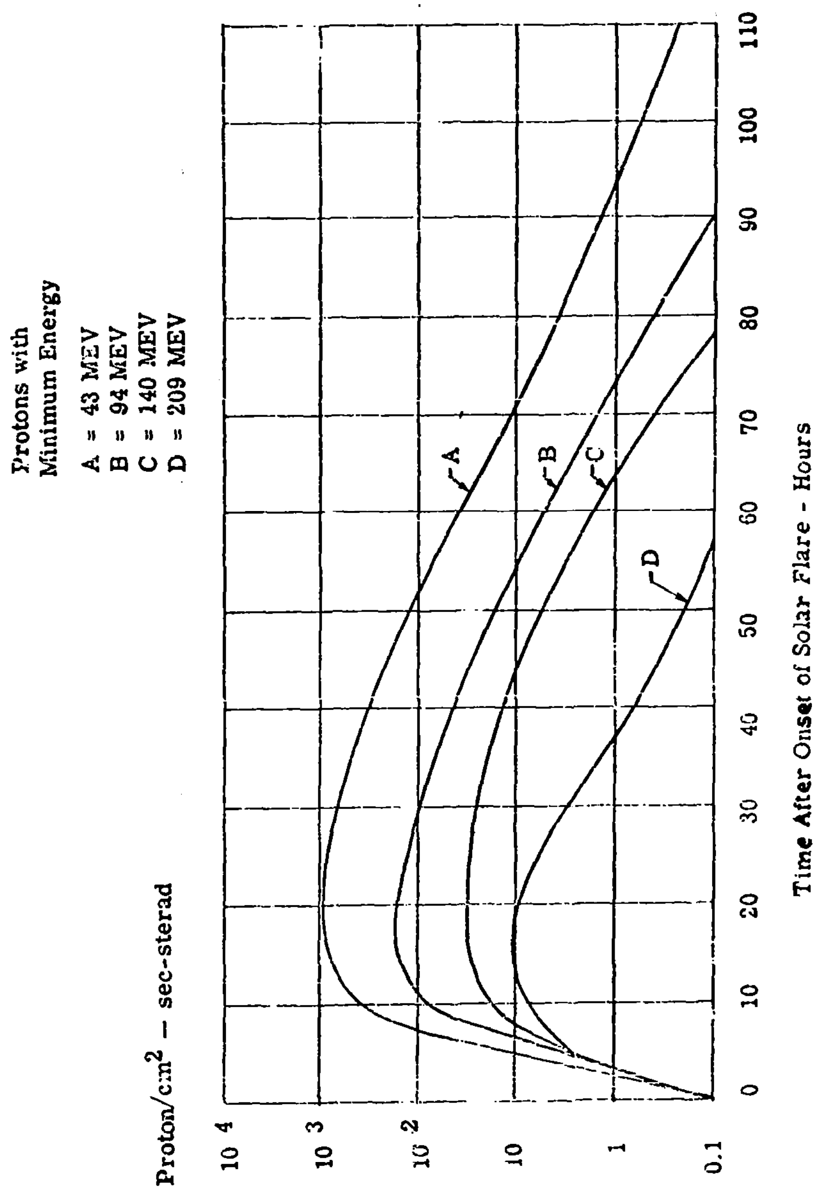
a. Electron Distribution in Outer Van Allen Belt



SOURCE: Study of Space Maintenance Techniques (182).

VAN ALLEN BELTS

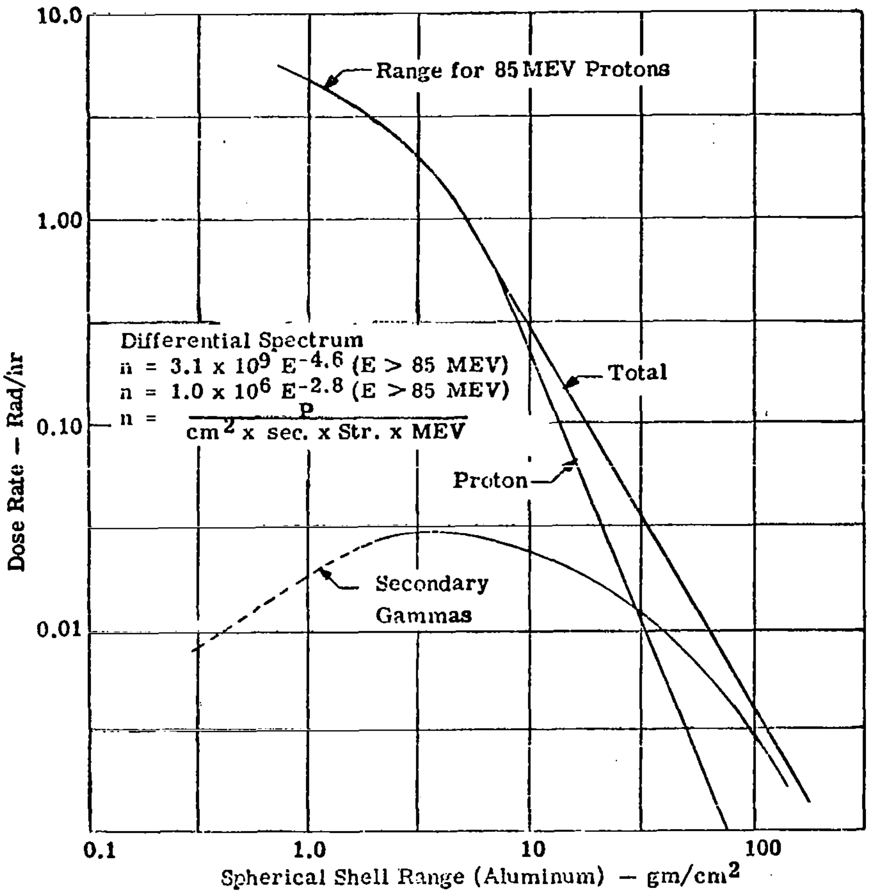
b. Solar Flare Decay With Time



SOURCE: Study of Space Maintenance Techniques (182).

VAN ALLEN BELTS

c. Gamma Dose for a Solar Flare



The principal sources of radiation for the mission in environments which lack an atmosphere will be unattenuated solar flares and galactic cosmic rays.

a. Internal Dose Rate Calculation Methods

The radiation flux levels and energies which will be encountered in space travel abouve 800 km altitude are a complex function of:

(1) Time - determining the presence or absence of solar flare or storms and if the outer Van Allen belt is extended or contracted due to solar storms.

SOURCE: Study of Space Maintenance Techniques (182).

VAN ALLEN BELTS

(2) Position - determining the number and energy of the radiation impinging on the vehicle due to the geomagnetic forces at the particular position.

Table d describes the radiation sources which will determine the radiation dose during each mission.

d. Radiation Sources for Various Space Missions

MISSION	VAN ALLEN BELTS	COSMIC RAYS	SOLAR FLARES
560 km orbit	outer only	attenuated	attenuated; time dependent
traversal for 24-hour (36,000 km) orbit	both inner and outer	variable attenuation	variable attenuation; time dependent
24-hour(36,000) orbit	outer only	unattenuated	unattenuated; time dependent
traversal for lunar mission	both inner and outer	variable attenuation	variable attenuation; time dependent
lunar site	none	unattenuated	unattenuated; time dependent

The principal cause of attenuation is the interaction between the solar flare and galactic cosmic rays with the earth's magnetic field and its atmosphere. As discussed previously, the time dependence is due to the 11 year solar flare cycle. A slight time dependence is also exhibited by galactic cosmic radiation, but because of their extremely high energy, the effect on absorbed radiation dose is slight. Thus, any time dependence of galactic rays is ignored in the following calculations.

SOURCE: Study of Space Maintenance Techniques (182).

RADIATION

VAN ALLEN BELTS

e. Doses for Various Solar Flares

RADIATION TYPE	INITIAL AVERAGE ENERGY	1.5 gm/cm^2 ALUMINUM
Relativistic Solar Flare	400 MEV	5×10^1 rad
High Energy High Flux Solar Flare	50 MEV	3×10^4 rad
High Energy High Flux Solar Flare	40 MEV	1×10 rad
High Energy Low Flux Solar Flare	40 MEV	1×10^{-2} rad

It can be seen in Table e that relativistic solar flares of high energy cause smaller doses than the less energetic flares. This difference can be explained by considering the proton energy loss per distance travel in an object. If the solar flare protons are highly energetic, they will penetrate an object without depositing much energy.

The absorbed proton dose rates (r/hour) behind wall surface densities of 0.08 and 1.5 gm/cm^2 for different missions is given in Table f.

f. Proton Dose Rates (Roentgen/Hour)

MISSION	RADIATION SOURCE					
	VAN ALLEN BELT		GALACTIC COSMIC RAYS		SOLAR FLARE	
	SUIT	VEHICLE	SUIT	VEHICLE	SUIT	VEHICLE
550 Km Orbit	9×10^{-3}	5×10^{-3}	1×10^{-3}	1×10^{-3}	3.2	2.0
36,000 km Orbit	1.9	1.2	3×10^{-3}	2×10^{-3}	5.3	3.3
Lunar Site	0	0	1.3×10^{-2}	8×10^{-3}	4.3	2.7*
*The Moon faces opposite the sun during full moon on earth.						
Traversal for						
550 km Orbit	-	5×10^{-3}	-	1×10^{-3}	-	2.0
36,000 km Orbit	-	1.1	-	2×10^{-3}	-	3.3
Lunar Trajectory	-	1.1	-	8×10^{-3}	-	2.7*

SOURCE: Study of Space Maintenance Techniques (182).

RADIATION

VAN ALLEN BELTS

The Van Allen belts will cause the highest constant dose rates behind the two shields considered with galactic rays being second highest. Secondary gamma doses from proton bombardment were not considered due to the low surface density of the shields considered.

Solar flare was the only sporadic source of radiation considered.

Electron Dose Rate Calculations

Electron bombardment gives rise to two effects: the Bremsstrahlung and the direct electron deposition to an internal component or occupant. The electron spectra employed in these calculations are for the outer Van Allen region (Explorer XII) shown in Figure a along with the electron spectra from the Explorer VI probe.

These spectra were considered most important because:

(1) The known Inner Van Allen belt electron spectra are composed primarily of low energy electrons, which are easily absorbed in the shields considered. Therefore, they would not significantly affect the absorbed dose for objects behind the shield.

(2) All other sources of electrons from proton-spallation products due to solar flare or galactic rays are considered small. The electrons from the albedo neutrons are considered part of the Van Allen belt environment.

In comparing these spectra, it will be noted that the Explorer VI spectrum contains a larger number of electrons of higher energies than the spectrum of Explorer XII. It should be noted, that all of the electrons will be stopped in the space vehicle wall, but only those electrons below 0.3 MEV will be stopped in the space suit. This direct deposition of electrons in the space suit occupant will increase the absorbed dose since a human body will stop all electrons from 0.3 to 5 MEV. The absorbed dose rates due to electron deposition from the spectra of Explorer XII and VI behind a 1.5 gm/cm^2 aluminum shield would be 10 and 80 rad/hour respectively.

Another factor which should be considered in Bremsstrahlung production is the atomic number (Z) of the structural material. For the nylon-rubber extravehicular suit (Z = 8, surface density = 0.08 gm/cm^2) the Bremsstrahlung dose rate is approximately 400 R/hour. The dose rates behind a comparable thickness of aluminum (Z = 13) and steel wall (Z = 26) for the peak electron flux in the Explorer VI spectrum are 650 R/hour and 1200 R/hour, respectively.

After adjusting for the surface densities of the walls considered, the dose rates for electron deposition and Bremsstrahlung were computed for the peak flux values and are shown in Table g.

SOURCE: Study of Space Maintenance Techniques (182).

EXTRAVEHICULAR ENVIRONMENT

RADIATION

VAN ALLEN BELTS

g. Internal Vehicle Dose Rate (R/Hour*)

	Suit**	Vehicle	24-HOUR ORBIT Suit**	24-HOUR ORBIT Vehicle	LUNAR TRAJECTORY*** Suit**	LUNAR TRAJECTORY*** Vehicle	LUNAR SITE Suit**	LUNAR SITE Vehicle
VAN ALLEN	9×10^{-3}	5×10^{-3}	1.9	1.2	16.0	8.0	0	0
GALACTIC COSMIC	2×10^{-3} to 2×10^{-4}	2×10^{-3} to 0.2×10^{-3}	3×10^{-3}	2×10^{-2}	1×10^{-2}	6×10^{-4}	1.3×10^{-2}	8×10^{-3}
	Depending on orbit inclination.	Depending on orbit inclination.						
MAXIMUM TOTAL DOSE RATE (VAN ALLEN AND GALACTIC COSMIC)	1.1×10^{-2}	7×10^{-3}	1.9	1.22	--	--	1.3×10^{-2}	8×10^{-3}

*R is defined as equal to roentgen, rad or rem
** Dose rate to which astronaut (not suit) is subjected
*** The man is exposed to the Van Allen belt radiation for approximately 4 hours during this trajectory.

h. Important Quantities of the Exosphere

Altitudes	Pressure mm Hg	Temperature °C	Concentration molecules, atoms or ions/cm^3	Composition
200 km	10^{-6}	10^{3}	10^{10}	N_2, O, O_2, O^+
800 km	10^{-9}	10^{3}	10^{6}	O, O^+, H
6500 km	10^{-13}	10^{3}	10^{3}	H^+, H
Above 20,000 km	10^{-12}	10^{3} to 10^{5}	10^{1} to 10^{2}	85% H^+, 15% H^{++}

SOURCE: Study of Space Maintenance Techniques (182).

GENERAL DATA

a. Composition of the Primary Cosmic Ray Flux Outside the Atmosphere at Northern Latitudes

	TYPE NUCLEUS					
	H PROTONS	He ALPHA PAR-TICLES	CNO	Mg	Ca	Fe
	Z[a] 1	2	7	12	20	26
Particle flux[b]	4,460	633	32	8.4	2.9	1.4
Absorbed dose contribution (mrads/24 hr)	4	2.3	1.4	0.99	0.13	0.28
LET(keV/μ tissue)						
Minimum	0.21	0.84	10.5	30.3	84	142
Maximum	57.8	252	1,230	1,780	2,570	3,500
Absorbed dose to centrally traversed cell (rads)[c]						
Minimum	0.07	0.24	0.36	1	2.85	4.8
Maximum	20	85	420	610	870	1,200

[a] Z numbers from 7 to 26 are group representatives.
[b] Particle intensity: particles traversing sphere of 1 cm^2 cross section per hour from all directions.
[c] Dose per particle calculated for a 10-μ cell at center of track.

SOURCE: Langham (108).

GENERAL DATA

b. Radiation Doses for 14 Largest Solar Particle Events of Solar Cycle 19

DATE OF EVENT	DOSE AT TISSUE SURFACE (rads)				DOSE AT 4-cm TISSUE DEPTH (rads)				
	1	2	5	10	1	2	4	6	10
Feb. 23, 1956	280 *	180 *	89 *	48 *	73 *	64 *	51 *	42 *	30 *
Mar. 23, 1958	148	54	10	2.1	6.4	4.5	2.55	1.53	0.66
July 7, 1958	150	54	9.5	1.93	6	4.3	2.35	1.4	0.59
Aug. 16, 1958	23.7	8.6	1.6	0.34	1.02	0.72	0.41	0.24	0.11
Aug. 22, 1958	45	14.7	2.24	0.38	1.33	0.91	0.49	0.27	0.11
Aug. 26, 1958	75	22.3	.3	0.43	1.76	1.17	0.57	0.3	0.11
May 10, 1959	470	206	55	15.6	38	29.3	18.2	12.5	6.4
July 10, 1959	420	210	69	24.5	50	40	27.5	19.5	11.5
July 14, 1959	650	273	72	19.5	48	36	22.8	15.1	7.5
July 16, 1959	382	191	63	22.3	46	36	25	17.7	10.5
Nov. 12, 1960	484	263	100	43	75	62	46	34	20.8
Nov. 15, 1960	288	151	53	20.5	39.6	31.7	23	16.6	10.1
July 12, 1961	25.7	8.4	1.28	0.22	0.76	0.52	0.28	0.15	0.06
July 18, 1961	128	63	20.4	7.2	15	12	8.1	5.7	3.3
Grand total of all 50 events of Cycle 19	3,914	1,837	584	217	426	342	241	176	107

*Shielding (g/cm^2)

c. Maximum and Minimum Doses* for Best and Worst Launch Dates During Active Period of Cycle 19

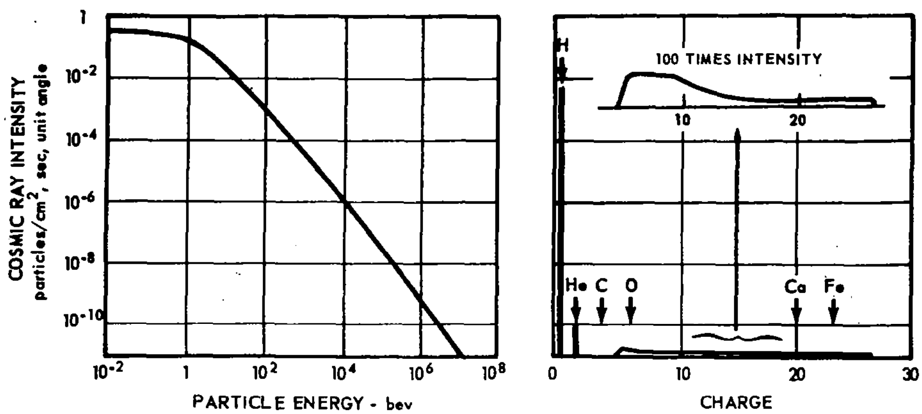
MISSION DURATION	MAXIMUM DOSE (rads)	MINIMUM DOSE (rads)
4 years	3,492	2,439
3 years	3,229	974
2 years	2,781	526
1.5 years	2,415	176
1 year	2,110	15
9 months	1,963	2
6 months	1,963	0
3 months	1,962	0
1.5 months	1,492	0
1 month	1,452	0
2 weeks	1,452	0
1 week	1,452	0

*Surface dose inside 1 g/cm^2 uniform aluminum shielding.

SOURCE: Langham (108).

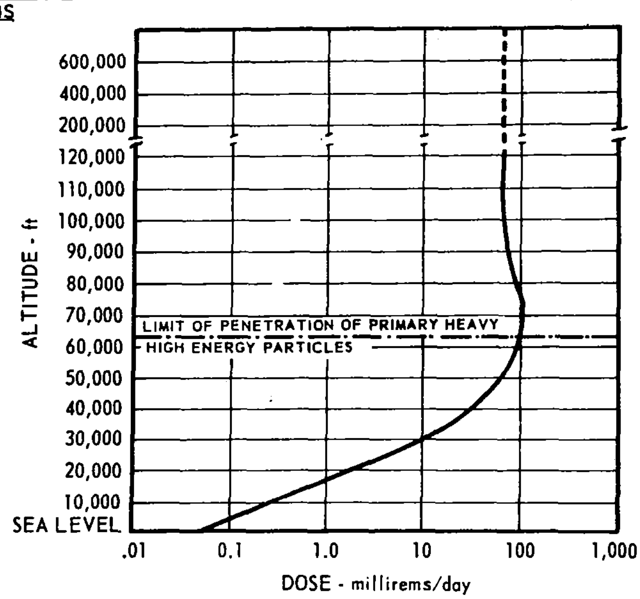
GENERAL DATA

d. Energies and Charges of Primary Cosmic Particles



Intensities of the particles with higher charges, C, O, Ca, and Fe, are so much less than those of H and He as to be barely perceptible on the base line of the graph. The inset shows a profile for these charges, magnified to 100 times intensity.

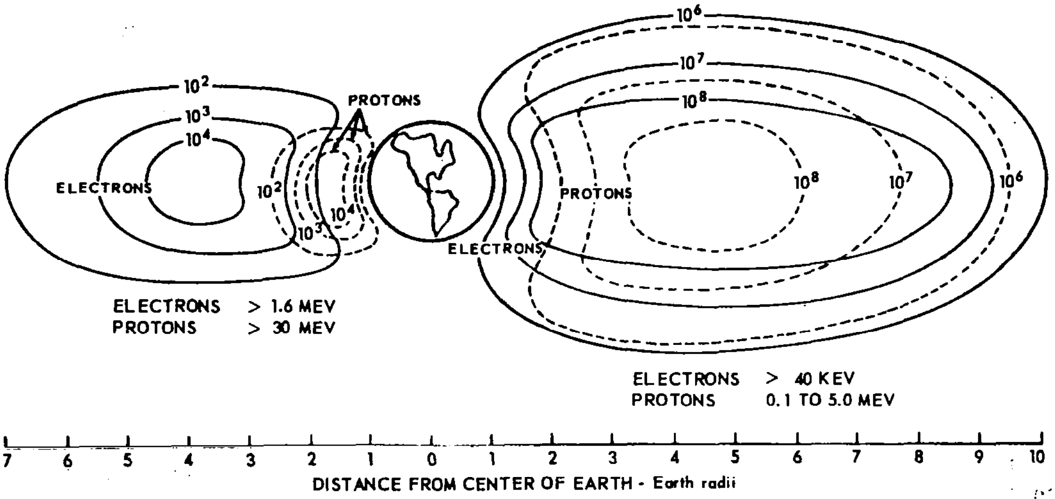
e. Estimated Whole Body Dose to an Unshielded Man from Primary Cosmic Radiations



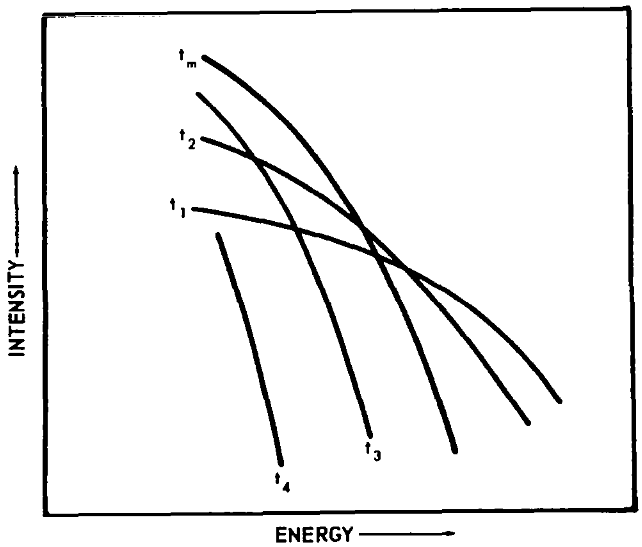
SOURCE: Webb (195).

