

16. ANTHROPOMETRY AND TEMPORO-SPATIAL ENVIRONMENT

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16. ANTHROPOMETRY AND TEMPORO-SPATIAL ENVIRONMENT

The management of workspace, clothing and time elements in space operations is a major factor in optimizing crew comfort and efficiency. The anthropometric sizing of the astronaut population will be used whenever these data are available. Alteration of optimum workspace by zero gravity has already been covered under zero gravity in Acceleration (No. 7). Confinement and biorhythmic factors will complete the section.

ANTHROPOMETRIC FACTORS IN WORKSPACE ANALYSIS

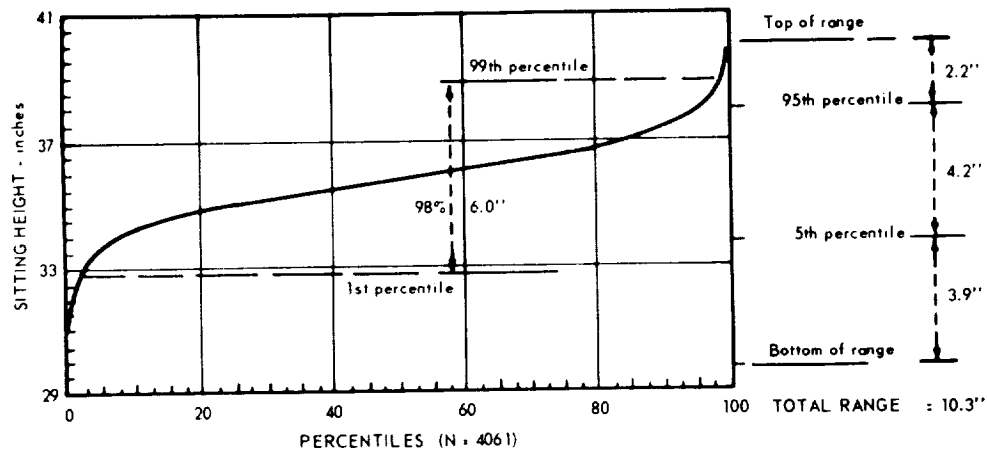
Several reviews are available of anthropometric factors in engineering design (71, 72, 145, 163, 164, 165, 213, 224, 234, 241, 246, 263, 294, 310). These cover static and dynamic body dimensions of the general population, as well as specific military groups. These may be used in the design of the appropriate ground based- as well as flight equipment whenever the specific dimensions of the astronaut group are not critical.

Those aspects of spacecraft design that are related to the anthropological (or physical) characteristics and the performance of the crew include: (25, 213, 224, 233, 234, 246)

- Design of protective clothing and portable life support systems (fit, mobility, task performance considerations) (129, 131, 232, 236, 243, 245, 246, 247, 331, 332, 333, 336, 371)
- Layout of the workspace in the spacecraft cabins (89, 129, 131, 232, 233, 236, 243, 245, 246, 247, 331, 333, 373)
- Design of the occupancy and restraint systems (fit, mobility, and support considerations (129, 131, 232, 246, 331, 332, 333, 336)
- Selection and design of displays and controls (88, 129, 130, 131, 160, 213, 224, 232, 233, 234, 243, 245, 247, 331, 332, 333, 336)
- Design of the equipment for maintainability (102, 333)
- Design of training equipment (to support crew performance) (130, 232, 332, 333, 336)
- Safety and hazard standards related to the spacecraft (123, 243, 245, 246, 247, 330, 331, 332, 333, 336)

Human Dimensions

Most of the anthropometric data are presented as percentiles of the population distribution. The use of percentile values as opposed to average or mean values is illustrated in Figure 16-1. In the charts presented in this section, whenever possible the size and composition of the population sample from which the data are derived are indicated (72).



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.

Figure 16-1

The Use of Percentile Values in Anthropometry

(After Hertzberg and Clauser⁽¹⁶⁴⁾)

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 was nude or clothed. Sketches accompany many of the charts to indicate how the measurements were taken.

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. For example, an access hatch should be large enough for the largest man to pass through; a switch for a panel to be operated by a seated, restrained operator should be

located at a distance no farther than that which the man with the shortest arm can efficiently reach to actuate the switch. A control should not require more force than the weakest man who is to use the equipment can be expected to apply, yet the control should be able to withstand more force than the strongest man can be expected to apply under normal conditions. For astronauts it is vital that the entire range be accommodated, but for non-astronauts using ground-based equipment, 95% or -- if space is critical -- 90% of the range may suffice. Furthermore, the principle of mock-up trials, using subjects who are physically representative of the using population, wearing typical outfits, and performing simulated tasks, should be used before final decisions on design are made. For ground-based operations, anthropometric data are required on the general population. The basic body dimensions of a generalized U. S. male population is noted in Figure 16-2. The U. S. National Health Examination Survey, conducted in 1962-64, gives 10 key dimensions for a truly representative sample of the U.S. population. Data are presented by age group (18-24, 25-29, etc., to age 79) covering the total population (71, 334).

Anthropometric data are required for design of equipment used in military aircraft supporting launch, recovery and in-flight monitoring operations. Dimensions of the USAF flying personnel are noted in Figure 16-3. Correlations between the dimensions of this population are available (164). Table 16-4 covers the overall head, body, and limb measurements of the astronaut population. The body dimensions of from 3 to 38 astronauts were used to establish means, standard deviations, and ranges (94).

The need for biomechanical data regarding the center of gravity (CG) and moments of inertia of the human body and body segments arises in several fields of application. Such data are useful in determining the stability and angular acceleration of equipment occupied or operated by persons in various postural attitudes; in the design of seats, particularly aircraft ejection seats and fastening devices; in dummy construction; in assessing the ability to apply torque while in the weightless state and the consequences of such application; and in the study of human biomechanics. An excellent review of the techniques of measurement is available (84). Data in the older literature (35, 201) have been updated by more recent studies (22, 23, 77).

Moment of inertia (I_{CG}) about the segment CG is equal to the product of segment mass and radius of gyration squared. Moment of inertia about a proximal joint center (I_0) is related to I_{CG} by the formula:

$$I_0 = I_{CG} + mD^2, \quad (1)$$

where m is the segment mass and D is the distance from the joint center to the CG. The moments of inertia of the segments can be determined by a free-swinging pendulum system. The segments were suspended from the proximal joint center, the oscillation period measured, and the moment of inertia determined by the relation:

$$I_0 = \frac{mgL}{4\pi^2 f^2} \quad (2)$$

where I_0 = moment of inertia about the point of suspension,
 m = mass of the segment (weight/g),

Body dimensions of United States males, as estimated and synthesized for use in commercial aircraft interior design. Adapted from a chart prepared by J. A. Roebuck, Douglas Aircraft Co., Inc., from data of Hooton (169), Randall et al (263), Daniels et al (73), Hertzberg et al (165), and McFarland et al (214).

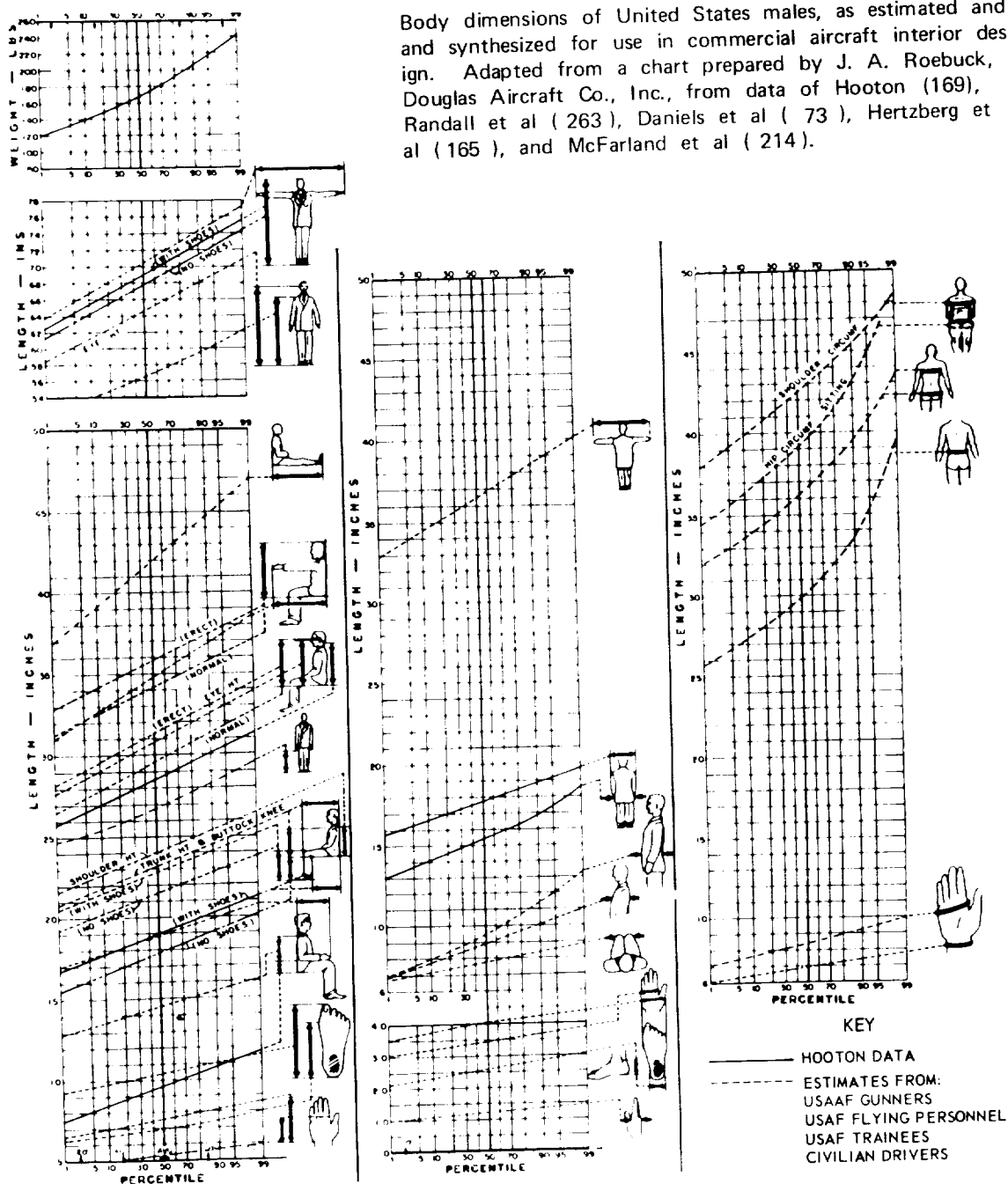
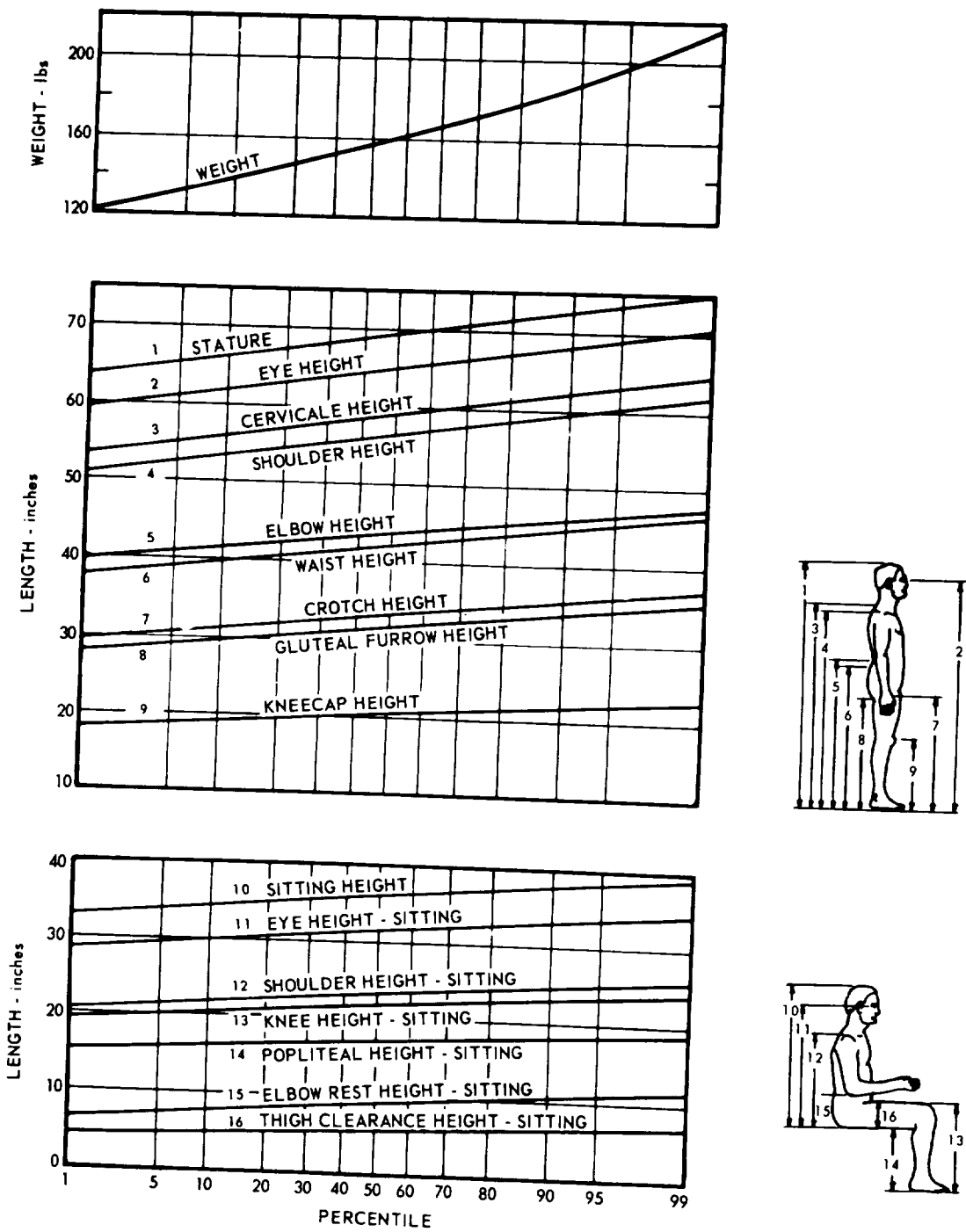


Figure 16-2

Body Dimensions of U. S. Males

(After Hertzberg and Clauser (164))



Body dimensions of a sample of approximately 4060 flying personnel of the U. S. Air Force.

Figure 16-3

Dimensions of Flying Personnel

(After Hertzberg and Clauser (164))

Figure 16-3 (continued)

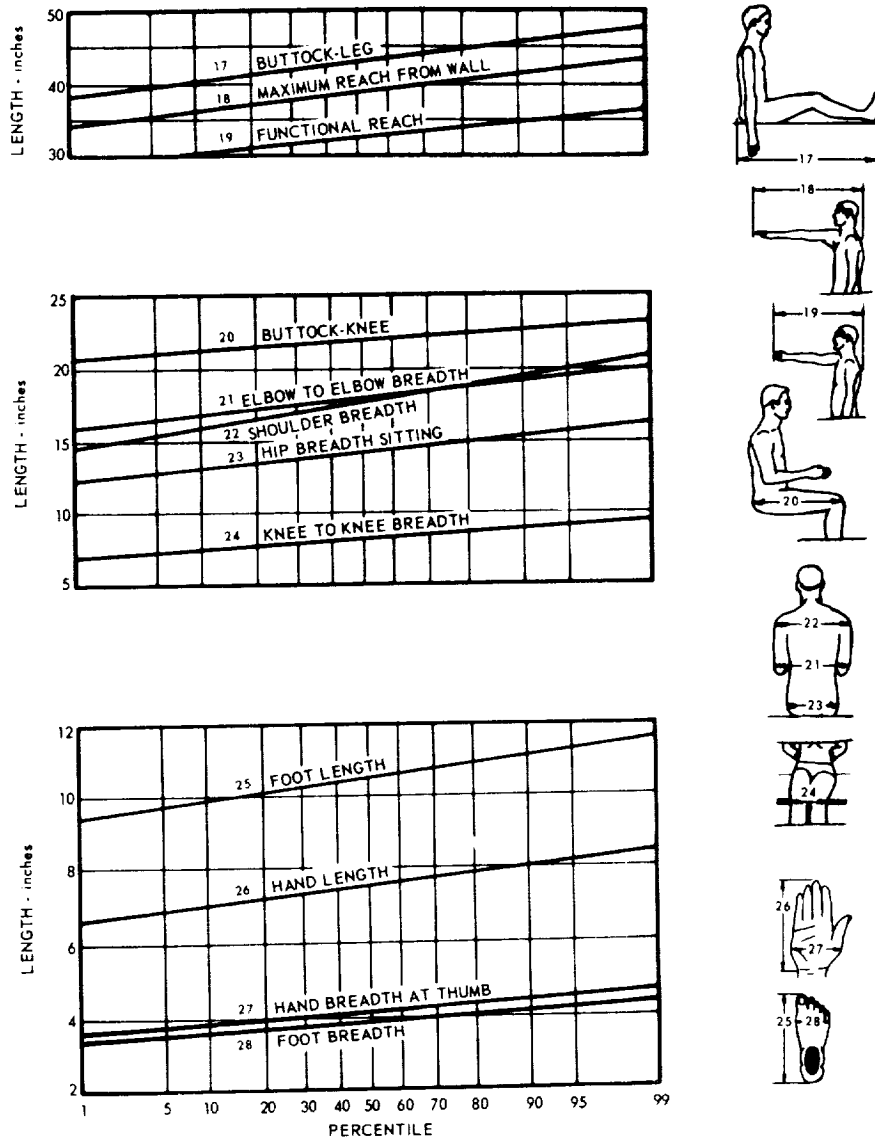


Table 16-4

Anthropometry of the Astronaut Population

(See end of table for description of non-standard measurements)*
(From the data of Feddersen and Reed(94))

| Measurement | Observations | Centimeters | | | | | Inches | | | | |
|--|--------------|-------------|-----------|--------|--------|--------|-----------|--------|--------|--|--|
| | | Mean | Std. Dev. | Range | | Mean | Std. Dev. | Range | | | |
| | | | | Low | High | | | Low | 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 Tragon, 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 Suprasternal 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 | | |

Table 16-4 (continued)

a. Overall Dimensions of the Head, Body, and Limbs of the Astronaut Population (continued)

| Measurement | Observations | Centimeters | | | Inches | | |
|--|--------------|-------------|-----------|-------------------|--------|-----------|-------------------|
| | | Mean | Std. Dev. | Range Low High | Mean | Std. Dev. | Range Low 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 |

b. Dimensions of the Head of the Astronaut Population

| Measurement | Observations | Centimeters | | | Inches | | |
|--------------------------|--------------|-------------|-----------|-------------------|--------|-----------|-------------------|
| | | Mean | Std. Dev. | Range Low High | Mean | Std. Dev. | Range Low 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 |

Table 16-4 (continued)

| Measurement | Observations | Centimeters | | | | | Inches | | | | |
|--|--------------|-------------|-----------|-------|-------|-------|-----------|-------|-------|--|--|
| | | Mean | Std. Dev. | Range | | Mean | Std. Dev. | Range | | | |
| | | | | Low | High | | | Low | High | | |
| 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 Tragon 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 Tragon 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 Tragon | 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 Tragon | 9 | 14.39 | 0.46 | 13.40 | 15.00 | 5.67 | 0.18 | 5.28 | 5.91 | | |
| 24. Length of Bitragon-Coronal Arc | 6 | 34.67 | 0.66 | 33.40 | 35.30 | 13.65 | 0.26 | 13.15 | 13.90 | | |
| 25. Length of Bitragon-Crinion Arc | 8 | 32.29 | 1.15 | 30.60 | 34.00 | 12.71 | 0.45 | 12.05 | 13.39 | | |
| 26. Length of Bitragon-Inion Arc | 6 | 28.93 | 1.16 | 27.70 | 30.60 | 11.39 | 0.46 | 10.91 | 12.05 | | |
| 27. Length of Bitragon-Menton Arc | 10 | 31.81 | 0.87 | 30.50 | 33.30 | 12.52 | 0.34 | 12.01 | 13.11 | | |

Table 16-4 (continued)

b. Dimensions of the Head of the Astronaut Population (continued)

| Measurement | Observations | Centimeters | | | Inches | | |
|--|--------------|-------------|-----------|-------------------|--------|-----------|-------------------|
| | | Mean | Std. Dev. | Range Low High | Mean | Std. Dev. | Range Low 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 | 0.70 | 27.50 29.50 | 11.21 | 0.28 | 10.83 11.61 |
| 30. Breadth between Gonias | 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 |

c. Dimensions of the Trunk and Torso of the Astronaut Population

| Measurement | Observations | Centimeters | | | Inches | | |
|--|--------------|-------------|-----------|-------------------|--------|-----------|-------------------|
| | | Mean | Std. Dev. | Range Low High | Mean | Std. Dev. | Range Low 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 |

Table 16-4 (continued)

| c. Dimensions of the Trunk and Torso of the Astronaut Population (continued) | Measurements | Observations | Centimeters | | | | | Inches | | | | |
|--|--|--------------|-------------|-----------|--------|--------|-------|-----------|-------|-------|--|--|
| | | | Mean | Std. Dev. | Range | | Mean | Std. Dev. | Range | | | |
| | | | | | Low | High | | | Low | High | | |
| 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 | | |

Table 16-4 (continued)

| Measurement | Observations | Centimeters | | | | Inches | | | |
|---|--------------|-------------|-----------|--------|--------|--------|-----------|-------|-------|
| | | Mean | Std. Dev. | Range | | Mean | Std. Dev. | Range | |
| | | | | Low | High | | | Low | High |
| <u>Arms</u> | | | | | | | | | |
| 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 |

d. Dimensions of the Arms and Hands of the Astronaut Population (continued)

| Measurement | Observations | Centimeters | | | Inches | | |
|---|--------------|-------------|-----------|-------------------|--------|-----------|-------------------|
| | | Mean | Std. Dev. | Range Low High | Mean | Std. Dev. | Range Low 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 |

e. Dimensions of the Legs and Feet of the Astronaut Population

| Measurement | Observations | Centimeters | | | Inches | | |
|---|--------------|-------------|-----------|-------------------|--------|-----------|-------------------|
| | | Mean | Std. Dev. | Range Low High | Mean | Std. Dev. | Range Low 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 |

Table 16-4 (continued)

| Measurement | | Observations | Centimeters | | | | Inches | | | | |
|--|--------------------------------------|--------------|-------------|-----------|-------------------|-------|-----------|-------------------|--|--|--|
| | | | Mean | Std. Dev. | Range Low High | Mean | Std. Dev. | Range Low High | | | |
| e. Dimensions of the Legs and Feet of the Astronaut Population (continued) | | | | | | | | | | | |
| 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 | | | |
| f. Dimensions of the Skinfolts of the Astronaut Population | | | | | | | | | | | |
| Measurement | | Observations | Mean | Std. Dev. | Range Low High | Mean | Std. Dev. | Range Low High | | | |
| 1. | Subscapular | 10 | 0.90 | 0.23 | 0.70 1.50 | 0.35 | 0.09 | 0.28 0.59 | | | |
| 2. | Juxta-Nipple | 10 | 0.56 | 0.18 | 0.40 0.95 | 0.22 | 0.07 | 0.16 0.37 | | | |
| 3. | Mid-Axillary Line-Xiphoid | 10 | 0.74 | 0.74 | 0.29 0.50 | 1.50 | 0.29 | 0.11 0.59 | | | |
| 4. | Triceps | 10 | 0.71 | 0.17 | 0.40 1.00 | 0.28 | 0.07 | 0.16 0.39 | | | |
| g. Reach with the Arm (Functional Arm Reach) of the Astronaut Population | | | | | | | | | | | |
| Measurement | | Observations | Mean | Std. Dev. | Range Low High | Mean | Std. Dev. | Range Low High | | | |
| 1. | Entire Arm | 24 | 79.83 | 3.20 | 73.90 87.50 | 31.43 | 1.26 | 29.10 34.45 | | | |
| 2. | Forearm | 9 | 41.84 | 1.24 | 39.00 43.10 | 16.47 | 0.49 | 15.35 16.97 | | | |
| 3. | Length of Extended Arm* | 11 | 72.13 | 2.20 | 68.26 74.61 | 28.40 | 0.87 | 26.88 29.38 | | | |

*Description of Non-Standard Measurements

- | | |
|---|--|
| 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 waistline through the crotch to the posterior waistline. |
| 7. Length of Gluteal Arc | Distance measured along the skin from the top of buttock fold, cranial, to posterior waist point. |
| 8. Mid-Shoulder | Point on top of shoulder at 4" 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 Circumference | 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. |

L = distance from the CG to the suspension point,
 f = frequency of oscillation and
 g = acceleration of gravity (980 cm/sec²);

and
$$I_{CG} = I_0 - mL^2, \quad (3)$$

where I_{CG} = moment of inertia about the CG.

A shift in whole body moment of inertia because of changes in posture or movement of limbs will be equivalent to the algebraic term of the individual segment changes in moment of inertia about the axis of rotation. The contribution of each segment to total moment of inertia is determined by the equation:

$$I_{Total} = (I_{CG} + mx^2), \quad (4)$$

where I_{CG} = moment of inertia about segment CG

m = mass of the segment,

x = distance of the segment CG from the axis of rotation.

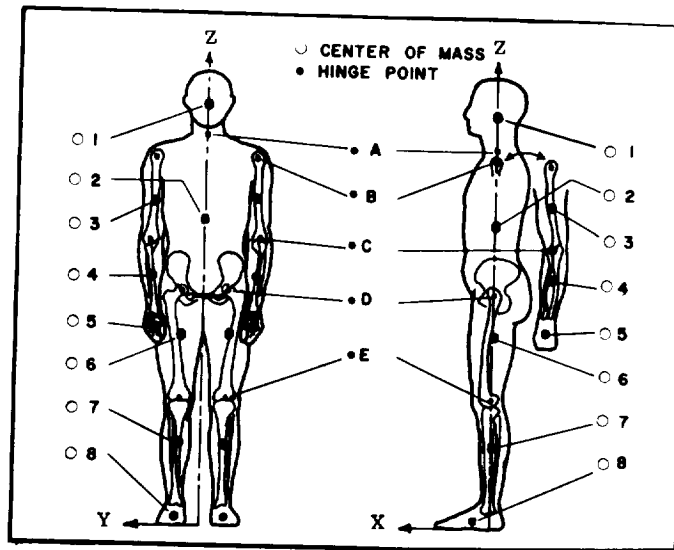
Consequently the change in I_{Total} is the difference between the sum of mx^2 before and after change in posture.

Table 16-5a shows diagrammatically the hinge points and centers of mass of the body segments. Table 16-5b gives the coordinates of these points. Table 16-5c represents the biomechanical properties of the body segments of the USAF 50th percentile man. Table 16-5d gives regression equations for computing the mass of body segments from total body weight. These were determined from a reanalysis of the data in references (35) and (77). Calculations have also been made of the CG's and moments of inertia. Table 16-6a presents the centers of gravity and moments of inertia of the total body of 50th percentile USAF male population in different postures given in British Engineering Units; Figure 16-6b gives similar data in the metric system with regression equations. Table 16-6c represents formulas which can be used to calculate moments of inertia of body segments. In Table 16-6d, the moments of inertia of these segments are shown for two body positions. Tables 16-11 b, c, and d present the effect of pressure suits on centers of gravity and moments of inertia of subjects in pressure suits (346).

Inertial data of these types have been used to predict with reasonable accuracy dynamic responses of man in orbital weightlessness (197, 206, 358) and for impact dynamics (47). In preliminary tests, these models appear to offer much in terms of semiquantitative prediction of body response to work tasks under subgravity as well as under the zero gravity condition. Prime use is in analysis of work, self-rotation maneuvers, and translation potentials of men in zero gravity. The data have also been used in the design of control systems for astronaut maneuvering units (AMU) and other EVA devices (189, 322). Computer models of these systems (86, 206, 281, 297, 358, 372) appear to offer a better solution to these dynamic problems. Problems of hydrodynamic mass and drag areas during underwater simulation of weightlessness are covered in the discussion of Figures 7-68 and Table 7-69.

Figure 16-5

Centers of Gravity and Specific Gravity of Man



a. Diagram of Hinge Points and Centers of Mass
(After Whitsett (358))

| 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 |

b. Coordinates of the Segment Hinge Points and Mass Centers of USAF 50th Percentile Man
(After Whitsett (358))

Figure 16-5 (continued)

| Segment | Weight (lbs) | Density (lbs/ft ³) | 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 |

c. Biomechanical Properties of the Segments of the USAF 50th Percentile Man

(After Whitsett⁽³⁵⁸⁾ from the data of Clauser, Hertzberg et al⁽¹⁶⁵⁾, and Dempster⁽⁷⁷⁾)

| 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.

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

(From Barter⁽²²⁾)

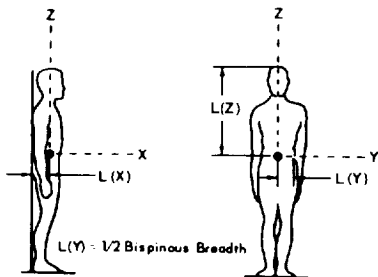
Figure 16-6

Centers of Gravity and Moments of Inertia of USAF Males in Different Postures

a. Whole-Body (British Engineering Units)

| | Axis | Center of Gravity (in.) | | Moment of Inertia (lb-in. -sec ²) | | |
|-----------------------------|------|----------------------------|-------|--|-------|--|
| | | Mean | S. D. | Mean | 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, fore-arms 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).

(After Hertzberg and Clauser⁽¹⁶⁴⁾, adapted from Santschi et al⁽²⁷⁹⁾)

Figure 16-6 (continued)

b. 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) | | Moment of Inertia (Gm Cm ² x 10 ⁶) | | R _{1, SW} | S.E. | Moment of Inertia Regression Equations ^b (Gm Cm ² x 10 ⁶) | | |
|------------------------------|------|--|------|--|------|--------------------|------|--|---------|---------|
| | | Mean | S.D. | Mean | S.D. | | | | | |
| 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.