GENERAL DATA

f. Van Allen Belts - Radiation Trapped in the Earth's Magnetic Field



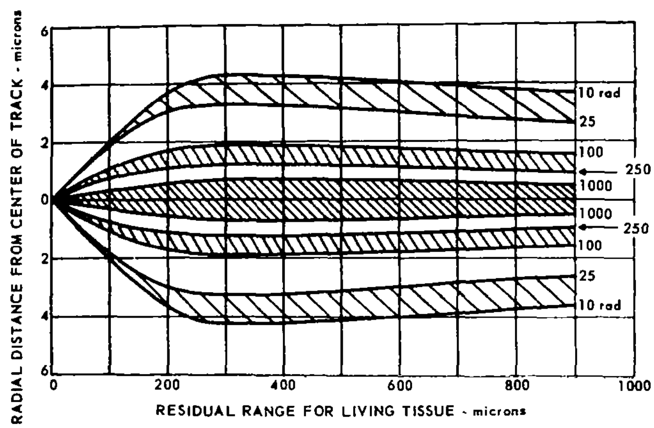
g. Energy Spectra Shown for Different Times ($t_1 < t_2 < t_m < t_3 < t_4$) During a Single Flare Event



SOURCE: Webb (195).

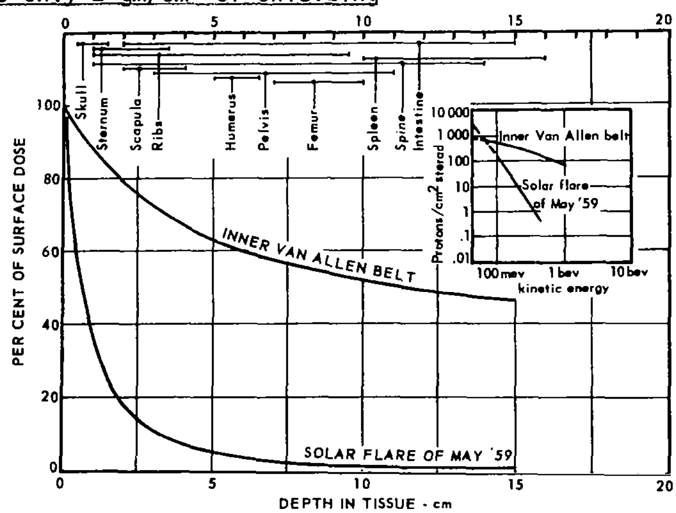
GENERAL DATA

h. Longitudinal Section of the Isodose Line Field in Tissue for the Terminal Section of a Cosmic Ray Heavy Nucleus of Z = 20 (Ca)



NOTE: Section from 280 to zero micron residual range is "thindown" part.

i. Calculated Dose from Protons at Various Depths in the Tissue from Inner Van Allen Belt and Solar Proton Event of 12 May 1959, Assuming Cabin Provides Only 2 gm/cm^2 of Shielding

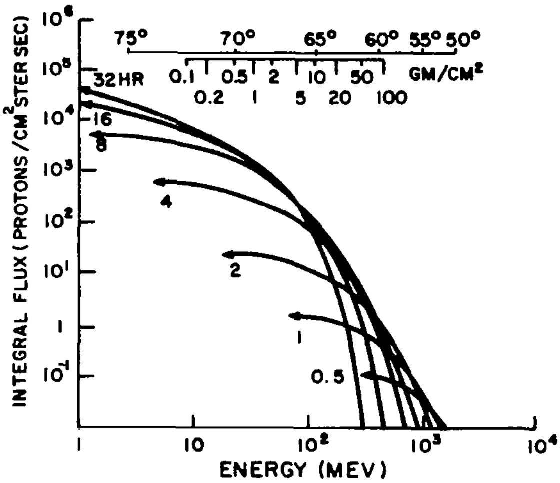


The greater drop of tissue depth-dose from flare protons as compared to Inner Belt protons is a function of the differences in the integral energy spectra(see inset); the greater frequency of higher energy protons in the Inner Belt increases

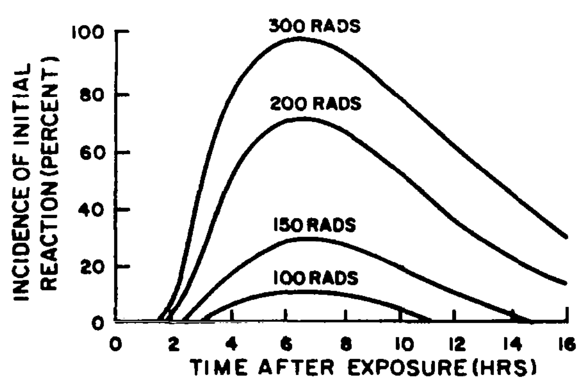
SOURCE: Webb (195).

the dose rate in deep tissues. Note the importance of knowing the integrated energy spectrum of the proton radiation when considering the critical targets--i.e., bone marrow, spleen, and intestinal locations beneath the surface.

j. Typical Development of a Solar High Energy Proton Event Indicating Change in Spectrum as a Function of Time



k. Dose-Incidence-Time Pattern of Initial Reaction to Acute Radiation Exposure



SOURCE: Biomedical Emergencies Requiring Mission Abort and/or Rescue Operations (26).

EXTRAVEHICULAR ENVIRONMENT

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GENERAL DATA

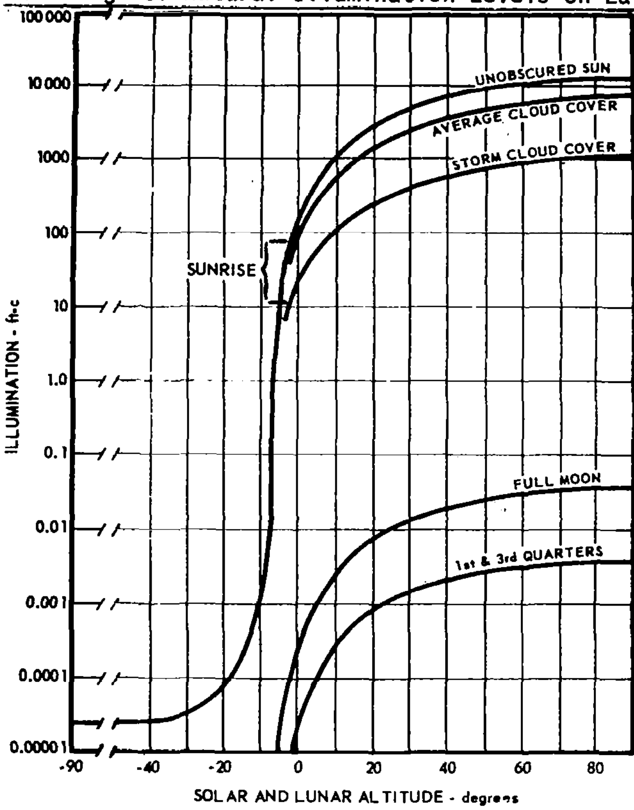
1. Solar Flare Data (1956 - 1960)

Solar Flare		Onset & Rise Time		Decay Time (Hours)		Integrated Intensity		Integrated Skin Dose (Rads)	
Date	Magnitude	>30 Mev	>100 Mev	>30 Mev	>100 Mev	>30 Mev	>100 Mev	>30 Mev	>100 Mev
2/23/56	3+	6-8	3-4	30	16	$6.5x10^8$	$3.2x10^8$	120	28
5/10/59	3+	18-22	12-18	22	10-14	$7x10^8$	$7.5x10^7$	170	10
7/10/59	3+	30-40	18-20	40	20	$8.8x10^8$	$1.0x10^8$	148	11
7/14/59	3+	16-20	12-18	18	9-12	$1.1x10^9$	$6.3x10^7$	177	7.4
7/16/59	3+	12-14	4-5	30	18	$8.1x10^8$	$1.3x10^8$	125	19
11/12/60	3+	12-16	8-10	18-24	14-18	$1.4x10^9$	$3.5x10^8$	205	33
11/15/60	3+	10-16	3-5	16-20	8-12	$5.2x10^8$	$1.2x10^8$	100	12
7/18/61	3+	6-10	2-3	24	12	$2.1x10^8$	$4.8x10^7$	27	3

SOURCE: Biomedical Emergencies Requiring Mission Abort and/or Rescue Operations (26).

LUMINANCE ON EARTH AND IN SPACE

a. Range of Natural Illumination Levels on Earth



This graph shows the range of natural illumination on earth from the sun and the moon, as the values increase from minimum before sun or moonrise to maximum at the zenith.

b. Luminance of Astronomical Phenomena as Viewed From Earth

Phenomenon	Luminance, foot-lamberts
Milky Way, dimmest region, near Perseus	2.9×10^{-5}
Gegenschein	4.6×10^{-5}
Visible night glow (zenith)	5.8×10^{-1}
Aurora IBC-I	$\sim6\times10^{-5}$
Milky Way brightest region, near Carina	1.1×10^{-4}
Zodiacal light (30° elongation)	3.5×10^{-4}
Visible night glow (edge-on)	1.7×10^{-3}
Great Orion nebula M42	1.6×10^{-2}
Full moon	1.2×10^{3}
Fluorescent lamp 4500 white	1.2×10^{3}

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50), Dunkelman, et al (59) and White (204).

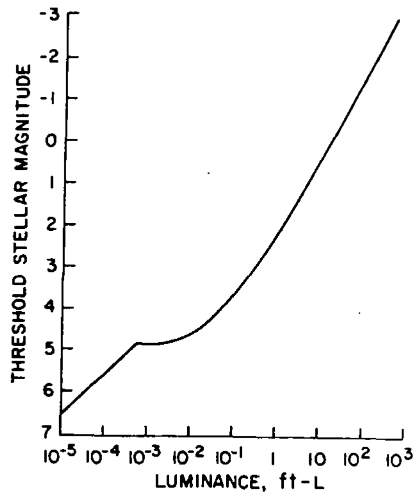
LUMINANCE ON EARTH AND IN SPACE

c. Visibility of the Stars

1. Stellar Visual Magnitude and Illuminance

M_V	Illuminance (ft-cd)
-2	1.55×10^{-6}
-1	6.18×10^{-7}
0	2.46×10^{-7}
1	9.79×10^{-8}
2	3.90×10^{-8}
3	1.55×10^{-8}
4	6.18×10^{-9}
5	2.46×10^{-9}
6	9.79×10^{-10}
7	3.89×10^{-10}
8	1.55×10^{-10}

2. Stellar Visibility Versus Background Luminance



The reflectance of the Earth as viewed from outside the atmosphere has a greater range than the range of observed reflectance from all other planets and satellites. The reflectance of the Earth varies from 0.03 for large bodies of water to 0.85 for cloud cover. Other solar system reflectance values range from 0.07 for Mercury to 0.7 for Neptune.

The intensity of the sunlight falling on the lunar surface is about 1.4 times that which reaches the surface of the Earth or 12,700 foot-candles. The solar disc has a liminance of 6.4×10^8 ft L subtending a visual angle of 0.5 degrees.

From telescopic data, the rough and broken lunar surfaces (craterwalls) reflect from 20 to 30% of the incident light while the smooth and darker layers of the maria between 6 and 7%. The Moon has a highly directional reflectance. The variation of reflectance with phase angles is shown in Figure e.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Allen (7).

LUMINANCE ON EARTH AND IN SPACE

d. Primary Parameters of the Visual Environment of Space

	90° SOLAR ILLUMINATION	SURFACE Reflectance	MEAN ATMOS. TRANSMISSION
Earth (Night illumination with full moon = 0.04 ft-c)	10,800 ft-c	Ocean .03 Ground .15 Snow .80	.70-.80*
EVA (Earth Orbit)	12,700 ft-c	Aluminum .55 Dark Paint .10 White Paint .80	1.00
Moon (Full earth = 1.25 ft-c 30° phase = 0.80 ft-c 90° phase = 0.26 ft-c)	12,700 ft-c	Maria .07 Crater Wall .20	1.00
Mars	7,600 ft-c	Maria .17 Continents .18	.80

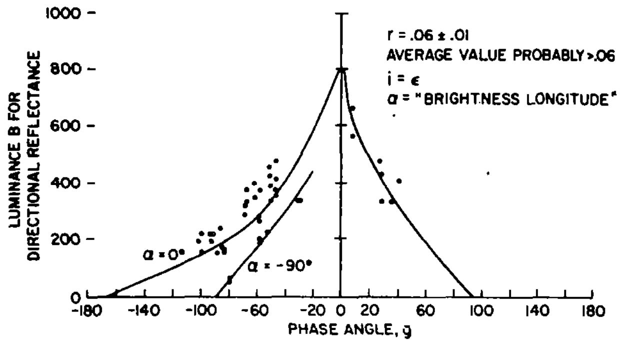
* Function of diameter and distribution of scattering particles.

The average normal albedo of the lunar surface in the vicinity of the Surveyor spacecraft was about 6%. The range of reflectance of local lunar areas is even greater than 0.06 to 0.30. The highest luminances (not in shadow) may vary from 0.08 to 0.42 of a white target in full sunlight on the surface of the Earth. "Limb darkening" on the lunar surface decreases the lower value to approximately 0.003. Thus, the apparent luminance varies from 0.003 to 0.40 of the luminance of the hypothetical white target, or a range approximately 100 to 1. In comparison, the range of luminance on Earth outdoors on a partially cloudy day, with part of the landscape in full sunlight and part in cloud shadow, can be more than 1000 to 1.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50) and Jones, et al (97).

LUMINANCE ON EARTH AND IN SPACE

e. Lunar Reflectance Values



The open circles are the data obtained from preliminary analysis of Surveyor I data. The solid lunar curve is the Federetz Curve obtained from telescopic observations from the earth.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50).

LUMINANCE ON EARTH AND IN SPACE

f. Characteristic Luminance on Earth and In Space

Luminance in mL		Object	Notes
1×10^{9}	7×10^{8}	Sun	Viewed from outside earth's atmosphere
	4.4×10^{8}	Sun	Viewed from the earth
1×10^{8}	8×10^{7}	A-Bomb	Fireball 4 miles from point of detonation of an 800 KT weapon.
1×10^{7}			
1×10^{6}			
1×10^{5}			
	1.58×10^{4}	Venus	Assume albedo (r) of 0.59 viewed from outside atmosphere
	9.4×10^{3}	Earth	Viewed from space with cloud cover (r=0.8)
1×10^{4}	6.4×10^{3}	*Mercury*	*Viewed from outside atmosphere (r=0.069)*
	4.3×10^{3}	Earth	Viewed in January from outside atmosphere, no clouds (r = 0.39)
	2.9×10^{3}	Jupiter	Viewed from outside atmosphere (r=0.56)
	2×10^{3}	Sky	Average sky on clear day
	1.2×10^{3}	Moon	Full moon viewed from outside of atmosphere (r = 0.073)
1×10^{3}	9.6×10^{2}	*Saturn*	*Viewed from outside atmosphere (r=0.63)*
	9×10^{2}	Mars	Viewed from outside atmosphere (r = 0.15)
	8×10^{2}	Moon	Full moon viewed from earth
	5×10^{2}	Sky	Average sky on cloudy day
	2.4×10^{2}	Uranus	Viewed from outside the earth (r = 0.63)
1×10^{2}	1.1×10^{2}	Neptune	Viewed from outside atmosphere (r=0.73)
	2×10^{1}	White paper in good reading light	
	1.6×10^{1}	Movie screen (indoors)	
1×10	1×10^{1}	TV screen	
	7×10^{0}	Pluto	Viewed from outside the atmosphere
1×10^{0}	8×10^{-1}	Snow in light of full moon	
1×10^{-1}			
	2×10^{-2}	Lower limit for useful color vision	
1×10^{-2}	7.5×10^{-3}	Earth	Viewed from outside atmosphere with full moon
	1×10^{-3}	*Upper limit for night vision*	
1×10^{-3}			
1×10^{-4}			
	3×10^{-5}	Earth	Viewed from outside atmosphere at night with airglow, starlight, and zodiacal light providing illumination
	1×10^{-5}	Absolute threshold for dark adapted human eye, lower limit for night vision	
1×10^{-5}	1×10^{-5}	Sky	Moonless night sky viewed from earth
5×10^{-6}			
4×10^{-6}			
3×10^{-6}			
2×10^{-6}			
1×10^{-6}	1×10^{-6}	Space background	Background luminance formed by starlight, zodiacal and galactic light.

SOURCE: Webb (195).

EXTRAVEHICULAR ENVIRONMENT

ILLUMINATION

VISOR DATA

CLEAR VISOR DATA

The effect of rapid alterations of high and low illumination levels and the effects of viewing a direct working area within a bright surrounding will have a critical influence on extravehicular performance.

Normally, the refractive power of the visor in any meridian should not exceed by more than $\pm$ 0.06 diopters the power inherent in a spherical lens with concentric surfaces having the properrradii of curvature and thickness. The inherent power of the visor is calculated by use of the following formulae:

$$F = F_1 + F_2 - \frac{t}{n} \quad ; \quad F_1F_2 \quad ; \quad F_1 = \frac{n - n}{r_1} \quad ; \quad F_2 = \frac{n - n}{r_2}$$

where

F = Power of the lens in diopters

F_1 = Power of the convex surface in diopters

F_2 = Power of the concave surface in diopters

n = Index of refraction of air

n' = Index of refraction of the material

r_1 = Radius of first or convex surface

r_2 = Radius of second or concave surface

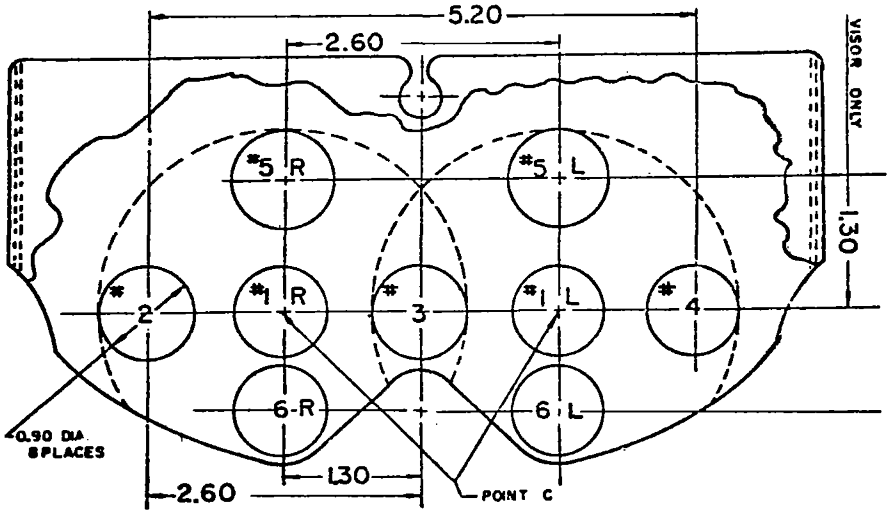
t = Thickness in meters

Figure a illustrates probably optical properties for the visor. The vertical prismatic deviation between point "C" for the right eye and point "C" for the left eye should not be more than 0.18 diopters nor shall the vertical prism at any point in the critical area of vision exceed 0.18 diopters. The algebraic sum of the horizontal prismatic deviation at point "C" for the right eye shall not exceed 0.75 diopters. The algebraic differences between the horizontal deviation at point "C" for the left eye and at point "C" for the right eye shall not exceed 0.18 diopters. The luminous transmittance should not be less than 90 percent throughout the critical area. The non-critical area should not vary in transmittance by more than $\pm$ 2 percent of the critical area transmittance. No visible distortion or optical defects detectable by the "unaided eye" (20/20) at the typical "as worn" position shall be visible. The haze value of the visor should not exceed 5 percent.

SOURCE: MOL Extravehicular Data Book (129).

VISOR DATA

a. Visor Critical and Noncritical Optical Areas



Critical areas are located within the dotted circles. Noncritical areas are located outside dotted circles. Numbered circles within the critical areas are designated as points of choice for prismatic and distortion tests. Points bearing the same number, for example, 5R and 5L, shall be compared with each other, except that point No. 2 shall be compared with point No. 3 and point No. 3 shall be compared with point No. 4 when measuring refractive power or prismatic deviations. This figure is intended to serve only as a guide since visor configurations differ.

The spectral transmittance may vary with wavelengths between 380 and 770 μ; the average percentage deviation within nine spectral bands should be less than 12%. The spectral distribution curve should show a reasonably even distribution throughout the visible spectrum to insure that color distortion will not be excessive.

The transmission of ultraviolet radiation in the range of 220 to 320μ should be such that the total energy incident on the cornea and facial skin shall not exceed 1.0 x 10^5 ergs cm^{-2} in any 24-hour period. In computing the total energy transmission:

(a) The maximum expected flux in the earth orbital environment, including reflected ultraviolet, should be determined for each of 10 spectral bands, each band being 10μ wide, between 220 and 320μ.

SOURCE: MOL Extravehicular Data Book (129).

EXTRAVEHICULAR ENVIRONMENT

ILLUMINATION

VISOR DATA

(b) The percentage transmittance of ultraviolet light in each of the 10 spectral bands, (10μ width) between 220 and 320μ shall be determined for Visor 1 by spectophotometry.

(c) The following weighting factors are normally used for each 10μ band:

220 - 230 μ	0.10
230 - 240 μ	0.15
240 - 250 μ	0.20
250 - 260 μ	0.25
260 - 270 μ	0.30
270 - 280 μ	0.35
280 - 290 μ	0.90
290 - 300 μ	0.50
300 - 310 μ	0.15
310 - 320 μ	0.10

These factors represent differential sensitivity of the cornea within the ultraviolet range.

(d) The flux is multiplied by the transmittance and by the weighting factor for each 10μ band. The resulting corrected transmitted fluxes for each 10 band shall be summed, and the sum multiplied by the maximum time of exposure. The resulting energy absorption shall not exceed 1.0×10^5 ergs cm^{-2}, in any one 24-hour period.

The transmittance of infrared radiation between 770 and 2500μ can be as low as possible and not exceed a total value of 30 $\pm$ 5 percent. The transmittance of infrared radiation between 2.5 and 100μ should not exceed 10 $\pm$ 5 percent.

SOURCE: MOL Extravehicular Data Book (129).

SPACESUIT DESIGN FOR LUNAR SURFACE

Figure a is a plot of the lunar surface temperature at various latitudes as a function of time angle, with noon being represented as 90°. During the lunar night the surface temperature appears to be independent of latitude. The ratio α/ϵ of objects on the surface of the Moon will determine the temperature history of these surfaces with respect to the time angle and latitude, but the actual time profiles will follow those of the lunar surface described in Figure a. A consideration of experimental errors, theoretical assumptions, and variations caused by surface inhomogeneities suggests that reported temperatures have a probable associated error of $\pm$ 20°C and that calculated temperature curves involving phase angle and latitude have a likely error of no less than 25°C over the most accurate portions of the curves.

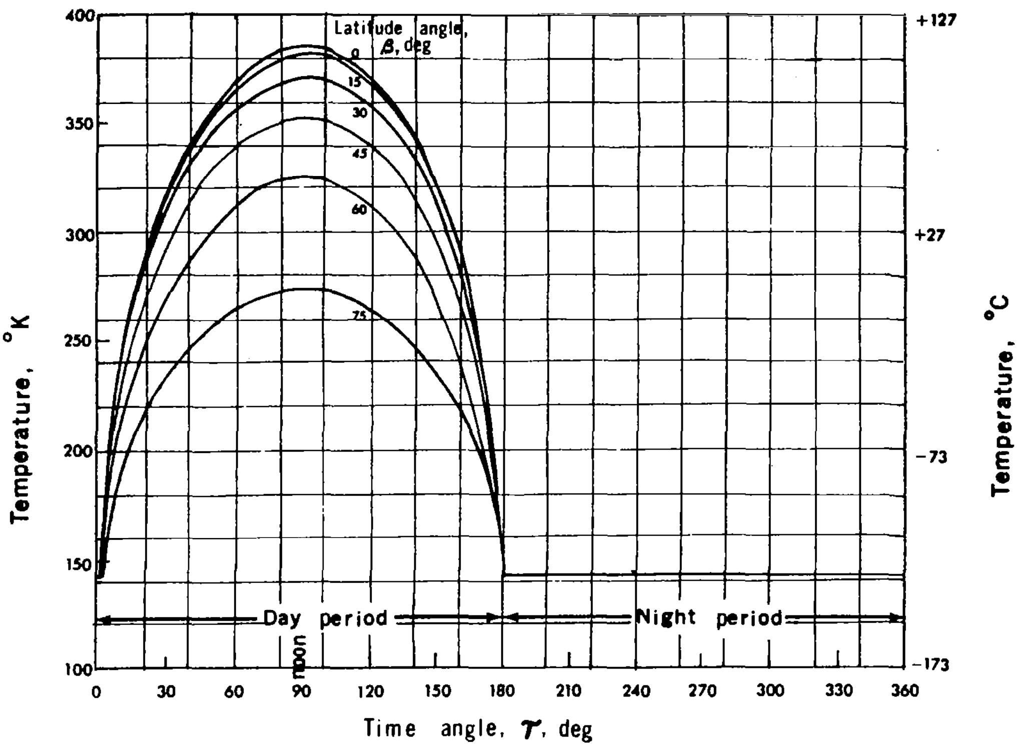
The rate of change of surface temperature during eclipses has been used to build a thermal inertia model of the lunar surface materials, to be discussed below. Radio measurements of lunar temperature have also been used to reveal equilibrium subsurface temperatures. Calculations of the potential surface temperatures within lunar crevices at different solar angles point out the severe gradients to be expected.

Past Russian radio-telescope observations and theoretical calculations appear to present temperatures somewhat lower than the American figures. The most recent figures reportedly presented by Troitskiy to the popular Russian press give a maximum surface temperature of + 115° C (240° F) during the daytime and a minimum of 150° C (-240° F) at night. A constant -50° C (-58° F) is calculated for a depth of 0.5 meter below the poorly conducting surface.

SOURCE: Roth (154).

SPACESUIT DESIGN FOR LUNAR SURFACE

a. Lunar Surface Temperature at Various Latitudes as a Function of Time Angle



SOURCE: Roth (154).

SPACESUIT DESIGN FOR LUNAR SURFACE

b. Thermal Inertia Constants

MATERIAL	THERMAL CONDUCTIVITY, K, cal/cm^2/sec	DENSITY, gm/cm^3	SPECIFIC HEAT, c, cal/gm	$(K c)^{-1/2}$
Copper	0.9	9	0.09	1
Rock	5×10^{-3}	3	.2	20
Pumice Pumice	3×10^{-4}	.6	.2	170
Powder in vacuum	$3\text{-}10 \times 10^{-6}$	2	.2	500-900

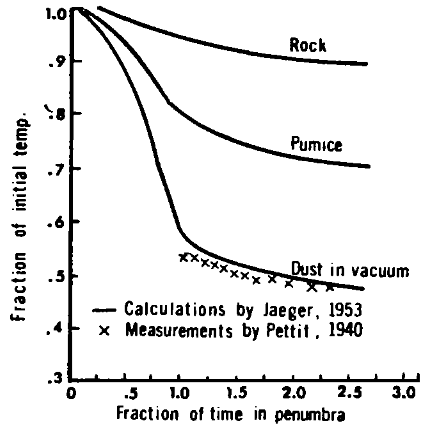
The design of space suits, especially the footwear and gloves, requires some knowledge of the thermal characteristics of surface materials. Table a indicates the pertinent constants to be considered, where $(K\rho c)^{-1/2}$ is the thermal inertia of the potential surface material. The lunation temperature changes suggest porous powder or powder-aggregate in vacuum as the surface material. Recent studies have corroborated the effects of a vacuum of 10^{-6} mm Hg on thermal diffusivity and conductivity of fine powders of olivine basalt. It is of interest that increasing the pressure from 5×10^{-6} to 5×10^{-3} mm Hg had no marked effect on the thermal conductivity of the crushed basalt. Had the pressure been decreased to 10^{-10} mm Hg or lower, there might well have been a sintering phenomenon with subsequent increase in conductivity. For the -150 mesh material, the thermal conductivity in the air and in vacuum was increased approximately 60% at all test temperatures when the packing density was increased from 1.14 to 1.57 gm/cm^3. Decreasing the average temperature of the crushed basalt specimen from 100° to -70° C caused a decrease in the thermal conductivity. For the particular distributions used, the particle size had a greater effect on the values of thermal conductivity measured in vacuum than on the values measured in air. The thermal conductivities of crushed olivine basalt and silica sand are not markedly different.

The underlying lunar rock should have thermal characteristics similar to terrestrial igneous rock. The actual heat-transfer characteristics of the surface depend on the layering, aggregation, and depth of the surface materials. All that can be said at this time, with density and specific-heat factors still unknown, is that the average surface probably has a low thermal conductivity.

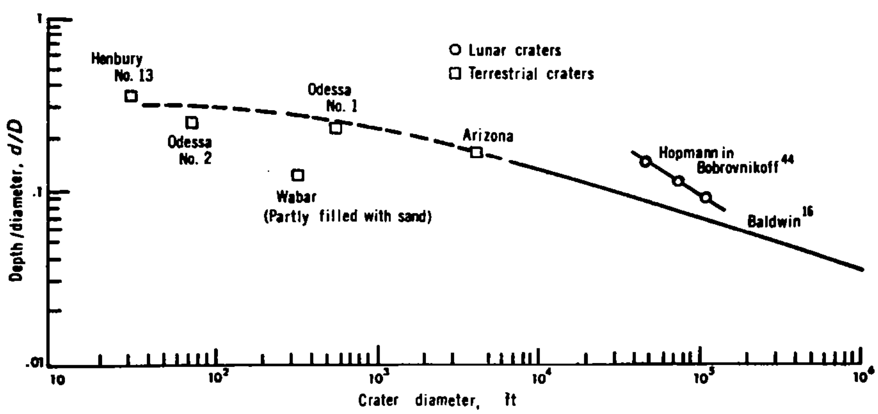
SOURCE: Roth (154).

SPACESUIT DESIGN FOR LUNAR SURFACE

c. Change of Temperature During a Lunar Eclipse



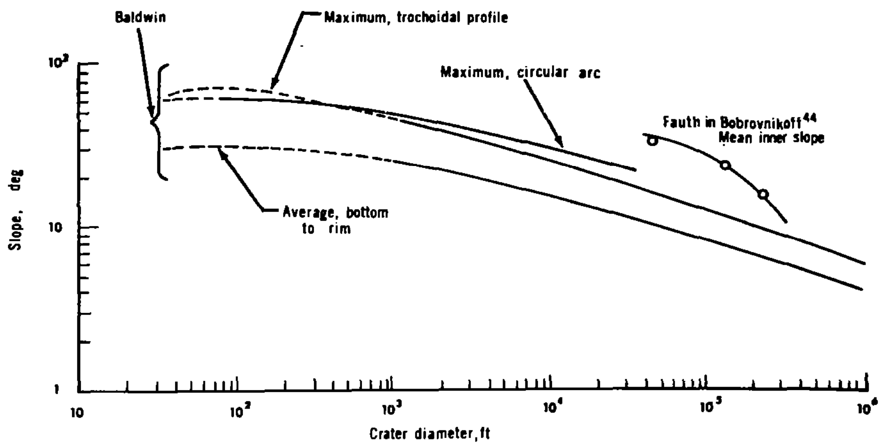
d. Overall Shapes of Lunar Craters



SOURCE: Roth (154).

SPACESUIT DESIGN FOR LUNAR SURFACE

e. Slopes in the Lunar Craters



SOURCE: Roth (154).

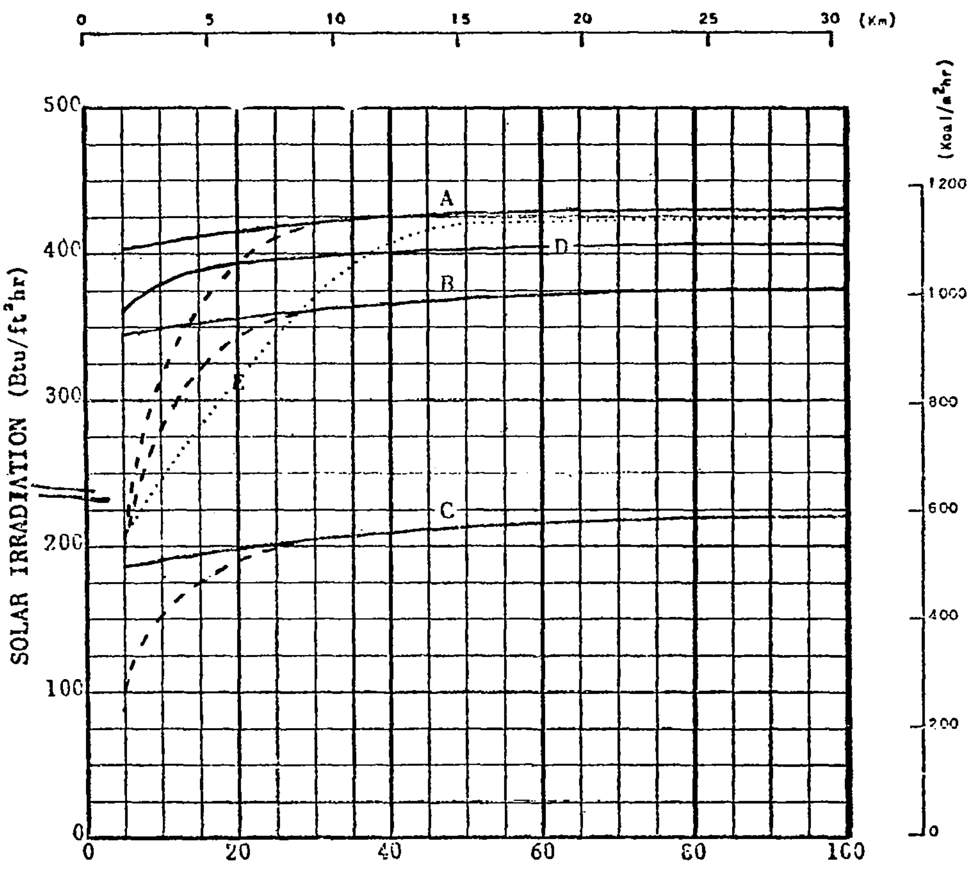
EXTRAVEHICULAR ENVIRONMENT

TEMPERATURE

ALTITUDE EFFORTS

Curves A, B, and C are for January zenith angles 0, 30, and 60 degrees respectively, clear sky. Dashed lines show irradiation with average cloudiness. Curve D is for July zenith angle 0 degrees, clear sky (Klein[7]). Curve E is the irradiation curve of Johnson et al[8].

a. Solar Irradiation



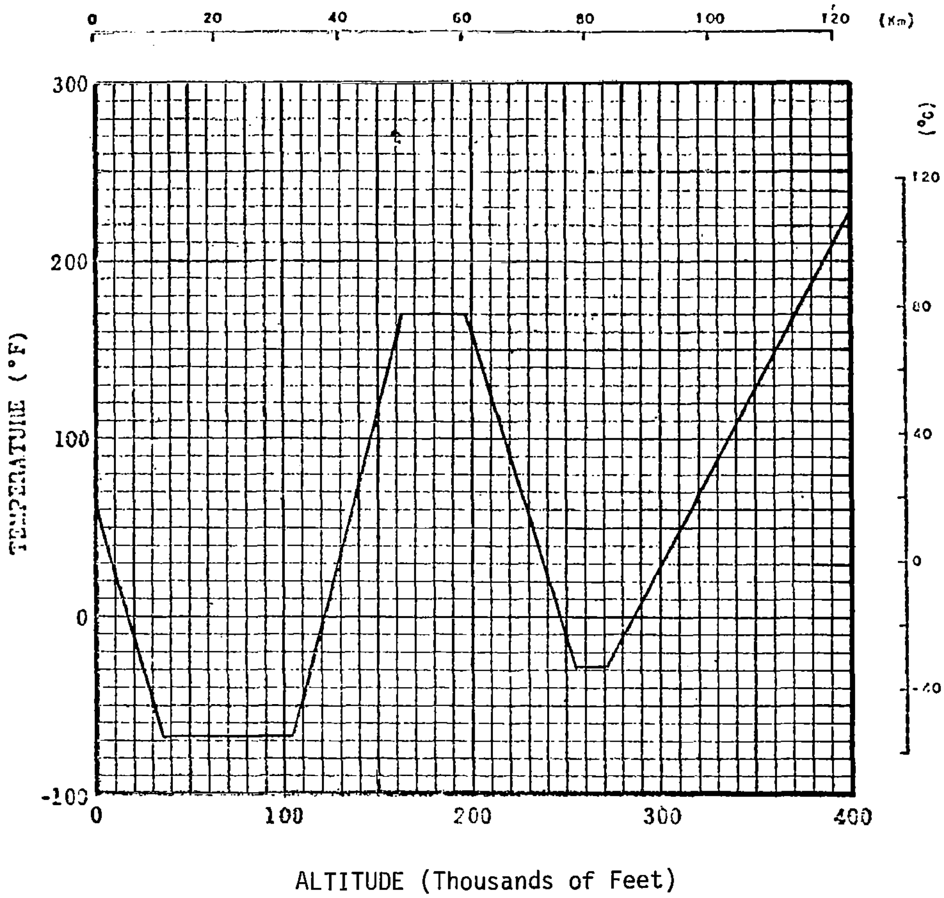
ALTITUDE (Thousands of Feet)

NACA standard temperature: 0-65,000 feet. NACA tentative standard temperature for upper atmosphere: 65,000-400,000 feet.

SOURCE: Blockley, McCutchan, et al (29).

ALTITUDE EFFORTS

b. Temperature of the Adopted Atmosphere



SOURCE: Blockley, McCutchan, et al (29).

SECTION 3

VEHICULAR CHARACTERISTICS

VEHICULAR CHARACTERISTICS

RESTRAINT AND TETHER POINTS

VEHICULAR CHARACTERISTICS

RESTRAINT AND TETHER POINTS

GEMINI EVA RESTRAINT AND TETHER HARDWARE

a. Summary of Gemini Extravehicular Task Vehicular Hardware

EVA tasks	Body restraints used	Forces required	Ease of accomplishment
Removal of 7 in^2 of nylon Velcro strip, Gemini XI	Handholds	Finger, hand, and body	Satisfactory
Translation between two points, Gemini X	None	Establish velocity vector when leaving first point	Satisfactory
GATV tether attachment to spacecraft docking bar, Gemini XI	Handholds	Body control and forces from hands, arms, legs, and torso	Unsatisfactory
Experiment package deployment or retrieval (S009, S010, and S012), Gemini IX-A, X, and XI	Handholds	Body control and forces from fingers, hand, and body	Satisfactory
Unstowage and extension of the AMU controller arm (during AMU checkout), Gemini IX-A	Foot stirrups	Torquing and forces from hands, arms, and body	Unsatisfactory
Unstowage and installation of the telescopic handrail, Gemini XII	Waist tethers	Alignment, body control, and forces from fingers, hands, and body	Satisfactory
GATV tether attachment to the spacecraft docking bar, Gemini XII	Waist tethers	Body control and forces from fingers, hands, and body	Satisfactory
Translation between two points along the surface of the spacecraft on Gemini IX-A, X, and XII	Handrail	Body control and forces from fingers, hands, and body	Satisfactory
Experiment package deployment; bolt-torquing operations, Gemini XII	Waist tethers	Alignment, torque, body control, and forces from finger, hand, and body	Satisfactory
Connector operations, Gemini XII	Waist tethers	Alignment, body control, and push/turn, blind push/turn, and push/push	Satisfactory
Cutting operations, Gemini XII	Foot restraints	Body control, finger, and hand	Satisfactory
Removal of 200 in^2 of nylon Velcro strip, Gemini XII	Foot restraints	Finger, hand, and body	Satisfactory

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51), Machell (118).

RESTRAINT AND TETHER POINTS

GEMINI EVA RESTRAINT AND TETHER HARDWARE

b. Restraint Devices Used During Gemini Extravehicular Activities

Configuration of restraint device	Gemini mission			
	IX-A	X	XI	XII
Rectangular handrail	X	X	X	X
Large cylindrical handbars (1.38-in. diameter)	X			X
Small cylindrical handrails (0.317-in. diameter)				X
Telescoping cylindrical handrail				X
Fixed handhold			X	X
Flexible Velcro-backed portable handhold	X			
Rigid Velcro-backed portable handhold				X
Waist tethers				X
Pip-pin handhold/tether attachment device				X
Pip-pin antirotation device				X
U-bolt handhold/tether attach device				X
Foot stirrups	X			
Foot restraints				X
Standup tether		X	X	X
Straps on space suit leg			X	X

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51), Machell (118).

VEHICULAR CHARACTERISTICS

MOBILITY AIDS

GEMINI MOBILITY AIDS

a. Extravehicular Activity in Gemini Program

Mission	Life support system	Umbilical length, ft	Maneuvering device	Umbilical EVA time,[a] hr:min	Standup EVA time,[a,b] hr:min	Total EVA time,[a] hr:min
Gemini IV	VCM[c]	25	HHMU[d]	0:36	--	0:36
Gemini VIII	ELSS[e] - ESP[f]	25	HHMU	--	--	--
Gemini IX-A	ELSS - AMU[g]	25	AMU	2:07	--	2:07
Gemini X	ELSS	50	HHMU	0:39	0:50	1:29
Gemini XI	ELSS	30	HHMU	0:33	2:10	2:43
Gemini XII	ELSS	25	--	2:06	3:24	5:30
EVA totals				6:01	6:24	12:25

[a]Time from hatch opening to hatch closure.
[b]Includes mission equipment jettison time.
[c]Ventilation Control Module.
[d]Hand Held Maneuvering Unit.
[e]Extravehicular Life Support System.
[f]Extravehicular Support Package.
[g]Astronaut Maneuvering Unit.

b. Hand-Held Maneuvering Unit Used in Gemini

Hand Held Maneuvering Unit Characteristics

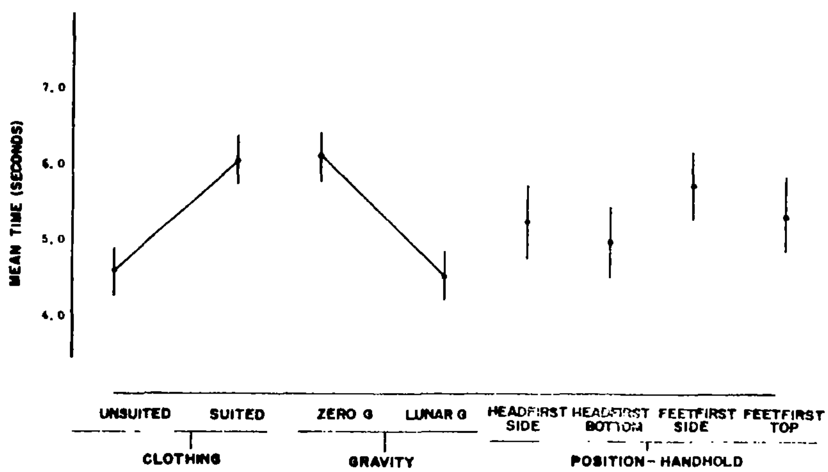
	Gemini IV	Gemini VIII	Gemini X
Propellant, gas	Oxygen	Freon-14	Nitrogen
Thrust, tractor or pusher, lb	0 to 2	0 to 2	0 to 2
Specific impulse (calculated), sec	-	33.4	63
Total impulse, lb-sec	40	600	677
Total available velocity increment, ft/sec	6	54	84
Trigger preload, lb	15	15	5
Trigger force at maximum thrust, lb	20	20	8
Storage tank pressure, psi	4000	5000	5000
Regulated pressure, psi	120	110 ± 15	125 ± 5
Nozzle area ratio	50 : 1	51 : 1	51 : 1
Weight of propellant, lb	?	18	10.75
HHMU weight, lb	7.5	3	3

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. II (51), Machell (118).