(After Damon et al⁽⁷¹⁾, adapted from Santschi et al⁽²⁷⁹⁾)

c. Formulas for Calculating Local Moments of Inertia of Body Segments

| Segment | Moments of Inertia | | |
|-------------------------------|--|---------------------------------|-------------------------------|
| | $I_{x_{CG}}$ | $I_{y_{CG}}$ | $I_{z_{CG}}$ |
| Head | $\frac{1}{5} m(a^2 + b^2)$ | $I_{x_{CG}}$ | $\frac{2}{5} m a^2$ |
| 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 ℓ = length
 a = semi-major axis A and B are constants for segments (see Ref.358)
 b = semi-minor axis c = instep length of foot
 d = diameter δ = average density

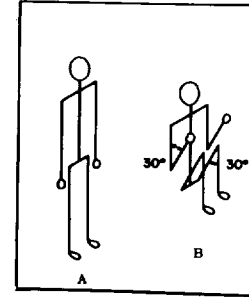
(After Whitsett (358))

Figure 16-6 (continued)

d. Moments of Inertia of the Segments of 50th Percentile USAF Man for Two Positions

| | | Segments* | | | | | | | | |
|----------|------------|-----------|--------|------------|------------|--------|------------|------------|--------|--------|
| | | Head | Torso | Upper Arms | Lower Arms | Hands | Upper Legs | Lower Legs | Feet | Total |
| I_{cc} | 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_r | 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_{cc} | 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_r | Position A | 1.5297 | 1.9425 | 0.1674 | 0.0056 | 0.0141 | 0.5358 | 1.3297 | 0.7389 | 9.0553 |
| | Position B | 0.8133 | 1.0034 | 0.0449 | 0.0058 | 0.0192 | 0.1966 | 0.1387 | 0.1588 | 2.9445 |
| I_{cc} | 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 | 0.0582 | 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_r | 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 | 0.0759 | 0.0841 | 0.0448 | 1.0004 |

*Positions A and B are shown in figure.
†All values are slug-ft².



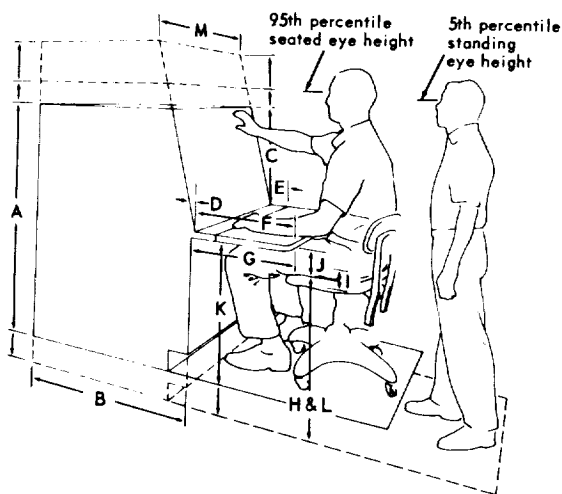
Determination of specific gravity can be made from anthropometric data (70). Attempts have been made to relate the specific gravity of different individuals to the somato type classification of Sheldon (85, 250). This formula for specific gravity works only for navy divers for which it was developed. It failed to predict densitometrically determined density (or specific gravity) or percentage of body fat among athletic young men (70). The best prediction of density is actually based on averaging two skin fold measurements by the equations (253): Density = 1.0923 - 0.0203 (triceps skinfold, in cm.); Density = 1.0896 - 0.0179 (subscapular skinfold, in cm.). To obtain fat from density, Fat = (4.0439/density - 3.6266). This formula of Grande is based on a reference man with 17.8% of total body fat (121).

The dimensions of a typical 5th to 95th percentile, seated, pilot operator are seen in Figure 16-7. Data are available on three-dimensional arm reach in the seated position (71, 192). Data are also available on the design of new seat concepts for aerospace vehicles (258) (see also sections on Impact No. 7, and Vibration No. 8. Figure 16-8 covers workspace requirements for the 95th percentile USAF population.

Body areas are needed for thermal and energetic analyses. (See Thermal Environment, (No. 6) and Oxygen-CO₂-Energy, (No. 10). Table 6-22 represents a cylindrical model of man for calculation of heat transfer coefficients. Figure 6-16 is a nomograph for calculation of the surface area of the USAF male population from height and weight data. Figure 10-13 is a graph which can be used in the same calculation for the average male population. In analysis of radiative heat transfer, the total radiation area (Figure 6-17) and the projected areas (Figure 6-18) can be used (133, 164, 291). Drag areas and hydrodynamic mass of suited subjects are presented in Figure 7-68 and

Table 16-8

Work Space Dimensions
(After Hertzberg and Clauser⁽¹⁶⁴⁾)



| Type of Console | Maximum console height from standing surface | Console depth at base | Vertical dimension of panel, including sills | Console panel angle-- from vertical | Minimum pencil-shelf depth | Minimum writing surface depth-- including pencil shelf | Minimum knee clearance | Foot support to seat ¹ | Seat adjustability | Minimum thigh clearance at midpoint of "I" | Writing surface height from standing surface | Seat height at midpoint of "I" | Maximum console panel breadth |
|--------------------------------|--|-----------------------|--|-------------------------------------|----------------------------|--|------------------------|-----------------------------------|--------------------|--|--|--------------------------------|-------------------------------|
| | A | B | C | D | E | F | G | H | I | J | K | L | M |
| 1. Sit-Stand | 62.0 | Opt. | 26 | 15° | 4 | 16 | 18 | 18 | 4 | 6.5 | 36.0 | 28.5 | 36 |
| 2. Sit (w/vision over top) | 47.5* to 58.0 | Opt. | 22 | 15° | 4 | 16 | 18 | 18 | 4 | 6.5 | 25.5 to 36.0 | 18.0 to 28.5 | 36 |
| 3. Sit (w/o vision over top) | 51.5** to 62.0 | Opt. | 26 | 15° | 4 | 16 | 18 | 18 | 4 | 6.5 | 25.5 to 36.0 | 18.0 to 28.5 | 36 |
| 4. Stand (w/vision over top) | 62.0 | Opt. | 26 | 15° | 4 | 16 | -- | -- | -- | -- | 36.0 | --- | 36 |
| 5. Stand (w/o vision over top) | 72.0 | Opt. | 36 | 15° | 4 | 16 | -- | -- | -- | -- | 36.0 | --- | 36 |

* "A" must never be more than 29.5 inches greater than "L".
 ** "A" must never be more than 33.5 inches greater than "L".

¹ When seat-to-standing surface exceeds 18", a heel catch should be provided.

Table of standard values for critical dimensions used in the design of instrument consoles for the seated and/or standing operator, with and without a requirement on the operator to maintain horizontal visual contact with other displays or test apparatus beyond the console. Design values for each console established to accommodate 95+ percent of USAF population.

Source: Anthropology Branch, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1963.

Table 7-69. Buttock contact areas and thigh dimensions for the specific population indicated are seen in Figure 16-9.

Presence of clothing increases the body dimensions. Group support equipment in space operations often makes use of military support. Figure 16-10 covers the increase dimensions to be expected from clothing on support personnel.

The increase in body dimensions resulting from pressure-suit wear will vary with design of the suit. Table 16-11a covers increases from the USAF MC-2 suits. Tables 16-11b and c present changes in body dimensions of astronauts in NASA soft and hard suits. Figure 16-11d shows the changes in center of gravity; and Tables 16d and e, the changes in center of gravity and moment of inertia of the whole body produced by space suits, pressurized and unpressurized. Table 16-11f gives regression equations which can be used to calculate these changes in moments of inertia from data on body weight.

Stowage volumes for soft (223) and hard (26) suits have been determined. The soft suit may be packed into a slab volume 64 x 27 x 7 inches and the slab arced along its length with a radius of 49 inches. The helmet can be considered a sphere of about 16 inches maximum diameter; and back pack, a volume of about 12 x 16 x 9 inches. The hard suit can be stowed in a volume of 46 x 25 x 16 inches including helmet. These dimensions are only approximate values for typical prototype suits.

Workspace Factors

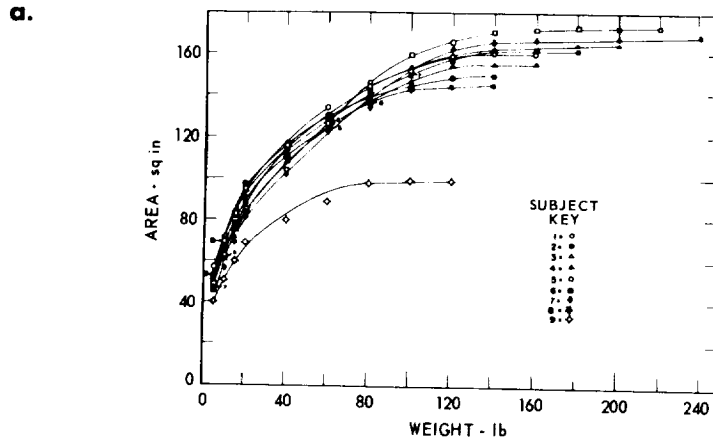
Division of workspace into functional compartments must also be considered (54, 93, 109, 266). (See also section on Confinement).

In the Mercury spacecraft there was an internal volume of approximately 54 cubic feet of which 4 cubic feet was occupied by the astronaut. Since the astronaut was never required to leave his couch for either personal or mission requirements, such a limited volume could be tolerated over the period of even the longest mission of 22 orbits. The Gemini spacecraft, on the other hand, provided an internal volume of approximately 88 cubic feet or 11 cubic feet less per man than that provided by Mercury. Details of Gemini cabins are available (217, 231). Since the Gemini missions were considerably more demanding due to duration and extravehicular activities, the lack of significant, useable work space was exhibited by the constraints placed upon work/rest cycles, stowage provisions in and around the hatches, headrest areas, and limited leg movement in the foot-well, to name a few.

Although the Apollo command module spacecraft provides an internal volume of approximately 320 cubic feet, it must be remembered that this space is distributed across three couch stations, two work stations in the lower equipment bay, a guidance and navigation station, and two sleep stations under the couches. The cubage at these stations, though marginal, is sufficient to meet mission requirements provided that the intravehicular activity at the various stations is properly sequenced (244). However, for missions of longer duration, considerably greater volume at each station would have to be provided to meet increased stowage requirements. Based on these and similar considerations, (see section below on Confinement), the following

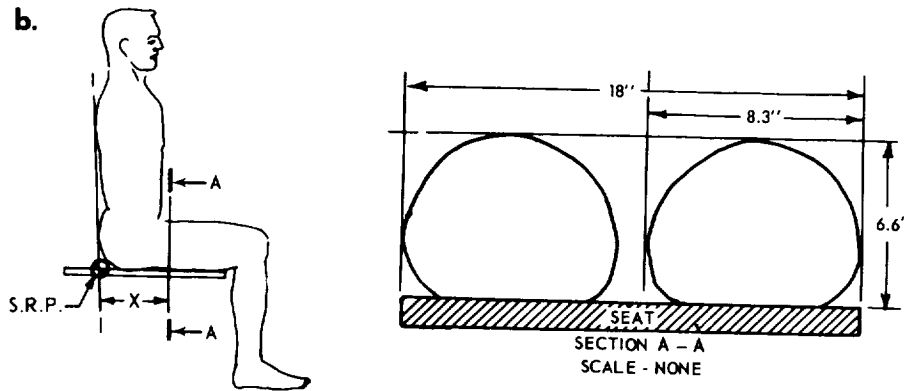
Figure 16-9

Buttock Areas and Thigh Dimensions
(After Hertzberg and Clauser⁽¹⁶⁴⁾)



Buttock contact areas of nine men who were gradually lowered onto a measuring plate until their full weights were supported. Subjects fell within the following ranges: age 27-41 years; height 66-74 inches; weight 120-269 pounds. When these contact areas had been established, loads were increased by having the subjects hold weights in their arms to determine what increase in contact area would result. Loads of 20, 40, and 60 pounds caused no measurable increase in buttock contact area.

(Adapted from Swearingen et al⁽³¹⁹⁾)



Height and width of the thighs, shown on the right, from a section taken just ahead of the intersection of thigh and trunk as shown in the drawing on the left. The x distance from the Seat Reference Point (SRP) to the section varied from 9.5 to 12 inches. Dimensions for the thigh are 95th percentiles, meaning that 5% of the AF flying population will have larger dimensions. The thigh heights were measured, the thigh widths computed from the relation: Width = 1.37 Height.

(Adapted from Esch⁽⁹¹⁾)

Table 16-10

Increase in Dimensions from Clothing
(After Hertzberg and Clauser⁽¹⁶⁴⁾)

| | Civilians | | Army | | | | Air Force | | |
|------------------------------|---------------------------|-----------------------------|-------------------|-----------------|-------------------|------------------|------------------------|-----------------------------|------------------------------|
| | Men street clothing | Women street clothing | summer uniform | fall uniform | winter uniform | winter combat | full flight gear | light flight assembly | winter flight assembly |
| weight (lbs) | 5.0 | 3.5 | 9.4 | 11.8 | 18.6 | 22.9 | | | 20.0 |
| stature | 1.0 | 0.5-3.0 | 2.65 | 2.65 | 2.65 | 2.75 | -2.0 | 3.3 | 1.9 |
| abdomen depth | | | 0.94 | 1.18 | 1.95 | 2.54 | 5.0 | | 1.4 |
| arm reach, anterior | | | 0.04 | 0.08 | 0.20 | 0.37 | | | 0.4 |
| buttock-knee length | | | 0.20 | 0.30 | 0.54 | 0.70 | 2.0 | | 0.5 |
| chest breadth | | | | | | | 2.5 | | 0.6 |
| chest depth | | | 0.41 | 0.96 | 1.80 | 1.54 | 4.5 | 0.8 | 1.4 |
| elbow breadth | | | 0.56 | 1.04 | 1.84 | 2.12 | 11.0 | | 4.4 |
| eye level height, sitting | | | 0.04 | 0.08 | 0.16 | 0.22 | | | 0.4 |
| foot breadth | 0.3 | | 0.20 | 0.20 | 0.20 | 0.20 | | | 1.2 |
| foot length | 1.2 | | 1.60 | 1.60 | 1.60 | 1.60 | | | 2.7 |
| hand breadth | | | | | | 0.30 | | | 0.4 |
| hand length | | | | | | 0.15 | | | 0.3 |
| head breadth | | | 2.8 | 2.8 | 2.8 | 2.8 | | | 0.4 |
| head length | | | 3.5 | 3.5 | 3.5 | 3.5 | | | 0.4 |
| head height | | | 1.35 | 1.35 | 1.35 | 1.45 | | | 0.2 |
| hip breadth | | | 0.56 | 0.76 | 1.08 | 1.40 | | | 1.3 |
| hip breadth, sitting | | | 0.56 | 0.76 | 1.08 | 1.40 | 5.5 | 2.9 | 1.7 |
| knee breadth | | | 0.48 | 0.48 | 0.72 | 1.68 | 9.5 | | 2.5 |
| knee height, sitting | | | 1.32 | 1.32 | 1.44 | 1.44 | | | 1.8 |
| shoulder breadth | | | 0.24 | 0.88 | 1.52 | 1.16 | 6.0 | 0.4 | 1.3 |
| shoulder-elbow length | | | 0.14 | 0.50 | 0.94 | 0.62 | | | 0.3 |
| shoulder height, sitting | | | 0.16 | 0.58 | 0.92 | 0.80 | | | 0.6 |
| sitting height | | | 1.39 | 1.43 | 1.61 | 1.67 | | 2.1 | 0.6 |

(All dimensions are given in inches)

Civilians, men: underwear, shirt, trousers, tie, socks, shoes.

Civilians, women: underwear, dress, or blouse or sweater and skirt, shoes.

Army, summer uniform: underwear, khakis or O. D. 's or fatigues, socks, shoes, helmet and liner.

Army, fall uniform: underwear, khakis or O. D. 's or fatigues, blouse or field jacket, socks, shoes, helmet and liner.

Army, winter uniform: underwear, khakis or O. D. 's or fatigues, blouse or field jacket, overcoat, socks, shoes, helmet and liner.

Army, winter combat: underwear, khakis or O. D. 's or fatigues, combat suit, overcoat, socks, shoes, gloves, wool cap, helmet and liner.

Air Force, full flight gear: T-1 partial pressure suit, inflated, ventilation suit, deflated, MD-1 anti-exposure suit and MD 3A liner, long cotton underwear.

Air Force, light flight assembly: T-5 partial pressure suit, uninflated, K-1 pressure helmet and boots.

Air Force, winter flight assembly: World War II heavy winter flying clothing, including jacket, trousers, helmet, boots, and gloves.

Source: Anthropology Branch, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1963.

Figure 16-11

Anthropometric Study of Pressure Suits

a. Increase in Dimensions from Soft, Full Pressure Suits

| 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 | (20.0-23.0) | 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 | (18.2-19.8) | 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.

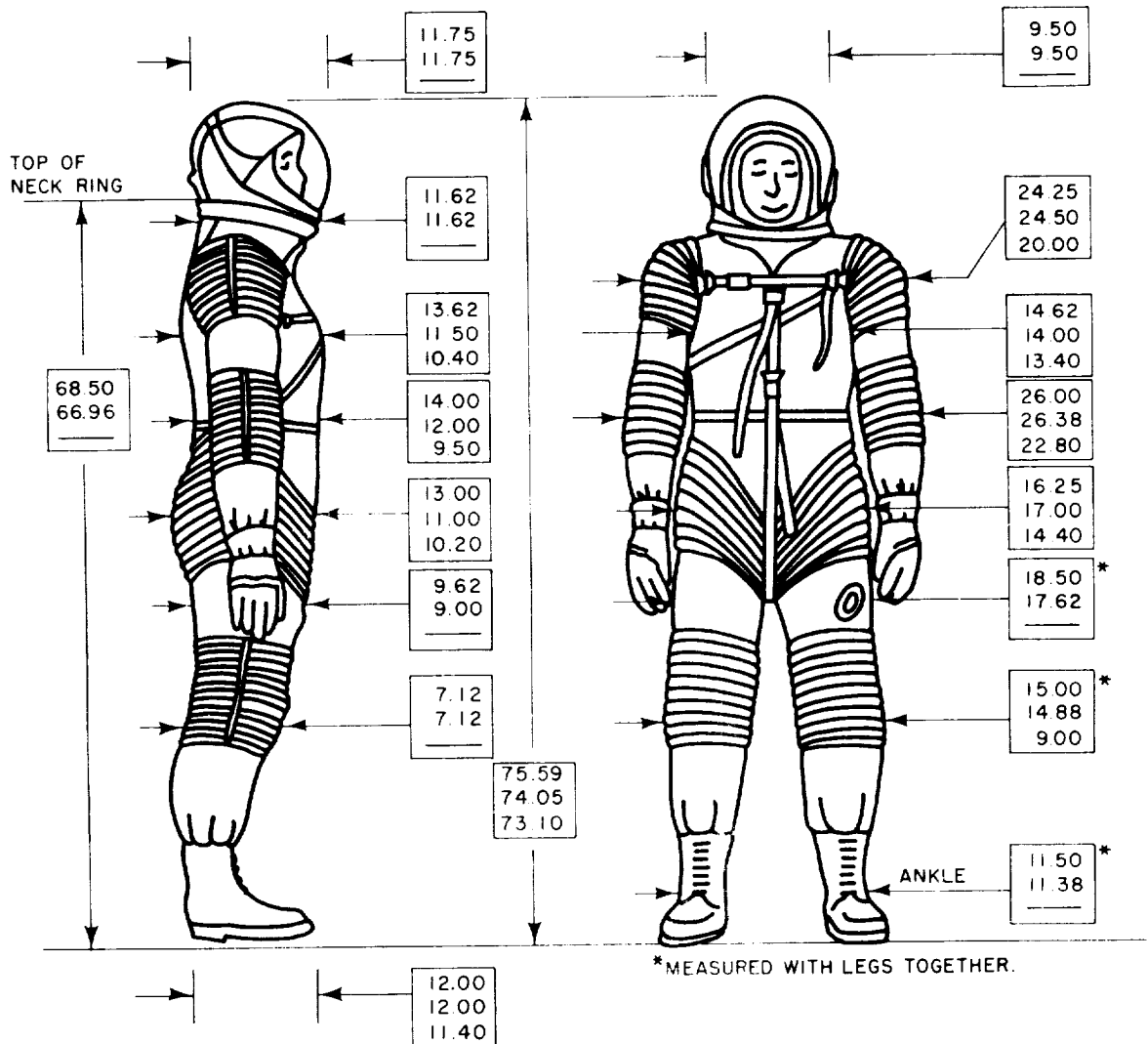
Source: Anthropology Branch, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1963.

(After Hertzberg and Clauser⁽¹⁶⁴⁾)

Figure 16-11 (continued)

b. Maximum Dimensions of a NASA Prototype, Soft, Full-Pressure Suit in the Unpressurized and Pressurized Condition

These data, noted in indices, cover the large-long size of a S/N007 or (A6L) PGA designed for a subject 6', 1.5" tall and 190 lbs weight, representing approximately the 95th percentile male. Extra vehicular operations require an addition to the total height of 1.5" for the EVVA visor assembly and 0.6" for EV boots giving a total standing height, pressurized, of 77.71 inches.



SUIT PRESSURIZED TO 3.7 PSIG.
 SUIT AMBIENT (HELMET AND GLOVES OFF). FLOW=16 cfm.
 NUDE OR 95th PERCENTILE MALE, STANDING, REF. (145).

ALL DIMENSIONS IN INCHES.

(After Fedderson and Reed⁽⁹⁴⁾)

Figure 16-11 (continued)

c. Anthropometry of the RX-5 Hard Space Suit

The hard suit is composed of 6 body elements, each with up to 6 different sizes noted by Roman numerals. The suit described below is a composite of different body elements assembled for a specific astronaut. Adjustments for other sizes are noted after each specific element. All dimensions are noted in inches.

| ELEMENT SIZES OF SUIT MEASURED | DIMENSION ADJUSTMENTS FOR OTHER SIZES |
|--|--|
| 1. UPPER TORSO - SIZE III | SHOULDER BREADTH SIZE IV +1.00 SIZE I & II NO CHANGE |
| 2. LOWER TORSO - SIZE III (Adjusted to the Short Position) (+.75" Adjustment possible) | LENGTH ONLY SIZE I -1.20 (Short Adjustment) II - .60 (Short Adjustment) IV +1.35 (Long Adjustment) V +1.95 (Long Adjustment) VI +2.55 (Long Adjustment) |
| 3. UPPER ARM - SIZE IV | LENGTH CHANGE ONLY SIZE V + .40 I -1.20 II - .80 III - .40 |
| 4. FOREARM - SIZE III | LENGTH CHANGE ONLY SIZE I -1.40 II - .70 IV + .70 |
| 5. THIGH - SIZE II (Adjusted to Short Position) (+.87" Adjustment possible) | LENGTH CHANGE ONLY SIZE I - .70 (Short Adjustment) III +1.56 (Long Adjustment) IV +2.26 (Long Adjustment) V +2.96 (Long Adjustment) |
| 6. CALF - SIZE II | LENGTH CHANGE ONLY SIZE I - .70 III + .60 IV +1.20 V +1.80 VI +2.40 |

(After Breslin, C. and Brosseau, P.L., Litton Systems, Inc.; Applied Technology Division, unpublished data, 1968)

Figure 16-11 (continued)

c. Anthropometry of the RX-5 Hard Space Suit (continued)

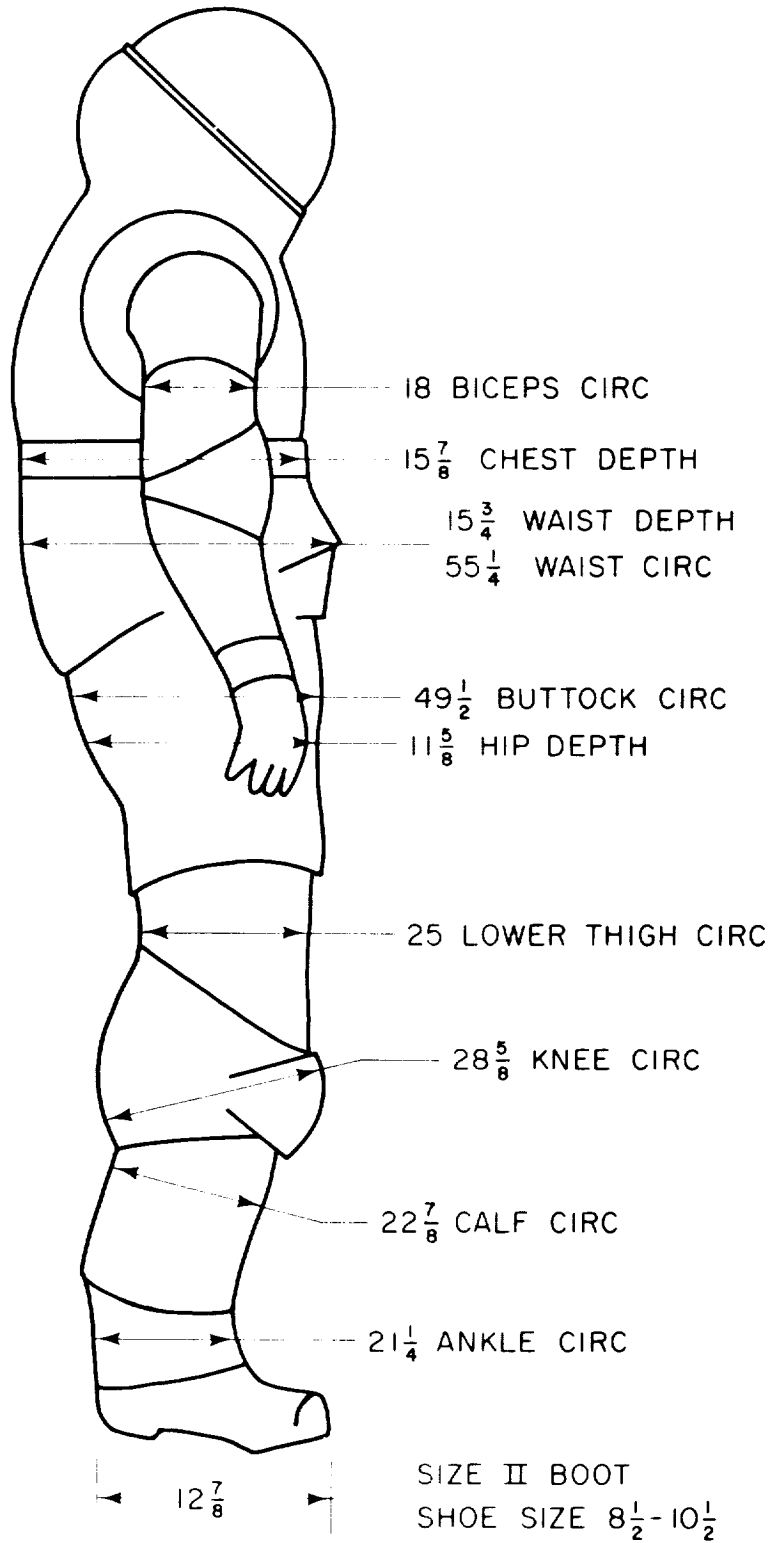


Figure 16-11 (continued)

c. Anthropometry of the RX-5 Hard Space Suit (continued)

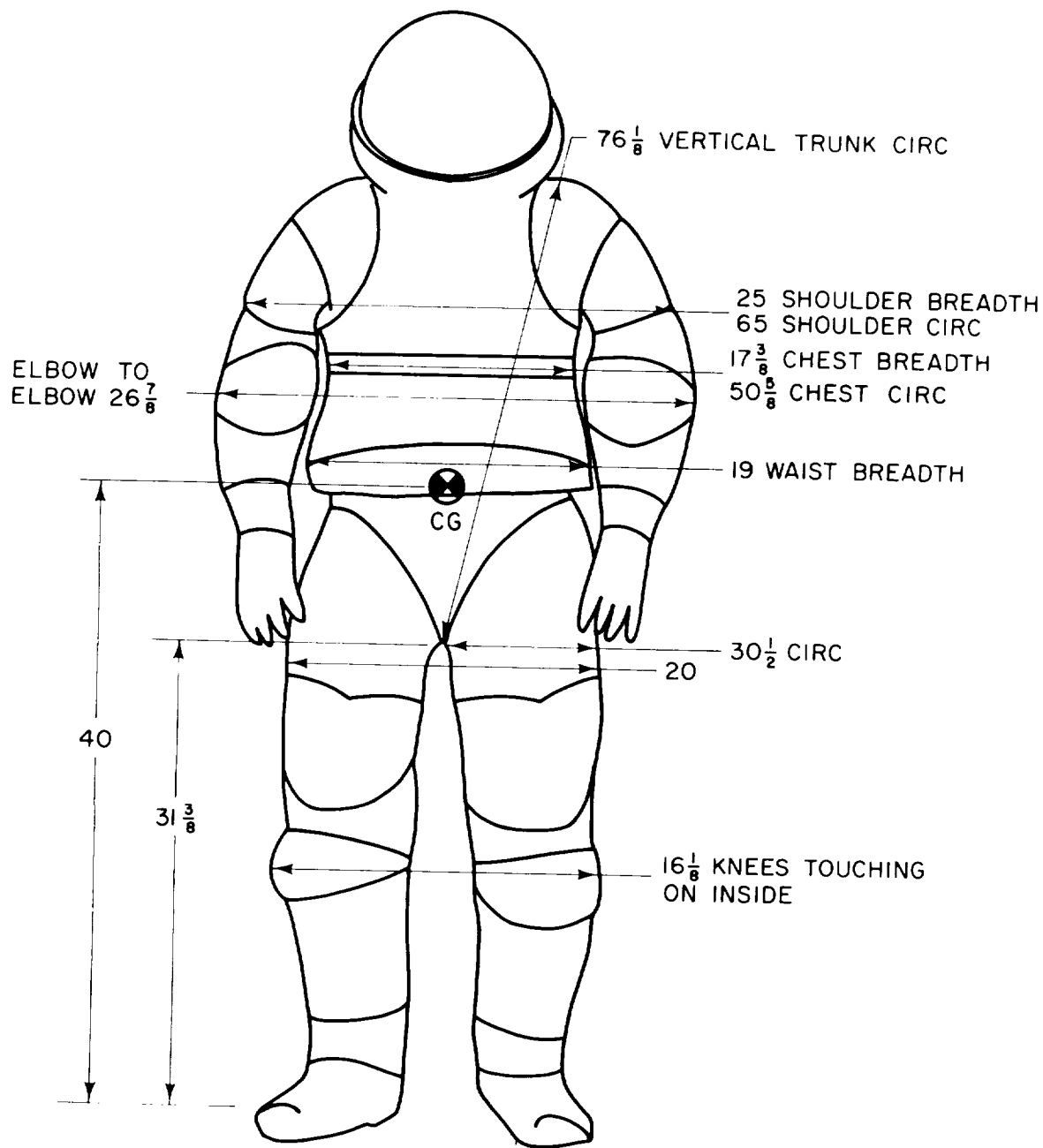


Figure 16-11 (continued)

c. Anthropometry of the RX-5 Hard Space Suit (continued)

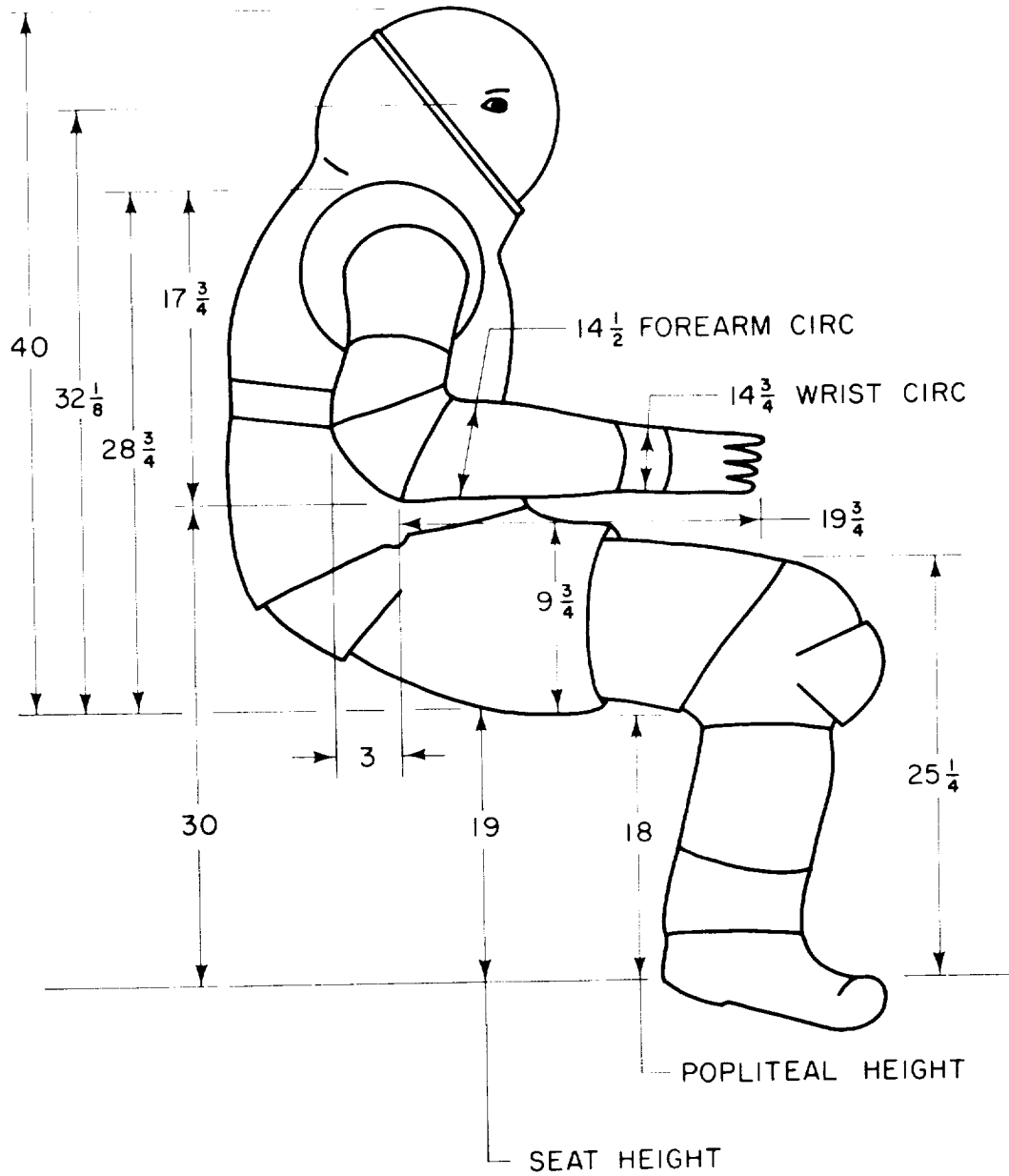
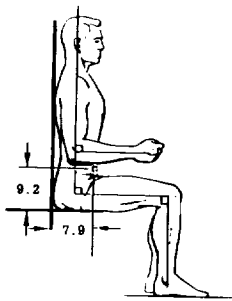
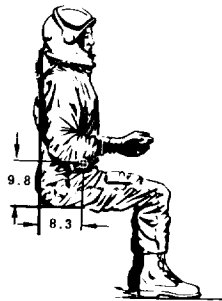


Figure 16-11 (continued)

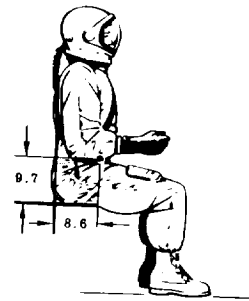
d. Mean Centers of Gravity of Pressure-Suited Subjects



Nude

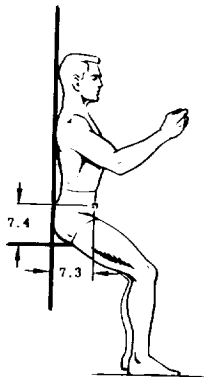


Unpressurized

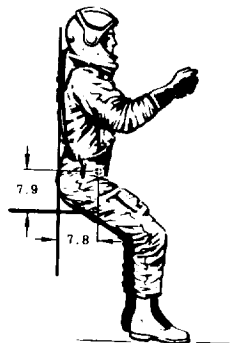


Pressurized

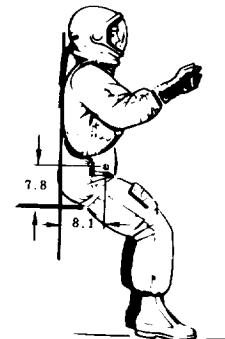
1. Sitting



Nude



Unpressurized



Pressurized

2. Relaxed (Weightless)

(After DuBois et al⁽⁸³⁾)

Figure 16-11 (continued)

e. 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. | | | | | |

(After DuBois et al⁽⁸³⁾)

Figure 16-11 (continued)

f. Correlation of Moment of Inertia with Stature and Weight
in Pressure-Suited Subjects (N = 19)

| | Axis | $R_{I,sw}$ | S.E.* | I_0 | Regression Equation* |
|-------------------------|------|------------|-------|--------|----------------------|
| 1. Sitting | | | | | |
| Nude | x | 0.95 | 2.67 | -105.0 | + 1.59S + 0.317W |
| | y | 0.91 | 4.07 | -135.0 | + 2.10S + 0.344W |
| | z | 0.97 | 1.17 | - 70.4 | + 0.923S + 0.212W |
| Unpressurized | x | 0.93 | 3.42 | -114.0 | + 1.82S + 0.337W |
| | y | 0.97 | 2.77 | -181.0 | + 2.96S + 0.362W |
| | z | 0.97 | 1.47 | - 79.5 | + 1.09S + 0.229W |
| Pressurized | x | 0.93 | 3.24 | -120.0 | + 2.06S + 0.281W |
| | y | 0.94 | 3.79 | -157.0 | + 2.54S + 0.389W |
| | z | 0.96 | 1.53 | - 78.1 | + 1.07S + 0.230W |
| 2. Relaxed (Weightless) | | | | | |
| Nude | x | 0.97 | 3.30 | -191.0 | + 2.88S + 0.556W |
| | y | 0.95 | 4.60 | -265.0 | + 4.04S + 0.461W |
| | z | 0.94 | 1.75 | - 46.0 | + 0.567S + 0.231W |
| Unpressurized | x | 0.95 | 4.62 | -197.0 | + 3.19S + 0.574W |
| | y | 0.96 | 4.38 | -217.0 | + 3.59S + 0.506W |
| | z | 0.96 | 1.33 | - 54.8 | + 0.801S + 0.217W |
| Pressurized | x | 0.97 | 3.93 | -208.0 | + 3.42S + 0.550W |
| | y | 0.96 | 4.44 | -254.0 | + 4.18S + 0.482W |
| | z | 0.96 | 1.36 | - 48.7 | + 0.720S + 0.214W |

$r_{sw} = 0.44$ S.E. = 2.02 in. $S = 59.58 + 0.057W$

* I_0 and S.E. in lb.in.sec.²

S in in.

W in lbs.

(After DuBois et al⁽⁸³⁾)

recommendations regarding minimal volumetric requirements for missions extending from a few months to a year may be made:

Sleep/rest station volume should not be less than 300 cubic feet per man and so configured as to accommodate stowage of spare clothing (constant-wear garments and flight coveralls), suit-inflation capability, and donning of the pressure suits.

Work station volume should be dictated by operational requirements and so designed as to meet the following criteria:

- Separate from sleep/rest station.
- Contingency functions designed for pressure suited interface and given priority consideration in location/placement.
- Individual pressurization capability.
- Unrestricted access to all controls and displays.
- Restraints and tethers to permit performance of all work functions with two hands if the need should arise.
- Non-interference between duty station crewmen if more than one is working.

Air locks and hatches should be designed so that the actuating mechanism is no higher than shoulder height and positioned for easy visual access in a standing, 1G position. For umbilical operations, the hatches should not be less than 31 inches in diameter and for operations with a self-contained life support system they should not be less than 43 inches in diameter to provide easy egress/ingress capability. Air locks should be designed to an inner diameter of at least 5 feet to provide pressurized turn-around capability and should contain a handrail or protruding handrails along the axis of body rotation. The air locks themselves should be designed for operation by one man with simple unlocking/locking mechanisms, with mechanical advantages for aid in overcoming residual pressure forces inside the spacecraft, and hinged for rotation to provide unencumbered access to tunnel areas.

Studies have been performed on the design of air locks and hatches in zero gravity operations. The subjects were filmed during repetitive trials and the position-velocity time profiles of the maneuvers were analyzed for three simulation modes; ground-normal gravity, aircraft-zero gravity, and water immersion neutral buoyancy. These simulation studies indicate that:

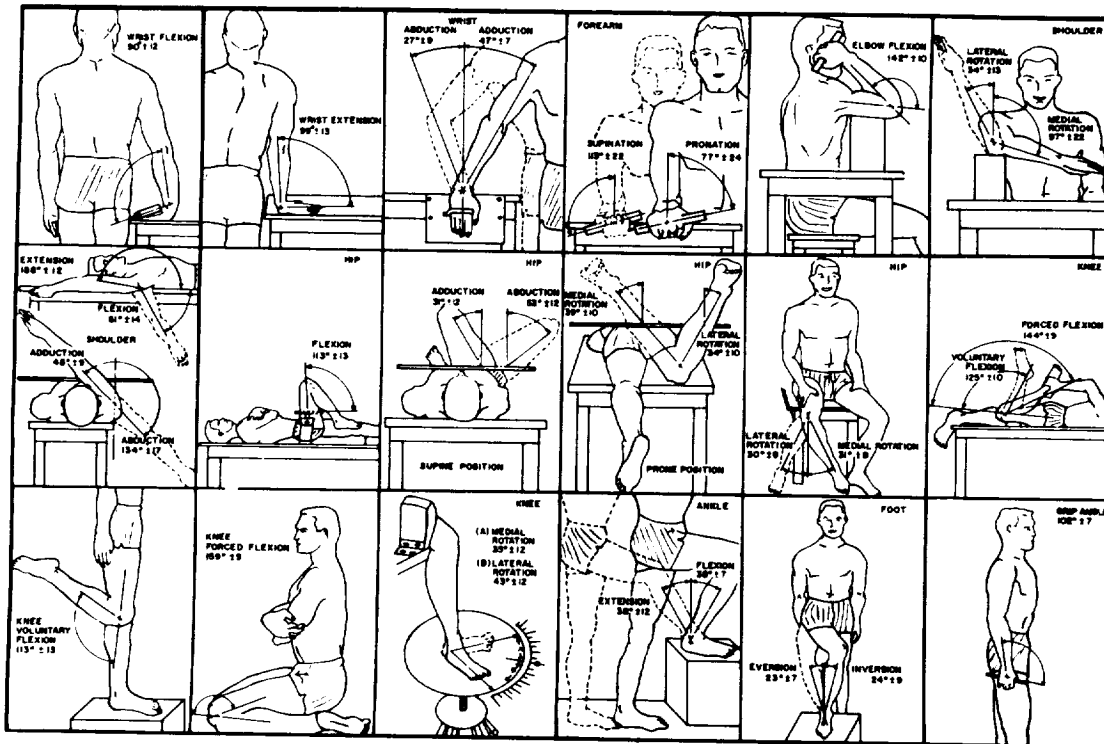
- A 48"-diameter, 6' length airlock passageway with 32" circular hatches is sufficient, from a space standpoint, for an astronaut to adequately perform a manual ingress-egress maneuver.
- Counter rotation to applied torques, and movement due to applied linear forces due to lack of gravity-dependent reaction forces of the body must be counteracted to insure adequate operation.
- Hatch diameters less than 26" should not be utilized due to impediment to free travel and suit interactions.

- Ingress-egress maneuvers in airlocks of 48" diameter or less, requiring internal turnaround of a pressure-suited astronaut, dictate strengthening of the suit faceplate to prevent accidental depressurization.
- Airlock hardware requiring operation by an astronaut in a pressurized suit must be sized to accommodate the lack of tactual and visual ability concomitant with pressure-suited operations.
- Airlock passageways should remain as free of hardware appurtenances as design factors dictate to prevent suit interaction.

Future space vehicles and lunar bases have been studied from the point of view of workspace. Optimization of laboratories and crew stations for large orbiting crafts (259) and other space vehicles (223) has received preliminary study. Workspace analysis has been performed for lunar laboratories and bases (49, 237).

Force-Motion Analysis

The range of body motion is an important factor in workspace and operations analysis. Figure 16-12 shows the joint motion capability of a young male population. The recorded motion range in the nude should not be much different for



Range of joint motion in 39 young men, showing the median value in degrees, ± 1 standard deviation. If ± 2 SD are taken, 95% of the sample of 39 is included. Compared with the 1950 Air Force survey of over 4000 flying men, this sample is 6.8 years younger, 6.0 lbs heavier, and 1.4 inches taller.

Figure 16-12
 Joint Motion Capability of a Young Male Population
 (After Hertzber and Clauser⁽¹⁶⁴⁾)

the typical astronaut in shirtsleeve environment. Dynamic characteristics and range of motions required for operation of lunar scientific equipment are given in References (115, 184) and in Tables 16-19 to 16-23.

Forces and angular motion exerted on sidearm controllers are noted in Figures 16-13a and b. Forces exerted on hand controls by male college students are noted in Figure 16-14a. Design of control devices can be quite complex. In the Gemini program, rudder pedals were initially envisaged; however, weight and space limitations forced abandonment of pedals in favor of placing a third axis on the manual controller (217). Either crew member could operate the controller while in the restrained position through wrist articulation and palm pivot motion only, to preclude body movements from being transmitted to the controller. The handle was spring loaded to provide an increasing resistance as the handle was moved away from neutral. Controller force/displacement originally had a step function designed in all three axes, but was later revised to a smooth curve as shown in Figure 6-14b for all three axes. Redundant switches were incorporated for selectivity energizing solenoid valves in the attitude control system. Total travel of the hand controller was 10 ± 1 degrees from neutral in pitch and yaw axes and 9 ± 1 degrees in the roll axis. Rotary movement of the handle about a transverse axis located at the palm pivot point effected a corresponding spacecraft motion about the pitch axis. Rotary displacement in a clockwise or counterclockwise direction in a transverse plane with respect to an adjustable canted axis below the pilot's wrist effected a similar movement about the spacecraft roll axis. Clockwise or counterclockwise rotation of the controller about the longitudinal axis of the handle effected a corresponding movement about the yaw axis. Due to extended operation in this mode, the resistant stick forces tended to cause wrist fatigue. Thus, the control stick was modified to assimilate a T at the top. This enabled the pilot to grasp the top of the stick palm down if desired for more ease of yaw control. A guard was built up on the top to prevent depressing the communications transmit buttons while grasping the stick in this manner. Evaluation of the many attitude controller designs included operation of the stick with a bare hand, a soft glove or a pressurized glove, as well as consideration of the man pressurized or unpressurized, in zero-g or under heavy re-entry g loads. The attitude controller worked best in conjunction with a rotary mode selector slightly forward and left of the stick. This was needed to allow the pilot minimal three-axis response for fine maneuvering such as docking (pulse) or larger orders of magnitude in response for gross corrections (rate command or direct). The modes made available to the pilot were:

a. HOR SCAN - The horizon sensors provided a reference in pitch and roll to automatically control a limit-cycle mode ± 5 degrees in these axes. The yaw axis was maintained by the pilot using the pulse mode which was maintained on all axes in this mode.

b. RATE CMD - Pitch, roll and yaw rate gyro outputs were compared with controller positions to produce attitude rates proportional to controller deflection. (Operationally, this mode was effective in correcting the fairly high cross-coupling rates developed when the maneuver controller was used to translate.)

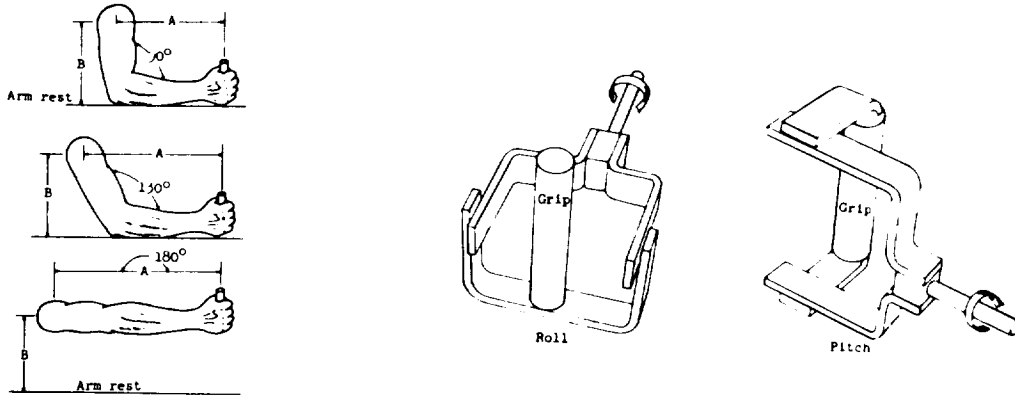
c. DIRECT - Provided direct control to open thrust chamber solenoids when the attitude controller was deflected approximately 25% of full travel. (The utmost discretion was used in this mode, as it tended to waste fuel.)

Figure 16-13

Forces Exerted on Side-Arm Controllers

(After Hertzberg and Clauser⁽¹⁶⁴⁾)

a.

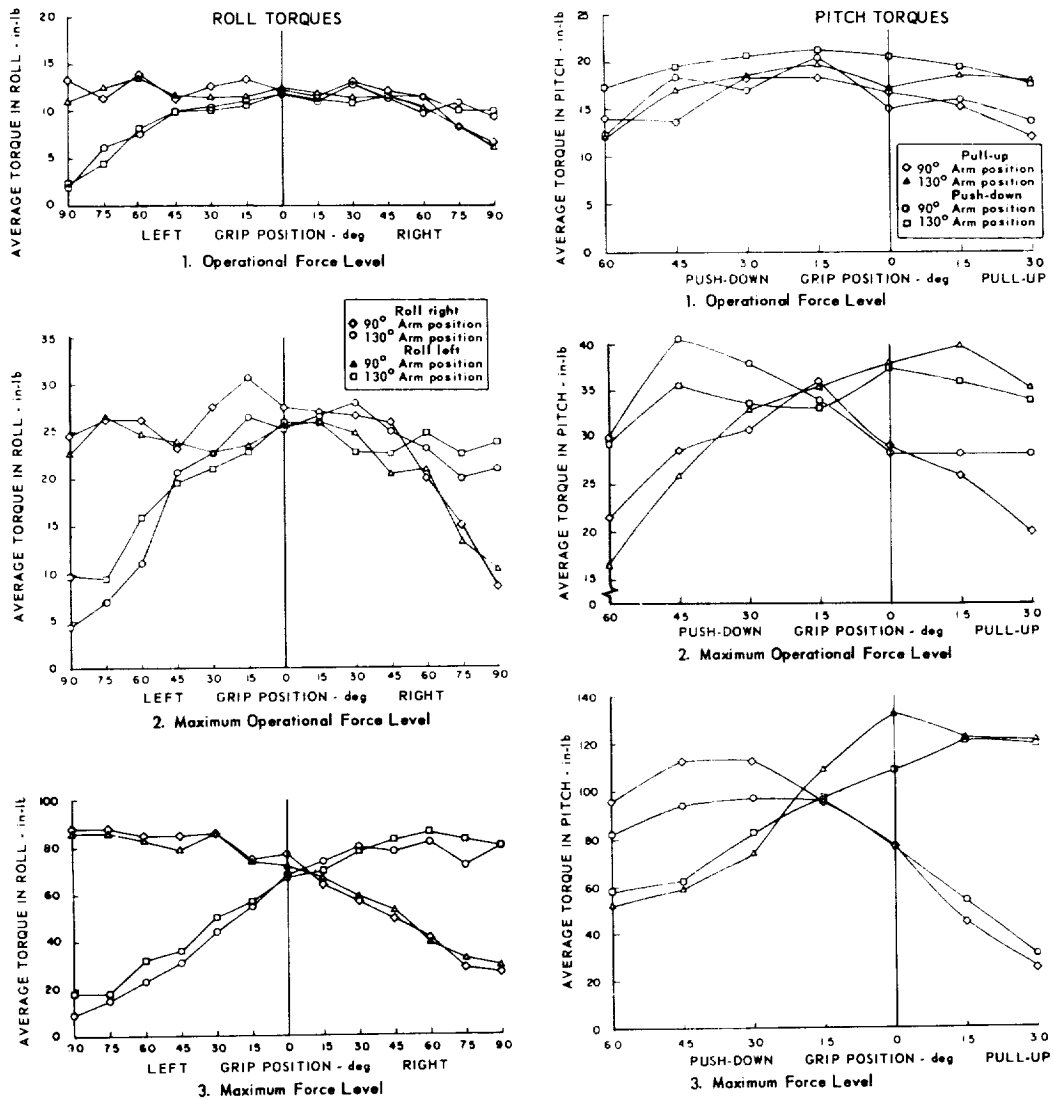


| Pilot | Distance A in. | | | Distance B, in. | | Maximum controller angle (unconstrained), deg | | | | | | | |
|---------|------------------------------|-------|-------|--------------------|-------|---|------|-----------|------|---------------|------|----------------|------|
| | | | | | | Right Roll | | Left Roll | | Forward Pitch | | Rearward Pitch | |
| | Measured at elbow angle of - | | | | | | | | | | | | |
| | 90° | 130° | 180° | 90° | 130° | 90° | 130° | 90° | 130° | 90° | 130° | 90° | 130° |
| 1 | 15.00 | 19.00 | 26.25 | 13.00 | 12.50 | 105 | 105 | 80 | 75 | 45 | 35 | 30 | 40 |
| 2 | 11.50 | 18.00 | 25.00 | 12.75 | 11.50 | 90 | 100 | 90 | 100 | 65 | 70 | 30 | 30 |
| 3 | 13.00 | 18.00 | 25.00 | 13.00 | 12.00 | 90 | 90 | 90 | 95 | 55 | 60 | 30 | 35 |
| 4 | 12.00 | 18.00 | 25.00 | 13.00 | 12.00 | 85 | 85 | 75 | 80 | 50 | 45 | 30 | 30 |
| 5 | 14.00 | 18.50 | 26.00 | 13.00 | 12.50 | 90 | 95 | 90 | 100 | 60 | 65 | 30 | 30 |
| 6 | 14.50 | 18.50 | 27.00 | 13.75 | 13.75 | 90 | 100 | 90 | 100 | 75 | 55 | 45 | 40 |
| 7 | 12.50 | 18.00 | 25.00 | 12.75 | 11.50 | 90 | 90 | 105 | 105 | 70 | 75 | 30 | 30 |
| 8 | 13.50 | 18.50 | 27.00 | 13.25 | 13.00 | 100 | 95 | 100 | 100 | 80 | 75 | 30 | 30 |
| 9 | 13.30 | 18.50 | 27.00 | 13.25 | 13.00 | 90 | 90 | 105 | 105 | 45 | 45 | 40 | 40 |
| 10 | 13.00 | 17.50 | 27.50 | 13.75 | 13.50 | 90 | 100 | 90 | 105 | 75 | 65 | 55 | 55 |
| 11 | 14.50 | 18.75 | 28.50 | 13.25 | 13.75 | 90 | 105 | 90 | 105 | 60 | 75 | 30 | 30 |
| Average | 13.35 | 18.30 | 26.30 | 13.15 | 12.63 | 91.8 | 96 | 91.4 | 97.3 | 61.8 | 60.4 | 34.5 | 35.0 |

Measurements of the arms of pilots using a mockup of a side-arm controller, and of the unconstrained angular deflections they could achieve in roll and pitch with the controller. Data were taken with the arm straight or flexed as shown. The preferred neutral position for the controller was found to be 8° to the right and 15° forward of the vertical. The preferred arm position was a slight forward extension from 90°.

Figure 16-13 (continued)

b.



Source: Brissenden (38)

These graphs show the forces the pilots could develop at two elbow angles. They were instructed to apply the following levels of exertion:

- (1) Operational force - chosen as the comfortable level for continuous control maneuvers.
- (2) Maximum Operational force - acceptable for short periods, applicable to any maneuver requiring maximum control capability.
- (3) Maximum force -- the greatest force pilots could exert in each grip position.

Figure 16-14

Design Factors for Hand Controls in Spacecraft

a. Forces Exerted on Hand Controls

| Vertical Handgrip | | | | | | | | | | | |
|--------------------|-------------------|-------------|------|------|----------|--------------------|-------------------|-------------|------|------|-------|
| Right Arm | | | | | Left Arm | | | | | | |
| N = 55 | | | | | | | | | | | |
| Direction of force | Elbow angle (deg) | Percentiles | | | S. D. | Direction of force | Elbow angle (deg) | Percentiles | | | S. D. |
| | | 5th | 50th | 95th | | | | 5th | 50th | 95th | |
| Push | 60 | 34 | 92 | 150 | 38 | Push | 60 | 22 | 79 | 164 | 31 |
| | 90 | 36 | 86 | 154 | 33 | | 90 | 22 | 83 | 172 | 35 |
| | 120 | 36 | 103 | 172 | 43 | | 120 | 26 | 99 | 180 | 42 |
| | 150 | 42 | 123 | 194 | 45 | | 150 | 30 | 111 | 192 | 46 |
| | 180 | 50 | 138 | 210 | 49 | | 180 | 42 | 126 | 196 | 47 |
| Pull | 60 | 24 | 63 | 74 | 23 | Pull | 60 | 26 | 64 | 110 | 23 |
| | 90 | 37 | 88 | 135 | 30 | | 90 | 32 | 80 | 122 | 28 |
| | 120 | 42 | 104 | 154 | 31 | | 120 | 34 | 94 | 152 | 34 |
| | 150 | 56 | 122 | 189 | 38 | | 150 | 42 | 112 | 168 | 37 |
| | 180 | 52 | 120 | 171 | 37 | | 180 | 50 | 116 | 172 | 37 |
| Left | 60 | 20 | 52 | 87 | 19 | Left | 60 | 12 | 32 | 62 | 17 |
| | 90 | 18 | 50 | 97 | 23 | | 90 | 10 | 33 | 72 | 19 |
| | 120 | 22 | 53 | 100 | 26 | | 120 | 10 | 30 | 68 | 18 |
| | 150 | 20 | 54 | 104 | 25 | | 150 | 8 | 29 | 66 | 20 |
| | 180 | 20 | 50 | 104 | 26 | | 180 | 8 | 30 | 64 | 20 |
| Right | 60 | 17 | 42 | 82 | 20 | Right | 60 | 17 | 50 | 83 | 21 |
| | 90 | 16 | 37 | 88 | 18 | | 90 | 16 | 48 | 87 | 22 |
| | 120 | 15 | 34 | 82 | 17 | | 120 | 20 | 45 | 89 | 21 |
| | 150 | 15 | 33 | 64 | 18 | | 150 | 15 | 47 | 113 | 27 |
| | 180 | 14 | 34 | 62 | 24 | | 180 | 13 | 43 | 92 | 22 |
| Up | 60 | 20 | 49 | 82 | 18 | Up | 60 | 15 | 44 | 82 | 18 |
| | 90 | 20 | 56 | 106 | 22 | | 90 | 17 | 52 | 100 | 22 |
| | 120 | 24 | 60 | 124 | 24 | | 120 | 17 | 54 | 102 | 25 |
| | 150 | 18 | 56 | 118 | 28 | | 150 | 15 | 52 | 110 | 27 |
| | 180 | 14 | 43 | 88 | 22 | | 180 | 9 | 41 | 83 | 23 |
| Down | 60 | 20 | 51 | 89 | 21 | Down | 60 | 18 | 46 | 76 | 18 |
| | 90 | 26 | 53 | 88 | 20 | | 90 | 21 | 49 | 92 | 20 |
| | 120 | 26 | 58 | 98 | 23 | | 120 | 21 | 51 | 102 | 23 |
| | 150 | 20 | 47 | 80 | 18 | | 150 | 18 | 41 | 74 | 16 |
| | 180 | 17 | 41 | 82 | 18 | | 180 | 13 | 35 | 72 | 15 |

Source: Hunsicker (171)