MOBILITY

Problems of moving through hatchways under zero and lunar gravity conditions, and related design problems of hatch size and shape, were investigated in flight. Subjects were timed and photographed as they accomplished various motions during weightless and lunar-gravity maneuvers of a large cabin aircraft. Performance data are presented for various combinations of clothing, gravity and body-position conditions. Time and contact data are presented for the egress motion as it is influenced by changes in the exit area. Orientation problems and maneuvering techniques, as influenced by area and volume restrictions, are discussed. Motions of pressure-suited subjects generally required 30% more time than corresponding motions of unsuited subjects. Most motions required 35% more time during zero G than during lunar G. No significant differences in egress times were found among four body-positions. Compared with 1 inch of exit clearance, 5 inches of clearance improved egress time by approximately 6%. Accuracy, rather than time of motion, appeared to be a more sensitive measure of operator performance for the egress task. A 95th percentile shoulder plane with a 19.4-inch major axis is proposed as a basic egress reference.

a. Total Time - Two Clothing Conditions, Two Gravity Conditions, Four Body-Handhold Positions



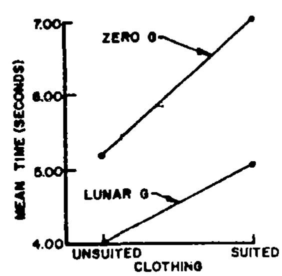
Dot represents mean and vertical bar indicates where the mean will fall 95 percent of the time.

SOURCE: Simons (168).

MOBILITY

Figure b indicates that approximately 30% more time was required under zero G than under lunar G when unsuited and 40% more time when suited. In approximate terms, a suited subject performed as well at lunar G as an unsuited subject at zero G. Apparently the mobility restrictions of the suit were matched by the poorer body control during the zero-G condition.

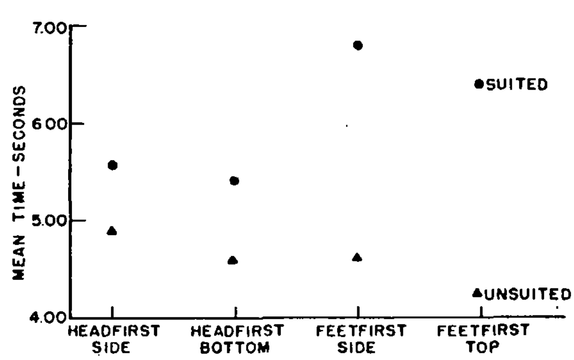
b. Total Time - Two Clothing Conditions for Two Gravity Conditions



Dot represents mean.

Figure c shows that for all body-handhold position combinations, the suited condition. was inferior to the unsuited condition under all gravity conditions.

c. Total Time - Time Plot of Four Body-Handhold Positions for Two Clothing Conditions



POSITION - HANDHOLD

SOURCE: Simons (168).

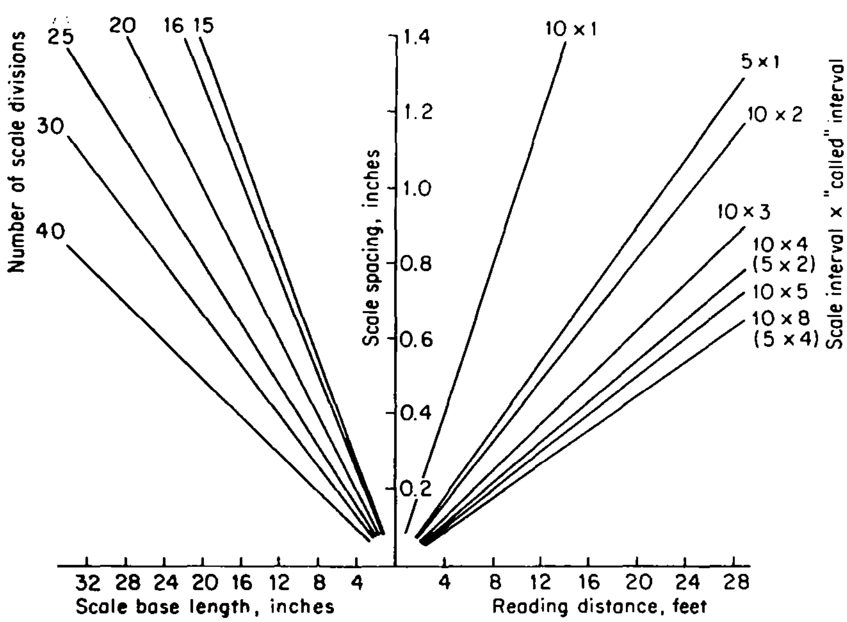
VEHICULAR CHARACTERISTICS

DISPLAYS AND CONTROLS

DIAL AND SCALE DESIGN

Nomograph showing relationship between reading distance, scale interval, "called" interval, and scale base length. The method of using the nomograph to find the dial size when the maximum reading distance is known can be illustrated by a 200-lb pressure gauge subdivided into 20 scale divisions at 10-lb intervals, to be read at a distance of 20 ft, to a "called" interval of 2 (the smallest value to be read). Enter the right side of the nomograph at 20 ft and more vertically until the 10 x 2 line is cut (10 x 2 is the scale interval, 10 multiplied by the "called" interval, 2 lb.). From this 10 x 2 line horizontally to the 20 line (there being 20 marked scale divisions) and down to the base line to give a scale base length of 17-1/2 in.; to obtain the diameter; divide by 2.36 to give 7.4 in. In practice this means using a standard gauge with an 8-in. dial blank. The nearness of scale base length of 17-1/2 in. at 20-ft reading distance to a 1:1 ratio has led the British Standard Institution to suggest the use of a scale base length of 1 in. for each 1-ft. reading distance as a useful working relationship. To obtain the maximum reading distance when the dial size is known, the procedure described above is reversed. It may be noted that should the 200-lb gauge be subdivided into 40 scale divisions, giving a 5 x 2 interpolation, the scale diameter will be 9.1 instead of 7.4 in. In fact, any method of a subdivision other than 10 x 2 gives a less favorable result, which suggests that for industrial scales, subdivision into 20 parts and interpolation into 5ths is optimum.

a. Dial and Scale Design Nomograph



Conversion factor: diameter of 270° scale = $\frac{\text{scale base length}}{2.36}$

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50), McCormick (119).

DIAL AND SCALE DESIGN

b. Mean and Standard Deviation of Maximum Torque by Knob Size (Torque in Inch-Ounces)

Knob Size (Inches)	RIM SURFACE					
	Rectangular Knurl		Diamond Knurl		Smooth	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
1/8	8.4	3.1	9.1	3.1	3.0	1.5
1/4	18.6	5.4	19.6	5.4	8.3	3.3
3/8	27.7	7.6	31.8	9.1	13.4	4.4
1/2	42.6	12.8	45.9	13.5	21.8	7.6
5/8	60.3	17.3	64.9	21.5	27.2	8.6
3/4	85.4	28.7	93.1	33.1	39.8	10.6
7/8	104.9	35.1	112.6	40.2	47.9	15.6
1	115.6	31.8	116.0	35.5	59.1	21.3
1-1/4	120.7	35.6	132.9	37.7	59.9	17.2
1-1/2	156.6	41.0	146.8	37.5	97.4	26.4
1-3/4	199.6	51.5	205.3	52.8	124.7	38.7
2	244.5	64.7	210.2	48.9	148.0	46.7
2-1/4	294.4	78.5	287.5	74.5	187.0	52.0
2-1/2	367.9	103.2	371.9	113.6	236.2	63.1
2-3/4	403.1	95.1	423.9	108.4	238.9	69.2
3	444.3	114.2	477.7	136.6	267.2	81.1
3-1/2	553.4	147.1	607.3	158.9	400.4	116.6
4	694.8	180.8	698.0	173.9	454.2	135.3
4-1/2	814.8	219.7	855.7	236.0	542.4	150.9
5	898.5	219.5	973.4	262.8	716.4	225.8

Performance (Controls)- Operator response time for three switches (push button, toggle and rotary) under 0-G as opposed to 1-G does not differ significantly as investigated by Wade (1962). The toggle switch shows the greatest decrement, the rotary switch the least while the push-button is operated most rapidly in both 1-G and 0-G conditions. This data is contained in Table c below.

c. Means of Performance Time in Seconds for Three Switches Under Two Conditions

	1 G	0 G	Difference	Percent Increase
Push Button	0.86	0.99	0.13	15
Toggle	1.04	1.26	0.22	21
Rotary	1.05	1.14	0.09	9
Average	0.98	1.13	0.15	15

SOURCE: Human Engineering Design Criteria (88) and Wade (194).

DIAL AND SCALE DESIGN

The desirable size of numerals and letters is affected by the distance at which they are to be read. For the usual reading distance of about 28 in., it has been reported that two different sizes of block capital letters seem to satisfy the concurrent desirability for uniform size with occasional larger letters for emphasis. These two sizes are 9/64 in. for the bulk of the letters and 11/64 in size for emphasis. Illumination, reading conditions, distance, and the importance of accuracy should of course be taken into account in selecting the size of letters or numerals for use as labels or markings.

A formula has been developed that takes into account illumination, reading conditions, viewing distance, and the importance of reading accuracy:

$$H \text{ (height of letter in inches)} = 0.0022\,D + K_1 + K_2$$

where D = viewing distance

K_1 = correction factor for illumination and viewing condition

K_2 = correction for importance (for important items such as emergency labels, $K_2 = 0.075$; for all other conditions, $K_2 = 0.0$).

This formula has been applied to various viewing distances, in combination with the other variables, and the heights of letters and numerals derived therefrom. These values are given in table d. It should be kept in mind that these are approximations of desirable heights; values within reason of those given would generally produce relatively comparable legibility. Needless to say, one should not apply such a formula arbitrarily, without taking into account special facets of the particular situation. A set of recommended heights for the Apollo System at 28" viewing distance, low brightness (down to 0.03 ft. L) range from 0.05 to 0.20 in. for noncritical, normal situations, up to a range of 0.20 to 0.30 in. for critical, adverse situations.

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I (50), McCormick (119) and Mote (136).

DIAL AND SCALE DESIGN

d. Heights of Letters and Numerals (H) Recommended for Labels and Markings on Panels, for Varying Distances and Conditions*

Viewing distance, inches	*0.0022 D value*	*Nonimportant markings*			*Important markings*		
		$K_1 = 0.06$	$K_1 = 0.16$	$K_1 = 0.26$	$K_1 = 0.06$	$K_1 = 0.16$	$K_1 = 0.26$
14	0.0308	0.09	0.19	0.29	0.17	0.27	0.37
28	0.0616	0.12	0.22	0.32	0.20	0.30	0.40
42	0.0926	0.15	0.25	0.35	0.23	0.33	0.43
56	0.1232	0.18	0.28	0.38	0.25	0.35	0.45

Illumination level, fc	*Reading situation*	*K_1 value*
Above 1.0	Favorable	0.06
Above 1.0	Unfavorable	0.16
Below 1.0	Favorable	0.16
Below 1.0	Unfavorable	0.26

*Derived from Formula H (in.) = $0.0022\ D + K_1 + K_2$

SOURCE: Compendium of Human Responses to the Aerospace Environment, Vol. I(50), McCormick (119)

DIAL AND SCALE DESIGN

e. Advantages and Disadvantages of Various Types of Coding

	TYPE OF CODING					
ADVANTAGES	LOCATION	SHAPE	SIZE	MODE OF OPERATION	LABELING	COLOR
Improves visual identification.	X	X	X		X	X
Improves nonvisual identification (tactual and kinesthetic).	X	X	X	X		
Helps standardization.	X	X	X	X	X	X
Aids identification under low levels of illumination and colored lighting.	X	X	X	X	(When trans-illuminated)	(When trans-illuminated)
May aid in identifying control position (settings).		X		X	X	
Requires little (if any) training; is not subject to forgetting.					X	
DISADVANTAGES						
May require extra space.	X	X	X	X	X	
Affects manipulation of the control (ease of use).	X	X	X	X		
Limited in number of available coding categories.	X	X	X	X		X
May be less effective if operator wears gloves.		X	X	X		
Controls must be viewed (i.e., must be within visual areas and with adequate illumination present).					X	X

SOURCE: Human Engineering Design Criteria for Military Systems (89).

VEHICULAR CHARACTERISTICS

FASTENERS

CONSIDERATIONS FOR THE SELECTION OF MECHANICAL FASTENERS
FOR USE IN A REDUCED GRAVITY ENVIRONMENT

In a reduced gravity environment the ability of a man to apply a force on a mechanical fastener (nut and bolt) is limited due to his decrease in weight in a reduced gravity environment. This section presents data on various types of fasteners and on the forces required to apply these fasteners.

Use of rivets, pins, retaining rings, spring clips, etc., are greatly dependent upon specific applications, therefore manufacturers data should be consulted.

Threaded Fasteners

Joint strength is affected more by the clamping force than by the rated tensile strength of the threaded fastener and the clamping force is proportional to the tightening torque.

Variations of the standard threaded fasteners include set screws, tapping screws, and single thread engaging nuts.

Set screws are essentially compression devices used as semi-permanent fasteners to hold collar and sheave or gear on a shaft against rotational or translational forces.

SOURCE: Design Fasteners (55).

a. Suggested Tightening Torque[1] Values to Produce Corresponding Bolt Clamping Loads

Size	Bolt Diam, D (in.)	SAE Grade 2 Bolts Clamp[2] Load P (lb)	SAE Grade 2 Tightening Torque Dry K=0.20	SAE Grade 2 Tightening Torque Lub. K=0.15	SAE Grade 5 Bolts Clamp[2] Load P (lb)	SAE Grade 5 Tightening Torque Dry K=0.20	SAE Grade 5 Tightening Torque Lub. K=0.15	SAE Grade 7[3] Clamp[2] Load P (lb)	SAE Grade 7 Tightening Torque Dry K=0.20	SAE Grade 7 Tightening Torque Lub. K=0.15	SAE Grade 8[4] Clamp[2] Load P (lb)	SAE Grade 8 Tightening Torque Dry K=0.20	SAE Grade 8 Tightening Torque Lub. K=0.15
			lb in.	lb in.		lb in.	lb in.		lb in.	lb in.		lb in.	lb in.
4-40	0.1120	240	5	4	380	8	6	480	11	8	540	12	9
4-48	0.1120	280	6	5	420	9	7	520	12	9	600	13	10
6-32	0.1380	380	10	8	580	16	12	720	20	15	820	23	17
6-40	0.1380	420	12	9	640	18	13	800	22	17	920	25	19
8-32	0.1640	580	19	14	900	30	22	1100	36	27	1260	41	31
8-36	0.1640	600	20	15	940	31	23	1160	38	29	1320	43	32
10-24	0.1900	720	27	21	1120	43	32	1380	52	39	1580	60	45
10-32	0.1900	820	31	23	1285	49	38	1580	60	45	1800	68	51
¼-20	0.2500	1320	66	49	2020	96	75	2500	120	96	2860	144	108
¼-28	0.2500	1500	76	56	2320	120	86	2860	144	108	3280	168	120
			lb ft	lb ft		lb ft	lb ft		lb ft	lb ft		lb ft	lb ft
5/16-18	0.3125	2160	11	8	3340	17	13	4120	21	16	4720	25	18
5/16-24	0.3125	2400	12	9	3700	19	14	4560	24	18	5220	25	20
⅜-16	0.3750	3200	20	15	4940	30	23	6100	40	30	7000	45	35
⅜-24	0.3750	3620	23	17	5600	35	25	6900	45	30	7900	50	35
7/16-14	0.4375	4380	30	24	6800	50	35	8400	60	45	9550	70	55
7/16-20	0.4375	4900	35	25	7550	55	40	9350	70	50	10700	80	60
½-13	0.5000	5840	50	35	9050	75	55	11200	95	70	12750	110	80
½-20	0.5000	6600	55	40	10700	90	65	12600	100	80	14400	120	90
9/16-12	0.5625	7500	70	55	11600	110	80	14350	135	100	16400	150	110
9/16-18	0.5625	8400	80	60	12950	120	90	16000	150	110	18250	170	130
⅝-11	0.6250	9300	100	75	14400	150	110	17800	190	140	20350	220	170
⅝-18	0.6250	10600	110	85	16300	170	130	20150	210	160	23000	240	180
¾-10	0.7500	13800	175	130	21300	260	200	26300	320	240	30100	380	280
¾-16	0.7500	15400	195	145	23800	300	220	29400	360	280	33600	420	320
⅞-9	0.8750	11400	165	125	29400	430	320	36400	520	400	41600	600	460
⅞-14	0.8750	12600	185	140	32400	470	350	40100	580	440	45800	660	500
1-8	1.0000	15000	250	190	38600	640	480	47700	800	600	54500	900	680
1-12	1.0000	16400	270	200	42200	700	530	52200	860	660	59700	1000	740
1⅛-7	1.1250	18900	350	270	42300	800	600	60100	1120	840	68700	1280	960
1⅛-12	1.1250	21200	400	300	47500	880	660	67400	1260	940	77000	1440	1080
1¼-7	1.2500	24000	500	380	53800	1120	840	76300	1580	1100	87200	1820	1360
1¼-12	1.2500	26600	550	420	59600	1240	920	84500	1760	1320	96600	2000	1500
1⅜-6	1.3750	28600	660	490	64100	1460	1100	91000	2080	1560	104000	2380	1780
1⅜-12	1.3750	32500	740	560	73000	1680	1260	104000	2380	1780	118400	2720	2040
1½-6	1.5000	34800	870	650	78000	1940	1460	111000	2780	2080	126500	3160	2360
1½-12	1.5000	39100	980	730	87700	2200	1640	124005	3100	2320	142200	3560	2660

Notes:
1. Tightening torque values are calculated from the formula $T = KDP$, where T = tightening torque, lb-in. K = torque-friction coefficient; D = nominal bolt diameter, in.; and P = bolt clamping load developed by tightening, lb.
2. Clamp load is also known as preload or initial load in tension on bolt. Clamp load (lb) is calculated by arbitrarily assuming usable bolt strength is 75% of bolt proof load (psi) times tensile stress area (sq in.) of threaded section of each bolt size. Higher or lower values of clamp load can be used depending on the application requirements and the judgment of the designer.
3. Tensile strength (min psi) of all Grade 7 bolts is 133,000. Proof load is 105,000 psi.
4. Tensile strength (min psi) of all Grade 8 bolts is 150,000 psi. Proof load is 120,000 psi.

SOURCE: Design Fasteners (55).

CONSIDERATIONS FOR THE SELECTION OF MECHANICAL FASTENERS
FOR USE IN A REDUCED GRAVITY ENVIRONMENT

b. Suggested Maximum Torque Values for Fasteners of Different Materials

Bolt Size	Maximum Torque (lb-in.)						
	Aluminum 2024-T4	Brass	Monel	Silicon Bronze	Steel, Low-Carbon	Steel, 18-8 Stainless	Steel, 316 Stainless
2-56	1.4	2.0	2.5	2.3	2.2	2.5	2.6
2-64	1.7	2.5	3.1	2.8	2.7	3.0	3.2
3-48	2.1	3.2	4.0	3.6	3.5	3.9	4.0
3-56	2.4	3.6	4.5	4.1	4.0	4.4	4.6
4-40	2.9	4.3	5.3	4.8	4.7	5.2	5.5
4-48	3.6	5.4	6.7	6.1	5.9	6.6	6.9
5-40	4.2	6.3	7.8	7.1	6.9	7.7	8.1
5-44	5.1	7.7	9.6	8.7	8.5	9.4	9.8
6-32	5.3	7.9	9.8	8.9	8.7	9.6	10.1
6-40	6.6	9.9	12.3	11.2	10.9	12.1	12.7
8-32	10.8	16.2	20.2	18.4	17.8	19.8	20.7
8-36	12.0	18.0	22.4	20.4	19.8	22.0	23.0
10-24	13.8	18.6	25.9	21.2	20.8	22.8	23.8
10-32	19.2	25.9	34.9	29.3	29.7	31.7	33.1
1/4"-20	45.6	61.5	85.3	68.8	65.0	75.2	78.8
1/4"-28	57.0	77.0	106.0	87.0	90.0	94.0	99.0
5/16"-18	80	107	149	123	129	132	138
5/16"-24	86	116	160	131	139	142	147
3/8"-16	143	192	266	219	212	236	247
3/8"-24	157	212	294	240	232	259	271
7/16"-14	228	317	427	349	338	376	393
7/16"-20	242	327	451	371	361	400	418
1/2"-13	313	422	584	480	465	517	542
1/2"-20	328	443	613	502	487	541	565
9/16"-12	413	558	774	632	613	682	713
9/16"-18	456	615	855	697	668	752	787
5/8"-11	715	907	1330	1030	1000	1110	1160
5/8"-18	798	1016	1482	1154	1140	1244	1301
3/4"-10	980	1249	1832	1416	1259	1530	1582
3/4"-16	958	1220	1790	1382	1230	1490	1558
7/8"-9	1495	1905	2775	2140	1919	2328	2430
7/8"-14	1490	1895	2755	2130	1911	2318	2420
1"-8	2205	2815	4130	3185	2832	3440	3595
1"-14	1995	2545	3730	2885	2562	3110	3250
	Maximum Torque (lb-ft.)						
1 1/8"-7	265	337	499	383	340	413	432
1 1/8"-12	251	318	470	361	322	390	408
1 1/4"-7	336	428	627	485	432	523	546
1 1/4"-12	308	394	575	447	396	480	504
1 1/2"-6	570	727	1064	822	732	888	930
1 1/2"-12	450	575	840	651	579	703	732

The torque values given here are to be used only as a guide for noncritical torquing application.

These values should develop bolt tension to slightly less than yield point. Ordinary dial type torque-wrench equipment was used in plotting torque value curves. Fasteners were torqued to failure in all cases. Washers were used only underneath the nut end. Fastener was brought under tension at point where nut would be mid-way in threaded section.

SOURCE: Design Fasteners (55).