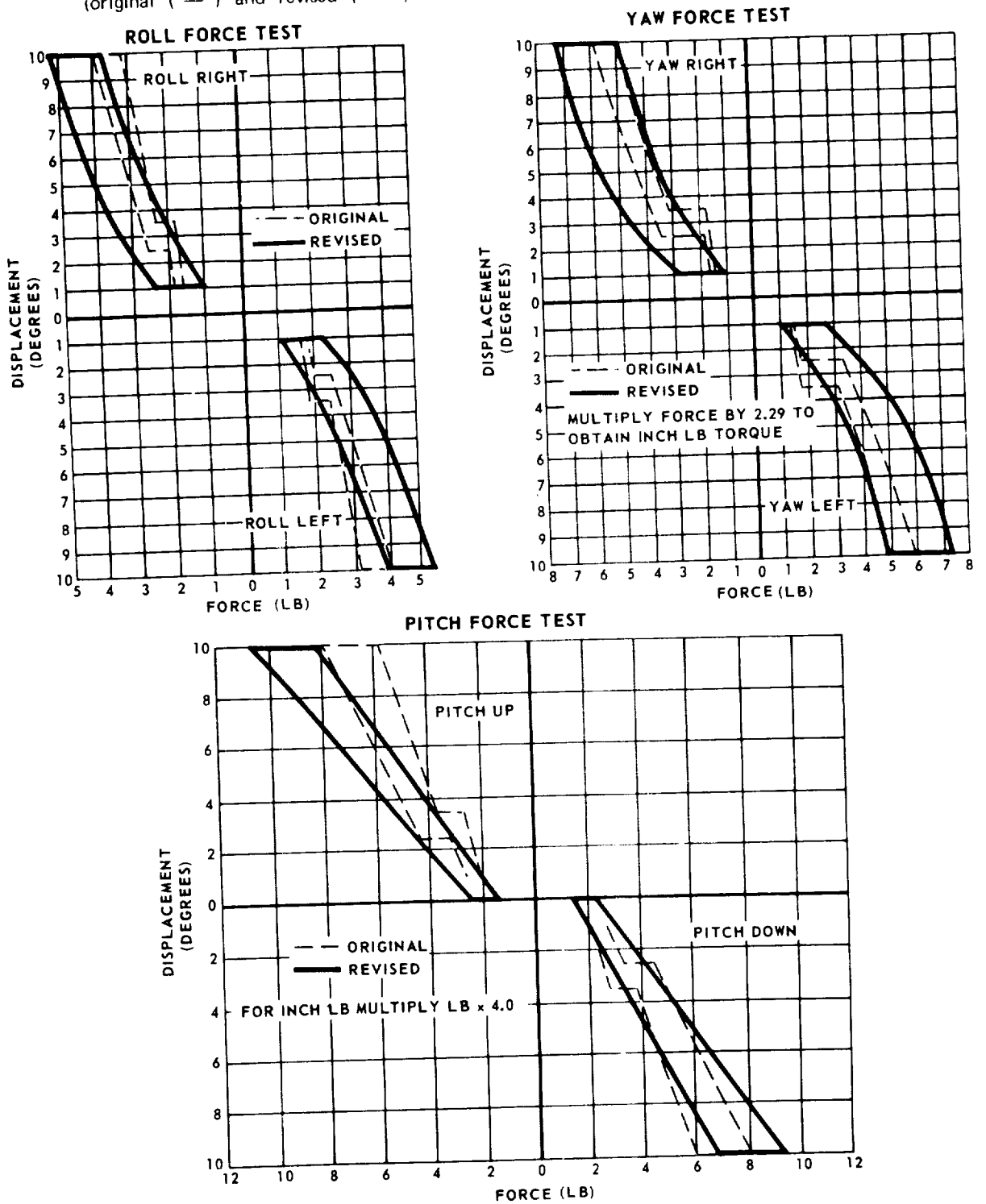
| Horizontal Handgrip | | | | | | | | | | | |
|---------------------------|-------------------|-------------|------|------|--------------------------|--------------------|-------------------|-------------|------|------|-------|
| Right Arm--Wrist Pronated | | | | | Left Arm--Wrist Pronated | | | | | | |
| N = 30 | | | | | | | | | | | |
| Direction of force | Elbow angle (deg) | Percentiles | | | S. D. | Direction of force | Elbow angle (deg) | Percentiles | | | S. D. |
| | | 5th | 50th | 95th | | | | 5th | 50th | 95th | |
| Push | 60 | 40 | 94 | 156 | 36 | Push | 60 | 33 | 86 | 138 | 35 |
| | 90 | 25 | 65 | 100 | 24 | | 90 | 27 | 60 | 93 | 28 |
| | 120 | 23 | 46 | 70 | 15 | | 120 | 17 | 43 | 71 | 17 |
| | 150 | 18 | 40 | 66 | 18 | | 150 | 15 | 37 | 69 | 18 |
| | 180 | 17 | 32 | 59 | 12 | | 180 | 12 | 32 | 59 | 13 |
| Pull | 60 | 13 | 37 | 50 | 16 | Pull | 60 | 20 | 39 | 64 | 18 |
| | 90 | 14 | 32 | 54 | 13 | | 90 | 17 | 37 | 63 | 18 |
| | 120 | 13 | 26 | 43 | 10 | | 120 | 12 | 30 | 56 | 14 |
| | 150 | 12 | 29 | 46 | 10 | | 150 | 15 | 32 | 52 | 13 |
| | 180 | 11 | 28 | 46 | 12 | | 180 | 16 | 34 | 61 | 15 |
| Left | 60 | 19 | 41 | 72 | 19 | Left | 60 | 20 | 42 | 66 | 15 |
| | 90 | 12 | 31 | 64 | 15 | | 90 | 17 | 38 | 60 | 12 |
| | 120 | 9 | 26 | 53 | 13 | | 120 | 17 | 34 | 53 | 8 |
| | 150 | 9 | 21 | 39 | 11 | | 150 | 17 | 31 | 54 | 11 |
| | 180 | 10 | 19 | 34 | 7 | | 180 | 15 | 28 | 41 | 8 |
| Right | 60 | 16 | 48 | 73 | 18 | Right | 60 | 18 | 36 | 51 | 15 |
| | 90 | 16 | 39 | 59 | 15 | | 90 | 11 | 27 | 54 | 11 |
| | 120 | 18 | 34 | 47 | 11 | | 120 | 10 | 22 | 39 | 10 |
| | 150 | 18 | 32 | 45 | 7 | | 150 | 9 | 23 | 53 | 16 |
| | 180 | 16 | 31 | 57 | 13 | | 180 | 10 | 20 | 49 | 13 |
| Up | 60 | 23 | 49 | 79 | 20 | Up | 60 | 22 | 57 | 100 | 22 |
| | 90 | 28 | 89 | 112 | 29 | | 90 | 37 | 77 | 123 | 24 |
| | 120 | 41 | 91 | 138 | 30 | | 120 | 45 | 91 | 145 | 30 |
| | 150 | 43 | 99 | 165 | 38 | | 150 | 58 | 100 | 159 | 32 |
| | 180 | 35 | 95 | 156 | 35 | | 180 | 47 | 101 | 171 | 31 |
| Down | 60 | 23 | 61 | 158 | 35 | Down | 60 | 18 | 74 | 139 | 35 |
| | 90 | 22 | 83 | 142 | 35 | | 90 | 23 | 75 | 136 | 34 |
| | 120 | 37 | 92 | 161 | 35 | | 120 | 29 | 75 | 148 | 39 |
| | 150 | 40 | 90 | 154 | 34 | | 150 | 39 | 79 | 136 | 19 |
| | 180 | 41 | 87 | 143 | 31 | | 180 | 34 | 76 | 138 | 31 |

Source: Hunsicker (172)

Controls designed to be actuated by human force should be operable by the weakest individuals of the using population but able to withstand the maximum force the strongest individuals of the using population can apply. The tables show the maximum forces (measured in pounds) exerted on vertical or horizontal handgrips by male college students, tested in a seated position.

Figure 16-14 (continued)

b. Hand Forces for Attitude Control in the Gemini Spacecraft
 (original (—) and revised (----))



- d. PULSE - For each deflection of the controller away from the center position, a single short duration (20 msec) pulse was applied to the appropriate axis.
- e. RATE CMD, RE-ENT - Similar to rate command with a wider neutral and gain crossfeed from roll to yaw. (Designed for use in manual re-entry.)
- f. RE-ENT - Pitch and yaw axes in rate damping control mode, with roll axis slaved to bank-angle command from the computer.
- g. PLAT - ACME accepted attitude information from the platform and provided outputs to the thrusters to maintain spacecraft attitude automatically within pitch, yaw and roll deadbands.
- h. PARA - A mode designed for use with a paraglider which was eliminated before the first manned flight. (On Spacecraft V and up, this selector position was used for the PLATFORM mode.)

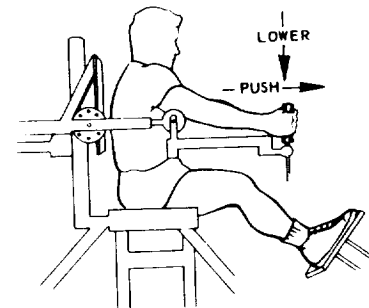
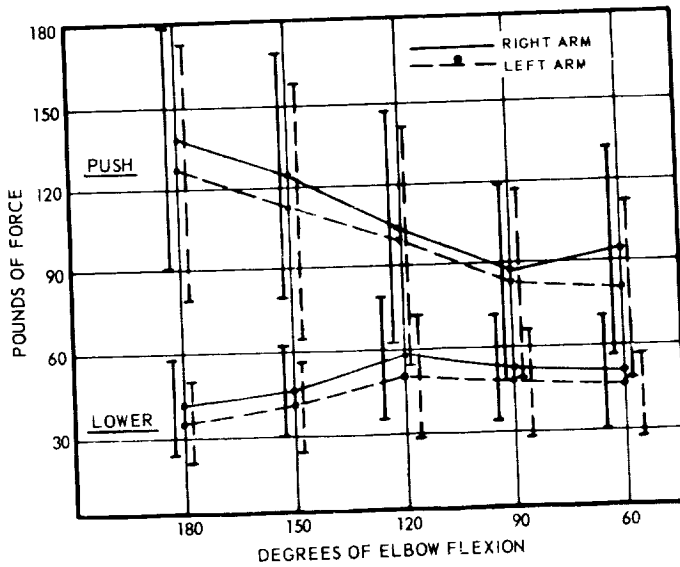
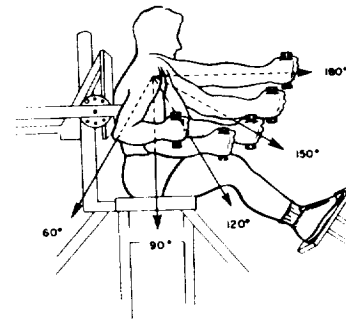
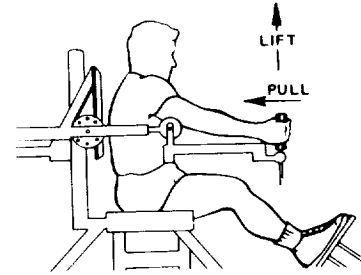
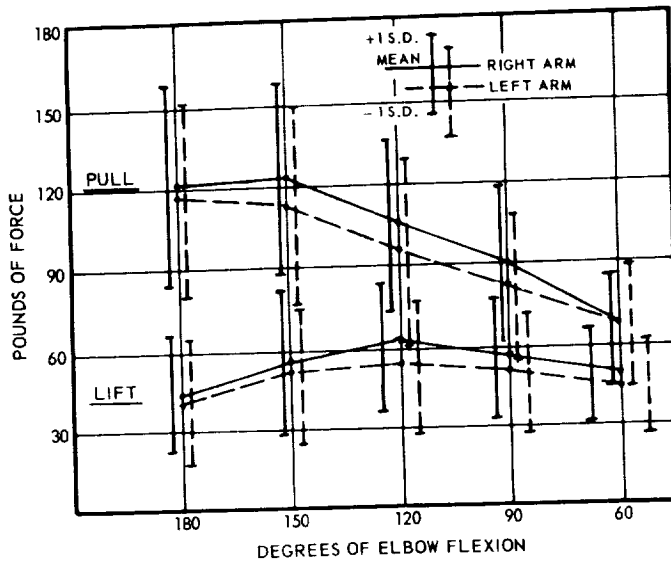
Arm strength with elbow flexion is recorded in Figure 16-15. Leg strength is recorded in Figure 16-16 and lifting strength in Figure 16-17. Cranking speeds and other motion factors for shirtsleeved males have recently been reviewed (71).

A handbook of control design for pressure-suited subjects has been published (295). Controls and displays used in Gemini have been reviewed (217, 31). Data are available on static and dynamic factors in design of wheeled vehicles for terrestrial (56) and lunar operations (132, 140); also, for manned space-simulation chambers (9, 10, 15, 58, 218, 227).

Complex motor control and integration of man into the machine control loop has received much study in relation to aircraft and spacecraft problems. Several major reviews and symposia are available (References 7-532, 7-694, 7-689) and (178, 238, 257, 262, 302, 317, 343, 345, 373). A Soviet review of this subject has also been presented (78). General assessments of optimal human performance in space systems have been made (238, 239, 292). More specific human control studies have been made of spaceflight tasks. These include: manual space navigation (242), orbital docking of large attitude-stabilized components and other systems (59, 272), lunar landing vehicles (9, 179, 205). The visual aspects of rendezvous and docking control has been reviewed on pages 2-96 to 2-108 of the section on Light, (No. 2). Finally, studies on the simulation of lunar missions with emphasis on learning and retention of complex skills have been published (69) and Reference (7-254).

Human performance in the different acceleration environments including microgravity and zero gravity has been covered in Oxygen-CO₂-Energy, (No. 10) and in Acceleration, (No. 7). Effects of training on the performance of motor skills during the Gemini EVA were reviewed on pages 7-129 to 7-154. Training plans for Apollo are available (248). Soviet studies of responses to intravehicular exercise in Voskhods I and II are now published. (See also pages 7-131 and 7-132.)

Human factors in the assembly and maintenance of large space structures are under current study (282, 372). The effects of human motions and forces on the stability of orbiting vehicles have been simulated (81, 321).



Mean values and standard deviations for the strength of pulling, lifting, pushing, and lowering with each arm and with the elbow flexed at the angles indicated, on the right. The sample group was 55 college men, selected to approximate the characteristics of aircrewmembers. Testing was done with a strain gauge dynamometer to record the forces on the isometric handgrip (which does not move appreciably).

Source: Hunsicker⁽¹⁷¹⁾, additional data may be found in Morgan et al⁽²²⁴⁾

Figure 16-15

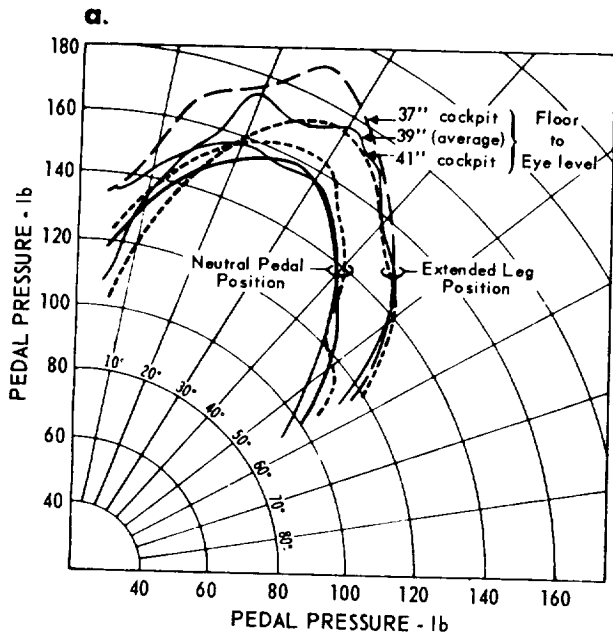
Arm Strength with Elbow Flexion

(After Hertzberg and Clauser⁽¹⁶⁴⁾)

Figure 16-16

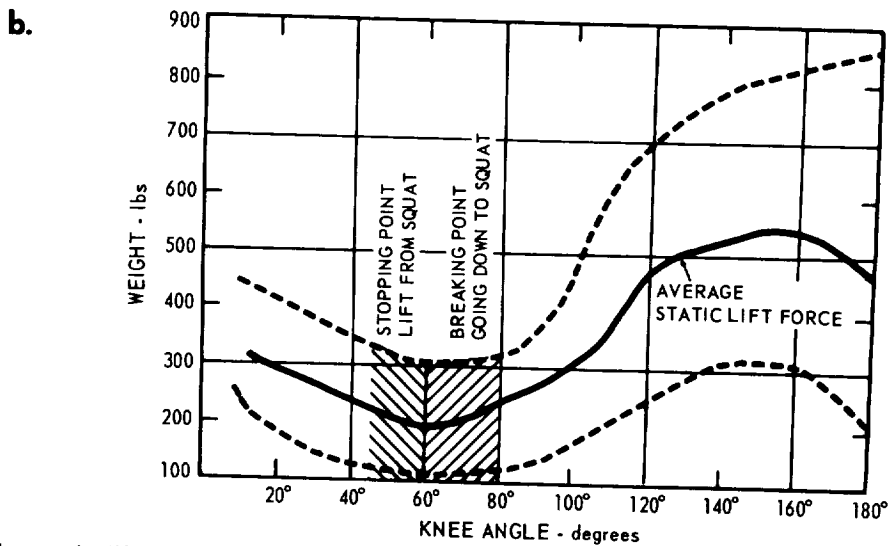
Leg Strength

(After Hertzberg and Clauser(164))



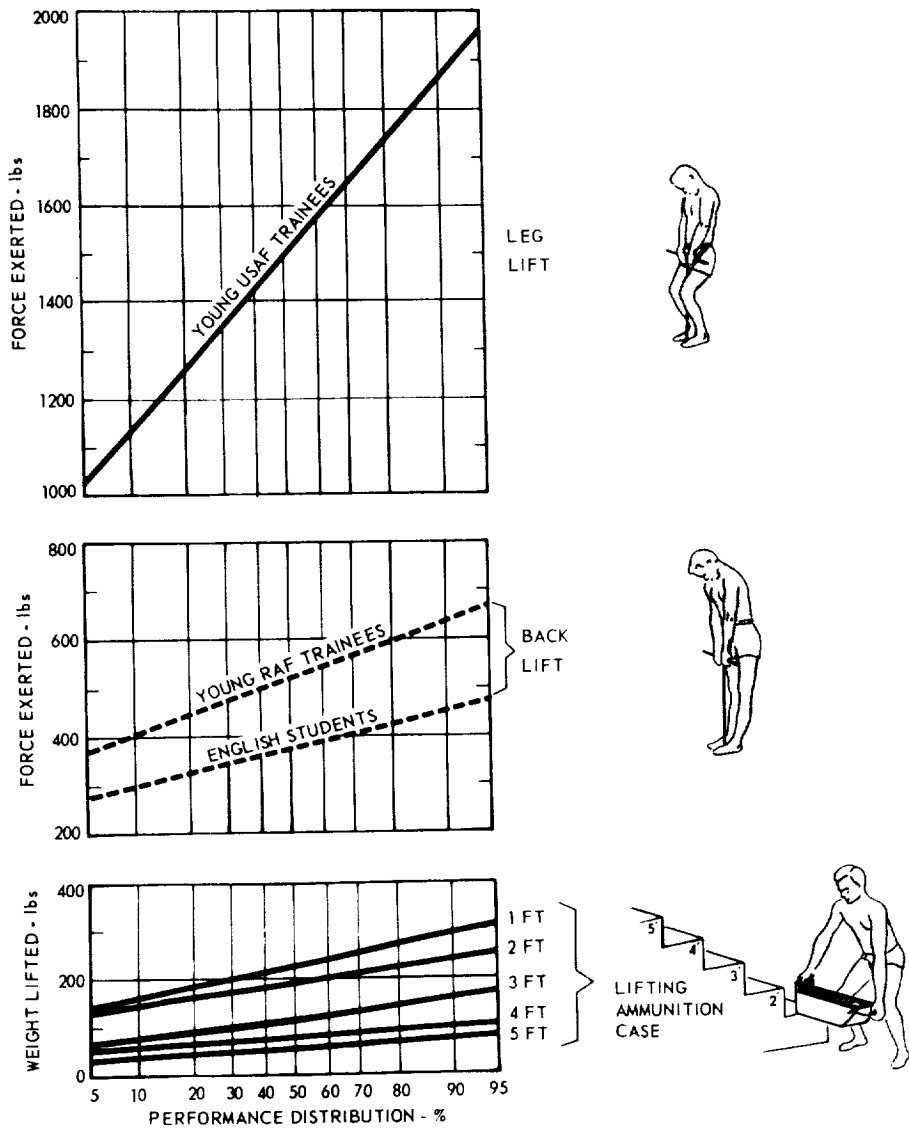
Foot rotation forces on an aircraft brake pedal measured at various angles of the brake pedal in neutral and extended leg positions. Floor to eye height was also varied from 37 to 41 inches. Data are averages of 100 subjects.

Source: Hertzberg(162)



The static lifting forces applied against dynamometers by 13 subjects with knees variously bent as shown by the scale of knee angles. The central line shows average values, and the outer dashed line shows the range of forces. In addition, subjects were tested in dynamic lift, shown by the two shaded areas, using bar bell weights on their shoulders. Maximum rise from full squatting posture is shown in the left hand shaded bar as the maximum angle of knee extension. The right hand shaded bar shows the "angle of break," determined by starting with weights on the shoulders and a full standing position, then gradually squatting until the leg could no longer restrain the motion and a rapid downward motion began.

Source: Swearingen et al(318)



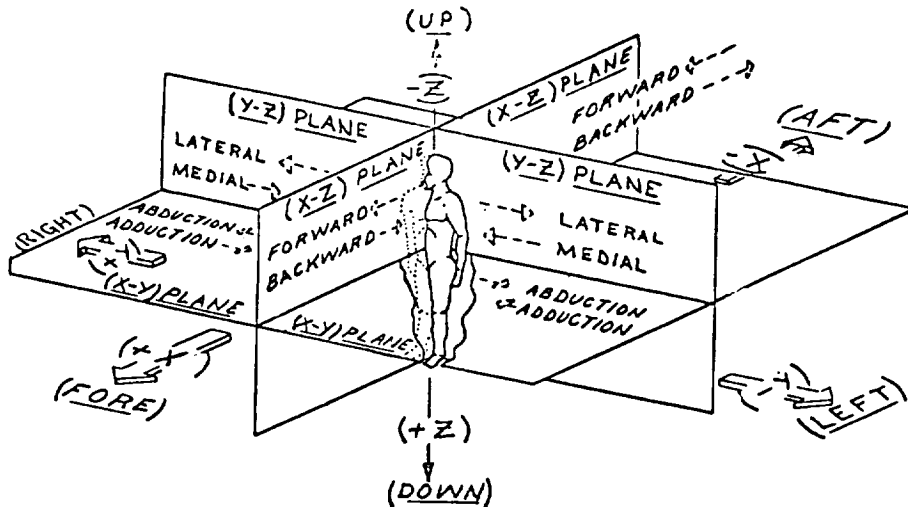
The variations in lifting strength as different lifting tasks are measured. Each of the three types of lift shown is plotted on a probability grid to show the percentile performances. Note the low values for lift when an awkward load (the ammunition case from the F-86H aircraft) must be raised. Note also the very high values when the strong leg muscles are ideally employed, as shown in the upper set labeled "Leg Lift". Here, not only the hands were used to grip the dynamometer bar; a special belt and fastener helped transfer the force to the handle. These data may be of value in planning post-landing survival maneuvers.

Adapted from Cathcart et al⁽⁵²⁾, Clarke⁽⁶⁴⁾, and Emanuel and Chaffee⁽⁹⁰⁾

Figure 16-17

Lifting Strength

(After Hertzberg and Clauser⁽¹⁶⁴⁾)



Plane Definitions:

- a. (Y - Z Plane) - Frontal Plane
- b. (X - Z Plane) - Sagittal Plane
- c. (X - Y Plane) - Transverse Plane

Direction of Limb Movement Terms:

Type of Limb Movement Terms:

- a. Flexion - Bending or decreasing the angle between parts of the body.
- b. Extension - Straightening or increasing the angle between parts of the body.
- c. Stretch - Lengthening of body part.
- d. Rotation - Revolution about the axis of a body part.
- e. Pronation - Face down.
- f. Supination - On back or Face up.
- a. Forward = +X Direction
- b. Backward = -X Direction
- c. Upward = -Z Direction
- d. Downward = +Z Direction
- e. Right = +Y Direction
- f. Left = -Y Direction
- g. Lateral = Away from (X-Z) plane (in Y-Z plane)
- h. Medial = Toward (X-Z) plane (in Y-Z plane)
- i. Abduction = Away from (X-Z) plane (in X-Y plane)
- j. Adduction = Toward (X-Z) plane (in X-Y plane)

Figure 16-18

Terminology and Definitions for Describing the Mobility of the Pressure Garment Assembly

(After NASA⁽³³⁶⁾)

Extravehicular Garments and Mobility

Special consideration must be given to anthropometric factors in planning extravehicular mobility. Suggestions have been made regarding critical areas in the design of the Apollo Extravehicular Mobility Unit (EMU) which consists of the following subsystems (336): Pressure Garment Assembly (PGA), Constant Wear Garment (CWG), Liquid Cooling Garment (LCG), Thermal and Meteoroid Garment (TMG), Extravehicular Visor Assembly (EVA), Portable Life Support System (PLSS), Emergency Oxygen System (EOS).

Design features should prevent impediments to astronaut in the performance of his tasks which include:

- Donning, doffing and checkout of applicable EMU subsystems within the command Module (CM) (185).
- Donning, doffing and checkout of the TMG, EVA, PLSS, and EOS within the LEM in both a pressurized and depressurized cabin (185).
- Egress and ingress through all the CM or the LM hatches in free space and/or (for LM only) on the lunar surface while carrying scientific or maintenance equipment (207, 346). (See discussion on page 16-36.)
- Descending and ascending LM vertical ladders (309).
- Walking over the lunar surface while carrying assorted tools, scientific and navigation equipment (Figure 7-73) (290, 309).
- Performing various scientific experiments on the lunar surface such as hook-up and emplacement of passive recording instruments, seismometers, geophones, radiation detection devices, magnetometers, power supplies; setup and operation of cameras, levels, transits, stud guns; collection and packaging of lunar soil specimens, etc. (115, 184, 185) (Figure 7-73).
- Performing specific mobility tasks on lunar surface, unassisted, such as crouching in a deep knee bend; kneeling on one and/or both knees; crawling forward and backward; getting up from a prone or supine position; bending and picking up small objects on the ground without kneeling (309).

Analyses of many of these tasks have been presented under performance in zero and subgravity of Acceleration, (No. 7). Intra and extravehicular activities of suited subjects in Gemini have been covered in great detail by NASA reviews (216, 231).

Pressure Garment Assemblies (Soft and Hard Suits)

The Pressure Garment Assembly (PGA) is an anthropomorphic pressure vessel encompassing the entire body. The Assembly is individually sized to the existing astronaut population (Figure 16-4). The PGA is tailored as close as possible to actual body contours and to necessary internal PGA components

and should provide break points at natural body break-points to enhance mobility and reduce excessive bulk. The crewman should be comfortable in a pressurized PGA, fully restrained in the Command Module couch under the effect of a sustained acceleration of 5 g's, +G_x, eyeballs in. It has been recommended that the following exterior dimensions not be exceeded:

1. Across shoulder: 23-3/4 inches;
2. Across elbows: 23-3/4 inches;
3. Across knees: 16 inches.

The combined center of gravity of the PGA and the crewman should be located within two (2) inches vertically and one (1) inch horizontally of the CG of a nude, standing crewman as noted in Figures 16-6, 16-7, and 6-11.

The mobility requirements for the PGA are described in terms of the terminology and definitions provided in Figure 16-18. The types of mobility of concern to PGA design include the following:

- Elementary movements, or movements of the body, limbs, or head in one plane.
- Complex movements, which are movements of the arms, wrists, hands and fingers which require a high degree of psychomotor coordination and movement in more than one plane (295).
- Total body movements, which include movements involved in walking, lifting objects, etc.
- Suit equilibrium positions, which are positions the garments tend to seek when no torque is being applied to the joints.

The movements of the head, body, limbs, and/or elementary movements, which the astronaut should be capable of performing with the PGA vented or pressurized to 3.7 ± .2 psi are indicated in Table 16-19. This table indicates the minimum range of movement in degrees for each of the movements and the maximum torque in inch-pounds (or foot-pounds) required to initiate and sustain the movement.

The complex movements of the arms, wrists, hands, and fingers which the Apollo crew should be capable of performing both extravehicularly and intravehicularly with the suit pressurized to 3.7 ± .2 psig are indicated in Tables 16-20 to 16-22. The coordinated movements of the torso, arms, legs, hands, feet, and head such as are required during lunar surface operations and during the extravehicular phase of orbital flight with the suit pressurized between 3.5 and 3.9 psig are indicated in Tables 16-22 a and b. Data for the design of equipment and altered movement patterns resulting from zero gravity have been covered in the section on zero gravity in Acceleration (No. 7).

As general anthropomorphic factors in the design of extravehicular garments, the following have been suggested (336). If equilibrium positions exist for the garments, i. e., positions into which the garments will spring to or seek if no restrictive force is applied by the crewman in the EMU, they

Table 16-19

Maximum Performance Requirements for the Elementary Body Movements
Intravehicular and Extravehicular Wear, Vented or at 3.7 Psia

(After NASA--CSD-A-096(336))

| MOVEMENTS | RANGE OF MOVEMENTS (In degrees) | MAXIMUM TORQUE REQUIRED |
|---|------------------------------------|----------------------------|
| A. NECK MOBILITY | | |
| Flexion (forward-backward) | 120 | 0 |
| Flexion (left-right) | 30 | 0 |
| Rotation (Abduction-Adduction) | 140 | 0 |
| B. SHOULDER MOBILITY | | |
| Adduction | 45 | 1 ft. lb _f |
| Abduction | 125 | 1 ft. lb _f |
| Lateral - Medial | 150 | 1 ft. lb _f |
| Flexion | 170 | 1 ft. lb _f |
| Extension | 50 | 1 ft. lb _f |
| Rotation (X-Z Plane) Down-up | 135 | 1 ft. lb _f |
| Rotation (Y-Z Plane): Lateral Rotation | 35 | 1 ft. lb _f |
| Medial Rotation | 95 | 1 ft. lb _f |
| C. ELBOW MOBILITY | | |
| Flexion - Extension | 140 | 1 ft. lb _f |
| D. FOREARM MOBILITY | | |
| Supination (Palms up) | 90 | .2 ft. lb _f |
| Pronation (Palms down) | 75 | .2 ft. lb _f |
| E. WRIST MOBILITY | | |
| Palmar Flexion | 75 | .2 ft. lb _f |
| Dorsiflexion | 65 | .2 ft. lb _f |
| Abduction | 50 | .2 ft. lb _f |
| Adduction | 30 | .2 ft. lb _f |
| F. TRUNK - TORSO MOBILITY | | |
| Trunk Rotation (abduction - adduction) | 70 | 2 ft. lb _f |
| Torso Flexion (lateral - medial) | 50 | 2 ft. lb _f |
| Torso Flexion (forward) | 90 | 2 ft. lb _f |
| Torso Flexion (backward) | 25 | 2 ft. lb _f |
| G. HIP MOBILITY | | |
| Abduction (leg straight) | 45 | 2 ft. lb _f |
| Adduction (knee bent) | 30 | 2 ft. lb _f |
| Abduction (knee bent) | 35 | 2 ft. lb _f |
| Rotation (sitting): Lateral | 30 | 2 ft. lb _f |
| Rotation (sitting): Medial | 30 | 2 ft. lb _f |
| Flexion | 115 | 2 ft. lb _f |
| Extension | 35 | 2 ft. lb _f |
| H. KNEE MOBILITY | | |
| Flexion (standing) | 110 | 1 ft. lb _f |
| Rotation (medial) | 35 | 1 ft. lb _f |
| Rotation (lateral) | 35 | 1 ft. lb _f |
| Flexion (kneeling) | 155 | 1 ft. lb _f |
| J. ANKLE MOBILITY | | |
| Extension | 40 | 3.0 ft. lb _f |
| Flexion | 35 | 3.0 ft. lb _f |
| Abduction | 25 | 3.0 ft. lb _f |
| Adduction | 25 | 3.0 ft. lb _f |

Table 16-20
Elemental Movements of the Wrist, Hands, and Fingers
Required in Apollo EMU Operations

(After NASA-CSD-A-096(336))

| Movements or Operations | Description of Performance | Intravehicular | | Extravehicular |
|--|--|----------------|----------------|----------------|
| | | 0. 18 PSIG | 3. 5-3. 9 PSIG | |
| Palmar | Write legibly with pencil | x | x | x |
| | Operate .375" dia. rotary knob | x | x | x |
| | Utilize small screwdriver | x | x | x |
| Tip Prehension | Pick up small objects as: | | | |
| | - Small screws - Small rocks | x | x | x |
| Lateral Prehension | Operate 2 and 3 position space- | | | |
| | craft toggle switches | | | |
| | - Vertically - Horizontally | x x | x x | x x |
| Grasp | Use a screwdriver | x | x | x |
| | Use pliers | x | x | x |
| | Use crescent wrench | x | x | x |
| | Use socket wrench | x | x | x |
| | Use hand-controller | x | x | |
| Finger: Pushbutton Ops. | Operate pushbutton within panel of pushbuttons | x | x | x |
| Finger: Pulling Ops. | Operate T-handle control | x | x | x |
| | Operate D-handle control | x | x | x |
| | Operate ring handle control | x | x | x |
| Thumb | Operate thumbwheel | x | x | x |
| | Operate button on control handle | x | x | |
| Hand Rotation | Operate discrete position rotary switch | x | x | x |
| Wrist Movements | Move wrist side to side while opening and closing fingers | x | x | x |
| | Move wrist up and down while opening and closing fingers | x | x | x |
| Whole Hand Movement | Hold hand at any desired position | x | x | x |
| Intravehicular wear = CWG and PGA or LCG and PGA | | x = required | | |

Table 16-21

Movements of the Wrist, Hands, and Fingers Related to the Intravehicular Operation of the Pressure Garment Assembly in Apollo

(After NASA-CSD-A-096⁽³³⁶⁾)

| Components of PGA Defining the Complex Movements Requirements | 0.18 PSIG (Suit Ventilated) | | | 3.5-3.9 PSIG | | |
|---|-----------------------------|--------------------|---------------------|---------------------|--------------------|---------------------|
| | CM (Couch Pos.) | CM (Vert. Pos.) | LEM (Vert. Pos.) | CM* (Couch Pos.) | CM (Vert. Pos.) | LEM (Vert. Pos.) |
| 1. Helmet Ring Disconnect | x | x | x | | | |
| 2. EV Visor Positioning | | | | | | |
| 3. EV Visor Attachment | | | x | | | x |
| 4. Medical Injection Fitting | x | x | x | x | x | x |
| 5. PLSS Controls and Attachments | | x | x | | x | x |
| 6. EOS Controls | | x | x | | | |
| 7. Multiple Gas Disconnect | x | x | x | x | x | x |
| 8. WMS Disconnect | x | x | x | x | x | x |
| 9. Multiple Water Disconnect | | x | x | | x | x |
| 10. Electrical Disconnect | x | x | x | x | x | x |

x = required

* Provided there is no interference from the restraint harness.

Table 16-22

Complex Total Body Mobility Requirements Required for Intravehicular and Extravehicular Phases of Apollo at 1/6 G and Zero G

(After NASA-CSD-A-096⁽³³⁶⁾)

a. Total Mobility Performance Criteria at 1/6 G, PGA Pressurized to 3.5 to 3.9 Psig

1. Climb ladder at slopes up to 27° with rungs spaced every 8 inches.
2. Remove equipment from LEM with LEM at 27° position.
3. Crouching in a deep knee bend for three minutes.
4. Kneeling on one knee for five minutes and working in kneeling position.
5. Crawling forward 5 feet, then backward to starting point.
6. Getting to and up from supine and prone positions (unassisted) within 30 seconds.
7. Pickup and carry 2nd astronaut.
8. Walking erect on 3° inclined treadmill at 3 mph for 10 minutes; jumping over small crevices; taking long strides.

Table 16-22 (continued)

a. Total Mobility Performance Criteria at 1/6 G, PGA Pressurized to 3.5 to 3.9 Psig (cont.)

9. Bending over to reach and pick up small objects on ground without the necessity of kneeling.
10. Operate PLSS controls.
11. Moving from standing erect to sitting position (unassisted) without making suit adjustments.
12. Lift without squatting.
13. Donning extravehicular wear with assistance, as necessary, while pressurized. This includes:
 - a. External Thermal Garment (ETG) (including boots, garment and supplementary visor)
 - b. Meteoroid Protection Garment (MPG)
 - c. Portable Life Support System (PLSS)
 - d. Emergency Oxygen System (EOS)
14. Forward reach while in kneeling position and torque at distance obtained.
15. Crawl face up or down thru LEM access hatch.
16. Capability to bend down in LEM and shut and lock LEM hatch.
17. Operate overhead hatch.
18. Change LiOH cannisters.
19. Handle equipment in torso-bent position in restricted area.
20. Self donning PLSS.

b. Complex Mobility Performance Criteria at Zero G

-
1. Operate stem unit (transfer).
 2. Handle equipment and carry out tunnel transfer.
 3. Don Extravehicular Mobility Unit
 4. Work at navigation and Guidance Consoles in the Command and Lunar modules.
 5. Handle Portable Life Support System in Lunar module
 6. Access to Command Module lower equipment bay and capability to handle equipment.
 7. Capability to carry out couch operations in Command Module.
 8. Capability to carry out free space transfer.
-

should correspond as closely as possible to the "natural" position for each related task. Design should be compatible with the quick donning requirements. Closing and sealing operations should be possible without requiring assistance and/or while donning in the dark. Design should permit donning within a single time period of at least fifteen minutes without assistance in an illuminated CM while at zero gravity. Design of elastic and foamed garments to replace pressurized suits has been suggested (161, 270, 346).

The following features may act as aids to facilitate donning of the PGA:

- Non-bunching, low bulk, inner layers which are resistant to dimensional buildup.
- Smooth inner surface containing no pockets, flaps, or discontinuities.
- Incorporation of positive alignment devices for engaging mating parts.
- Minimum number of components requiring connections prior to pressurization.
- Positive indications of correct installation of mating parts.
- Engagement of a locking latch at the neck should be accomplished with a force of no more than 10 pounds.

Within the pressure garment, the liquid cooled garment, LCG, should be a moderately form-fitting flexible garment encompassing the entire body with the exception of the head and hands. (270) It should resist bunching, not bind or restrict the crewman or cause pressure points, and be constructed of absorbent loose weave material to permit capillary wicking of body moisture for evaporation. The flexible liquid coolant tubes should be located in a pattern which assures intimate contact with the typical astronaut skin surface at all times. (See section on liquid-cooled garments in Thermal Environment No. 6).

In the Apollo program it is planned that the Thermal-Meteoroid Garment (TMG) will encompass the entire EMU with the exception of the PLSS and the helmet assembly which will incorporate separate thermal and meteoroid protection (270). The TMG will consist of a parka, trousers, a pair of lunar boots and a pair of mittens. It will be conformal to the PGA and not contain excessive material which may cause folds or bunching. The outer layer of the TMG will be abrasion resistant, particularly in the area of the knees. The performance of the TMG should not be altered by adhesion of lunar dust. Provision should be made for the attachment of indicators and dosimeter devices in the areas which are readily accessible to the crewman during the lunar surface mission. Access should be permitted to the intravehicular-extravehicular controls, displays, connectors, and adjustment devices while in a pressurized PGA as noted in Tables 16-19 and 16-20. Design of the meteoroid garment of Gemini is covered in Pressure (No. 12) and reference (216). Data for the design of radiant insulations of the TMG are covered in Thermal Environment (No. 6); and for meteoroid protection, in Pressure, (No. 12).

A detailed analysis of the several different Gemini suits has been published (217). Data are also available on current prototype suits. The range of weight, volumes, mobilities and visual fields attained in prototype Apollo suits are

covered in Table 16-23 (75, 185, 206, 270). Table 16-23 a and b review component weights of the soft and hard suits. Table 16-23 c gives the gaseous volumes of individual components of hard and soft suits (276). The residual volumes of Table 12-19 represent the volumes remaining in the suit after disruption of major seals. The total gaseous volume of a typical soft suit and PLSS (excluding respiratory tract of the astronaut) is 28 liters. The gaseous volume of the soft-suit helmets vary from 2 to 3 liters. The total gaseous volume of a typical hard suit and back pack is about 75 liters. The helmet of the hard suit is a hemisphere of about 12 inches in diameter. The total volume of the helmet is about 7400 cc; the volume of the head, about 3000 cc; and the free gaseous volume inside the helmet, about 4400 cc. Table 16-23c also gives the orifice areas at major seals and cross section areas of the body at seal sites. These data can be used for calculating pressure decay curves during explosive decompression (276).

Figures 23-d and e cover range of mobilities for 3 different soft suits. Wearing the LCG, the test subject was appropriately positioned and restrained on the mobility-notation table, and the angular excursion for the following movements were obtained for the unsuited, vented, and pressurized (3.7 psig). Figure 12-23 e presents data on restriction of movement relative to the nude. Using these data, and a weighting system developed for this study (185) the space suits were rated as follows: In the vented condition, suit C ranked first, suit A second, and suit B third; pressurized to 3.7 psig, suit A ranked first, suit C second, and suit B third. In a final rating for the angular-range study, suit C ranked first, suit A second, and suit B third. After studying the stroboscopic motion series and viewing the movies of mobility sequences, the three space suits were rated by the evaluation team. For the 3.7 psig condition, with and without the TMG, suit A was ranked first, suit C second, and suit B third. The two evaluations (angular-range study along with the strobe and movie sequences) were considered together in arriving at a final rating on general mobility. Since the strobe and cine sequences included a broader

Table 16-23

Range of Weights, Volumes, Mobilities, and Visual Fields
Attained in Prototype Apollo Space Suits

a. Component Weights of Prototype Apollo Soft Suits (in grams and pounds)

| Type of suit | Helmet with communications | Gloves, pair | Limb-torso suit | PGA (a) | EV Visor assembly | Water garment | Constant wear garment |
|--------------|----------------------------|--------------|-----------------|----------|-------------------|---------------|-----------------------|
| Suit B | 1865 | 494.5 | 10 870 | 13 229.5 | 1325 | 1483 | 268 |
| | 4.10 | 1.89 | 2.38 | 29.2 | 2.94 | 3.26 | .59 |
| Suit A | 1216 | 638 | 10 590 | 12 444 | 1007 | 0 | 0 |
| | 2.68 | 1.40 | 23.3 | 27.4 | 2.22 | | |
| Suit C | 1203 | 649.5 | 8 730.5 | 10 583 | 1169.5 | b1029.5 | 312 |
| | 2.65 | 1.43 | 19.3 | 23.3 | 2.57 | 2.26 | .69 |

^aWeight of PGA represents sum of weights for helmet, gloves, and limb-torso suit.

^bWeight included no connectors.

(After Jones⁽¹⁸⁵⁾)

Table 16-23 (continued)

b. Weight of Hard Suit Components (in pounds)

| <u>Component</u> | <u>RX-2A</u> | <u>RX-3 Goals</u> | <u>Current Estimates</u> | <u>Micrometeoroid Protection (Honeycomb Layup)</u> |
|---|--------------|-----------------------|------------------------------|--|
| Helmet and Sun Visor | 3.67 | 4.5 | 5.0 | 0.5 |
| Gloves | 1.30 | 1.0 | 1.0 | - |
| Wrist Joints | - | 1.0 | 1.6 | - |
| Lower Arm | 1.04 | 1.2 | 1.4 | 0.2 |
| Elbow Joints | 2.80 | 1.0 | 1.0 | - |
| Upper Arm | 2.30 | 2.0 | 2.4 | 0.2 |
| Shoulder Joints | 7.34 | 6.4 | 6.4 | - |
| Torso, Upper | 9.85 | 4.8 | 4.8 | 0.1 |
| Torso, Lower | 5.80 | 5.2 | 5.2 | 0.1 |
| Waist Joint | 6.26 | 5.1 | 5.1 | 0.1 |
| Body Seal Mechanism | 4.76 | 1.5 | 1.5 | - |
| Pants | 3.94 | 2.9 | 2.9 | 0.1 |
| Thigh Joints | 10.52 | 8.0 | 8.4 | 0.9 |
| Knee Joints | 5.48 | 3.6 | 3.6 | - |
| Calves | 3.24 | 3.0 | 3.0 | 1.4 |
| Ankles | 3.40 | 1.0 | 2.2 | - |
| Boots | 4.08 | 3.0 | 3.0 | - |
| Internal Pads and Ducting | 4.37 | 2.8 | 2.8 | - |
| Misc. (Head rest — inter-com, connec- tors, etc.) | - | 2.0 | 2.0 | - |
| Total | 80.15 | 60.0 | 63.3 | 3.6 |

RX-3 Suit Weight minus Micrometeoroid Protection - 59.7

Shoulder Breadth of Both Suits - 23 inches

Leakage Rate - 25 Scc/min (2.1×10^{-3} cfm)

Maximum Joint Torque - 0.28 m-kp (2.0 lb-ft)

(After Litton Industries⁽²⁰⁶⁾)

Table 16-23 (continued)

c. Effective Volumes and Orifices During Explosive Decompression of Soft and Hard Space Suits by Seal Disruption

| <u>Critical Volumes</u> | <u>Apollo Soft Suit</u> | <u>Apollo Hard Suit</u> |
|--|-----------------------------|-----------------------------|
| Total free volume of suit, PLSS, and hoses | 28 liters | 75 liters |
| Free volume of helmet | ~2.5 liters | 4.4 liters |
| Free volume in PLSS and hoses (2 hoses, 3/4" ID, and 2 1/2 feet and 6 feet long) | 3.8 liters | 3.8 liters |
| Free volume of suit below neck ring | 22 liters | 67 liters |
| <u>Neck Seal</u> | | |
| Diameter of seal | 9" ID | 11.8" ID |
| X-area | 411 cm ² | 706 cm ² |
| Angle of elevation of seal | 17° | 40° |
| X-area of neck subtended by seal | 116 cm ² | 145 cm ² |
| Orifice at neck seal | 295 cm ² | 561 cm ² |
| <u>Wrist Seal</u> | | |
| Diameter Seal | 4" ID | 3.87" ID |
| X-area of seal | 81.4 cm ² | 76 cm ² |
| X-area of wrist at seal | 21.5 cm ² | 21.5 cm ² |
| Orifice at wrist seal | 60 cm ² | 54 cm ² |
| <u>Thigh Seal</u> | | |
| Diameter | - | (RX 4 and 5) 7 7/8" |
| X-area seal | - | 314 cm ² |
| X-area of lower thigh | - | 137 cm ² |
| Orifice of thigh seal | - | 177 cm ² |

(After Roth⁽²⁷⁶⁾)

Table 16-23 (continued)

c. Effective Volumes and Orifices During Explosive Decompression
of Soft and Hard Space Suits by Seal Disruption (cont.)

| | <u>Apollo Soft Suit</u> | <u>Apollo Hard Suit</u> |
|--|-----------------------------|---|
| <u>Ankle Seal</u> | | |
| Major axes of ellipse | - | (RX 3 and 4 only) 5 9/16" and 7 5/32" |
| X-area of seal | - | 207 cm ² |
| Ankle area (6 1/2" from ground) | - | 39 cm ² |
| Orifice at ankle seal | - | 168 cm ² |
| <u>Waist Seal</u> | | |
| Diameter | - | 16" ID |
| X-area of body seal | - | 1300 cm ² |
| Area of abdomen (1" above umbilicus) | - | 490 cm ² |
| Orifice at waist seal | - | 810 cm ² |
| <u>Fingers</u> | | |
| Diameter of glove finger | 1" ID | 1" ID |
| X-area of glove finger | 5.1 cm ² | 5.1 cm ² |
| X-section of finger (1/16" clearance) | 3.9 cm ² | 3.9 cm ² |
| Orifice at finger | 1.2 cm ² | 1.2 cm ² |
| <u>Gas Umbilical Hose from Space Chamber</u> | | |
| Diameter | 1 1/4" | 1 1/4" |
| X-area | 7.9 cm ² | 7.9 cm ² |
| <u>Gas Umbilicals from PLSS</u> | | |
| Diameter | 3/4" | 3/4" |
| X-area per hose | 2.8 cm ² | 2.8 cm ² |

Table 16-23 (continued)

d. Summary of Mobility Table Analysis of 3 Prototype Apollo Soft Suits

| Movement a. | Nude base- line, deg | Angles of excursion | | | | | | Percent of motion: nude to vent and vent to 3.7 psig | | | | | |
|---|-------------------------------|---------------------|-------------|--------|-------------|--------|-------------|---|---------------|---------------|---------------|---------------|---------------|
| | | Suit C | | Suit A | | Suit B | | Suit C | | Suit A | | Suit B | |
| | | Vent | 3.7 psig | Vent | 3.7 psig | Vent | 3.7 psig | N to V (b) | V to P (c) | N to V (b) | V to P (c) | N to V (b) | V to P (c) |
| 1. Forearm, supination-pronation | 180 | 194 | 175 | 168 | 179 | 180 | 180 | 100 | 90 | 93 | 100 | 100 | 100 |
| 2. Wrist, flexion-extension | 160 | 178 | 132 | 140 | 125 | 146 | 132 | 100 | 74 | 87.5 | 89 | 91 | 90 |
| 3. Hip, adduction-abduction | 180 | 41 | 32 | 35 | 15 | 40 | 35 | 23 | 78 | 19.4 | 43 | 22 | 87.5 |
| 4. Hip, flexion-extension | 120 | 90 | 40 | 80 | 65 | 70 | 62 | 75 | 45 | 67 | 81 | 58 | 89 |
| 5. Shoulder, flexion-extension | 250 | 216 | 190 | 182 | 168 | 160 | 139 | 86.5 | 88 | 73 | 92 | 64 | 87 |
| 6. Shoulder, frontal plane, adduction-abduction | 155 | 115 | 95 | 125 | 117 | 80 | 86 | 74 | 83 | 81 | 94 | 52 | 100 |
| 7. Shoulder rotation | 160 | 170 | 204 | 185 | 165 | 164 | 150 | 100 | 100 | 100 | 89 | 100 | 91 |
| 8. Elbow, flexion-extension | 150 | 167 | 106 | 162 | 150 | 145 | 127 | 100 | 63 | 100 | 93 | 97 | 88 |
| 9. Wrist-forearm, flexion-extension | 120 | 125 | 112 | 105 | 89 | 98 | 105 | 100 | 90 | 87.5 | 85 | 82 | 100 |
| 10. Hip, rotation | 133 | 130 | 101 | 125 | 106 | 126 | 78 | 98 | 78 | 94 | 85 | 95 | 62 |
| 11. Ankle, flexion-extension | 78 | 79 | 82 | 70 | 56 | 68 | 70 | 100 | 100 | 90 | 80 | 87 | 100 |
| 12. Trunk, rotation | 100 | 70 | | 60 | | 48 | | 70 | | 60 | | 48 | |
| 13. Shoulder, transverse plane, adduction-abduction | 193 | 168 | 121 | 112 | 102 | 118 | 132 | 87 | 72 | 58 | 91 | 61 | 100 |
| 14. Knee, flexion-extension | 140 | 160 | 125 | 143 | 145 | 135 | 130 | 100 | 78 | 100 | 100 | 96.5 | 96 |
| 15. Foot, flexion | 43 | 53 | | | | | | 100 | | | | | |
| 16. Trunk-hip, flexion-extension | 68 | 80 | | 44 | | 54 | | 100 | | 65 | | 79 | |
| 17. Trunk-hip, lateral flexion | 78 | 50 | | 32 | | 16 | | 64 | | 41 | | 21 | |

^aSeventeen movements are described in the paragraph entitled "Angular range study" in Ref.(185).

^bNude measures compared with vent measures.

^cVent measures compared with pressurized measures.

(After Jones (185))

Table 16-23 (continued)

e. Angular Data for Restriction of Pressurized Joint Mobility and Suit-Joint Interface of Three Prototype Soft Suits Relative to the Nude Condition

| Movement | Suit C | | | | Suit A | | | | Suit B | | | |
|--------------------------|--------|----------|-------|--------------------|--------|----------|-------|--------------------|--------|----------|-------|--------------------|
| | Nude | 3.7 psig | Diff. | Percent at 3.7 (a) | Nude | 3.7 psig | Diff. | Percent at 3.7 (a) | Nude | 3.7 psig | Diff. | Percent at 3.7 (a) |
| Wrist Adduction | 37 | 24 | 13 | 64.8 | 34 | 34 | 0 | 100 | 30 | 24 | 6 | 80.0 |
| Abduction ^b | 40 | 48 | -8 | 120 | 34 | 42 | -8 | 123.5 | 35 | 30 | 5 | 85.6 |
| Dorsiflexion | 62 | 56 | 6 | 90.3 | 63 | 57 | 7 | 90.4 | 75 | 68 | 7 | 90.6 |
| Palmar flexion | 87 | 68 | 19 | 78 | 60 | 56 | 4 | 93.3 | 70 | 53 | 17 | 75.7 |
| Elbow Flexion | 152 | 122 | 30 | 80.2 | 153 | 137 | 16 | 89.5 | 151 | 122 | 29 | 80.8 |
| Extension ^c | -- | -- | -- | -- | 0 | 5 | -5 | | 7 | 11 | -4 | 157.0 |
| Shoulder Neutral lateral | 0 | -10 | -10 | | -4 | -7 | 3 | | -18 | | | |
| Neutral (front view) | 11 | 39 | 28 | 35.5 | 4 | 20 | 16 | | | 35 | | |
| Abduction | 158 | 83 | 75 | 52.5 | 167 | 125 | 42 | 74.8 | 146 | 78 | 68 | 53.4 |
| Flexion | 163 | 92 | 61 | 56.4 | 189 | 136 | 53 | 71.9 | 145 | 63 | 82 | 43.4 |
| Extension | 66 | 65 | 1 | 98.4 | 83 | 47 | 36 | 56.6 | 59 | | | |
| Hip Flexion | 99 | 57 | 42 | 57.5 | 123 | 55 | 68 | 44.7 | 114 | 58 | 56 | 50.9 |
| Knee Neutral position | -4 | -2 | 2 | 50 | -2 | 20 | 22 | | 3 | 3 | 0 | 100 |
| Flexion ^c | 130 | 93 | 37 | 71.5 | 96 | -- | -- | -- | 95 | 87 | 8 | 91.5 |

^aPercent of motion retained in the pressurized state (percent of nude).

^bThis measure will be repeated at a later data.

^cThis measure is, as yet, incomplete.

(After Jones⁽¹⁸⁵⁾)

Table 16-23 (continued)

f. Mobility Ranges at 5 Psia Pressurization and Other Performance Data on the Apollo Hard Suit

These data represent the mobility ranges of each of the articulations provided by the Apollo Chamber Suit. These limits are achieved at torque levels under 2 ft-lbs. in every case.

| <u>Shoulder Mobility</u> | % of Nude Range | Maximum Range |
|--------------------------|-----------------|---------------|
| Adduction | 73 | 35° |
| Abduction | 90 | 120° |
| Lateral/Medial | 89 | 108° |
| Flexion | 87 | 123° |
| Extension | 62 | 38° |
| Rotation/Lateral | 100 | 35° |
| Medial | 100 | 120° |
| <u>Waist Mobility</u> | | |
| Flexion | 90 | 40° |
| Side-to-Side | 95 | ±15° |
| <u>Hip Mobility</u> | | |
| Flexion | 80 | 90° |
| Extension | 60 | 10° |
| Abduction | 38 | 20° |
| <u>Knee Mobility</u> | | |
| Flexion | 88 | 140° |
| <u>Ankle Mobility</u> | | |
| Adduction/Abduction | 85 | ±20° |
| Flexion/Extension | 96 | ±35° |
| <u>Elbow Mobility</u> | | |
| Flexion | 85 | 120° |
| <u>Wrist Mobility</u> | | |
| Adduction/Abduction | 81 | ±30° |
| Flexion/Extension | 64 | ±60° |
| Rotary Motion | 100 | 360° |

LEAK RATE. 30±10 scc/min, unaffected by repeated donnings and doffings. OPERATING PRESSURE. Design operating pressure is 5 psia; however normal operation is assured within the 3.5-7.0 psia range accommodating an atmosphere, 100% oxygen...or mixed gases at the higher pressure. CENTER OF GRAVITY. The center of gravity of the suit complements that of the human occupant assuring stability throughout the entire mobility range. DON/DOFF CAPABILITY. Self donning and doffing can be accomplished within 60 second periods.

(After Litton Industries⁽²⁰⁶⁾)

Table 16-23 (continued)

g. Barehand Sums Compared with Soft-Suited Raw Scores on the Purdue Pegboard Hand Dexterity Test

| | Right hand | | Left hand | | Both hands | | Sum of scores on all hands | | Assembly | |
|----------------------------------|------------|-------------|-----------|-------------|------------|-------------|----------------------------|-------------|----------|-------------|
| | Score | Percent (a) | Score | Percent (a) | Score | Percent (a) | Score | Percent (a) | Score | Percent (a) |
| Barehanded (Optimal performance) | 108 | 100 | 111 | 100 | 80 | 100 | 299 | 100 | 253 | 100 |
| Vented | | | | | | | | | | |
| Suit C | 68 | 62.96 | 66 | 59.46 | 45.5 | 56.88 | 179.5 | 60.03 | 106 | 41.90 |
| Suit B | 76 | 70.37 | 78 | 70.27 | 52 | 65.00 | 206 | 68.90 | 133 | 52.57 |
| Suit A | 75 | 69.44 | 75 | 67.57 | 55 | 68.75 | 205 | 68.56 | 146 | 57.71 |
| Pressurized | | | | | | | | | | |
| Suit C | 33 | 30.56 | 36 | 32.43 | 18 | 22.50 | 87 | 29.10 | 45 | 17.79 |
| Suit B | 49 | 45.37 | 49 | 44.14 | 32.5 | 40.63 | 130.5 | 43.65 | 79 | 31.23 |
| Suit A | 57 | 52.78 | 48 | 43.24 | 33.5 | 41.88 | 138.5 | 46.32 | 82 | 32.41 |

^aPercent of performance retained.

The differences were analyzed by the Kruskal-Wallis one way analysis variance. Analysis of the four parts of the pegboard test indicated that the difference was significant at 0.01 level in all cases except in the left-hand and both-hands test sequences under the vented condition. The both-hands test was significant at the 0.05 level, and the left-hand test was significant at the 0.10 level.

(After Jones⁽¹⁸⁵⁾,

range of mission-related movements, this portion of the test received a high weighting. In the final rating on general mobility, suit A placed first, suit C second, and suit B third.

For the strobe and cine sequences, suit A showed a clear superiority over the other two suits for pressurized mobility, both with and without the TMG. The arm and shoulder mobility was particularly good; and the subject could hold his hands over his head, relaxing and allowing his arms to remain elevated without having to fight a severe torque to keep them there. Hip flexion was also particularly good, for the pressurized subject could raise his leg more than 1 to 20 inches without leaning back and swinging around sideways to carry out the maneuver as was necessary in the other two suits. A factor of considerable significance was the ease and smoothness of motion carried out with suit A during pressurized mobility. The other two suits did not allow this ease of motion. The mobility concepts manifested in suit A have the most developmental impact. However, it would appear that an ankle joint would add much to walking, and an improvement in wrist stability and mobility is certainly needed. In addition, a method of allowing torso-bending should be investigated. Another factor to be considered is the improvement in pressurized shoulder mobility brought about by the suit C TMG top. An increase of 54° in shoulder flexion-extension and an increase of 62° in shoulder rotation were noted when data were compared with the suit B TMG top. While there is a great deal of improvement

to be made in the area of pressurized mobility in the TMG, it is noted that this concept has a great deal to offer, and it was recommended that further developmental study be carried out to improve the concept. Data are also available on the eye-heart angle in the pressurized state on contour couches (185). Data are available on the reach capabilities of prototype soft suits along all the complex planes (185).

Table 16-23 f gives the mobility restriction and other performance data for the Rx-3 hard suit.

Gloves and Boots

The intravehicular glove should be a conformal flexible envelope designed to promote hand dexterity, high tactile sensitivity, mobility, and free articulation of the hand and wrist when pressurized (270). Adequate restraint should be available to maintain normal curvature at the palm area, to prevent ballooning and the resultant loss of hand mobility. The restraint elements utilized should be located such that the glove's lines of greatest articulation will closely correspond to the natural bending lines of the palm and the fingers. Mobility features and glove restraints should be compatible with dimensional changes in the hand, such as foreshortening of the palm and lengthening of the back of the hand for clenching; or changes in surface length due to differences in band radius, as in bending the wrist. The design of the glove must be such that when pressurized or unpressurized, it will allow the crewman to realize the mobility described in Table 16-20 without fatigue, strain or discomfort. The size, flexibility and materials of the glove should be such as to enable the wearer to perform all tasks required for spacecraft operations (295), and provide for the abrasion and scuffing which results from the use of the hand and fingers within the spacecraft. If possible, the intravehicular glove should incorporate a removable GFE fingertip lighting system for each glove. The fingertip lighting system should consist of light sources to be installed on the back tip of the index and second finger of each glove.

In the design of the pressure retaining extravehicular gloves provided for use with the PGA during all extravehicular operations, thermal and abrasion protection are foremost problems. The gloves should allow the wearer free articulation of the hand for motions described in Table 16-20 and should not restrict the crewman's dexterity or tactility in performing emergency and maintenance tasks, in manipulating intravehicular and extravehicular task equipment, and in performing the tasks proposed (181, 295, 372). Especially important is facility in operation of PLSS controls during normal and emergency operation. (See Table 16-21). The gloves and fasteners used for attaching the PLSS to the PGA should be designed such that they can be fastened or unfastened with one hand.