CONSIDERATIONS FOR THE SELECTION OF MECHANICAL FASTENERS
FOR USE IN A REDUCED GRAVITY ENVIRONMENT

c. Torsional Holding Power (Inch-Pounds) for Cup-Point Set Screws

Shaft Diameter (in.)	No. 0	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 8	No. 10	1/4 in.	5/16 in.	3/8 in.	7/16 in.	1/2 in.	9/16 in.	5/8 in.	3/4 in.	7/8 in.	1 in.
	Nominal Screw Size																		
Seating Torque (lb-in.)	0.5	1.5	1.5	5.0	5.0	9.0	9.0	20	33	87	165	290	430	620	620	1225	2125	5000	7000
Axial Holding Power (lb)	50	65	85	120	160	200	250	385	540	1000	1500	2000	2500	3000	3500	4000	5000	6000	7000
3/32	1.5	2.0	2.6	3.2															
7/64	2.3	3.0	4.0	5.6	7.5														
1/8	3.1	4.0	5.3	7.5	10.0	12.5													
5/32	3.9	5.0	6.6	9.3	12.5	15.6	19	30											
3/16	4.7	6.1	8.0	11.3	15.0	18.7	23	36	51										
7/32	5.4	7.1	9.3	13.0	17.5	21.8	27	42	59										
1/4	6.2	8.1	10.6	15.0	20.0	25.0	31	48	68	125									
5/16		10.0	13.2	18.7	25.0	31.2	39	60	84	156	234								
3/8			16.0	22.5	30.0	37.5	47	72	101	187	280	375							
7/16				26.3	35.0	43.7	55	84	118	218	327	437	545						
1/2					40.0	50.0	62	96	135	250	375	500	625	750					
9/16						56.2	70	108	152	261	421	562	702	843	985				
5/8						62	78	120	169	312	468	625	780	937	1090	1250			
3/4							94	144	202	375	562	750	937	1125	1310	1500	1875		
7/8							109	168	236	437	656	875	1095	1310	1530	1750	2190	2620	
1								192	270	500	750	1000	1250	1500	1750	2000	2500	3000	3500
1 1/4									338	625	937	1250	1560	1875	2190	2500	3125	3750	4375
1 1/2										750	1125	1500	1875	2250	2620	3000	3750	4500	5250
1 3/4											1310	1750	2210	2620	3030	3500	4375	5250	6120
2											1500	2000	2500	3000	3500	4000	5000	6000	7000
2 1/2													3125	3750	4370	5000	6250	7500	8750
3														4500	5250	6000	7500	9000	10500
3 1/2															6120	7000	8750	10500	12250
4																8000	10000	12000	14000

Note: Experimental data were obtained by seating an alloy-steel, cup-point screw against a steel shaft with a hardness of Rockwell C 15. Screw threads were Class 3A, tapped holes were Class 2B. Holding power was defined as the minimum load necessary to produce 0.01 in. of relative movement between the shaft and the collar. Rustproofing oil on screws only.

SOURCE: Design Fasteners (55).

FASTENERS

CONSIDERATIONS FOR THE SELECTION OF MECHANICAL FASTENERS
FOR USE IN A REDUCED GRAVITY ENVIRONMENT

Tapping screws cut or forms a mating thread in metal, plastics, and other materials without the need of pretapped holes. These one piece fasteners permit rapid installation since nuts are not used and access is required from one side of the joint. General specifications and dimensions for standard tapping screws are listed in USA Standard Slotted Head Tapping Screws and Metallic Drive Screws, USAS B18.6.4-1967.

d. Minimum Torsional Strength (Inch-Pounds) for Tapping Screws

Nominal Screw Size	A	AB, B, BF, BP and BT	C		D, F, G and T	
			Coarse	Fine	Coarse	Fine
2	4	4	5	6	5	6
3	9	9	9	10	9	10
4	12	13	13	15	13	15
5	18	18	18	20	18	20
6	24	24	23	27	23	27
7	30	30	..	..	..	..
8	39	39	42	47	42	47
10	48	56	56	74	56	74
12	83	88	93	108	93	108
14	125	...	...	...	...	...
1/4	...	142	140	179	140	179
16	152	...	...	...	...	...
18	196	...	...	...	...	...
5/16	...	290	306	370	306	370
20	250	...	...	...	...	...
24	492	...	...	...	...	...
3/8	...	590	560	710	560	710
7/16	...	...	...	...	...	...
1/2	...	...	...	...	...	...

Single thread engaging nuts generally are used for lighter duty applications than multiple thread nuts of the same size. This type of fastener can be applied quickly and easily in most applications without any special tools, skills or equipment. The holding power and resistance to vibration loosening is dependent solely on the spring action of this type of fastener.

e. Single-Piece, Flat, Single-Thread Engaging Nut

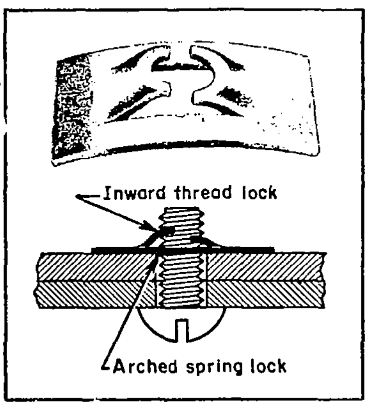


Fig. e - Single-piece, flat version of a single-thread engaging nut will not freeze to threads and is reusable. Locking action is provided by the spring-base arch compressing and producing an upward thrust against the screw threads, and the thread-engaging prongs working inward against the screw thread root.

SOURCE: Design Fasteners (55).

CONSIDERATIONS FOR THE SELECTION OF MECHANICAL FASTENERS
FOR USE IN A REDUCED GRAVITY ENVIRONMENT

f. Standard Flat-Type, Conical-Thread Engaging Nut

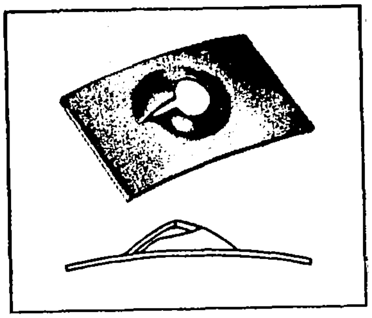


Fig. f - Standard, flat-type, conical-thread engaging nut. Tightening of the screw constricts the opening in this fastener, providing a binding action to lock the screw to the nut. The fastener is made with a large base area to eliminate the need for spanner washers. These nuts can be formed from low-carbon or spring steel. Low-carbon steel should be used only with coarse-threaded, sheetmetal screws.

g. Single-Thread Engaging Locknuts Made From Spring-Tempered Steel

Fig. g - Single-thread engaging locknuts made from spring-tempered steel (or other special materials as specified). The thread engaging elements are spirally formed to match the pitch of the screw threads. Reacts similar to the truncated-cone type when tightened.

h. Typical Torque and Tensile Load Limits - For Use With Machine Screws

Screw Size	Recommended Installation Torque (lb-in.)	Tensile Load Limit (lb)
4-36	3	100
4-40	3	100
6-32	5	150
8-32	7	250
10-24	12	350
$\frac{3}{16}$-24	12	350
$\frac{1}{4}$-20	30	600
$\frac{5}{16}$-18	30	1000

i. Typical Torque and Tensile Load Limits - For Use With Sheet-Metal Screws

Screw Size	Recommended Installation Torque (lb-in.)	Tensile Load Limit (lb)
4A & B (Z)	9	300
6A & B (Z)	11	400
8A & B (Z)	17	600
10A & B (Z)	31	800
12A & B (Z)	34	900
14A & B (Z)	48	1150
$\frac{5}{16}$ B (Z)	16	1200
$\frac{3}{8}$ B (Z)	19	2500

SOURCE: Design Fasteners (55).

CONSIDERATIONS FOR THE SELECTION OF MECHANICAL FASTENERS FOR USE IN A REDUCED GRAVITY ENVIRONMENT

Quick operating fasteners are used in cases where repeated operation of a fastener is necessary.

j. Comparative Properties

Fastener Properties	Lever-Actuated Fasteners				Turn-Operated Fasteners						Slide-Action Fasteners			Push-Pull Fasteners		
	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1. Speed of operation	1	1	1	1	1	2	3	1	2	1	2	1	1	1	1	1
2. Impact resistance	3	1	1	3	1	2	2	4	2	—	—	—	—	4	4	4
Vibration resistance	2	1	1	1	1	2	•	2	2	1	3	2	2	2	2	3
Fatigue strength	..	2	2	2	1	1	1	2	1	1	—	—	—	2	2	2
Shear strength	4	4	3	3	2*	1	4	4	4	1*	2	3	2	4	4	4
Tensile strength	2	3	2	2	2	1	2	3	2	2	—	—	3	—	4	3
3. Space conservation:																
Inside	1	1	4	1	2	2	1	3	2	2	1	1	1	3	3	2
Outside	3	3	1	4	1	1	2	3	2	1	3	3	2	1	1	3
4. Gasket compression	2	2	1	2	2	1	1	3	1	1	1	4	4	4	4	4
5. Light weight	3	3	4	4	1	1	1	2	4	3	2	3	3	2	2	1
6. Misalignment tolerability	4	2	3	3	2	1	3	1	1	4	2	3	4	4	2	4
7. Compensates for deformed or sprung panels	N	Y	N	Y	N	Y	Y	Y	Y	Y	Y	N	N	4	4	4
8. Keeper, striker or other receiver required on frame	Y	Y	Y	Y	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y	N
9. Latched condition, self-indicating	Y	Y	Y	Y	Y	N	N	Y	N	—	Y	Y	Y	N	N	Y
10. Installation on finished surface without damage	2	2	3	3	1	1	2	1	2	2	2	3	2	3	3	3
11. Outer panel components installed as a unit	Y	Y	Y	Y	N	N	Y	N	Y	N	Y	Y	N	N	Y	N
12. Mating components separately installed	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N
13. Skill required to install correctly	Y	N	Y	N	N	N	N	N	N	Y	N	N	N	—	N	N
14. Tools are required to operate fastener	N	N	N	N	Y&N	Y&N	Y&N	N	N	Y	N	N	N	N	N	N

*Shear strength high when shear bushing is used with the stud.
Code: Excellent—1, Good—2, Fair—3, Not suitable—4, Yes—Y, No—N.

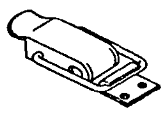
SOURCE: Design Fasteners (55).

FASTENERS

CONSIDERATIONS FOR THE SELECTION OF MECHANICAL FASTENERS FOR USE IN A REDUCED GRAVITY ENVIRONMENT

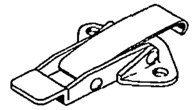
k. Quick-Operating Fastener Types

LEVER ACTUATED



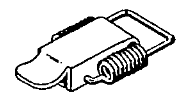
A—Draw-Pull Catch, Bail Type

A spring or drawhook assembly, with operating lever engaging a keeper or striker. Will handle edge-to-edge applications. Good leverage for pulling parts together. No parts inside assembly.



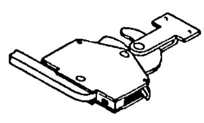
B—Draw-Pull Catch, Hook Type

A spring or drawhook assembly, with operating lever engaging a keeper or striker. Will handle edge-to-edge applications. Good leverage for pulling parts together. No parts inside assembly.



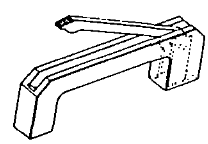
C—Draw-Pull Catch, Spring-Loaded

A spring or drawhook assembly, with operating lever engaging a keeper or striker. Will handle edge-to-edge applications. Good leverage for pulling parts together. No parts inside assembly. Spring-loaded for high shock loading and vibration resistance.



D—Cam-Action Fastener

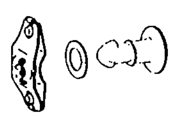
A cam assembly, operated by a lever or handle, engaging a keeper. Quick disconnect (positive travel can be used to break or set up a circuit). Good resistance to shock, pull-out, and vibration. Actuating lever can serve as carrying handle for subassembly.



E—Lever-Type Chassis Latch

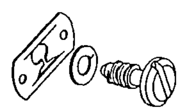
A cam surface integral with a lever pivoted on a handle. Cam surface engages with a keeper. Positive pull-in and eject action. Good locking action. Handles serve as means to lift out, pivot, or carry electronic drawer packages.

TURN OPERATED



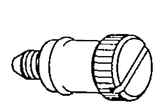
F—Quarter-Turn Fastener

A stud, locked into the door or cover panel by a retainer and engaging into a receptacle on the frame or chassis. Very fast actuation. Good resistance to vibration and shock. Light weight. Conserves space. Variety of head styles available.



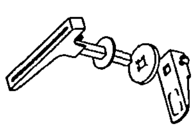
G—Fast Lead-Screw Fastener

A screw assembly with heavy square thread, a retainer, and a receptacle. Usually actuated with two or three turns. Good tolerance for varying material thickness and misaligned parts. Easy to install. High strength, and good resistance to vibration, shock, and fatigue. Not fouled by paint. Available in a variety of head styles.



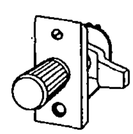
H—Standoff Thumbscrew

A polished screw and a retaining device, which captivates the screw into a standoff. Widely accepted for use on electronic equipment. Attractive appearance. Can be fully disengaged without backing panel off door. Will operate in a tapped hole. Screw retracts completely for providing zero inside projection where panels move laterally with respect to each other.



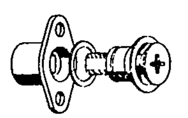
I—Pawl Fastener

A shaft with knob, a retaining device, and a pawl which catches against the door frame or keeper. Quarter-turn operated. Easily installed. Can be set to fit varying door or frame thickness.



J—Adjustable Pawl Fastener

A single unit with spring-loaded pawl traveling along a threaded shaft set in a housing which is riveted, screwed, or welded to the door. Quarter-turn operated. Preassembled for quick installation. Fits any door or frame thickness (grip range can be changed by turning the knob). Additional turning will apply any desired pressure to door. Requires no striker. Excellent for gasketed doors.



K—Stressed Panel Fastener

A multithread screw with a shear bushing, a retainer, and a threaded receptacle. Usually actuated with ½ to 1½ revolutions. Requires close tolerance installation. High-shear high-tensile fastener used on aircraft and missile access panels which are load-bearing. Sometimes the stud is hollow and tapped with threads which mate with a screw mounted in the receptacle.

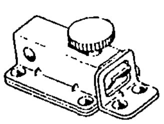
SOURCE: Design Fasteners (55).

FASTENERS

CONSIDERATIONS FOR THE SELECTION OF MECHANICAL FASTENERS FOR USE IN A REDUCED GRAVITY ENVIRONMENT

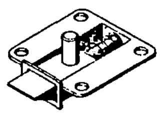
k. Quick-Operating Fastener Types (Cont.)

SLIDE ACTION



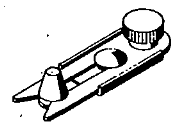
L—Sliding Latch, Adjustable Pull Up

A sliding pawl engaging in a keeper. Variations include use of a tightening knob. All parts on outside of assembly. Good general strength. Some types can be used as an automatic-locking drop latch when used at the bottom of a top-hinged door.



M—Slide Bolt, Spring-Loaded

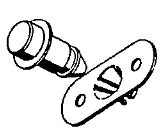
A spring-loaded sliding pawl with actuating stud. Usually mounted internally. Does not compress panel to frame. Good latching action.



N—Snap-Slide Latch

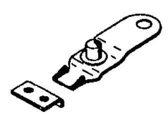
A slide latch moving in a guide affixed to removable panel with a rivet stud. A locking stud is mounted on the fixed or frame member. Locking stud passes through holé in panel to be engaged by slide latch at shoulder.

PUSH-PULL



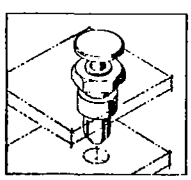
O—Pin-Spring Finger Latch

Sliding pin mounted in removable panel moves forward to engage behind fingers of receptacle. Further pressure on pin causes collar behind conical pin head to spread fingers on receptacle, allowing pin to retract and disengage when pressure is removed. Good latch for light load applications.



P—Button Lever Latch

Spring lever inside panel is actuated by button projecting through hole in panel. Hooked end of lever engages behind lip of fixed panel or cooperating keeper. Quick latching action on light panels or box lids.



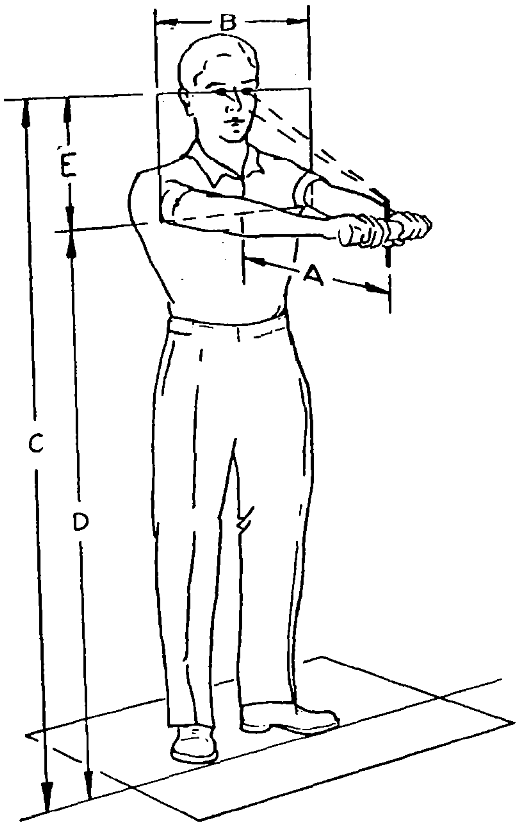
Q—Expandable-Prong Latch

A headed stud, operable from outside panel, actuates prongs on pliable member fixed to panel and projecting inwardly. Prongs engage through hole in fixed panel, expand and retain behind hole. Good insulating fastener. Tight hold-down for light to medium applications.

SOURCE: Design Fasteners (55).

SIZING AND CONFIGURATION FOR ACCESS

a. Standing, Forward Reach (Both Arms)



The subject assumed his natural standing posture against the front of the measuring apparatus and, holding the target grip so that the rod was vertical, he extended both arms horizontally through the greatly enlarged aperture. Both shoulders were thrust forward, increasing reach to a comfortable maximum. The lower horizontal member was brought up to touch the under-surface of the arms and was locked. The upper horizontal member was adjusted so that the subject could touch his forehead against its vertical surface. The upper horizontal member was then lowered further until the subject could just see the upper end of the rod of the target grip, and was also locked. The subject maintained this position while Breadth of Aperture and Depth of Reach were measured.

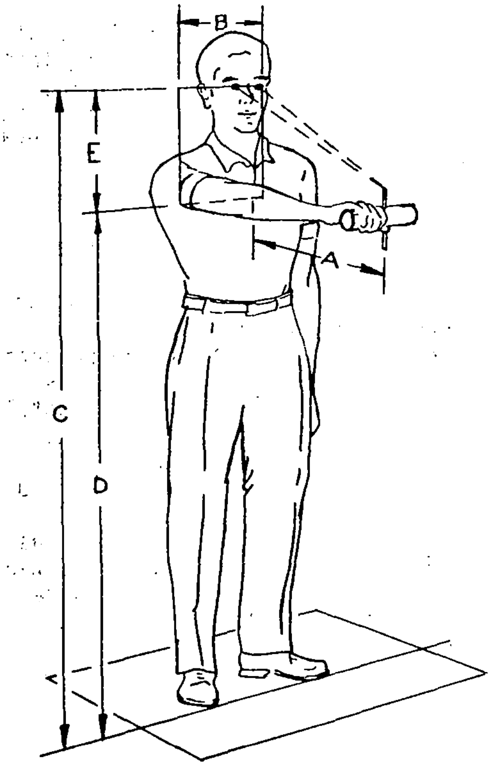
b. Range of Reach

	PERCENTILE*				
	5th	25th	50th	75th	95th
A. Depth of Reach Range: 17.50 to 25.25 Mean: 21.98 SD: 1.50	19.25	21.00	22.25	22.75	24.50
B. Breadth of Aperture Range: 15.00 to 20.25 Mean: 17.69 SD: 1.19	15.50	17.00	17.75	18.50	19.50
C. Floor to Top of Aperture Range: 58.75 to 70.50 Mean: 65.04 SD: 2.34	61.00	63.50	65.25	66.50	69.00
D. Floor to Bottom of Aperture Range: 51.25 to 61.75 Mean: 56.09 SD: 2.05	52.25	54.75	56.00	57.25	59.00

SOURCE: Kennedy and Feller (101).

SIZING AND CONFIGURATION FOR ACCESS

c. Standing, Forward Reach (Preferred Arm)



The subject assumed his natural standing posture against the front of the measuring apparatus and holding the target grip so that the rod was vertical, he extended his preferred arm horizontally through the greatly enlarged aperture. The corresponding shoulder was thrust forward, increasing reach to a comfortable maximum. The lower horizontal member was brought up to touch the undersurface of the arm and was locked. The upper horizontal member was adjusted so that the subject could touch his forehead against its vertical surface. The upper horizontal member was then lowered until the subject could just see the upper end of the rod of the target grip, and was locked. The subject maintained this position while Depth of Reach was measured.

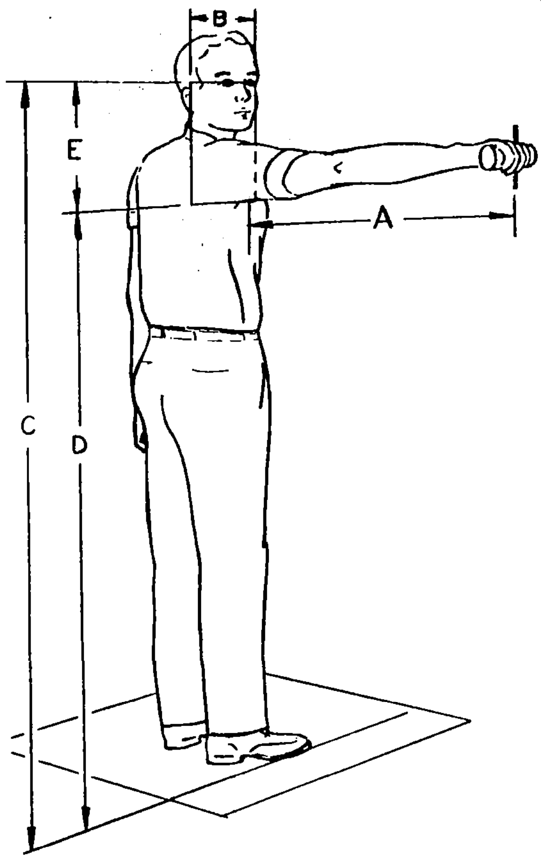
d. Range of Reach

	PERCENTILE				
	5th	25th	50th	75th	95th
A. Depth of Reach Range: 19.50 to 27.50 Mean: 23.61 SD: 1.82	20.25	22.25	23.75	25.00	26.75
B. Breadth of Aperture 12.00					
C. Floor to Top of Aperture Range: 58.25 to 70.50 Mean: 64.88 SD: 2.36	61.00	63.25	65.00	66.25	69.00
D. Floor to Bottom of Aperture Range: 51.25 to 61.75 Mean: 56.09 SD: 2.05	52.25	54.75	56.00	57.25	59.00

SOURCE: Kennedy and Feller (101).