Thermal limits for finger pain in glove design have been covered in Thermal (No. 6).

Glove and boot design in the Gemini extravehicular program has been recently reviewed (217). Hand dexterity data are available on the Apollo soft-suit prototypes. The Purdue Pegboard Test was administered to the suited test

subject in the vented and pressurized (3.7 psig) suit conditions. During two sessions of testing, six trials per suit were given for each of the two suit conditions. The test conductor turned the pegboard 180° for all trials so that wrist and finger mobility, rather than arm-reach mobility, was the influential factor. The subject was also given six trials of the test while he was bare-handed, and these data were considered to represent optimal performance.

Table 16-23g shows a comparison between barehand (optimal = 100 percent) performance and the performance retained with each suit under each condition. The fourth column of this table is the combined score of the three preceding test sequences in which only pins were used. This comparison shows clear differences in the performances of the three suits.

Ratings placed suit A in first place, suit B in second, and suit C in third. Suit C allowed considerably less wrist and finger dexterity than either of the other suits. The reduction in dexterity from the barehand level, a reduction applying to all the suits, had several causes. Fingertip lights were detrimental especially in suit C. Also, the gloves of suit C were the thickest and most cumbersome. On this suit, the wire fingernails in the thumb of the left glove came loose and interfered with test performance, and the gloves cut the subject's knuckles. Since fingertip lights interfered with hand dexterity, it was recommended that the placement of these lights be improved. The concept of fingernails on the gloves appears worthy and should be developed further, but definite improvement is necessary because the fingernails on the gloves of suit C became bent and actually interfered with dexterity. Another factor needing further development is the thickness of the material encasing the fingers. The thin material used in the gloves of suits A and B showed definite advantages over the thick material in the fingers of suit C.

Placement of the palm-restraint device should be optimized in order to allow the hand to bend below the knuckles. If the restraint device is too high and near the fingers, the subject is unable to grasp and can only flex the upper part of the fingers. Wrist stability should also be improved in all gloves, especially in the gloves of suits A and C.

All of the gloves produced pressure points at the base of the thumb and on top of the hand. These pressure points brought about excessive tiring of the hand and forearm, and induced cramping in the thumb and forearm. Consequently, considerable developmental work is needed to improve the gloves, because none of these gloves would meet the multiplicity of requirements involved in long-term pressurized wear.

Optimum design of footwear for lunar and planetary operations is now under study. (See Ref. 10-2111 for review of soil factors.)

Helmet and Visors

The optical aspects of helmet and visor design have been covered in Light (No. 2). Anthropomorphic factors must also be considered. Data on the Gemini helmet and visor systems are available (217, 231). The following are recommendations made for the Apollo program (336). The crewman should be able to see all PGA components which require visual aid for connecti-

and/or adjustment, particularly downward to a point on the front torso center-line six (6) inches below the neck ring. With the crewman standing and nodding in an erect PGA, he should be able to see the toes of his boots. The vertical field of vision of a crewman in a pressurized PGA and secured to the CM couch must not be reduced by fault of the helmet, upward or downward, when the crewman is subjected to a sustained acceleration of $+10G_x$, eyeballs in. Unrestricted range of vision should be as follows:

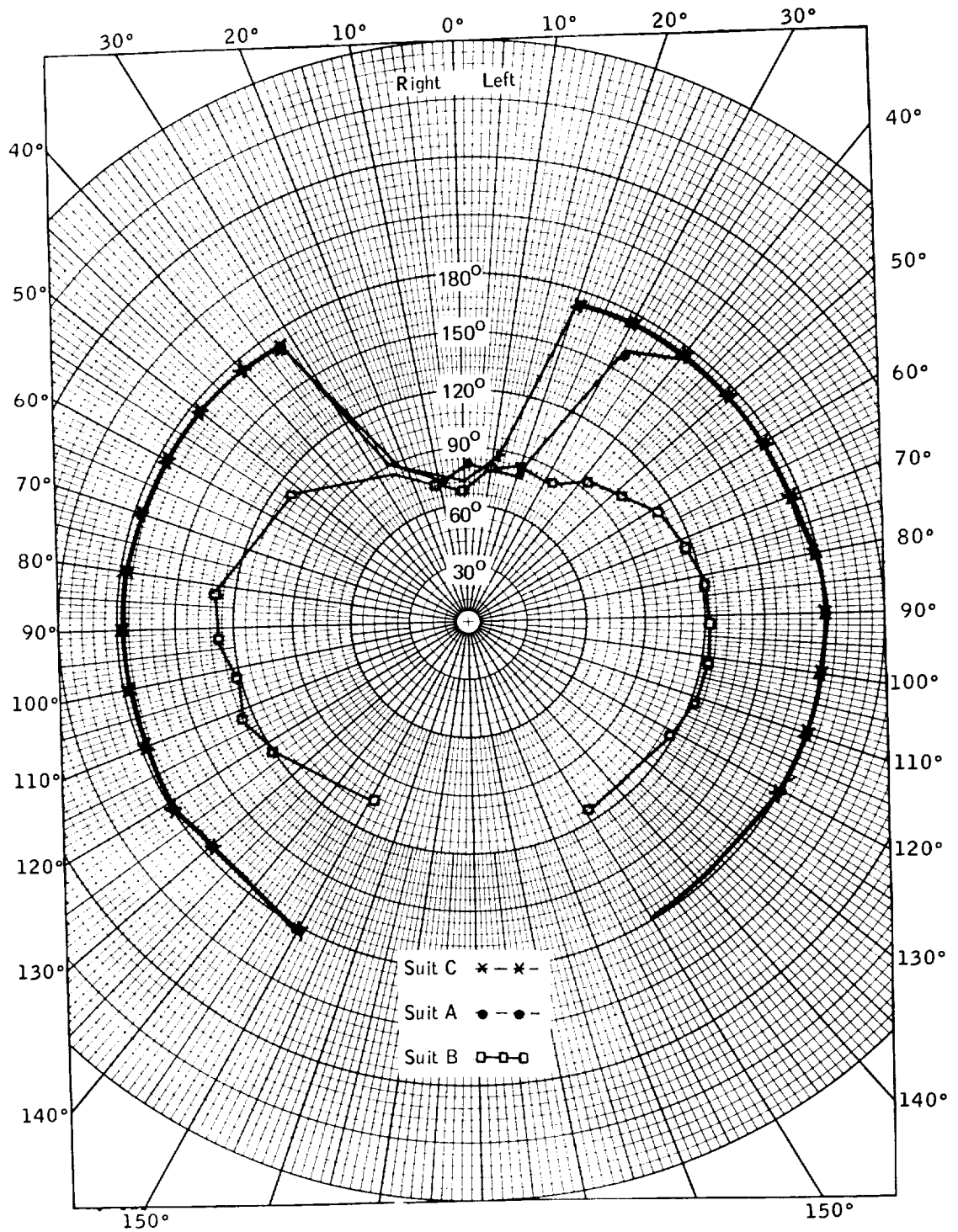
| | |
|-------------------|-----------------------|
| Horizontal Plane: | 120° left, 120° right |
| Vertical Plane: | 105° down, 90° up |

With the head moved forward, eye relief for the primary pressure retention visor should be 2.06 inches. This eye relief must apply over a vertical range from 45° up to 10° down.

Table 16-24 covers the visual field capability of several prototype Apollo suits (185). In positioning the subject and the helmet in relation to the optical perimeter, the test helmet was rotated on the neck ring to align the helmet center mark with the neck ring center mark; the subject's head was then positioned inside the helmet to align the longitudinal center line of the head with the helmet and center marks of the neck ring. The complete system (head and helmet) was then positioned with the center of the subject's eye pupil normal to both the 90° and the 0° positions on the optical perimeter; and the helmet neck ring angle with the horizontal, positioned according to manufacturer's specifications. After completing this zeroing procedure, the helmet was secured in this zero position. During the test, the subject was allowed complete freedom of movement in the helmet, since the objective of the test was to ascertain the visual-field capabilities of each helmet as opposed to the subject's visual-field capabilities. Subsequent to the test, the subject was instructed to indicate the point at which he could no longer see the target as it was moved on the perimeter arm of 29 inch radius from directly in front (0°) to directly behind (180°). This procedure was followed for each angular increment of the perimeter arm, with four readings taken at each increment. The target was a disc one cm in diameter. Two additional measures were used to determine the downward and upward "operational" visual capabilities of each suit. These measures were taken with the subject standing and zeroed under the perimeter. To determine upward visual capabilities, the subject was instructed to follow the target on the perimeter arm as it was moved directly over him (the subject was allowed to bend his torso). To determine downward visual capabilities, the same test configuration was used; that is, the subject was standing and zeroed under the perimeter, but was allowed to bend his torso. The subject was instructed to indicate the highest point on his suit that he could see. A line from this point on the suit through the center of the eye pupil to the perimeter arm was then constructed to determine the downward visual angle measured from the horizontal. All of the above measures were taken under two conditions, pressurized (3.7 psig) and vented. To control test-subject variability, the same test subject was used throughout the visual-field test.

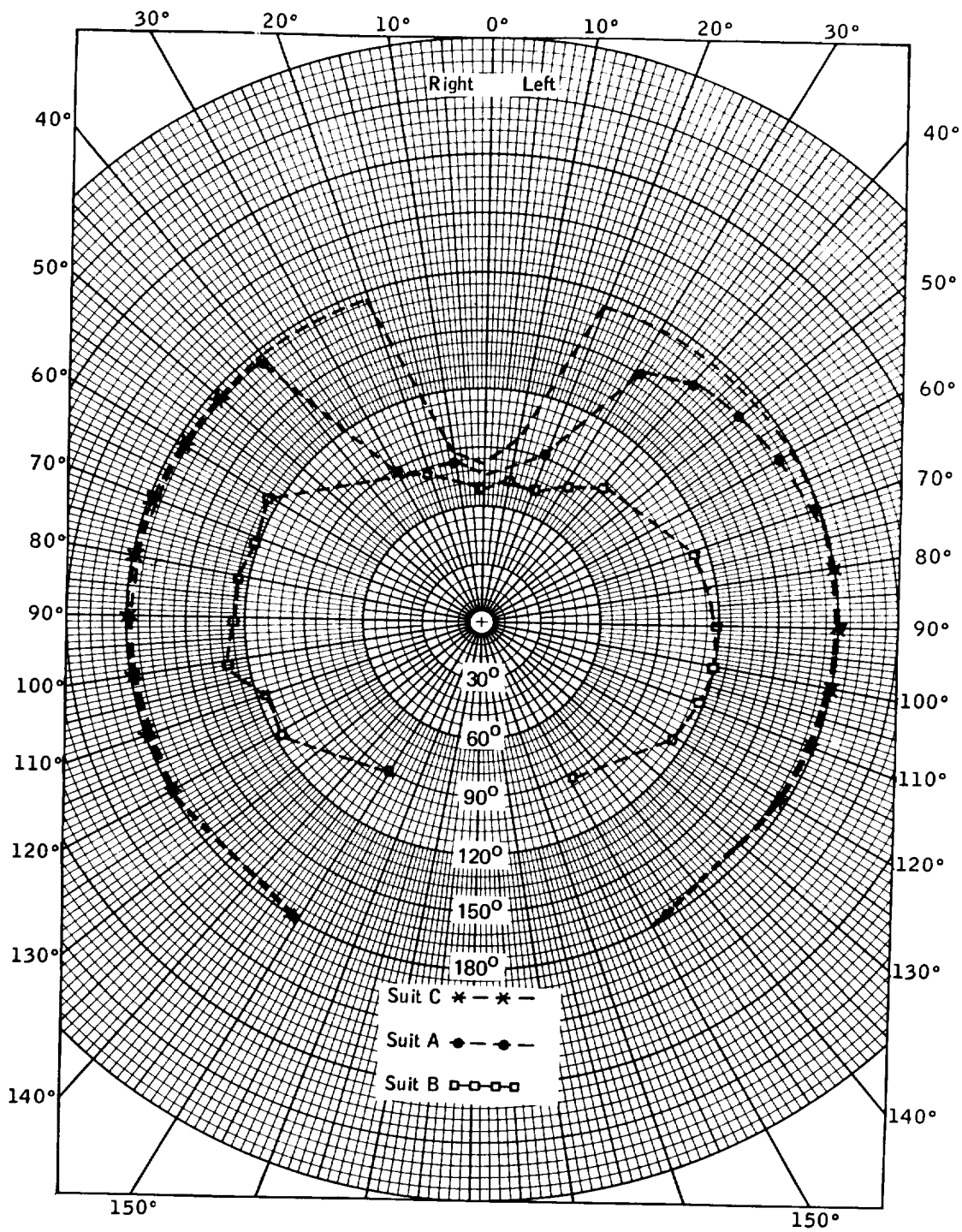
The mean value of the four trials for each angular increment of the perimeter was computed and plotted as shown in Figures 16-24 a and b. Table 16-24c shows the restriction under the "operational test and percent of specifications (see above and p 2-79 in Light No. 2). Upward visual-field restrictions

Figure 16-24
 Dynamic Visual Fields within Soft-Suit Helmets
 (After Jones⁽¹⁸⁵⁾)



a. Visual-Field Capability of 3 Prototype Soft Suits, Pressurized Condition
 (Torso bending not allowed - See text)

Figure 16-24 (continued)



b. Visual-Field Capability of 3 Prototype Soft Suits, Vented Condition
(Torso bending not allowed - See text)

Figure 16-24 (continued)

c. Suit Visual Capabilities - Up, Down, and Lateral Under "Operational" Conditions
(Torso bending allowed)

| | Suit B, visual angle, degrees | Percent of specification (a) | Suit C, visual angle, degrees | Percent of specification (a) | Suit A, visual angle, degrees | Percent of specification (a) |
|-------------------------------|-------------------------------------|------------------------------------|-------------------------------------|------------------------------------|-------------------------------------|------------------------------------|
| Vented, UP, ^b | 120 | 133 | 118 | 131 | 140 | 155 |
| 3.7 psig | 110 | 122 | 115 | 127 | 105 | 116 |
| Vented, DOWN, ^b | 96 | 91 | 95 | 90 | 97 | 92 |
| 3.7 psig | 91 | 87 | 95 | 90 | 95 | 90 |
| Vented, LATERAL, | 245.8 | 102 | 360 | 150 | 355 | 148 |
| 3.7 psig | 249.1 | 104 | 360 | 150 | 355 | 148 |

^aSpecification: Up 90°; Down 105°; Lateral 240°.

^bOperational measurements. (See text for details.)

in both suit A and suit C are intensified because the helmet of each suit is positioned in front of the suit longitudinal center line. This position limits the upward visual capabilities because ventrodorsal (backward) movement of the subject's head is restricted in each helmet. This helmet configuration also increases the eye-heart angle of both suit A and suit C. Suit A is superior in downward and upward visual capabilities, when the pressurized and vented conditions are considered as a single unit of interest rather than being considered separately. Operationally, this is a valid conclusion. It should be noted, however, that insofar as operational downward vision is concerned, each suit possesses the capability for the subject to see his respective gas connectors. Left visual-field restrictions for the suit A helmet are due to asymmetry of the helmet exterior painting rather than to any structural defect. It was recommended that the helmet of suit A be repositioned to a configuration more congruent with suit centering, thereby eliminating downward visual and eye-heart angle disadvantages. It was also recommended that the possibilities of a totally transparent helmet shell be explored to allow maximum visual field.

In the final rating, suit A rated first, suit C second, and suit B third. Under static and operational conditions, suit A provided evidence of superior visual-field capabilities. It should be pointed out that there was little difference between suit A and suit C, but there was a significant difference between these two suits and suit B which rated third.

CONFINEMENT, ISOLATION AND SENSORY DEPRIVATION

The confinement, social isolation and sensory deprivation factors are to be considered in space operations (99, 109, 236, 313, 326). The semantic problem may be dissected by the following classification (108):

- | <u>Confinement</u> | <u>Isolation</u> |
|--------------------|---------------------------------------|
| a) <u>Physical</u> | a) <u>Social</u> |
| i) Restrictive | i) Solitude |
| ii) Determinative | A. Single |
| | B. Group |
| | ii) Rejection |
| | A. Single |
| | B. Group |
| | b) Sensory-Perceptual |
| | i) Sensory and perceptual reduction |
| | ii) Sensory and perceptual distortion |

Confinement may be physical, temporal, or both. Physical confinement may be restrictive, in the form of physical restraint, or determinative in that the subject is free to move within his confines. Temporal confinement may be restrictive if the subject is forcibly limited in his activities for an imposed time, or determinative if he has to accomplish some achievement within an independently determined time. Social isolation involves isolation of individuals or small groups. It may be found in the presence of full sensory stimulation. Rarely, if ever, do confinement and isolation exist as single entities. Sensory or perceptual isolation, which involves essentially disturbances of perception, may arise from sensory reduction, or be associated with sensory distortion. It also may arise when stimuli do not provide adequate pattern information. Sensation may be present without perception. These are usually related to forced individual isolation.

It should be emphasized that there has been relatively little research in this general area. Much of the written material comprises reviews of a few basic experiments. The data in this section must be used with great caution.

Confinement

Confinement may be defined as a physical and temporal limitation on the activities and translational motions of an individual or group, occasioned by constraint, and sometimes associated with elements of perceptual and social isolation (11, 108, 230). The following section is taken directly from a recent review (108).

Along with many other modulating factors the response of the individual to confinement is primarily dependent upon the stress imposed by closeness of confinement, the extent of restriction, and the duration (11, 350). The initial response is one of general physiological activation, with an increased heart rate, respiratory rate, and blood pressure. Excretion of ketosteroids

and catecholamines tends to increase, while evidence of increased autonomic activation is given by a decrease in skin resistance, or increased skin conductance. These findings suggest a non-specific response to stress. Within about 3 to 7 days a new threshold is established and physiologic activity begins to recede to preconfinement level or below, although the pattern can be re-activated by emergencies. Continuation of the confinement, with reduced mobility and limited exercise, gives rise to signs of physical deconditioning, manifest particularly in the cardiovascular system, in musculoskeletal deconditioning, in fluid balance, and in hemopoietic system (45). These mimic the response to weightlessness (108). (See also zero gravity environment in Acceleration (No. 7)).

In a well-motivated, trained individual, if habitability is close to acceptable, there may well be no overt psychological effects; and even a covert response, as judged by interview, diaries, and measurement techniques, may be negligible (108). The occurrence of aberrant subjective and behavioral reactions, in particular, is to a considerable extent influenced by training, motivation, and experience. When manifest, they may occur in the form of overt or covert resentment, hostility, and frustration, directed in the case of the single confinee, at the environment itself, or at the unseen investigators or remote controllers (11, 108, 137, 158, 325, 361). Among multiple confinees, it is apparent that maintenance of good interpersonal relations can be considered of major significance. Among two-man crews in close proximity, considerable irritation can develop from the repetition of seemingly innocuous habits, inadequacies of personal hygiene, or divisions of labor, while three-man groups may be even more unstable, since any two can unite against the third. With multi-man groups the formation of cliques can become a real possibility. Personal space factors are important correlates of social emotional states for humans as well as for other animals (51, 207). Territoriality needs are known to be important to a very wide phylogenetic range of animal forms, including man. In the confined group, territoriality preferences may be difficult to satisfy (158). It has, nevertheless, been clearly and repeatedly shown that with careful selection, common motivation and wise leadership, crews can unite to minimize difficulty and ensure the success of a mission, although covert hostilities may be revealed later (289). However, details of this situation and training are still research questions.

Physical discomfort in terrestrial conditions can be severe. The discomfort, however, is more a function of immobility than confinement, as has been demonstrated in conditions where the same free volume per man is available, but in the one case the subjects are restricted, and in the other they have space-sharing mobility. Furthermore, since the discomfort is largely associated with the development of pressure points from the gravitational vector, it has not been a major feature of actual space operation.

The occurrence of perceptual aberrations, in the form of illusions and hallucinations, has been widely disseminated in the anecdotal and experimental literature. It is apparent, however, that this phenomenon is primarily associated with isolation and not with confinement (308). In fact where two individuals are simultaneously confined it is rarely recorded, and never with three or more. The occurrence of perceptual aberrations is, in fact, a feature of reduced or distorted sensory input, and does not take place in the presence

of good consensual validation. Numerous studies have been undertaken to examine such capacities as constructive thinking capability, memory, problem solving, performance skills, etc. under conditions of confinement (108). It is characteristic of the findings that while impairment may occur under conditions of isolation and reduced sensory input, there is little or no interference with intellectual function and performance capacity in confinement, per se, unless the demands of the tasks are inappropriate, or unless the confinement is extreme, or is accompanied by very adverse environmental conditions of heat, humidity, noise, etc.

Sixty studies of confinement under terrestrial and space conditions have been compared in Table 16-25a and the relation of symptoms to the volume and duration, plotted in Figure 16-25b. Classification is on a three point scale according to the amount of impairment observed, namely: no impairment (grade 1), detectable impairment (grade 2), and marked impairment (grade 3). Marked impairment was considered to be manifest psychophysiological change which might prejudice the safety or successful outcome of a mission. Detectable impairment was considered to be present in a situation which was tolerable, but was accompanied by measurable evidence of disturbance which could reduce proficiency. The classification of no impairment included those situations where some disturbance of homeostasis or comfort might have existed without loss of proficiency. It is considered that a classification scheme of this nature even though it makes use of widely different criteria for volumes and responses and is of a subjective nature, provides distinctions sufficiently obvious as to permit unobjectionable grading (108).

Three impairment zones can be defined in terms of duration and volume as indicated by the broad demarcation lines. The upper line defines a threshold of minimum volume per man which will be acceptable in most circumstances, even when modifying factors are not optimum. The lower line defines a threshold which will be unacceptable in most circumstances even if modifying factors are optimum. Between lies a zone where acceptability depends to some degree on optimum habitability, and personal factors. Extrapolation of the two lines suggests a junction at about 60 days at a volume which may represent the minimum acceptable for prolonged durations. The further direction of the curves is not known at this time, but it is interesting to note that Soviet work suggests that there is a resurgence of stress phenomena at about 60 days, in which case the threshold curve may again rise (108, 202). It is considered that the impairment which was demonstrated in the "Hope" studies resulted from the rigors of demanding work schedules, and not from confinement per se (5, 6). The marked impairment in the 152 days of confinement in the University of Maryland study is believed to be due to the nature of the programmed environment, publicity etc., and not to the confinement which, in fact, was minimal (97). The third and most significant exception is found in the Gemini series of flights. Since these were successful, the impairment cannot be classified as a grade three. Nevertheless, despite enthusiastic reports, considerable impairment did exist, particularly in the Gemini VII mission, as manifested by post-flight testing. In fact, it is probable that only the dedicated motivation and discipline of the crews, along with the added benefits of space sharing, made the missions as successful as they were.

Key factors altering the curve are motivation, discipline, and experience. The habitability of the confined chamber both with respect to environmental

Table 16-25

Confinement Studies on Humans

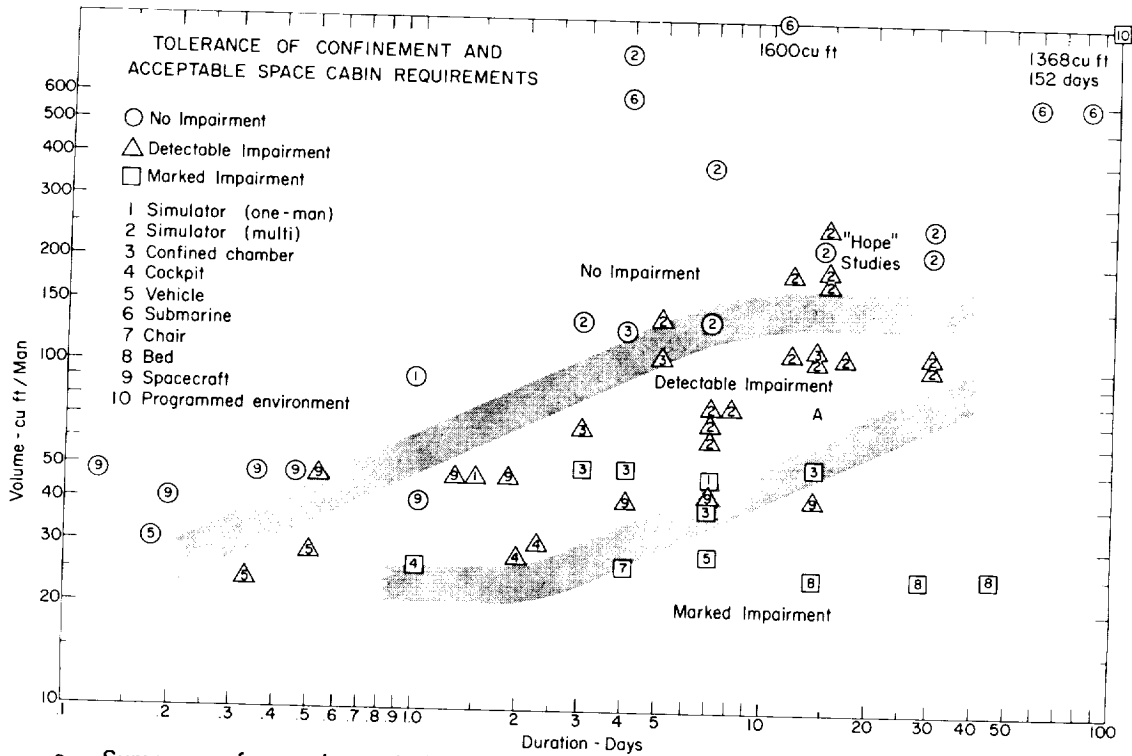
a. Extent of Impairment Resulting from Confinement (See text for details)

| Type of Study | Operational Conditions | Volume per man (cu. ft.) | Duration (days) | Impairment | | References |
|---------------------|---|--------------------------|-----------------|------------|--------------------------------------|--|
| | | | | Psych | Physio | |
| Simulator Single | SAM one-man | 47 | 7 | 3 | 2 | AF-SAM-59-101, 1959 |
| | SAM one-man | 47 | 1½ | 2 | 1 | AF-SAM-60-80, 1960 |
| | Vostok one-man | 90 | ?1 | 1 | 1 | FTD-TT-62-1619, 1962 |
| Simulator Multi | Lockheed-Georgia OPN-360 | 183-250 | 15 | 2 | 2 | WADD-TR-60-248, 1960 |
| | HOPE II | 187 | 15 | 2 | 2 | WADD-AMRL-TDR-63-87, 1963 |
| | HOPE III | 110 | 30 | 2 | 2 | WADD-AMRL-TDR-63-87, 1963 |
| | HOPE IV & V | 110 | 12 | 2 | 2 | WADD-AMRL-TDR-64-63, 1964 |
| | HOPE VI & VII | 187 | 12 | 2 | 2 | WADD-AMRL-TDR-64-63, 1964 |
| | Navy ACEL | 75 | 7 | 2 | 2 | NAMC-ACEL-383, 1958 |
| | Navy ACEL | 75 | 8 | 2 | 2 | NAMC-ACEL-413, 1959 |
| | N. A. A. conical | 67 | 7 | 2 | 2 | IAS Meeting, Los Angeles, 1962 |
| | N. A. A. cylindrical | 375 | 7 | 1 | 1 | AIAA and ASMA Conf., L. A., 1963 |
| | N. A. A. disc | 800 | 4 | 1 | 1 | AIAA and ASMA Conf., L. A., 1963 |
| | SAM two-man | 106 | 14 | 2 | 2 | <u>Aerospace Med.</u> , 30:722, 1959 |
| | SAM two-man | 106 | 17 | 2 | 2 | <u>Aerospace Med.</u> , 32:603, 1961 |
| | SAM two-man | 106 | 30 | 2 | 2 | SAM-TDR-63-27, 1963 |
| | Republic | 211 | 14 | 1 | 1 | RAC-393-1, 1962 |
| | Douglas | 250 | 30 | 1 | 1 | ASME Conf., Los Angeles, 1965 |
| | GE | 215 | 30 | 1 | 1 | GE Doc 64-SD-679, 1964 |
| | Martin Baltimore | 133 | 3 | 1 | 1 | MAR-ER-12693, 1962 |
| Martin Baltimore | 133 | 7 | 1 | 1 | IAS-63-18, 1963 | |
| NASA Ames | 61.5 | 7 | 2 | 2 | NASA-TN-D-2065, 1964 | |
| WADC long range | 140 | 5 | 2 | 2 | <u>Aerospace Med.</u> , 30:599, 1959 | |
| Confined Chamber | U. of Maryland (Single) | 1368 | 152 | 3 | 3 | Univ. of Maryland, 1963 |
| | U. of Georgia (Multi) | 65 | 3 | 2 | 2 | GEOU 226-FR, 1963 |
| | U. of Georgia " | 52 | 3 | 3 | 2 | GEOU 226-FR, 1963 |
| | U. of Georgia " | 52 | 4 | 3 | 2 | GEOU 226-FR, 1963 |
| | U. of Georgia " | 52 | 14 | 3 | 2 | GEOU 226-FR, 1963 |
| | U. of Georgia " | 39 | 7 | 3 | 2 | GEOU 226-FR, 1963 |
| | USNRDL " | 117 | 14 | 2 | 2 | USNRDL-TR-418, 1960 |
| | USNRDL " | 117 | 5 | 2 | 2 | USNRDL-TR-502, 1961 |
| | Lockheed-Georgia (Multi) "Coffin" (Single) | 125 28 | 4 7 | 1 3 | 1 3 | WADD-TR-60-248, 1960 <u>Science</u> , 140:306, 1963 |
| Cockpit | F-84 | <30 | 2 1/3 | 2 | 2 | WADD-TR-55-395, 1955 |
| | WADD capsule | 27.5 | 2 | 2 | 1 | WADD-ASD-TR 61-577, 1961 |
| Vehicle | APC M59 | 30 | 1/6 | 1 | 1 | AHEL-TM-3-60, 1960 |
| | APC M113 | 23.3 | 1/3 | 2 | 2 | AHEL-TM-17-60, 1960 |
| | APC M113 | 28 | 1/2 | 2 | 2 | AHEL-TM-1-61, 1961 |
| | APC M113 | 25.5 | 1 | 3 | ? | AHEL-TM-23-61, 1961 |
| | APC M113 | 25.5 | 1 | 3 | 3 | AHEL-TM-7-62, 1962 |
| Submarine | Nautilus | 1600 | 11 | 1 | 1 | USN Med. Res. Lab. Rept. 281, 1957 |
| | Seawolf | 570 | 60 | 1 | 1 | USN Med. Res. Lab Rept. 358, 1961 |
| | Nautilus | 570 | 4 | 1 | 1 | <u>USAF Med. J.</u> , 10:451, 1959 |
| | Triton | 570 | 83 | 1 | 1 | "Unusual Environments and "Human Behavior" 1963 |
| Chair | SAM | < 25 | 4 | 1 | 3 | <u>Aerospace Med.</u> , 35: 646, 1964 |
| Bed | Lankenau | < 25 | 45 | 1 | 3 | WADD-AMRL-TDR-63-37, 1963 |
| | SAM | < 25 | 28 | 1 | 3 | <u>Aerospace Med.</u> , 12:1194, 1964 |
| | SAM | < 25 | 14 | 1 | 3 | <u>Aerospace Med.</u> , 35:931, 1964 |
| Spacecraft | MA-6 | 47 | 1/3 | 1 | 1 | NASA Doc 398, 1962 |
| | MA-7, 8 | 47 | 1/2 | 1 | 2 | NASA SP-6, 1962 |
| | MA-9 | 47 | 1 1/2 | 1 | 2 | NASA SP-45, 1963 |
| | Vostok I | 90 | 1/2 | 1 | 1 | FTD-TT-62-1619, 1962 |
| | Vostok II | 90 | >1 | 1 | 2 | FTD-TT-62-1619, 1962 |
| | Gemini III | 40 | 1/5 | 1 | 1 | |
| | Gemini IV | 40 | 4 | 1 | 2 | |
| | Gemini V | 40 | 8 | 1 | 2 | |
| | Gemini VI | 40 | 1 | 1 | 1 | |
| | Gemini VII | 40 | 14 | 1 | 2 | |
| | | | | | | { Gemini Mid-Program Conf. Proceedings, Part 1 & 2 MSC, Houston, Texas, 1966 |

(After Fraser⁽¹⁰⁷⁾)

Table 16-25 (continued)

b. Free Volume-Duration Tolerance Factors in Confinement



a. Summary of experimental data.

(After Fraser (108))

c. Threshold Volume Requirements According to Duration of Mission

| Duration (days) | Threshold of acceptable volume - Cubic Feet | Threshold of unacceptable volume - Cubic Feet |
|-----------------|---|---|
| 1 | 50 | 25 |
| 2 | 75 | 25 |
| 3 | 90 | 25 |
| 4 | 105 | 30 |
| 5 | 115 | 35 |
| 6 | 120 | 35 |
| 7 | 125 | 40 |
| 10 | 135 | 50 |
| 20 | 140 | 70 |
| 30 | 150 | 85 |
| >60 | ? 150 | ? 150 |

(After Fraser (109))

factors such as atmospheric pressure and composition, heat, humidity, and noise, and with respect to hygiene, dietetic, recreational, and work facilities, is another factor. The nature of the actual activities and tasks demanded is also a significant factor, particularly the meaningfulness, and the degree of complexity. The requirement for realism and/or relevance in simulated tasks is also significant, in order to prevent disinterest. Knowledge of the expected duration of confinement is still another factor which affects tolerance not only subjectively, but objectively, in that a characteristic rise in morale and activity can be shown to occur at the midpoint of a known period, and again a day or so before the end. A most significant factor concerns physical fitness and exercise. There is no doubt that in terrestrial confinement, adequate exercise and mobility not only prevent deconditioning, but improve morale, and may even be associated with improved task performance. How much is adequate, however, is not clear and furthermore it must be remembered that weightlessness and immobility may well be synergistic in their causative relation to physical deconditioning. A final modifying factor relates to the number of confinees. As already noted, an increase in the number of confinees reduces some and creates other problems. At the same time it allows the possibilities of space-sharing, which effectively increases the available free-volume per men.

Disregarding cultural and other variables which may alter these thresholds Figure 16-25b indicates that for durations of 7 to 30 days, for small group crews, about 125-150 cubic feet per man of free space would be the minimum acceptable volume (134 - 138). Acceptability could be still further improved by promoting optimum habitability and working conditions (see below). Marked impairment would be expected with a free volume per man of less than 40 cubic feet for 7 days, or less than 85 cubic feet per man for 30 days.

For missions of months and years duration the critical volume factor is not as clear (109). (See Figure 16-26). An additive model of crew space for long duration missions includes the following (36):

$$\begin{aligned}
 \text{Volume} &= (\text{Seated volume per man} + \text{work volume per man} + \\
 &\quad \text{ingress volume per man}) \times (\text{Number of men}) \\
 &+ \text{Transfer volume per station} \\
 &+ \text{Intercompartmental transfer volume} \\
 &+ \text{Rest volume per crew off duty} \\
 &+ \text{Sustenance volume per crew} \\
 &+ \text{Logistics work space or equipment station} \\
 &+ \text{Equipment and storage volume for sustenance} \\
 &+ \text{Volume for waste}
 \end{aligned}$$

From anthropometric and other data, adequacy was defined as a minimum volume of 50 cubic feet per man (multiman) for 2 days, 260 cubic feet per man for one or two months, and 600 cubic feet per man for many months in Figure 16-26, Reference (36). Another approach using these criteria with an

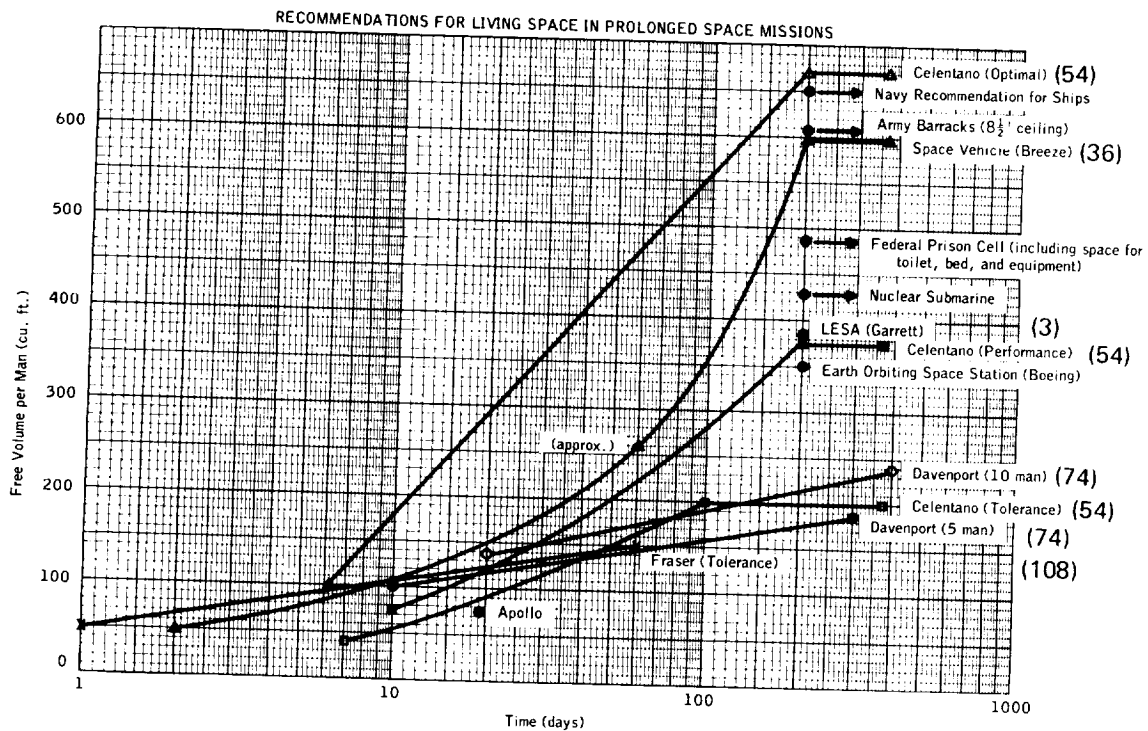


Figure 16-26

Recommendations for Living Space in Prolonged Space Missions
(See text)
(After Fraser (109))

adjustment for the debatable fact that an increased volume per man becomes necessary with increase in the number of crew, is also presented for 5 and 10 man crews in Figure 16-26, Reference (74).

Others have argued and shown in simulator studies that the occupants of a cabin allowing a large area, and other habitable features, would show little if any physiological differences from those in a normal life situation with a relatively sedentary occupation, such as that of an office worker (54). This study resulted in the curve of tolerability, the curves of acceptable performance, and the curve of optimal habitability shown in Figure 16-26. While the tolerance curve falls in line with other suggestions (74, 109), and may well represent minimal acceptability, there is some doubt as to whether the other two curves actually demarcate volumes for adequate and optimal habitability with the degree of accuracy implied. At the same time, the fact that free volumes found in certain operational situations, such as Army barrack allowances, Federal Prison allowances, and nuclear submarine allotments, lie within that range, suggests that the curves (54) are reasonable approximations. The data for Army barracks, prison, and nuclear submarines (11) are shown at the 200 day level for convenience. The arrows alongside indicate that the volumes designated may be occupied for longer periods.

Some other recommended volumes are also found to lie in the range suggested by Figure 16-26 (3, 235). On the basis of requirements for Arctic expeditions, a free volume of as much as 2000 cubic feet per man has been suggested for multiman operations (57). A volume of this size appears

unnecessarily large and luxurious for space vehicle conditions.

Although the volume requirements per man cannot be specified with any degree of authority, it would seem that for durations of 300-400 days, or perhaps beyond, the absolute minimal acceptable volume for multiman operations would be in the region of 200-250 cubic feet per man; the acceptable would be about 350-400 cubic feet; and the optimal, about 600-700 cubic feet, utilizing the volume for all purposes related to living conditions. To maximize habitability for long-duration missions, it has been suggested that design requirements should be based on the optimal level of 600-700 cubic feet per man (109)

The mode of utilization and configuration of available space can be examined from different points of view, but several ground rules can be assumed. Thus, space must be provided for conduct of tasks relating to the mission, to vehicle management, and psychophysiological support. Space is also required for rest and off-duty time, for dining and food management, and for hygienic provisions. Under some circumstances, minimum hygienic facilities can be tolerated for long periods of time (296). Therefore, it is convenient to think of configuration in terms of functional units relating to these activities, although it should be realized that functional units are not necessarily topographical units. In other words, the volume allocated to one unit need not necessarily be located in one region of a vehicle. Except by invoking tradition, custom, and usage, it is difficult to justify logically the need for separating available volume into distinct regions, nor is it easy to determine how many such regions there should be. There is no doubt that highly motivated individuals, such as astronauts, can work, eat, rest, and sleep for days without leaving their seats, and still maintain acceptable performance. At the same time, various studies of habitable conditions (92, 109, 144, 368) have emphasized the need for variety, change, relief of monotony, and perhaps most of all, the desire to protect some modicum of voluntary privacy and storage of personal possessions.

It has been suggested that four functional units might therefore be delineated namely:

Work unit: for the conduct of operational tasks, vehicle management, and psychophysiological support.

Public unit: for use in dining, food management, communal recreation, leisure, and exercise.

Personal unit: for sleeping, personal privacy, and personal storage.

Service unit: for toilet purposes, laundry, and public storage.

Several studies of the partition of this space for long duration mission have suggested the relative volumes of available space which might be occupied by each functional unit as follows (3, 74, 109):

| | |
|----------------|-----|
| Work unit: | 40% |
| Public unit: | 25% |
| Personal unit: | 20% |
| Service unit: | 15% |

It is emphasized that these suggested proportions are approximate and tentative and represent merely a relative breakdown of available volume under what might be considered optimal conditions. In each case the actual proportions would be influenced by the requirements of the mission and the capacities of the vehicle and dwelling, and would need to be determined empirically by analysis of the requirements and the use of models and mock-ups.

Social Isolation (158)

Social isolation represents a separate source of potential difficulty in confined environments (6, 7, 8, 11, 34, 44, 49, 109, 135, 137, 155, 156, 157, 159, 160, 168, 240, 357, 360, 368). Confinement, however, is not a necessary component of social isolation (134, 305). Man is a social animal, highly dependent on other men in a variety of ways. The human personality typically includes a variety of social needs such as dominance and affiliation that can only be satisfied in interaction with other people. In a small isolated group, these needs are more likely to be frustrated than in a normal social situation where a wider variety of other people can be found (134, 135, 138, 158, 159, 361,). The small, isolated group also provides its members with fewer opportunities to make social comparisons, a process thought to be important in the development and maintenance of stable, accurate self evaluations. Men use social comparisons for testing the validity of their own performance, and the appropriateness of their own emotional reactions (15, 182). Both social need satisfactions and opportunities for social reality testing can be severely impaired in a small, isolated group. This can result in a heightened sense of frustration, decreased accuracy and stability of self concepts, and development inappropriate, invalid group norms that may be at variance with or irrelevant to the group's initial primary mission.

Another aspect of being confined with a relatively few other people is the degree to which it accelerates the social acquaintance or social penetration process. Anecdotal reports suggest that certain people in such situations use each other as significant sources of stimuli to a greater degree than is normal, and get to know the intimate details of each other's lives very thoroughly. The rate at which intimate information about each other is acquired, however, may exceed the rate at which individuals can learn to accept individual idiosyncracies or markedly different value systems (158). The theory of social balance holds that tensions are created between individuals when they have different attitudes or oral opinions about a third person, object, or set of objects. The more central these attitudes and opinions are to the personalities involved, the greater amount of tension social imbalance will create. In the normal course of social existence, men avoid intimate contact with others whose value systems are markedly different. In the confined group, such avoidance may be impossible.

The accumulation and escalation of interpersonal tensions generated by lack of social need-satisfactions and social imbalance makes interpersonal conflict in confined groups a more difficult problem to manage than it normally would be. Lack of privacy, inability to establish and maintain territorial ownership, inability to find convenient scapegoats outside the group for displaced aggression, and restricted opportunities for releasing tension through

muscular activity all may contribute to evermounting interpersonal hostility. Pairs of men hypothetically incompatible with regard to people showed a high degree of territoriality behavior, whereas incompatibility with regard to non-people-oriented considerations, such as dogmatism and need achievement, did not particularly produce territoriality (318). Incompatibility with regard to egocentric frames of reference, such as dominance needs and dogmatism, produced a high rate of "together activity"--largely argumentive in nature--while incompatibility on sociocentric frames of reference such as needs for affiliation and achievement generated a tendency towards social withdrawal--more alone than together activity.

Even though reporting higher levels of subjective stress, isolated pairs of subjects tend to perform better on group task than do unconfined controls (158). This appears to be due to the performance enhancement value of moderate levels of stress in isolation (96). A high rate of test mission aborts, can be generated by simply reducing the variety of tasks required of subjects and increasing their expectations regarding duration of confinement from unspecified to time-limited exposures (158). The stresses of stimulus reduction, isolation, and confinement can be considerably relieved by stimulus enrichment procedures, increased communication with the outside world, and careful attention to group composition considerations (158, 159). It is clear from anecdotal literature that small groups of men can survive four months of social isolation and confinement. Longer periods of time are considerably more doubtful. More thought and research needs to be given to these aspects of man in a closed system for prolonged periods of time (182, 304). Model building and computer simulation of the problems is continuing (119, 273). Selection of group members and leadership criteria are also under study (134, 135, 138, 139, 219, 255, 264, 284, 285, 286, 287, 288, 289, 322).

Sensory and Perceptual Deprivation

Exposure to this condition may be expected in space operations most often when other members of a crew are dead or lost and the lone survivor is cut off from communication with earth. However, monotonous confinement of groups can result in problems in this sphere. Stimulus reduction or comparative monotony is not necessarily associated with confinement (301). It is now generally recognized that man needs a minimum level of stimulus variety below which somewhat bizarre, maladaptive behavior and subjective experiences are reported (13, 44, 67, 110, 158, 167, 191, 196, 203, 210, 228, 250, 308, 310, 348, 349, 375, 377, 378, 380). These may include a tendency to withdraw into ones self, intense fears of losing ones rationality, hallucinatory behavior, decrements in certain perceptual and cognitive functions, increased need for stimulus inputs of almost any nature, and changes in sensory acuity, generally in the direction of heightened tactile and auditory sensitivity. Darkness or monotonous, diffuse light patterns of low intensity predispose to the hallucinating behavior (110) Marked reduction in frequency of EEG alpha-rhythms have been seen as possibly indicative of a central nervous system change (312, 348, 349, 376, 379). Significantly, the EEG does not return to normal for several days following a two week period of sensory deprivation. These results have been reported from studies of sensory and/or perceptual deprivation, but such data as are available suggest that similar phenomena perhaps to a less intense degree occur in group confinement situations involv-

ing a relatively monotonous existence even though not stimulus-deprived in the traditional sense (158, 174, 301). Internal time consciousness is altered by such conditions (101, 220, 314), but exposure of more than 3 hours is probably required (283).

A great deal of attention should be given to developing a habitable living arrangement, in particular with private areas affording relief from constant interaction with other crew members (108, 109) (see also page 16-76). Provisions should be made for both active and passive types of recreation (109). It is also important that optimum amounts of communication with Earth be provided, to minimize the sense of isolation, but avoid excessive communication. One must avoid aggravating conflicts which often arise from interaction between isolated group and "external controllers" (325).

The possibility of giving the men experience in the situation of confinement, social isolation and sensory deprivation for training purposes should be mandatory (255). If handled properly, this would give the men a chance to experience some of the frustrations inherent in these situations, some of the behaviors that may appear in themselves and others, and to practice ways of handling them. Such experiences, perhaps repeated several times, with an opportunity for discussions intervening, could provide the means for effectively handling such occurrences as they arise during the mission itself. Giving the astronauts such experiences is in accordance with the current philosophy of their training program, in that emphasis has been placed upon their experiencing, in as great a degree of realism as possible, all anticipated situations of space flight prior to their undertaking the mission itself. Experience with detailed simulation of a lunar mission is available (124, 125, 126, 127). These may be used as models of operational study of crew interaction and efficiency. However, a problem arises regarding how much simulation would be required for longer missions of many months (109). A compromise that seems attractive would be to prepare a series of films showing groups of men in laboratory situations of confinement, demonstrating examples of boredom, aggression and conflict, both overt and covert, and the methods, good and bad, used by the personnel to deal with these events (100). This could then constitute a basis for round-table discussions by the astronauts, along the lines of evaluating how likely it would be that such situations would arise in space flight, how effectively the situations were dealt with by the personnel in the films, and what methods might be more effective in space flight.

A general review of problem areas in the handling of confinement, social isolation and sensory deprivation is available (369). A review of Soviet studies in this area has been published (196).

WORK-REST-SLEEP CYCLES (WRS)

Man is influenced by the diurnal periodicity of the physical world surrounding him. His typical work-rest-sleep cycle (WRS) is thus based on a 4-hour rhythm (16, 17, 20, 260, 307, 326). His physiological function and, as a result, his psychological performance vary according to this rhythm. As a result, any alteration in the WRS to which the man is adapted will cause

variations in physiological functions and psychological performance (6).

Diurnal or Circadian Rhythms

Figure 16-27 is an example of some of the diurnal or circadian rhythms. At least 50 are known (19). The variations in function are the result of discrepancies in phase relationships between man's endogenous metabolic clock, according to which many physiologic functions are moderated with regular periodicity, and the external environment (65, 141, 260, 278, 280, 298, 307, 326, 353, 354, 355, 356). The biological functions, the most easily measured of which are pulse rate and body temperature, become "entrained to" or synchronized with this schedule. These functions follow a rather consistent course with a daily high point sometime during the early evening hours (between 1600 and 2000) and a low during the early morning hours (between 0400 and 1000). This cycling occurs whether the man is awake or

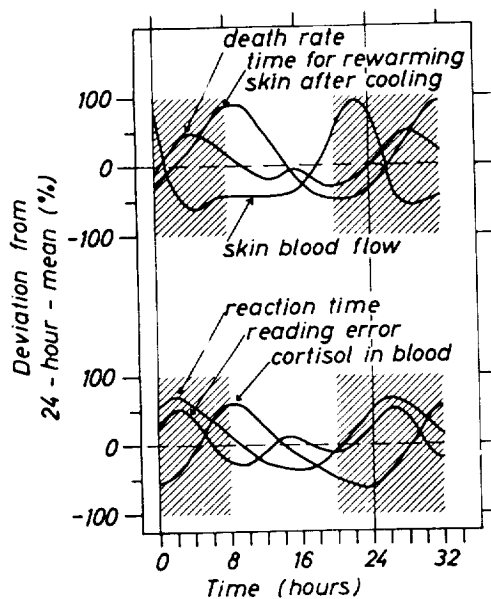


Figure 16-27

Schematically Drawn Curves, Indicating the Approximate Phase and Range for 6 Circadian Functions in Man.

(From several publications of text)

Dashed area represents dark-time.

(After Aschoff (19))

asleep. A further relevant point is that this curve is maintained for a period of four to six days after a marked change in the day/night relationship (153 154). It is also relevant that this curve is generally maintained by individuals working night shifts. This presumably results from social factors governing the man's off-duty activities. When the endogenous metabolic clock is out of phase with the external environment (e. g., when one remains awake from 2200 to 0800, a time when one is usually accustomed to sleeping), human performance decreases and a man is said to be in a state of asynchrony (153 154, 314). In this state, hunger and somnolence or insomnia will be present at the "wrong" times. This can be demonstrated by taking various physiological measurements during asynchrony (body temperature (193), endocrine and salt excretion patterns in urine (24, 117, 141), heart rate (193), EEG (103), and gastrointestinal motility (193)) and comparing them with those obtained on the same individual when in synchrony with his external environment. There is a suggestion that physical immobilization reduces the intensity of the usual physiological cycles (251).

Studies of phase shift in free-running cycles without time cues are now under way (16, 37, 280). These are of vital importance to WRS programming. When men are kept isolated in a constant light, temperature, and sound environment where no time cues are available, their endogenous rhythms begin to override the previously entrained functions. There is a continuous delay in the time of getting up as well as in the time of urine calcium and potassium excretion and body temperature rise. The average period for all functions is 25.1 hours. The urine volume, calcium and potassium have a 26.1 hour cycle. Little is known of the mechanisms of these internal, oscillating control systems (16). Cyclic change in light intensity entrains the rhythm more than does temperature cycle (19). Alteration of the key cuing mechanism or "Zeitgeber" can desynchronize the different physiological cycles from one another. Personalities and activity habits of isolated individuals interact to modulate physiological and performance responses to environments free of time cues (280). Theoretical studies suggest that organisms with a natural period which is relatively short as compared to the time-cue cycle become entrained with a leading phase, the amount of phase angle difference depending on the ratio of the two natural frequencies (18, 19, 353). The longer the natural period, the more it lags in phase behind the time cue during entrainment. It is possible to train animals and man to an artificial time cue which is a multiple of 1:3 to the natural cue. This suggests that scheduling of the WRS cycle should be so devised as to have the time cue cycle a submultiple of 24 hours. Evidence that this is so will be discussed below (2, 6).

The problem created by scheduling WRS cycles for long aerospace mission is complicated by the cumulative effects of prolonged alteration in W, R, and S on performance (79, 267). It is compounded by the possibility that an emergency may require continuous performance of alertness at high levels for unknown lengths of time. Most of the present knowledge about work-rest-sleep cycles comes from ground-based studies obtained over periods of less than 24 hours. Small numbers of subjects, variability of motivation, and diversified backgrounds make generalization from the literature difficult. Both temporal and non-temporal factors affect work, rest, and sleep. The temporal components are summarized in Figure 16-28.

Major emphasis in the literature has been placed on the durations of the work (dw) and sleep (ds) periods, moderate emphasis on the total "daily" periodicity (DT), and very little on the ratios of work to rest (dw/dr) and sleep to wakefulness (ds/daw).

Sleep Duration

Satisfactory psychological performance is dependent upon an adequate sleep-wakefulness cycle, but few studies have been done to determine the optimum number of hours of sleep required per hours of waking time, i. e., ds/daw. The usual study has investigated the ratios, ds/DT, (DT = 24 hours) to determine the amount of sleep spontaneously taken per day without regard to performance. It has not been demonstrated at this point whether man needs 6-8 hours of sleep in every 24 or if, up to a limit, man can take any number of hours of wakefulness as long as they are offset by hours spent sleeping in the ratio ds/daw = 1/2-3. On the short side, the quality of afternoon performance improves almost linearly as sleep duration is increased from one to six

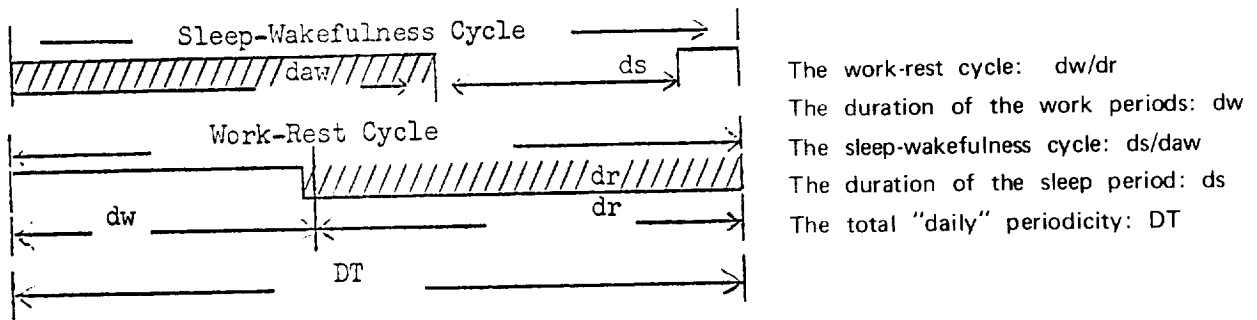


Figure 16-28

Man's Daily Activities Categorized to Form a Sleep-Wakefulness Cycle and a Work-Rest Cycle. (The two cycles are not habitually in phase with each other.)

(After Deutsch⁽⁷⁹⁾, adapted from Kleitman⁽¹⁹³⁾)

hours (338). Beyond a duration of six hours of sleep, improvement is less marked and is completely absent when sleep is lengthened from 8 to 10 hours in every 24.

One could infer that the ds/daw ratio for optimum performance is 1/2-3. This is consistent with the results of Table 16-30 in which a ration $ds/daw = 1/3$ was found adequate (1).

It is known that some finite amount of sleep is required to preserve the physiological balance between waste and repair. The exact amount needed can be expected to vary with the individual's metabolic state and the type of work being done. Relatively large variations in needs have been demonstrated in the literature (142, 193, 195, 249, 327, 370). Statistical evaluation of ds ($DT = 24$ hours), as observed in large numbers of normal volunteers, points to a mean value of 7.5-8 hours required per 24 (66, 193, 194). S's in one study stated they "felt better" after an 8-hour sleep period than after 6 (327). Performance measures did not bear out this difference in "feeling," however, as the S's with 6 hours sleep performed equally as well as those with 8. Although there may be no physiological need for the extra two hours sleep as far as performance is concerned, it still has a beneficial effect upon the subjective feelings of the subjects and is, therefore, probably desirable.

Under normal conditions, a man goes to bed when he is tired and ready for sleep, and, generally, he has difficulty falling asleep at other times, presumably because of the influence of the "activation period" of his previously entrained cycle. This problem comes into focus when there has been a drastic alteration in the sleep/wakefulness schedule in relation to the activation curve. The individual has difficulty getting to sleep even when he has been awake for well beyond his normal span of wakefulness. Even though the activation curve may continue its normal course, there is an apparent psychological adaptation after about four days on a new schedule. This underscores the desirability of preadaptation to a given schedule if that schedule is to differ significantly from the normal regime of 16 hours of wakefulness and 8 hours of rest (62).

Weightlessness will undoubtedly have some effect on the ds required.

Speculation has it that less sleep will probably be required since the decreased metabolic energy needed to function in a weightless field may decrease the need for sleep, thus creating additional waking hours (314). Experimental attempts, however, to simulate weightlessness using water immersion techniques have led to conflicting results. A ratio of $ds/DT = 2/24$ was found to be the maximum required during one seven-day study (122). Other subjects immersed 10 hours out of 24 noted no alteration in their pre-test ds/DT ratio of $8/24$ (123).

The following have been the experiences in orbital flight (27). Astronaut Gordon Cooper --22 orbits, 34 hr., 20 min., 1963--found that even early in flight, when he had no tasks to perform and the spacecraft was oriented so that the earth was not in view from the window, he easily dozed off for brief naps. During the period designated for sleep he slept only in a series of naps lasting no more than one hour each. His total sleep time was about four and one-half hours. He stated that if there had been another person along to monitor the systems he could have slept for much longer periods. He further stated that he slept perhaps a little more soundly than on earth (53). The long period of alertness, of course, enabled Cooper to utilize his orbital time to the optimum for his operational and exploratory tasks.

In 1965 two more orbital flights by American astronauts were made, in which special attention was given to the sleep and wakefulness cycle (29). Difficulty in sleep programming was elucidated by the problems in this flight. The GT-4 and 5 crews (4 and 8-day missions) reported no difficulty in performance related to the 45 minute darkness and daylight cycle created by orbital flight. There were some definite sleep problems. A great deal of difficulty was encountered in obtaining satisfactory sleep periods on the 4-day mission. Even though the flight plan was modified during the mission in order to allow extra time for sleep, it was apparent, post-flight, that no long sleep period was obtained by either crewman. The longest consecutive sleep period appeared to be 4 hours, and the command pilot estimated that he did not get more than 7-1/2 to 8 hours good sleep in the entire 4 days. Factors contributing to this lack of sleep included: (1) the firing of the thrusters by the pilot who was awake; (2) the communications contacts, because the communications could not be completely turned off; and (3) the requirements of housekeeping and observing, which made it difficult to settle down to sleep. Also the responsibility felt by the crew tended to interfere with adequate sleep.

An attempt was made to remove a few of these variables on the 8-day mission and to program the sleep periods in conjunction with normal nighttime at Cape Kennedy. This required the command pilot to sleep from 6 p. m. until midnight, Eastern-Standard Time, and the pilot to sleep from midnight until 6 a. m., each getting a 2-hour nap during the day. This program did not work out well due to flight plan activities and the fact that the crew tended to retain the midnight to 6 a. m. - Cape Kennedy nighttime period. The 8-day crew also commented that the spacecraft was so quiet that any communication or noise, such as removing items attached with Velcro, aroused them.