SIZING AND CONFIGURATION FOR ACCESS

e. Standing, Lateral Reach (Preferred Arm)



The subject assumed his natural standing posture with his preferred side against the front of the measuring apparatus and, holding the target grip so that the rod was vertical, he extended his preferred arm horizontally through the greatly enlarged aperture. The preferred shoulder was extended laterally, increasing reach to a comfortable maximum. The lower horizontal member was brought up to touch the under-surface of the arm and was locked. The upper horizontal member was adjusted so that the subject could touch his forehead against its vertical surface. The upper horizontal member was then lowered further until the subject could just see the upper end of the rod of the target grip, and was locked. The subject maintained this position while Depth of Reach was measured. The subject was then allowed to withdraw from the measuring device while the remaining dimensions were measured.

f. Range of Reach

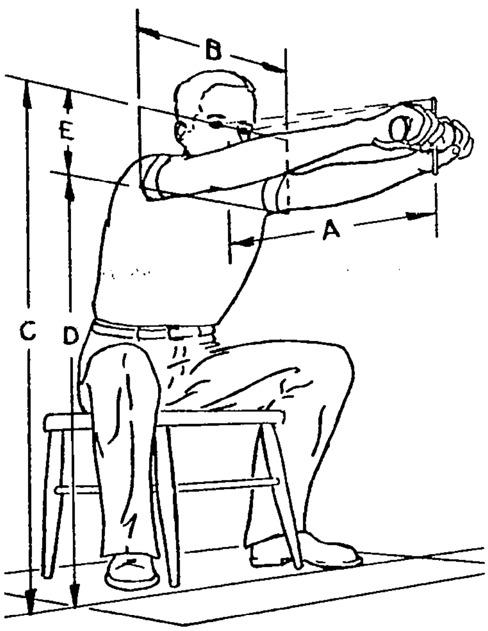
	PERCENTILE				
	5th	25th	50th	75th	95th
A. Depth of Reach Range: 21.75 to 28.63 Mean: 24.65 SD: 1.51	22.00	23.50	24.75	25.75	26.75
B. Breadth of Aperture†, * 10.00					
C. Floor to Top of Aperture Range: 58.25 to 70.00 Mean: 64.70 SD: 2.32	60.75	63.25	64.25	66.00	68.75
D. Floor to Bottom of Aperture Range: 51.25 to 61.75 Mean: 56.09 SD: 2.05	52.25	54.75	56.00	57.25	59.00

* A breadth of 10.00 inches will accommodate approximately 95 percent of the Air Force population.

SOURCE: Kennedy and Feller (101).

SIZING AND CONFIGURATION FOR ACCESS

g. Seated, Forward Reach (Both Arms)



The subject assumed a natural sitting posture in the chair provided. The subject's knees touched the front of the measuring device. Holding the target grip so that the rod was vertical, he extended both arms horizontally through the greatly enlarged aperture. Both shoulders were thrust forward, increasing reach to a comfortable maximum. The lower horizontal member was brought up to touch the under surface of the arms and was then locked. The upper horizontal member was adjusted so that the subject could touch his forehead against the vertical surface. The upper horizontal member was then lowered further until the subject could just see the upper end of the rod of the target grip. The horizontal member was then locked. The subjects maintained this position while Breadth of Aperture and Depth of Reach were measured. The subject was then allowed to withdraw from the measuring device while the remaining dimensions were measured.

h. Range of Reach

	PERCENTILE				
	5th	25th	50th	75th	95th
A. Depth of Reach Range: 14.00 to 23.50 Mean: 18.26 SD: 2.15	15.00	16.50	17.75	19.50	22.25
B. Breadth of Aperture Range: 13.50 to 18.75 Mean: 16.12 SD: 1.25	13.75	15.25	16.00	17.00	18.25
C. Floor to Top of Aperture Range: 39.25 to 51.00 Mean 43.25 SD: 2.05	39.75	41.75	43.00	44.25	46.50
D. Floor to Bottom of Aperture Range: 32.50 to 41.75 Mean: 36.59 SD: 1.59	34.25	35.50	36.50	37.50	39.00

SOURCE: Kennedy and Feller (101).

SIZING AND CONFIGURATION FOR ACCESS

i. Recommended Aperture Sizes and Depths of Reach for Shirt-Sleeved Technicians

	Standing Positions		
	Forward Reach, Both Arms	Forward Reach, Preferred Arm	Lateral Reach Preferred Arm
A. Depth of Reach, 5th Percentile	19.25	20.25	22.00
B. Breadth of Aperture, 95th Percentile	19.50	12.00	10.00
C. Floor to Top of Aperture, 95th Percentile	69.00	69.00	68.75
D. Floor to Bottom of Aperture, 5th Percentile	52.25	52.25	52.25
E. Vertical Dimension of Aperture (C minus D)	16.75	16.75	16.50

	Seated Positions	
	Normal, Both Arms	Cross-Legged, Both Arms
A. Depth of Reach, 5th Percentile	15.00	13.75
B. Breadth of Aperture, 95th Percentile	18.25	17.75
C. Floor to Top of Aperture, 95th Percentile	46.50	28.00
D. Floor to Bottom of Aperture, 5th Percentile	34.25	17.00
E. Vertical Dimension of Aperture (C minus D)	12.25	11.00

SOURCE: Kennedy and Feller (101).

SIZING AND CONFIGURATION FOR ACCESS

j. Aperture Sizes and Depths of Reach for Technicians Wearing the A/P 22S-2 Full-Pressure Suit

Standing, Lateral Reach (Preferred Arm)	5th	95th	Mean	SD	Range
A. Depth of Reach					
Vented	20.00		22.52	1.17	20.00 to 24.75
1 psi	19.25		21.70	1.45	19.00 to 25.00
3-1/2 psi	15.25		19.56	1.88	15.00 to 22.00
B. Breadth of Aperture					
Vented		10.25	9.84	0.37	9.00 to 10.25
1 psi		11.50	10.73	0.71	9.75 to 11.50
3-1/2 psi		14.00	12.76	0.89	11.25 to 14.00
C. Floor to Top of Aperture					
Vented		66.75	62.70	2.79	58.75 to 67.00
1 psi		65.75	61.54	2.15	57.75 to 66.00
3-1/2 psi		62.75	58.78	2.07	55.75 to 63.00
D. Floor to Bottom of Aperture					
Vented	50.50		53.49	2.58	50.25 to 57.50
1 psi	50.00		52.38	1.78	49.75 to 55.50
3-1/2 psi	46.50		50.80	2.33	46.25 to 55.50
E. Vertical Dimension of Aperture (C minus D)					
Vented		16.25			
1 psi		15.75			
3-1/2 psi		16.25			

SOURCE: Kennedy and Feller (101).

SIZING AND CONFIGURATION FOR ACCESS

k. Aperture Sizes and Depths of Reach for Technicians Wearing the A/P 22S-2 Full-Pressure Suit (Cont.)

	Seated, Forward Reach (Both Arms)				
	5th	95th	Mean	SD	Range
A. Depth of Reach					
Vented	13.00		15.82	1.44	13.00 to 18.00
1 psi	11.50		13.96	1.39	11.50 to 15.50
3-1/2 psi	5.00		8.05	2.02	5.00 to 12.00
B. Breadth of Aperture					
Vented		22.50	19.03	1.68	16.25 to 22.75
1 psi		25.00	21.08	1.94	17.50 to 25.00
3-1/2 psi		22.50	19.57	2.22	14.50 to 22.50
C. Floor to Top of Aperture					
Vented		45.75	43.62	1.70	40.25 to 45.75
1 psi		46.50	43.46	1.41	40.50 to 46.50
3-1/2 psi		46.50	43.31	1.79	39.25 to 46.50
D. Floor to Bottom of Aperture					
Vented	32.25		35.59	1.50	32.25 to 38.00
1 psi	32.25		35.49	1.36	32.25 to 38.00
3-1/2 psi	33.50		35.46	1.24	32.25 to 38.00
E. Vertical Dimension of Aperture (C minus D)					
Vented	13.25				
1 psi	14.00				
3-1/2 psi	12.75				

SOURCE: Altman, Marchese, et al (8), Human Engineering Design Criteria (88), and Kennedy and Feller (101).

SIZING AND CONFIGURATION FOR ACCESS

1. Space Envelope for Plug-In Operations (Tubes of Various Sizes Removed and Replaced)

DISTANCE FROM END OF FINGERS	HORIZONTAL AXIS				VERTICAL AXIS			
	LEFT WIDTH		RIGHT WIDTH		UP		DOWN	
	MEAN	RANGE	MEAN	RANGE	MEAN	RANGE	MEAN	RANGE
1 INCH	1.19	.56-2.05	1.69	1.18-2.45	1.23	.41-1.91	1.31	.41-2.66
2 INCHES	1.43	.68-2.40	2.04	1.41-2.68	1.74	.75-2.91	1.64	.83-3.33
3 INCHES	1.53	.68-2.40	2.23	1.90-2.56	2.06	1.16-3.25	1.70	.83-3.41
4 INCHES	1.59	.62-2.35	2.24	1.75-2.81	2.30	1.58-3.75	1.55	.66-3.16
5 INCHES	1.58	.56-2.30	2.16	1.37-2.87	2.46	1.50-3.91	1.30	.41-2.66
6 INCHES	1.55	.56-2.30	2.07	.87-2.75	2.56	1.80-3.91	1.08	.25-2.50

m. Space Envelope for Grasping and Turning Tools (Pliers and Wire Cutters)

DISTANCE FROM END OF FINGERS	HORIZONTAL AXIS				VERTICAL AXIS			
	LEFT WIDTH		RIGHT WIDTH		UP		DOWN	
	MEAN	RANGE	MEAN	RANGE	MEAN	RANGE	MEAN	RANGE
1 INCH	1.64	.50-2.65	1.67	.66-2.25	1.20	.50-1.83	1.69	.66-3.08
2 INCHES	1.96	.68-3.20	2.19	1.18-2.68	1.61	.66-2.16	2.26	1.00-3.16
3 INCHES	2.08	.81-3.50	2.44	1.50-3.12	1.72	.75-2.16	2.66	1.00-2.91
4 INCHES	1.86	.56-3.40	2.49	1.68-3.37	1.74	.83-2.41	1.88	.91-2.41
5 INCHES	1.49	.47-3.20	2.89	1.68-3.00	1.83	1.00-2.50	1.52	.83-2.08
6 INCHES	1.29	.50-2.80	2.36	1.62-2.99	1.83	1.08-2.50	1.40	.66-2.08

SOURCE: Altman, Marchese, et al (8), Human Engineering Design Criteria (88), and Kennedy and Feller (101).

SIZING AND CONFIGURATION FOR ACCESS

n. Space Envelope Required for Using an Average-Sized Socket Allen Wrench to Remove a Knob (2 Inches in Length)

DISTANCE FROM END OF FINGERS	HORIZONTAL AXIS				VERTICAL AXIS			
	LEFT WIDTH		RIGHT WIDTH		UP		DOWN	
	MEAN	RANGE	MEAN	RANGE	MEAN	RANGE	MEAN	RANGE
1 INCH	1.02	.00-1.87	2.95	2.12-4.00	3.36	2.50-4.50	1.79	.33-5.33
2 INCHES	1.12	.00-2.00	3.38	2.12-4.56	3.72	3.00-4.41	2.26	.66-5.41
3 INCHES	1.22	.00-2.13	3.38	2.12-4.35	3.59	3.00-4.08	2.54	.66-5.08
4 INCHES	1.31	.00-2.18	3.07	1 93-3.87	3.31	2.25-3.75	2.50	.66-4.16
5 INCHES	1.36	.00-2.18	2.64	1.62-3.37	2.91	1.25-3.40	2.25	.66-3.83
6 INCHES	1.42	.00-2.13	2.31	1.41-3.12	2.77	1.16-3.41	2.01	.58-3.41

o. Space Envelope Required for Using an Average-Sized Socket Wrench to Turn a Nut (3/8 Inch Base with 3-1/4 Inch Shaft)

DISTANCE FROM END OF FINGERS	HORIZONTAL AXIS				VERTICAL AXIS			
	LEFT WIDTH		RIGHT WIDTH		UP		DOWN	
	MEAN	RANGE	MEAN	RANGE	MEAN	RANGE	MEAN	RANGE
1 INCH	2.09	.47-3.20	2.92	2.25-4.30	2.73	2.00-3.75	2.88	2.08-3.33
2 INCHES	2.12	.50-3.35	3.25	2.37-4.55	2.86	1.75-3.75	2.65	1.66-3.41
3 INCHES	2.04	.56-3.31	3.13	2.43-4.35	3.10	1.83-4.25	2.10	1.33-2.50
4 INCHES	1.86	.68-3.18	2.94	2.06-4.35	3.23	2.08-4.41	1.65	1.08-2.08
5 INCHES	1.54	.56-2.81	2.73	1.93-4.35	3.25	2.33-4.08	1.10	0.66-1.75
6 INCHES	1.31	.47-2.50	2.55	1.37-4.25	3.11	2.50-4.16	0.76	0.50-1.25

SOURCE: Altman, Marchese, et al (8), Human Engineering Design Criteria (88), and Kennedy and Feller (101).

SIZING AND CONFIGURATION FOR ACCESS

p. Workspace for Hand Tool Tasks

TASK	DEPTH OF REACH (Z) (INCHES FROM ACCESS TO WORK POINT)	MAXIMUM SPACE USED AT ANY DEPTH							
		UNCLOTHED ARM				ARCTIC JACKET AND LEATHER GLOVE			
		WIDTH RIGHT	(X)** LEFT	HEIGHT DOWN	(Y) UP	WIDTH RIGHT	(X) LEFT	HEIGHT DOWN	(Y) UP
TURNING BOLT WITH	6	2.0	1.2	2.2	1.7	2.3	1.9	2.3	1.9
COMMON SCREWDRIVER	12	2.3	2.0	2.3	1.7	3.4	3.1	3.1	2.4
(VERTICAL PLANE)	18	2.8	1.8	2.3	2.0	3.8	2.9	3.2	3.8
	24	3.3	1.8	2.3	2.0	3.8	2.5	4.1	2.9
TURNING BOLT WITH	6	2.4	2.2	0.3	8.3	2.8	1.6	0.7	8.6
COMMON SCREWDRIVER	12	2.9	1.4	1.9	8.3	3.2	2.3	2.3	8.4
(HORIZONTAL PLANE)	18	3.4	1.5	2.2	8.3	4.0	2.8	2.8	8.0
	24*								
TURNING BOLT WITH	6	3.8	2.5	3.8	1.1	2.8	4.6	4.4	1.1
OFFSET SCREWDRIVER	12	2.3	4.4	4.1	1.4	2.8	5.3	5.2	2.4
(VERTICAL PLANE)	18	2.7	4.3	4.4	2.9	2.9	5.3	5.4	2.5
	24	3.3	4.2	4.4	1.2	4.0	4.4	4.4	3.1
TURNING BOLT WITH	6	2.5	4.8	1.4	2.8	2.5	4.3	1.5	3.6
OFFSET SCREWDRIVER	12	3.3	4.3	2.1	3.7	3.2	5.2	2.7	3.3
(HORIZONTAL PLANE)	18	3.1	4.2	2.8	3.7	3.7	4.5	2.8	3.8
	24	3.5	4.4	3.4	4.1	3.7	5.3	4.4	3.4
CUTTING WIRE	6	2.3	1.9	1.8	2.2	[illegible]	2.3	2.4	2.3
(VERTICAL PLANE)	12	2.5	2.0	2.3	2.2	3.7	2.0	3.1	2.4
	18	3.0	2.1	2.3	2.3	3.5	2.9	3.4	2.8
	24	1.9	3.3	3.5	1.7	4.1	3.1	4.2	3.4
CUTTING WIRE	6	2.8	0.6	1.4	2.9	3.1	1.2	3.2	1.8
(HORIZONTAL PLANE)	12	2.7	1.0	2.3	2.1	3.2	2.1	3.2	2.7
	18	2.9	1.5	2.3	3.2	3.6	2.9	3.0	2.8
	24	3.8	1.7	3.7	1.8	4.2	2.9	4.5	2.8

ALL MEASUREMENTS ARE IN INCHES DEPTH IS ALONG AN IMAGINARY LINE FROM THE CENTER OF THE WORK POINT TO THE CENTER OF THE EXTERNAL ACCESS HEIGHT AND WIDTH MEASURES ARE TAKEN FROM THE SAME IMAGINARY LINE

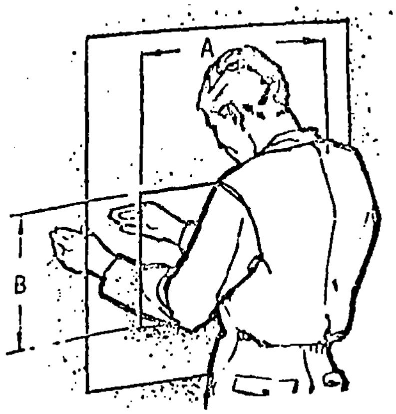
* *SUBJECT WAS UNABLE TO REACH THE WORK POINT THROUGH THE ACCESS AT THIS DISTANCE*

** LEFT AND RIGHT DIRECTIONS ARE IN RESPECT TO SUBJECT FACING THE TASK.

SOURCE: Altman, Marchese, et al (8), Human Engineering Design Criteria (88), and Kennedy and Feller (101).

SIZING AND CONFIGURATION FOR ACCESS

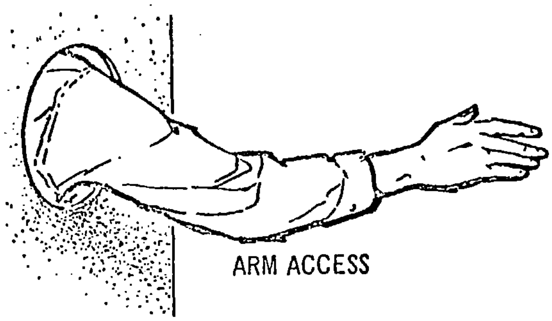
q. Work Space Requirements



TWO HAND REACH 6 TO 25 INCHES IN DEPTH

BLIND ACCESS

LIGHT CLOTHING	A	8" OR 75% OF REACH
	B	5"
BULKY PROTECTIVE CLOTHING	A	6" PLUS 75% OF REACH
	B	7"
VISIBLE ACCESS		
	B	22.6"



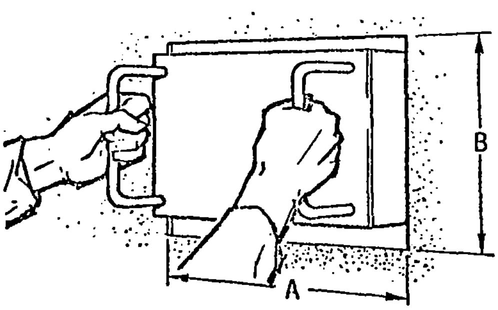
ARM ACCESS

ARM TO ELBOW

LIGHT CLOTHING	4.5" X 4.5" DIA OR 3.5" AROUND OBJECT
BULKY PROTECTIVE CLOTHING	7" X 7" DIA OR 3.5" AROUND OBJECT

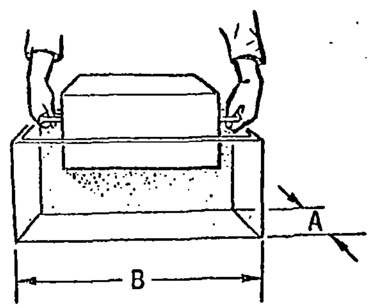
ARM TO SHOULDER

LIGHT CLOTHING	5" X 5", 5" DIA OR 3.5" AROUND OBJECT
BULKY PROTECTIVE CLOTHING	8.5" X 8.5", 8.5" DIA OR 3.5" AROUND OBJECT



INSERT OBJECT WITH HANDLES ON FACE

A	BOX PLUS 1.5"
B	8.5" OR BOX PLUS 1.5" WHICHEVER IS GREATER



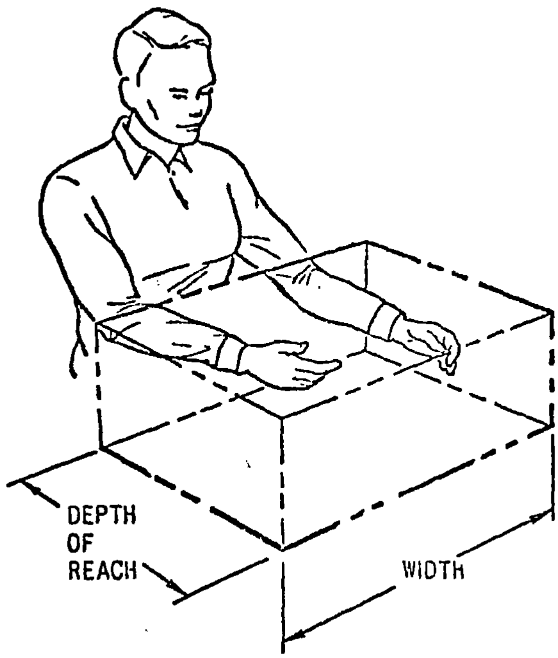
INSERT OBJECT WITH HANDS ON SIDES

A	BOX PLUS 1.5"
B	BOX PLUS 4.5" (LIGHT CLOTHING)
	BOX PLUS 7" (BULKY PROTECTIVE CLOTHING)

SOURCE: Human Engineering Design Criteria (88).

SIZING AND CONFIGURATION FOR ACCESS

q. Work Space Requirements (Cont.)



FOR INSERTING EMPTY HANDS, APERTURE SHOULD BE 4" HIGH BY 3/4 X DEPTH OF REACH

r. Curvature of Handle or Edge

WEIGHT OF ITEM	RADIUS OF CURVATURE (MINIMUM)
UP TO 15 LBS:	R – 1/8 IN.
15 TO 20 LBS:	R – 1/4 IN.
OVER 20 LBS:	R – 3/8 IN. BUT 1/5 IN.
T-BAR POST:	T – 1/2 IN.

GRIPPING EFFICIENCY IS BEST IF FINGERS CAN CURL AROUND HANDLE OR EDGE TO AN ANGLE OF 120 DEGREES OR BETTER.

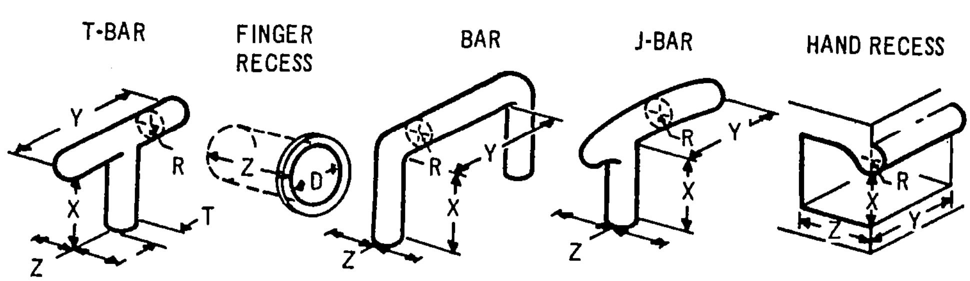
SOURCE: Human Engineering Design Criteria (88).

SIZING AND CONFIGURATION FOR ACCESS

s. Dimensions of Handle.

DIMENSIONS OF HANDLE	EXPECTED USER CLOTHING								
	BARE HAND			GLOVED HAND			ARCTIC MITTEN		
TYPE OF HANDLE:	X	Y	Z	X	Y	Z	X	Y	Z
ONE-HAND BAR	2.0	4.25	2.0	2.5	4.75	2.0	3.0	5.5	3.0
TWO-HAND BAR	2.0	8.5	2.0	2.5	9.5	2.0	3.0	11.0	3.0
TWO-FINGER BAR	1.25	2.5	1.5	1.5	3.0	1.5	DON'T USE		
ONE-HAND RECESS	2.0	4.25	3.5	2.5	4.75	4.0	3.0	5.5	5.0
TWO-FINGER RECESS	1.25-DIA		2.0	1.5-DIA		2.0	DON'T USE		
ONE-FINGER RECESS	1.25-DIA		2.0	1.5-DIA		2.0	DON'T USE		
FINGER-TIP RECESS	0.75-DIA		0.5	1.0-DIA		0.75	DON'T USE		
T-BAR	1.5	4.0	1.5	2.0	4.5	2.0	DON'T USE		
J-BAR	2.0	4.0	2.0	2.0	4.5	2.0	3.0	5.0	3.0

t. Types of Handles



SOURCE: Human Engineering Design Criteria (88).

VEHICULAR CHARACTERISTICS

MAINTAINABILITY

SIZING AND CONFIGURATION FOR ACCESS

u. Minimal Finger Access to First Joint

PUSH BUTTON ACCESS:

- Bare Hand: 1.25" dia.
- Gloved Hand: 1.5" dia.

TWO FINGER TWIST ACCESS:

- Bare Hand: 2.0" dia. clearance around object
- Gloved Hand: 2.5" dia. clearance around object

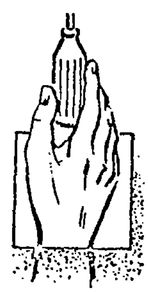
VACCUM TUBE INSERT (tube held as at right):

- Miniature tube: 2.0" dia. clearance around object
- Large tube: 4.0" dia. clearance around object

v. Minimal One Hand Access Openings

EMPTY HAND TO WRIST: WIDTH HEIGHT

- Bare hand, rolled: 3.75" sq. or dia.
- Bare hand, flat: 2.25" x 4.0" or 4.0" dia.
- Glove or mitten: 4.0" x 6.0" or 6.0" dia.
- Bulky Protective mitten: 5.0" x 6.5" or 6.5" dia.

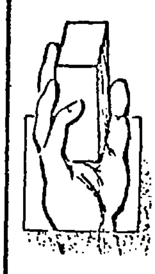


HAND PLUS 1" DIA OBJECT, TO WRIST:

- Bare hand: 3.75" sq. or dia.
- Glove or mitten: 6.0" sq. or dia.
- Bulky Protective mitten: 7.0" sq. or dia.

CLENCHED HAND TO WRIST:

- Bare hand: 3.5" x 5.0" or 5.0" dia.
- Glove or mitten: 4.5" x 6.0" or 6.0" dia.
- Bulky Protective mitten: 7.0" x 8.5" or 8.5" dia.



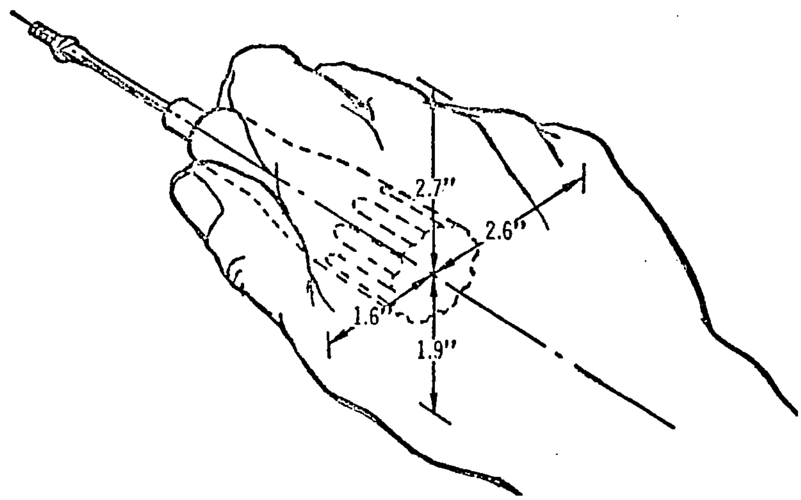
HAND PLUS OBJECT OVER 1" IN DIA TO WRIST:

- Bare hand: 1.75" clearance around object
- Glove or mitten: 2.5" clearance around object
- Bulky Protective mitten: 3.5" clearance around object

SOURCE: Human Engineering Design Criteria (88).

SIZING AND CONFIGURATION FOR ACCESS

w. Space Envelope For Tools Which Require Hand Rotation (Screw Drivers, Spintites)



DISTANCE FROM END OF FINGERS	HORIZONTAL AXIS				VERTICAL AXIS			
	LEFT WIDTH MEAN RANGE		RIGHT WIDTH MEAN RANGE		UP MEAN RANGE		DOWN MEAN RANGE	
1 IN.	1.16	.68–2.00	1.90	1.37–2.50	1.51	.66–2.25	1.26	.50–2.08
2 IN.	1.45	.92–2.25	2.31	1.75–2.85	2.00	1.08–2.91	1.62	.58–2.33
3 IN.	1.49	.93–2.25	2.42	1.88–2.81	2.26	1.25–3.33	1.67	.58–2.58
4 IN.	1.45	.65–2.20	2.40	1.75–3.00	2.39	1.25–3.33	1.52	.58–2.50
5 IN.	1.41	.40–1.95	2.32	1.63–2.95	2.31	1.25–3.50	1.36	.58–2.25
6 IN.	1.31	.35–2.50	2.21	1.68–2.90	2.44	1.83–3.58	1.04	.33–1.83

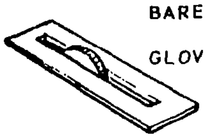
NOTE: The points are given in inches from an imaginary line extending along the axis of the tool involved. When all four underlined points are plotted on perpendicular axes they describe the maximum average volume required for the operation. A more generous and comfortable envelope is described by using the maximum range values instead of the maximum mean values.

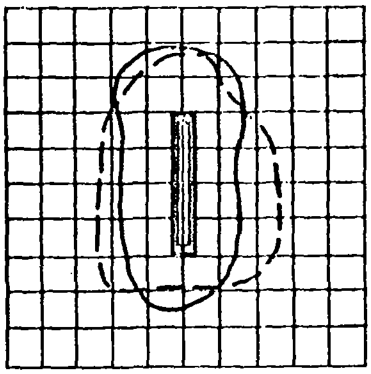
SOURCE: Human Engineering Design Criteria (88).

SIZING AND CONFIGURATION FOR ACCESS

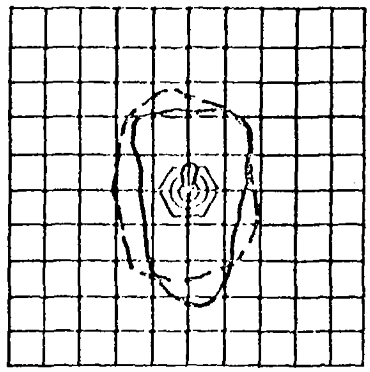
x. Limited Spacing Between Control

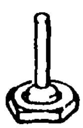
TYPE: ROLLER (CONTINUOUS)
LENGTH = 1.000
WIDTH = .375
SWEPT AREA:
BARE HAND: MAJOR AXIS = .8
MINOR AXIS = 1.8
GLOVED HAND:
MAJOR AXIS = 2.12
MINOR AXIS = 1.25



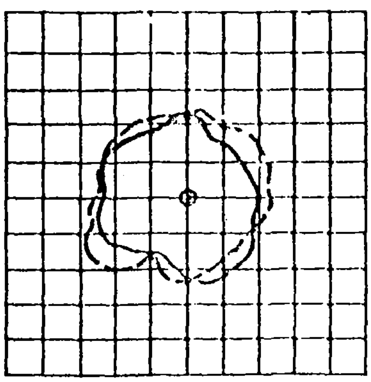


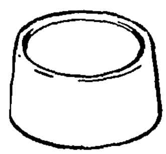
TYPE: TOGGLE SWITCH
DIAMETER = .125
HEIGHT = .375
SWEPT AREA:
BARE HAND: MAJOR AXIS = 1.30
MINOR AXIS = .85
GLOVED HAND: MAJOR AXIS = 1.30
MINOR AXIS = .85



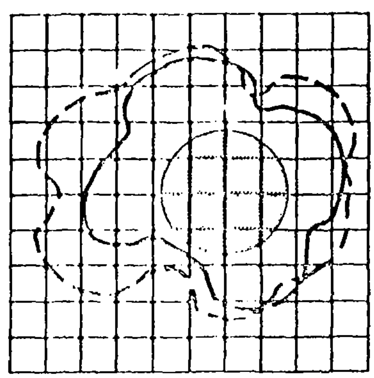


TYPE: ROUND KNOB
DIAMETER = .125
HEIGHT = .500
SWEPT AREA:
BARE HAND: DIA = 1.2
GLOVED HAND: DIA = 1.4





TYPE: ROUND KNOB
DIAMETER = .875
HEIGHT = .500
SWEPT AREA:
BARE HAND: DIA = 1.8
GLOVED HAND: DIA = 2.4



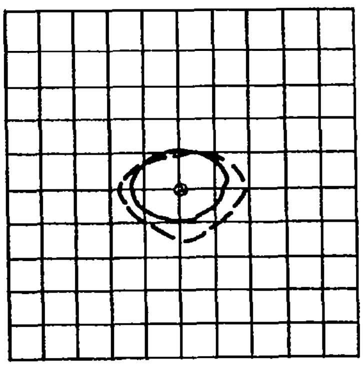
BARE HAND ———— GLOVED HAND --------

SOURCE: Human Engineering Design Criteria (88).

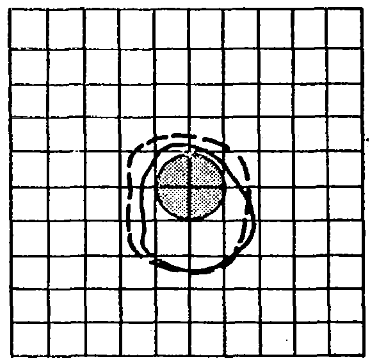
SIZING AND CONFIGURATION FOR ACCESS

x. Limited Spacing Between Control (Cont.)

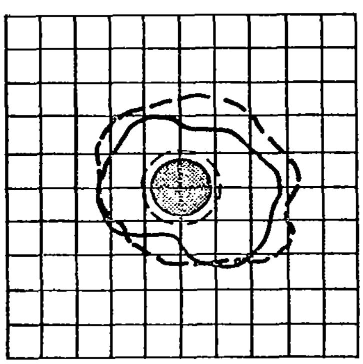
TYPE: PUSHBUTTON
DIAMETER = .125
HEIGHT = .187
SWEPT AREA:
BARE HAND: DIA = .65
GLOVED HAND: DIA = .85



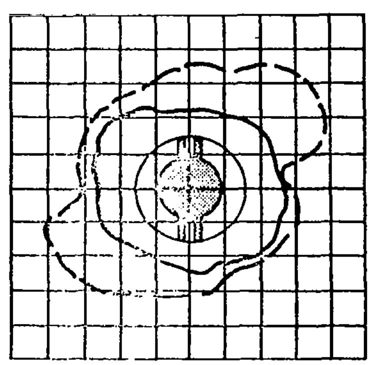
TYPE: PUSHBUTTON
DIAMETER = .500
HEIGHT = .375
SWEPT AREA:
BARE HAND: DIA = .90
GLOVED HAND: DIA = .90



TYPE: ROUND SELECTOR KNOB
DIAMETER = .425
HEIGHT = .625
SWEPT AREA:
BARE HAND: MAJOR AXIS = 1.2
MINOR AXIS = .9
GLOVED HAND: DIA = 1.5



TYPE: BLADE KNOB
WIDTH OF BLADE = .375
LENGTH = .500
HEIGHT = .500
SWEPT AREA:
BARE HAND: DIA = 1.35
GLOVED HAND:
MAJOR AXIS = 2.19
MINOR AXIS = 1.50



BARE HAND ————— GLOVED HAND --------

SOURCE: Human Engineering Design Criteria (88).

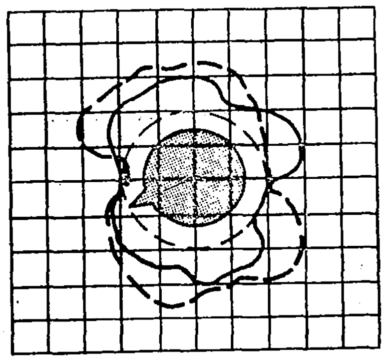
VEHICULAR CHARACTERISTICS

MAINTAINABILITY

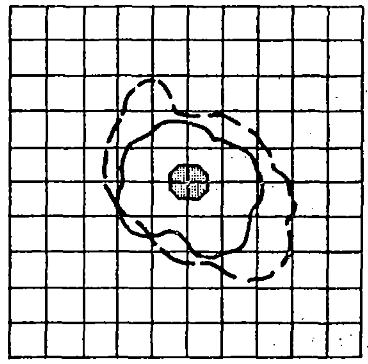
SIZING AND CONFIGURATION FOR ACCESS

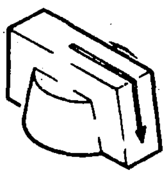
x. Limited Spacing Between Control (Cont.)

TYPE: ROUND SELECTOR KNOB
DIAMETER = .62
HEIGHT = .50
SWEPT AREA:
BARE HAND: DIA = 1.40
GLOVED HAND:
MAJOR AXIS = 1.75
MINOR AXIS = 1.25

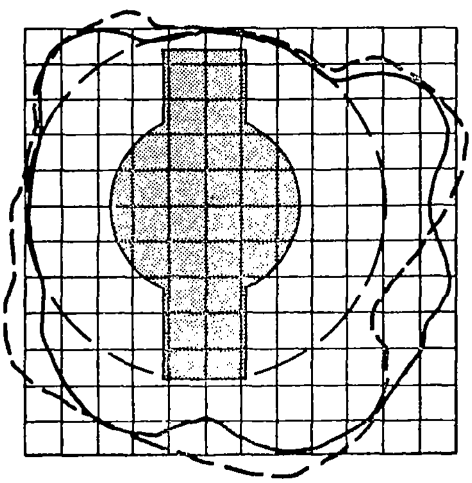


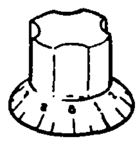
TYPE: HEXAGONAL KNOB
DIAMETER = .250
HEIGHT = .375
SWEPT AREA:
BARE HAND: DIA = 1.0
GLOVED HAND:
MAJOR AXIS = 1.65
MINOR AXIS = 1.0



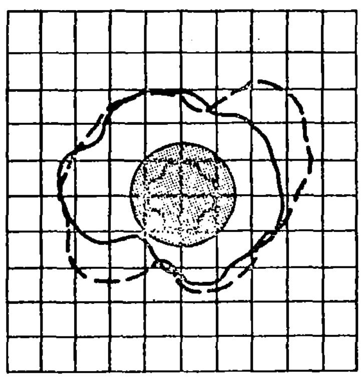


TYPE: BLADE KNOB
LENGTH = 2.37
HEIGHT = 1.00
SWEPT AREA:
BARE HAND: DIA = 3.37
GLOVED HAND: DIA = 3.50





TYPE: SKIRTED KNOB
DIAMETER = .500
HEIGHT = .375
SWEPT AREA:
BARE HAND: DIA = 1.6
GLOVED HAND: DIA = 2.0



BARE HAND ——— GLOVED HAND ------

SOURCE: Human Engineering Design Criteria (88).

SIZING AND CONFIGURATION FOR ACCESS

y. Aperture Sizes and Depths of Reach for Technicians Wearing the A/P 22S-2 Full-Pressure Suit - Standing, Forward Reach (Both Arms)

	5th*	95th*	Mean	SD	Range
A. Depth of Reach					
Vented	16.00		19.26	1.57	16.00 to 21.75
1 psi	14.25		17.01	1.62	14.00 to 19.50
3-1/2 psi	7.50		11.30	2.60	7.50 to 15.75
B. Breadth of Aperture					
Vented		23.00	19.24	1.34	17.00 to 23.25
1 psi		25.00	21.18	1.81	18.50 to 25.25
3-1/2 psi		26.00	23.60	1.84	19.25 to 26.00
C. Floor to Top of Aperture					
Vented		68.00	63.86	2.88	59.75 to 68.00
1 psi		65.75	62.61	2.01	59.75 to 66.00
3-1/2 psi		66.25	60.38	2.58	56.25 to 66.50
D. Floor to Bottom of Aperture					
Vented	50.75		53.49	2.58	50.25 to 57.50
1 psi	50.00		52.38	1.78	49.75 to 55.50
3-1/2 psi	46.50		50.80	2.33	46.25 to 55.50
E. Vertical Dimension of Aperture (C minus D)**					
Vented	17.25				
1 psi	15.75				
3-1/2 psi	19.75				

SOURCE: Human Engineering Design Criteria (88).

SIZING AND CONFIGURATION FOR ACCESS

z. Aperture Sizes and Depths of Reach for Technicians Wearing the A/P 22S-2 Full-Pressure Suit - Standing, Forward Reach (Preferred Arm)

	5th*	95th*	Mean	SD	Range
A. Depth of Reach					
Vented	18.00		20.91	1.78	18.00 to 24.00
1 psi	15.25		18.25	1.77	15.00 to 21.00
3-1/2 psi	11.00		14.46	2.25	10.75 to 20.00
B. Breadth of Aperture					
Vented		11.50	10.17	0.79	9.25 to 11.50
1 psi		12.50	11.40	0.85	9.75 to 12.50
3-1/2 psi		14.00	13.09	0.91	11.00 to 14.00
C. Floor to Top of Aperture					
Vented		67.75	63.71	2.77	60.25 to 68.00
1 psi		65.75	62.19	2.09	58.75 to 66.00
3-1/2 psi		64.25	59.53	2.31	55.75 to 64.50
D. Floor to Bottom of Aperture					
Vented	50.50		53.49	2.58	50.25 to 57.50
1 psi	50.00		52.38	1.78	49.75 to 55.50
3-1/2 psi	46.50		50.80	2.33	46.25 to 55.50
E. Vertical Dimension of Aperture (C minus D)					
Vented	17.25				
1 psi	15.75				
3-1/2 psi	17.75				

SOURCE: Human Engineering Design Criteria (88).

SIZING AND CONFIGURATION FOR ACCESS

aa. Mean Work Times and Standard Deviations for Removing Two Nuts Using an Open-End Wrench (Values in Seconds)

15-cm (6-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	174.1(16.9)	128.6(12.8)	99.4(12.8)	92.0(7.6)	85.0(7.4)
Right Side	196.9(24.9)	145.4(9.8)	106.4(9.6)	107.7(11.6)	79.0(7.7)
Top	176.6(22.3)	123.7(18.1)	88.9(5.8)	91.1(12.1)	87.1(10.1)
Bottom	197.0(23.5)	141.0(19.9)	88.1(9.0)	79.6(7.9)	79.0(4.1)
Rear	160.3(31.6)	100.3(21.1)	61.4(7.8)	52.1(3.6)	43.9(8.6)
Baseline	50.1				

30-cm (12-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	217.3(39.0)	141.3(21.3)	115.6(19.0)	109.9(21.1)	90.3(12.2)
Right Side	225.6(39.8)	198.0(53.5)	114.7(23.9)	94.6(13.6)	96.4(10.7)
Top	233.6(32.4)	142.1(30.9)	98.7(11.0)	100.7(17.7)	87.7(11.2)
Bottom	211.6(15.3)	146.0(23.4)	98.3(13.0)	77.7(9.8)	89.1(8.1)
Rear	189.6(49.9)	107.1(16.6)	80.1(8.5)	64.0(6.0)	56.0(5.0)
Baseline	52.8				

45-cm (18-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	207.0(30.8)	168.4(30.4)	114.7(22.5)	96.4(13.9)	96.0(18.0)
Right Side	221.1(55.6)	164.4(40.3)	96.7(14.0)	98.7(14.8)	93.7(21.2)
Top	237.3(37.2)	155.6(34.4)	95.0(17.2)	88.4(9.9)	84.6(18.1)
Bottom	228.0(59.6)	117.0(22.8)	94.9(13.5)	102.1(18.2)	94.9(29.8)
Rear	247.9(50.7)	116.4(24.6)	65.4(7.9)	52.4(3.2)	51.4(4.4)
Baseline	58.2				

( ) = Standard Deviations

SOURCE: Kama (100).

SIZING AND CONFIGURATION ACCESS

ab. Mean Work Times and Standard Deviations for Replacing Two Nuts Using an Open-End Wrench (Values in Seconds)

15-cm (6-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	200.6(24.5)	112.3(7.9)	100.3(6.6)	85.3(6.0)	83.3(8.6)
Right Side	206.4(26.8)	179.4(23.1)	122.3(13.7)	143.9(14.5)	93.6(5.7)
Top	223.1(25.6)	127.6(24.2)	102.6(7.2)	123.1(22.5)	110.1(16.2)
Bottom	204.3(24.5)	130.6(21.3)	100.4(19.5)	92.9(10.8)	78.9(6.8)
Rear	154.3(24.6)	146.6(27.1)	77.9(5.8)	56.7(5.2)	54.9(3.1)
Baseline	57.0				

30-cm (12-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	226.6(52.7)	141.6(24.2)	110.9(22.3)	113.4(22.9)	119.9(21.7)
Right Side	252.7(49.6)	195.7(58.1)	151.1(35.4)	105.7(19.3)	130.1(17.2)
Top	274.9(43.6)	147.3(35.7)	125.1(13.1)	109.9(21.0)	110.4(15.9)
Bottom	249.0(29.5)	169.1(26.7)	111.9(12.9)	114.7(28.8)	117.4(20.1)
Rear	218.7(59.3)	127.3(60.1)	99.3(18.1)	69.4(7.3)	64.0(6.4)
Baseline	61.7				

45-cm (18-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	198.3(60.5)	124.9(15.9)	100.1(12.0)	93.7(7.4)	89.6(14.5)
Right Side	319.0(61.0)	207.6(50.4)	131.3(22.4)	129.9(17.1)	127.6(36.8)
Top	248.7(49.4)	126.4(17.7)	87.1(12.2)	105.4(17.8)	82.3(8.7)
Bottom	243.6(38.9)	150.3(33.5)	117.0(26.2)	103.3(16.2)	125.7(35.5)
Rear	332.6(77.6)	151.6(29.5)	90.1(14.4)	62.7(5.4)	63.9(9.5)
Baseline	51.2				

( ) = Standard Deviations

SOURCE: Kama (100).

VEHICULAR CHARACTERISTICS

MAINTAINABILITY

SIZING AND CONFIGURATION FOR ACCESS

ac. Mean Work Times and Standard Deviations for Removing Two Nuts Using a Ratchet Wrench (Values in Seconds)

15-cm (6-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	81.4(45.1)	66.1(10.9)	61.0(11.3)	61.0(8.2)	67.4(12.7)
Right Side	89.6(17.2)	81.7(24.5)	62.7(11.8)	68.7(10.0)	66.6(11.5)
Top	99.6(17.0)	80.0(15.7)	72.1(7.5)	74.4(13.5)	80.6(20.2)
Bottom	76.9(17.0)	72.4(13.0)	63.9(11.6)	67.4(3.2)	60.7(10.2)
Rear	129.0(83.1)	77.9(11.2)	49.1(13.7)	49.1(14.8)	36.7(15.6)
Baseline	32.7				

30-cm (12-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	80.0(14.2)	71.4(13.1)	62.6(12.7)	62.1(10.2)	61.0(14.7)
Right Side	88.3(15.5)	83.3(23.9)	68.9(11.6)	62.6(14.1)	63.6(18.8)
Top	107.1(39.8)	95.4(36.5)	75.0(10.1)	79.0(17.5)	65.9(18.1)
Bottom	89.4(21.3)	86.6(41.7)	67.6(13.9)	64.3(14.6)	63.9(16.1)
Rear	77.7(15.2)	76.1(24.7)	60.3(16.2)	47.9(15.7)	35.6(19.7)
Baseline	31.6				

45-cm (18-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	112.4(37.7)	91.6(24.6)	86.1(27.8)	74.7(18.8)	76.9(21.4)
Right Side	134.6(54.3)	90.7(23.3)	84.0(19.0)	73.9(18.1)	68.3(16.9)
Top	182.7(76.9)	138.6(51.4)	105.0(24.5)	98.7(35.4)	78.7(22.0)
Bottom	127.4(46.8)	97.3(26.5)	81.6(29.3)	79.3(27.0)	85.0(26.8)
Rear	....	87.5(22.4)	77.3(22.0)	71.0(17.2)	30.9(10.8)
Baseline	28.0				

SOURCE: Kama (100).

SIZING AND CONFIGURATION FOR ACCESS

ad. Mean Work Times and Standard Deviations for Replacing Two Nuts Using a Ratchet Wrench (Values in Seconds)

15-cm (6-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	81.9(18.5)	66.3(14.2)	64.4(15.7)	71.0(18.2)	72.4(19.2)
Right Side	100.1(42.6)	86.4(26.8)	65.1(13.1)	71.3(9.2)	68.1(13.5)
Top	89.4(27.1)	93.3(31.5)	70.3(12.4)	78.4(15.1)	69.9(7.2)
Bottom	78.1(18.7)	74.9(16.7)	61.7(15.4)	65.0(11.9)	63.6(17.7)
Rear	135.5(88.0)	79.3(12.1)	52.4(13.7)	52.7(15.4)	39.4(17.8)
Baseline	33.6				

30-cm (12-inch) Depth

Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	85.1(20.1)	78.7(21.4)	69.0(15.3)	61.7(9.4)	60.0(14.4)
Right Side	99.6(27.7)	87.3(21.4)	85.6(15.1)	72.7(19.2)	68.7(13.3)
Top	105.1(48.3)	83.9(19.0)	88.0(19.6)	78.9(16.8)	66.7(13.6)
Bottom	93.1(22.4)	81.3(29.8)	72.7(19.5)	67.1(17.4)	63.9(14.3)
Rear	90.7(30.7)	77.1(24.3)	65.9(20.5)	49.0(13.7)	42.4(22.5)
Baseline	31.5				

45-cm (18-inch) Depth

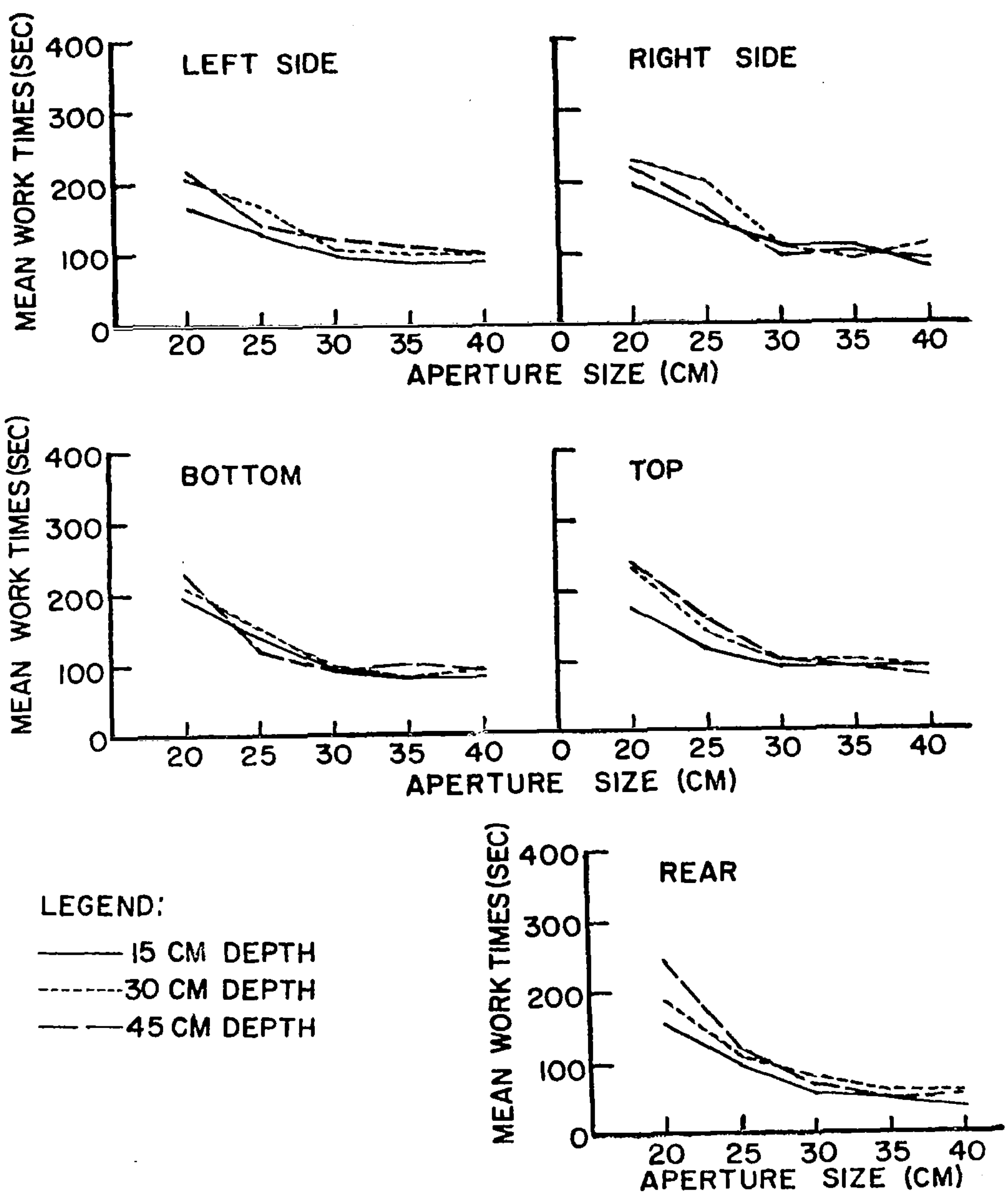
Task Location	Aperture Sizes (cm) 20	25	30	35	40
Left Side	122.3(42.8)	89.4(26.8)	85.9(28.3)	83.0(30.8)	77.4(18.7)
Right Side	129.4(43.4)	131.0(37.0)	95.1(25.3)	88.3(27.9)	84.0(27.2)
Top	188.1(80.6)	134.0(38.8)	100.3(32.6)	99.1(34.8)	100.4(40.0)
Bottom	137.7(57.8)	110.0(27.5)	87.0(24.1)	80.6(28.3)	82.9(23.6)
Rear	....	99.3(25.5)	81.6(21.2)	75.7(18.1)	33.7(7.6)
Baseline	27.4				

( ) = Standard Deviations

SOURCE: Kama(100).

SIZING AND CONFIGURATION FOR ACCESS

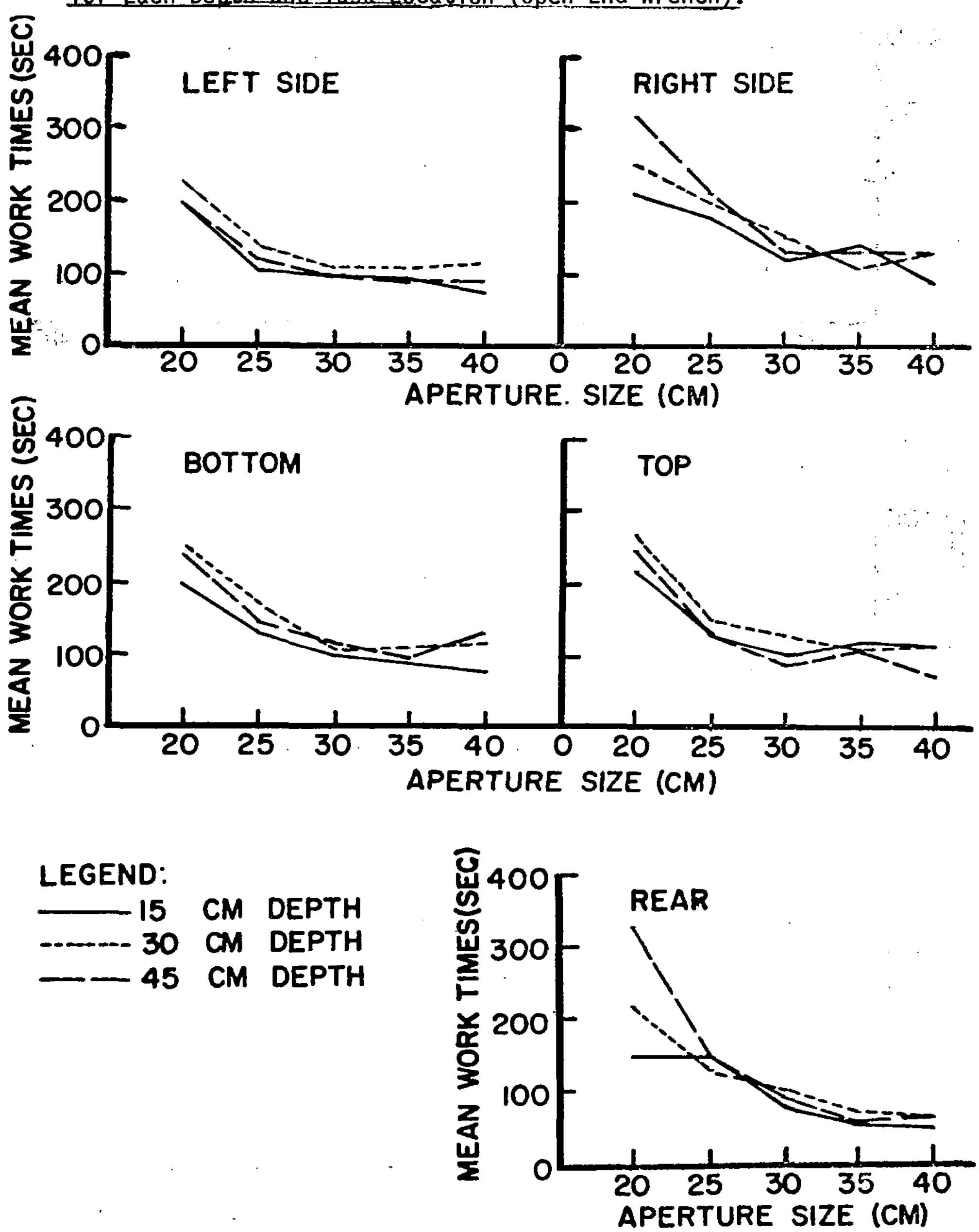
ae. Performance Curves for Removing Two Nuts as a Function of Aperture Size for Each Depth and Task Location (Open-End Wrench).



SOURCE: Kama (100).

SIZING AND CONFIGURATION FOR ACCESS

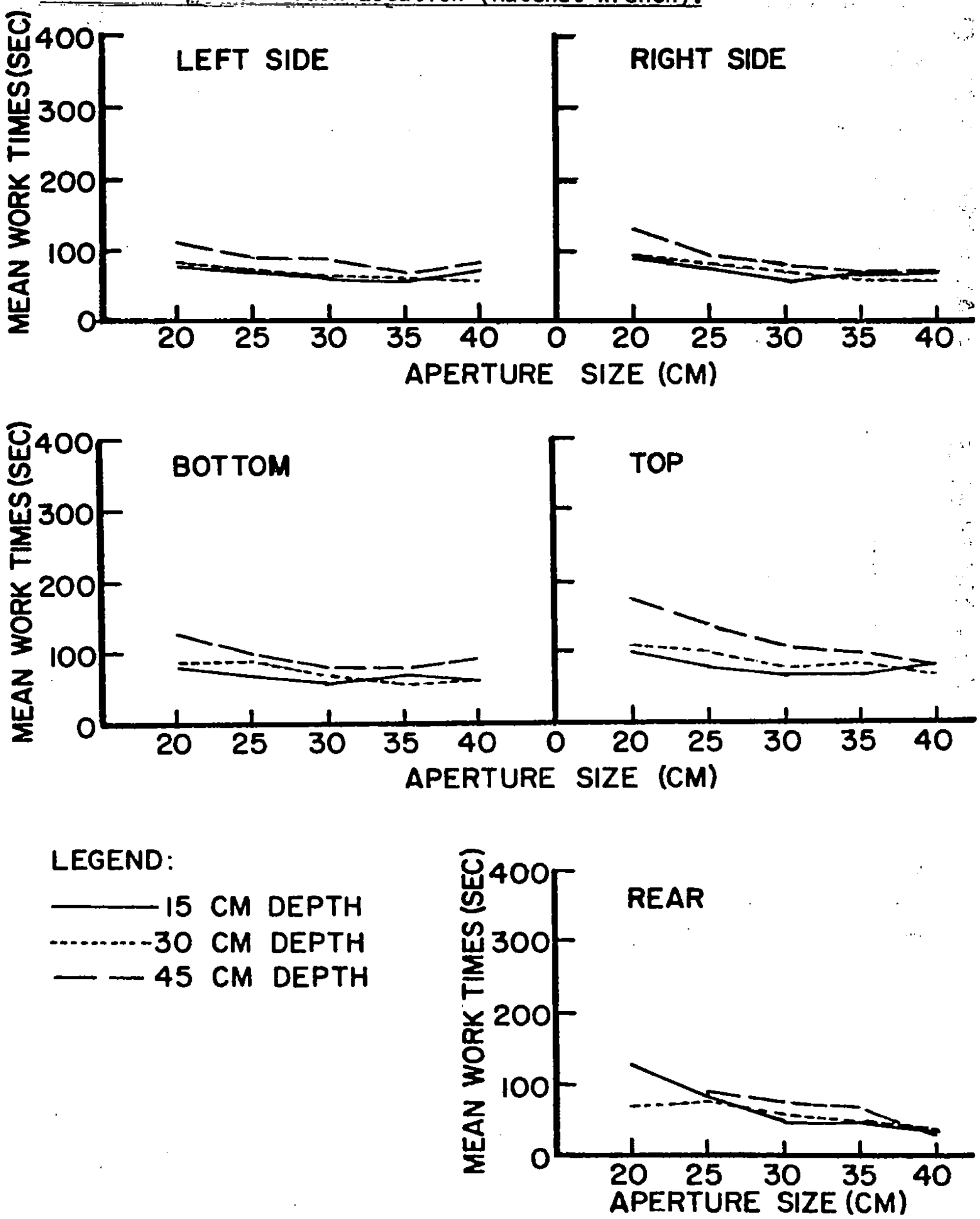
af. Performance Curves for Replacing Two Nuts as a Function of Aperture Size for Each Depth and Task Location (Open-End Wrench).



SOURCE: Kama (100).

SIZING AND CONFIGURATION FOR ACCESS

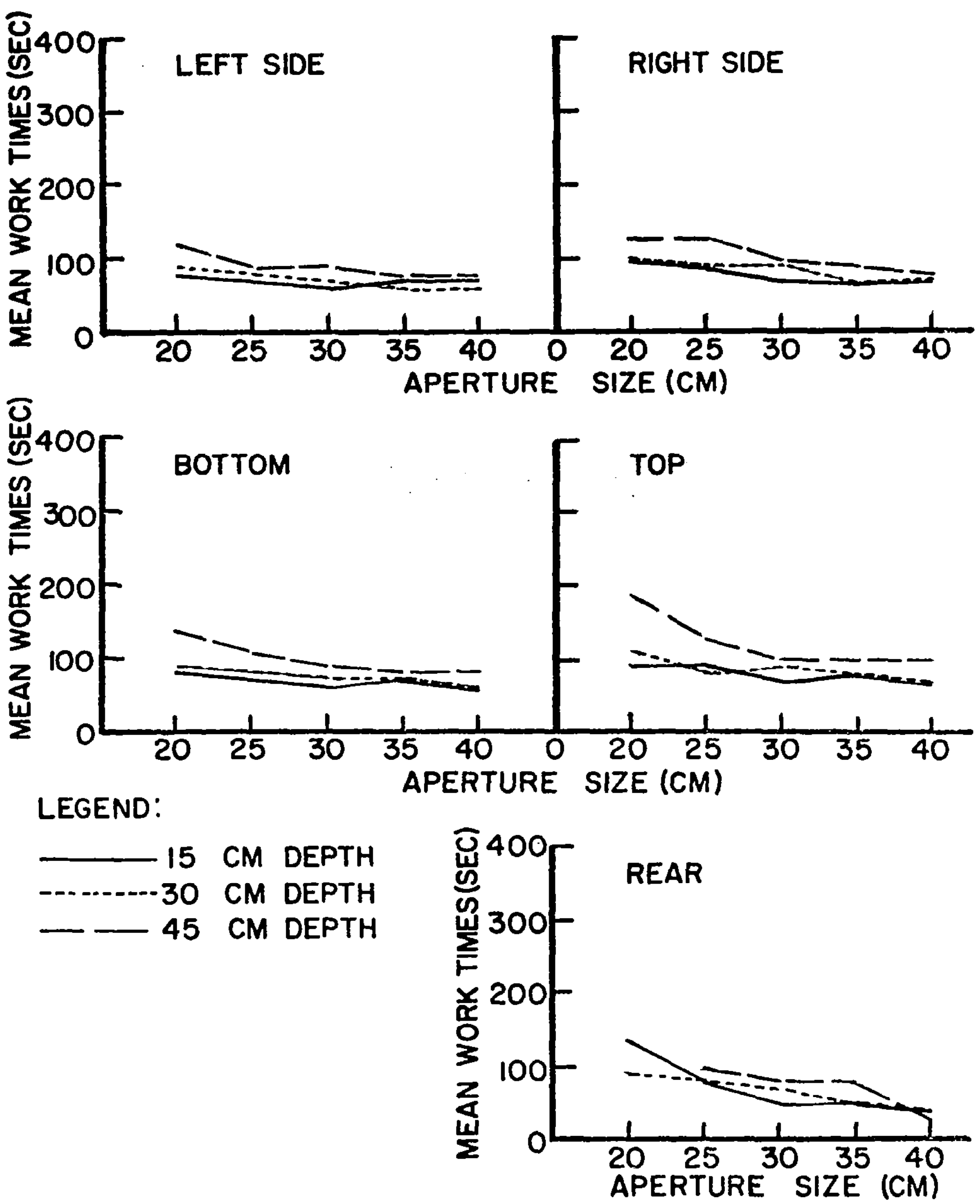
ag. Performance Curves for Removing Two Nuts as a Function of Aperture Size for Each Depth and Task Location (Ratchet Wrench).



SOURCE: Kama (100).

SIZING AND CONFIGURATION FOR ACCESS

ah. Performance Curves for Replacing Two Nuts as a Function of Aperture Size for Each Depth and Task Location (Ratchet Wrench).



SOURCE: Kama (100).

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