On the 14-day flight, the flight plan was designed to allow the crew to sleep during hours which generally corresponded to nighttime at Cape Kennedy. There was a 10-hour period established for this sleep, and it worked out very

well with their normal schedule (Figure 16-29). In addition, both crewmen slept at the same time, thus eliminating unnecessary noise from the actions of the other crew member. The beginning of the scheduled rest and sleep period was altered to move it one-half hour earlier each night during the mission in order to allow the crew to be up and active throughout the series of passes across the southern United States. Neither crewman slept as soundly in orbit as he did on earth, and this inflight observation was confirmed in the post-flight debriefing. The pilot seemed to fall asleep more easily and could sleep more restfully than the command pilot. The command pilot felt that it was unnatural to sleep in a seated position, and he continued to awaken spontaneously during his sleep period and would monitor the cabin displays. He did become increasingly fatigued over a period of several days, then would sleep soundly and start his cycle of light, intermittent sleep to the point of fatigue all over again. This response may represent inability to sleep in a seat or natural reaction to responsibility. The cabin was kept quite comfortable during the sleep periods by the use of the Polaroid screen and some foil from the food packs on the windows. The noise of the pneumatic pressure cuff for Experiment M-1 did interfere with sleep on both the 8- and 14-day missions. The crew of the 4-day flight was markedly fatigued following the mission. The 8-day crew were less so, and the 14-day crew the least fatigued of all. The 14-day crew did feel there was some irritability and loss of patience during the last 2 days of the mission, but they continued to be alert and sharp in their responses, and no evidence of performance decrement was noted. (See electroencephalographic data below.)

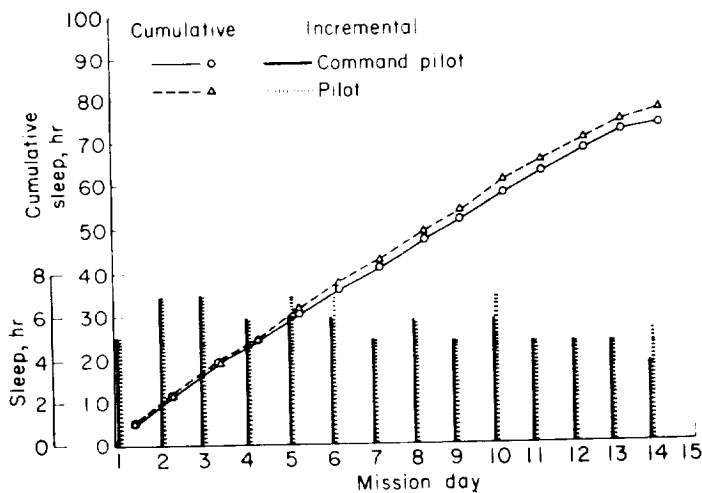


Figure 16-29

Sleep Data for Gemini VII Flight Crew
(After Berry et al⁽²⁹⁾)

Soviet experience with sleep in orbit is of interest. The sleep of Soviet cosmonaut, Gherman Titov - 17 orbits, 25 hr., 18 min., 1961-- was not without interruptions (323). After seven orbits he felt a definite state of fatigue. When he flew over Moscow at 6:15 p. m., he prepared for sleep, according to schedule, by releasing special belts from the side of the pilot's seat. He strapped his body to the contour seat, and after adjusting the seat to the bed position, he promptly fell asleep, but awakened much earlier than scheduled. This happened during the eighth orbit. When he opened his eyes he saw his arms dangling weightlessly, and his hands floating in mid-air. "The sight was incredible," Titov reports. "I pulled my arms down and

folded them across my chest. Everything was fine--until I relaxed. My arms floated away from me again as quickly as the conscious pressure of my muscles relaxed and I passed into sleep. Two or three attempts at sleep in this manner proved fruitless. Finally I tucked my arms beneath a belt. In seconds I was again sound asleep." Titov further states: "Once you have your arms and legs arranged properly, space sleep is fine. There is no need to turn over from time to time as a man normally does in his own bed. Because of the condition of weightlessness there is no pressure on the body; nothing goes numb. It is marvelous; the body is astoundingly light and buoyant...I slept like a baby." He awoke at 2:37 a. m., Moscow time, and was a full 30 minutes behind schedule because of oversleeping. He immediately started the required "morning calisthenics." Thereafter he carried out all scheduled assignments. Only his motion sickness interfered with normal performance. It is of interest to note that Titov's sleeping period coincided largely with nighttime over Russia. This also was true of the other Russian cosmonauts, and may have been so planned.

Valery Bykovsky - 81 orbits, 119 hr., 1963--slept four times for periods of eight hours, alternating with periods of sixteen hours of wakefulness (252). During this flight and that of Valentina Tereshkova - 47 orbits, 71 hr., 1963--"the diurnal periodicity of physiological functions changed only during the first and last days of the weightless state, which was most probably associated with the emotional strain." During the phases of wakefulness, brief rest periods were usually scheduled for times when the spaceship was not over Russia. "It should also be noted that at night, during sleep, nearly all cosmonauts displayed a greater reduction in pulse rate than that recorded during the same hours in earlier space simulated flight." (116).

The three-man team of the spaceship Voskhod - 16 orbits, 24 hr., 17 min., 1964 - rested and slept in shifts during their 24-hour flight.

The reported sleep and wakefulness time patterns in orbital space flight reflect, by and large, the physiological circadian cycle of 24 hours. For orbiting astronauts, the earth temporal zones are irrelevant to the sleep cycle. With regard to these zones they are--in a state of asynchrony. Their basic guiding time has been Greenwich time or Universal Time (U. T.). Nevertheless, for physiological and operational reasons it seems to be very desirable that their physiological clocks remain synchronized with the local time of the launch time zone, or in a broader sense, to the time zone range of the home country to which they were adapted during the prelaunch period (314). But in extended (geocentric and heliocentric) space flights, the astronauts probably will follow a physiological sleep and wakefulness cycle adjusted to their duties, and not necessarily completely corresponding to the temporal pattern of the physiological circadian cycle on earth. If operational necessity requires that the basic sleep-wakefulness cycle be of a non-24-hour periodicity, then an artificial cycle that is longer than 24 hours might be better than one that is shorter (37, 194, 195). This suggestion might be questioned, however, in view of the long and successful experience of the United States Navy in maintaining watch schedules based on work-rest and sleep-wakefulness cycles of 12-hour duration. However, since the 24-hour schedule is a multiple of 12, it may be that the 12-hour schedule is qualitatively more similar to the 24-hour schedule than is an 18-hour schedule. (see below)

On the moon, the physiological sleep and activity cycle will be completely independent of the physical or selenographic day-night cycle, which is 27 terrestrial days in length. In addition to sunshine, with an illuminance of 140,000 lux (lumens per square meter), the earthshine at full earth with an illuminance 75 times stronger than that of the moonshine on earth at full moon, provides a photic situation approaching a dim daylight situation on earth (314). Furthermore, there may be locations with no effective illumination at all (caverns), or places with constant sunlight as on the "mountains of eternal light" near the south pole. Be that as it may, the photic environment on the moon does not provide a "Zeitgeber" comparable to the 24-hour dark-light cycle on earth. Therefore, the astronauts might adopt a sleep and activity cycle of the terrestrial circadian pattern, modified by their special tasks and by the lower gravity on the moon.

On the planet Mars, the day-night cycle is only 37 minutes longer than that on earth (314). The sky is dark bluish in color, excepting regions covered with thin whitish clouds. Solar illuminance on the Martian surface at noon may reach one-third of that on earth. Thus, the temporal dark-light alternation on Mars offers time cues similar to those on earth.

Duration of the Work Periods (dw)

Studies of the work periods (dw) have been typically conducted using a total "daily" periodicity (DT) of 24 hours, and have measured performance as a function of the total duration of the work period in industrial settings. The primary factors to be considered in the selection of the length of the duty period relate to the nature of the activity required of the operator in the performance of his duties (62). Account must be taken of both the levels and varieties of the demands placed on him in carrying out his tasks. For example, some tasks involve only passive performance on the part of the operator in that several minutes may elapse during which no event to which he must respond will occur; this sort of task is exemplified in radar watchkeeping. At the other extreme are tasks that require active participation of the man by more or less continually taking actions of some sort, e. g., manual control of the vehicle on re-entry. An important psychological factor underlying this distinction is the effect that these two different kinds of tasks exert on the operator's level of alertness. Passive tasks produce or contribute to decreased alertness whereas, at least up to some level of workload, active tasks tend to sustain or increase alertness. The variety of tasks --again up to some level of workload--also tends to promote alertness. However, moderately high workloads on tasks that require the "simultaneous performance" of psychologically disparate functions (e. g., mental calculations and code solving) are quite vulnerable to losses in alertness, and this is especially true for task combinations in which timing is critical. Thus, in a sense, an alertness paradox is produced (62).

Many of the conditions under which performance decrements have been observed in laboratory studies are not at all likely to occur in properly human-engineered man-machine systems. Typical of this class of studies is the vigilance experiment. Here, the occurrence of decrements is largely dependent upon the presentation of a single task using infrequently occurring, near-threshold signals of uncertain nature to which the man must respond (303). With these conditions, decrements are exhibited over performance intervals

as short as 30 minutes. However, even with single tasks, when the signals have high attention value or are alternated or made redundant, performance can be maintained for much longer periods without apparent decrement (39 , 40, 128, 212). Electrophysiological (EEG, EOG, GSR and nuchal electrogram) correlates of vigilance are under study (28, 30, 225).

With tasks in which the operator has control over his rate of activity (as in industrial situations involving piece-work production), the man typically works at a near maximum rate for a period; he then takes either an official or unofficial rest break, after which he resumes his original rate. Thus the period of continuous work in most industrial jobs is typically about two hours is seldom longer than four hours.

The optimum length of duty period has not been investigated except within rather narrowly defined limits as regards the numbers and kinds of tasks the man is required to perform. Thus, even though the operational work situation and performance requirements can be specified exactly, substantive data relevant to the determination of the appropriate length of duty periods are in short supply. However, the data that do exist suggest that work periods on the order of four hours represent the duration of performance that should be expected as a matter of routine without encroaching on the maximum efficiency of which the operator is capable (Figure 16-30). When the level of performance necessary to satisfy the mission requirements is substantially below the operator's maximum capabilities, this figure can be increased. But, in determining how much it can be increased, importance attaches to the probability that an emergency might arise that would require maximum capabilities and to the speed with which the operator would have to be able to exercise those capabilities. Fortunately, except when his condition has reached a point of extreme deterioration, man can rather quickly rise to most any situation. The critical questions are, "How rapidly must he rise? how far? and for how long?" (62).

The Work-Rest Cycle

The ideal work-rest cycle would be one in which the total "daily" periodicity (DT) equaled 24 hours, distributed in a manner to which humans are already adapted. The 90 minute day-night cycle of orbital flight makes this ideal rather difficult to attain in the operational situation.

The most common division, used in the U. S. submarine fleet, is the 4-on and 8-off schedule of standing watch, which is operation on an artificial 12-hour cycle (193, 194). Reports in the literature would indicate that while the duties of a submariner may be satisfactorily carried out on such a schedule, efforts to establish a 12-hour physiologic rhythm in man have been uniformly unsuccessful on subjective, biochemical and hematological bases (142, 221, 222).

Experiments have been performed to discover what dw/dr ratios and durations yield the best performance. The results of this experimentation are summarized in Table 16-30. Unfortunately the durations are not very long. The consistency, however, within experiments and the consistency between recommendations is interesting. Both authors of earlier studies, (References 1 and 43), recommended a dw/dr ratio of 2/1 (hours:4/2) and indicate a general agreement of little or no performance decrement being

Table 16-30

Results of Experiments Relative to Performance During Various Work-Rest Cycles

| Ratio dw/dr | Hours dw/dr | Comments | DT | Subjects # | Days N | Ref. |
|----------------|----------------|--|----|---------------|-----------|------|
| 2/1* | 4/2 | "Wide variation in individual performance; subjects worked effectively." | 6 | 11 | 15 | 1 |
| 2/1* | 4/2 | "Experiment too short" but "no difference in performance", data indicated trend toward better 4/2 performance if experiment had been prolonged." | 6 | 12 | 4 | 1 |
| 3/1 | 6/2* | | 8 | 10 | 4 | 1 |
| 1/1 | 8/8 | 4/4 and 2/2 adjusted "better" than did 8/8 and 6/6. | | | | 1 |
| 1/1 | 6/6 | | | | | 1 |
| 1/1* | 4/4 | | | | | 1 |
| 1/1 | 2/2 | Maximum severity--not recommended for routine use. | | | | 1 |
| 2/1* | 4/2* | No marked performance decrement; recommended over 6/2. | 6 | | 8 | 43 |
| 1/2 | 4/8 | Confirms that it is difficult to establish a physiological 12-hour (DT)--See Ref. 90. | 12 | | | 193 |
| 1/1 | 4/4 | | 8 | 2 | 7 | 265 |
| 1/1 | 4/4 | | 8 | | | 311 |
| 2/1 | 4/2 | With proper selection and motivation this schedule can be attained with no degradation in performance. | 6 | 6 | 15 | 6 |
| 1/1 | 4/4 | Best schedule studied. Function appeared normal; physiological phase shift toward end of period noted. | 8 | 10 | 30 | 6 |
| 2/1 | 4/2 | Steady work period of 40 hours on day 6 and 7 poorly tolerated; performance is generally poorer than equivalent 4/4 schedule. | 8 | 6 | 12 | 5 |
| 1/1 | 4/4 | Steady work period of 44 hours on day 6 and 7 well tolerated; performance was good. | 6 | 10 | 12 | 5 |

noted. In addition, the dw/dr = 2/1 ratio is recommended by both over the dw/dr = 3/1 ratio on a subjective and objective basis. One group feels that it is probably feasible to expect a highly motivated man to maintain acceptable performance levels on a 4/2 schedule for a period as long as 15 days, and, probably, 30 on the basis of some subjective statements. The results of other subjective studies indicated that some individuals adjust more favorably in groups where a 4-on and 4-off schedule was used (1, 61, 265, 311).

Recent laboratory studies have shown that most subjects can maintain satisfactory performance without decrements over a period of 30 days while following a 4-hours work, 4-hours rest schedule around the clock (5, 6). A modified control study was conducted using a 4-hours work, 4-hours rest, 4-hours work, 12-hours rest schedule. No limitations were placed on subjects

during the 12-hour rest period. The performance of this group of subjects over a period of 12 days was essentially the same as that of subjects working 12 hours per day while confined to a simulated crew compartment. On the assumption that a 30 day period was sufficient to reveal any adverse reactions, one can conclude from these results that the short (4-hour) sleep periods were sufficient to maintain the "psychological status" of the operators. These subjects, who were rated pilots, felt that they could have performed their normal flying duties on a 4/4 schedule throughout the period of the study and the majority thought they could have continued to do so indefinitely. Periods of sleeplessness during the 4/4 schedule were better tolerated than on a 4/2 schedule.

In the 30-day study with subjects following a 4-work/4-rest schedule, there was some evidence that the magnitude of the normal physiological periodicity was reduced toward the end of a month. Specifically, whereas for the first 25 days of the study the fluctuations were significant, during the 26th through the 30th days the cycling was not significant. In studies of submarine personnel it was found that crewmen on a 12-hour duty/rest cycle showed a double, body-temperature curve (193). These results suggest the possibility that the subjects in the 30-day study on a 4/4 schedule may have been tending toward a "triple" curve of physiological cycling. Further work is required on the mechanism behind these phase shifts. It may be that the 4/4 schedules do not present sufficient time cues. Not all of the physiological functions appeared to behave similarly. In only one of the groups did pulse rate really reach a new steady phase-angle difference. The cause of delay in phase angle shift is also not clear. An understanding of these phenomena will permit more valid extrapolation to missions of longer duration.

Human variation in ability to adapt to an atypical (non-24 hour) WRS cycle has ranged from one week to six years (37, 122, 193, 204, 267). Average times required seem to be in range of 2-3 weeks for complete adaptation (335). Reports of abrupt, rapid adaptation are more surprising than failures to adapt. All investigators seem to agree on the wide degree of variation in the rate and completeness of adaptation and the work out-put after adaptation (112). It is possible that only a five day adaptation period may be required for normal function (1, 261).

The ratio of mean temperature range (MR) to the range of the mean temperature (RM) has been used as a measure of adaptability (193). The degree of fit of observed temperature cycle to expected changes after being on new cycle 24 hours has also been used as a measure of adaptability.

The maintenance of a stable sleep-wakefulness cycle, as indicated by a superimposable body-temperature curve, peaking during wakefulness and dropping during sleep, serves a dual purpose. It promotes greater alertness and efficiency during working hours, and easier onset of sleep. The consistent, day-to-day adherence of a stable sleep-wakefulness cycle is, therefore, to be recommended.

Efficiency During Wakefulness

Efficiency during wakefulness is a major criterion. Efficiency of performance follows a 24-hour rhythm (193). It is low upon arising, shows an initial

ascent phase, a plateau in the middle of the day, and a terminal descent phase. Performance immediately upon getting up from a period of sleep is often poorer than it was just before retiring and is worse after deeper stages of sleep (148 , 149, 338). During split, sleep-wakefulness cycles (4 hours asleep, 4 hours awake, 4 hours asleep), a "very low" capacity for work through the middle four-hour waking period is seen (193). Similar findings were noted using a 3-hour sleep, 3-hour awake, 3-hour sleep schedule (173).

Over a long period of time these circadian periodicities in efficiency have direct implications on the performance levels to be expected of the operator. These implications are borne out in data obtained in laboratory confinement studies. The performance of the man on some tasks and task combinations reflects the same sort of periodicity that is found in the biological measures.

In the 30-day study with the 4/4 schedule referred to in Table 16-30, this cycling was present even though the low point of the performance curve always exceeded in efficiency the high point of comparable subjects following a more demanding schedule (6). In this regard, it should be noted that it may well be that the data obtained using a 4/4 schedule actually give an optimistic view of the criticality of the association between the biological and performance data (62). Specifically, since the duty periods never exceeded four hours, the potentially detrimental effect of the boredom resulting from continuous confrontation by the tasks might not have developed to the extent that would very likely be the case with longer duty periods. Although one cannot rule out the possibility that performance was depressed by the short sleep periods, the control data (4-work, 4-rest, 4-work, and 12-rest) tend to contradict this hypothesis. Sleeplessness periods during these schedules are better tolerated than in 4/2 schedules especially for tasks requiring sustained attention (5). Performance returns to approximately the level that would be expected had there been no period of sleep loss after the subjects on the 4/4 schedule had had two sleep periods (8 hours of sleep - 12 hours by the clock) and those on the 4/2 schedule had had three sleep periods (6 hours of sleep - 14 hours by the clock).

Superficially, it would appear that a schedule should be selected that would require the man to perform only during the high portion of his daily curve of activation. This would, in theory, provide on the order of 10 to 12 hours per day of "high-level" performance. However, examination of the industrial literature as well as laboratory and field research related to military operations suggests that ten hours represent too long a period of work at one stretch to expect performance to be maintained without at least an increase in the probability of errors and/or decrements.

Non-Temporal Factors

Non-temporal factors affecting the WRS cycle include:

1. The number of crew members on board.
2. The duty assignments or responsibilities of each crew member.
3. The need for time sharing of work space and facilities.

4. The need for equal division of task loading, rest and sleep time.
5. The need for completion of all tasks.
6. Emergency situations.

These non-temporal factors will probably dictate the initial WRS cycles on the first orbital lab flights. The best WRS cycle will be one adjusted to duties, independent of the ambient sun-shadow cycle (i. e., the earth-orbital space environment) and not necessarily corresponding to the time pattern of the earth day-night cycle. This non-24-hour cycle should be one to which the astronaut should be able to adapt in a reasonable amount of time and with which he can maintain synchronization of his metabolic clock to ensure his best psychological performance.

The use of shorter work periods provides an advantage in the event that an unusual requirement for man-hours should arise either because of a particular feature of a mission segment or because of an emergency (62, 147). That advantage would be realized during the period in which the system is "recovering" from the increased demand. Specifically, the man may have suffered a period of partial or even total sleep loss while coping with an emergency. Should that have been the case, he probably would find it substantially easier to maintain a satisfactory degree of alertness for a 4-hour duty period as compared to, for example, a 10-hour period until such time as he regains his pre-emergency status. Preliminary studies suggest that subjects in a 16/8 schedule tend to tolerate sleep deprivation for 2 days (on day 6 and 7) and recover faster than subjects on 4/2 and 4/4 work/rest schedules (147).

To the extent that a high level of performance will be required on what will approach a twenty-four hour per day basis, then serious consideration must be given to the selection of the work-rest schedule. The duration of the duty periods should be limited to a figure that will preclude the development of task-specific fatigue or boredom. With the anticipated exposures to the tasks to be on a day-after-day basis, a work period that seems to be suitable at the beginning of a mission may become intolerably long after a period of several weeks or months. This requires specific study. In addition, sleep periods should be arranged so that they will come at essentially the same time each day so that adjustment to (or in) the circadian rhythms will be facilitated. These two factors considered together imply a trade-off between the necessary or desirable duration and numbers of sleep periods and the duration of the individual duty periods.

The general conclusion reached from these past studies is that man is fairly well accustomed to a sleep-wakefulness cycle of a 24-hour duration and that he had diurnal variations in both performance and physiological functioning that coincide with this rhythm. When an atypical cycle is imposed, his physiological rhythms may be expected to show some adaptation to the non-24-hour periodicity--but adaptation is not likely to be complete nor to be uniform for all individuals. Concomitant decrements in performance, however, may not occur, especially if the sleep-wakefulness ratio is held constant. The performance decrement, whatever its degree, precipitated by the imposition of a typical work-rest-sleep cycle can be minimized in the following ways:

- The ideal solution is to avoid any non-24-hour work-rest-sleep cycle (i. e. , use 8-on, 16-off).
- Where this is impossible, employ pre-flight, pre-synchronization periods for crews using the non-24-hour cycle proposed for that flight.
- Coordinate pre-flight pre-synchronization with the abilities of the individual crew members to adapt (those who adapt least well should be kept close to their typical schedule).
- Drugs may be utilized as a useful, but undesirable, tool if synchronization is found to be difficult, but more information is required on drug influence on cyclical phenomena.
- Local (orbital) adaptation to a typical cycle can be accomplished by new crew members as they are rotated to the lab (if they are not required to go on duty immediately upon arrival).

Further experimentation with various combinations of non-24-hour cycles in the weightless environment may yield additional, useful information.

Ground controllers and other operations personnel are often faced with asynchronous patterns during unusual work schedules or when flying to duty posts across several time zones (95, 152, 153, 199, 200, 267, 314, 315, 337). The asynchrony in both east to west and west to east flights produce subjective fatigue and temporal changes in heart rate and body temperature, but significant physiological deficit has been found only in the east to west flights. North-south flights do produce fatigue, but do not show asynchronous physiological patterns along with the psychological deficits (154). The duration of fatigue is usually shorter than the time lag in physiological phase shifts. Large inter-individual differences are noted with some individuals requiring up to 5 days for phase shift after Oklahoma City to Tokyo jet flights. Older individuals appear more subjectively sensitive to the asynchrony than younger ones. First, if a traveler to a distant location requires full alertness for a certain occasion he should, if possible, travel to his destination several days in advance, so that he will be adjusted to the new locality before he is called on to perform his tasks. Secondly, a coordination of the physiological with the physical day-night cycle can be achieved by presetting his physiological clock; i. e. , by adopting 3 to 5 days in advance of the trip, a sleep and wakefulness pattern which corresponds to the physical day-night cycle of the place of destination (315).

Sleep Depth and Deprivation

The general sleep requirements in space operations were covered above. Depth of sleep can be measured by electroencephalographic techniques. Wave patterns can be distinguished for the awake state, eyes closed and the four stages of increasing depth of sleep (76, 365). The physiological basis for these patterns as well as oculomotor patterns are under study (187, 188, 211, 226, 268, 269, 279, 320, 347). As noted above, sleep patterns recorded in the first 51 hours of orbital flight are similar to those on earth. Irregular and aperiodic fluctuations in depth of sleep are normal occurrences (41, 76). They are often associated with dream states (76, 150, 166, 211,

229, 274, 306).

An electroencephalographic study of sleep was carried out in Gemini VII (42, 190). Baseline, multi-channeled EEG and other psychophysiological data were recorded on Borman during all stages of sleep and the working state on earth and compared with those in flight. Fifty-four hours of inflight data were obtained at which time the scalp electrode was dislodged. Eight hours after liftoff the command pilot closed his eyes and remained quiet for almost 2 hours without showing signs of drowsiness or sleep.

"The first inflight sleep period showed marked fluctuations between light sleep and arousal, with occasional brief episodes of stage 3 sleep for the first 80 minutes. At that time stage 4 sleep was reached, but in less than 15 minutes abrupt arousal and termination of sleep occurred.

On the second day, at 33 hours and 10 minutes after lift-off, the command pilot again closed his eyes and showed immediate evidence of drowsiness. Within 34 minutes he was in the deepest level of sleep (stage 4). During this prolonged period of sleep, there were cyclic alterations in level similar to those which occur in this astronaut during a full night of sleep under normal conditions. Generally, each successive swing toward deeper sleep, after the first period of stage 4 has been obtained, only reaches successively lighter levels; but, in Borman's second night of sleep, stage 4 was reached and maintained for 20 minutes or more at three different times after the first episode. It is interesting to speculate as to whether this increase in the number of stage 4 periods reflected an effect of deprivation of sleep during the first 24 hours.

After approximately 7 hours of sleep, a partial arousal from stage 4 sleep occurred, and, after a brief period (12 minutes) of fluctuating between stages 2 and 3, Borman remained in a state fluctuating between drowsiness and stage 1 sleep until finally fully aroused about 1.5 hours later. Whether any periods of so-called "paradoxical" sleep, rapid eye movement sleep, or dreaming sleep occurred during this oscillant period cannot be determined with certainty from these records because of the absence of eye movement records and because paradoxical sleep is generally very similar in its character to ordinary stage 1 sleep. However, two periods of a pattern which resemble an admixture of certain characteristics of stage 1 and stage 2 sleep, and which resemble some of the activity which this group and other investigators have observed in paradoxical sleep, were recorded for relatively long periods in the second day's sleep (at 11:05 G. M. T. and 14:20 G. M. T.) (187, 188). These consist of runs of 3 per second "saw-tooth" waves, runs of low-voltage theta and alpha activity, low-voltage beta activity without spindles, and occasional slow transients with a time course of about 1 second."

For further study of sleep and other neurological phenomena, data banks EEG taken on the astronauts are available (113, 341).

One must also consider sleep deprivation. This acute or chronic stress is accompanied by only a few consistent physiological changes (114, 118, 210, 326). The only marked changes consistently found are those that occur in neurological testing and in the electrical activity of the brain with increased convulsive tendency (14, 27, 31, 186, 275, 329). Decrease in pulse rate is not always found (254, 310). Blood sugar, hemoglobin, red and white cell count, excretion of 17-ketosteroids, total nitrogen and creatine, and the level of adrenal-like substances in the blood may be unchanged (328). Bioenergetics may be altered at a biochemical level (114). Body weight, blood pressure, hand steadiness, auditory acuity, depth perception, and dark adaptation also have shown no significant changes as a function of sleep loss (87). Only after 46 hours of sleeplessness has minor decrement been noted in visual acuity, muscle balance and stereoscopic function (256). After 5 hours of sleep, a return to normal was noted. Factors in the repayment of sleep debt have also been studied (98, 347). Specific deprivation of paradoxical and other stages of sleep are now under study (186, 187, 367).

Changes in estimates of fatigue have been reported, but marked differences in subjective factors among some of the studies prevent the drawing of direct conclusions (13). Correlation with performance degradation is variable. A moderate correlation has been reported between feelings of fatigue and the performance of mental multiplication (12). Correlations have also been found between a subject's estimation of fatigue and his actual performance of vigilance, interpretive, and grid-matching tasks (105, 106, 351). In contrast, air traffic controllers, on the job, developed feelings of weariness with sleep deprivation. These were not accompanied by performance decrements (293). There are also indications that judgements based on the appearance of a subject do not necessarily correlate with the subject's performance. Changes in behavior, personality, and physical appearance resulting from a 50-hour period of sleep deprivation have been found more pronounced than would be suggested by any performance decrements observed (63). A number of investigators have reported that increased irritability is among the first signs of pilot fatigue (80, 82, 215). Psychotic hallucinatory and regressive behavior is often brought about especially when confinement and isolation are superimposed on sleep deprivation (6, 101, 118, 277, 352). The symptoms appear to be related to the specific phase of sleep being deprived (367). Stage 4 deprivation produces depressive responses; stage 1-REM, irritability and emotional lability.

Of interest to contingency planners and commanders is the sequence of progressive deterioration of performance as sleep deprivation is prolonged. A review of this pattern has been made from which the following is taken directly (326). Following denial of one night's rest, detection of visual targets deteriorates markedly (364); choice behavior demands more time and exhibits more error (363); reading rate decreases although comprehension does not (170). Visual blurring and diplopia are accompanied with the beginning of misperception (364, 366), and where learning of a complex mental task is still taking place, the increment is reduced (60).

As the sleepless period begins to involve longer periods, effects are reported when noted. Thus, after 40 hours, mental work in arithmetic and color naming appear to suffer (344), as do ability to recall names and objects

from recent conversation. After 50 to 65 hours, momentary hallucinations are reported (364). Critical flicker frequency and speed of manual and leg movement decrease after 60 hours with the diurnal pattern of coordination and travel movements persisting, indicating some more basic physiological determinant (146). Memory as represented in the ACE test of intelligence, deteriorates after 72 hours. Serious lapses now seem to appear with the deterioration in function reflecting the involvement of or dependence upon alertness and sensory checking (363, 366). It seems that the performance and sensory deficit has been established by about 65 hours, for no appreciable drop is noted in these factors, temporal disorientation, or cognitive organization after that period (364). As one passes this three-night period, the personality factors reflect perceptual changes or deterioration as manifest in emotional disturbances (50), which seem to predominate until psychotic episodes (persecutory) appear after 120 hours without sleep (364).

Several studies have demonstrated decreases in performance as the cumulative effects of sustaining slightly reduced daily sleep over prolonged periods of time. Measures of performance and muscle tonus have been compared as they were affected by four successive periods of nightly sleep -- 4, 10, 8, and 6 hours, respectively--repeated 7 times over an interval of 28 days (111). Greater work output was accompanied by greater tonus, and muscle tonus appeared to vary more with sleep loss than did performance. This suggests the presence of some form of tonic muscular compensation during performance testing. Also, the cumulative effects of prolonged sleep loss tended to offset the efficacy of the tonic muscular compensation. The experimental effects in this study, however, were confounded, to a degree, by the different durations of sleep allowed on each day of every replication. This was particularly noticeable in the scores that followed 10 hours of sleep because they more nearly approximated those following the 4-hour sleep period than those following the 6- or 8-hour sleep periods. Since the 10-hour sleep period was always preceded by the 4-hour, it is very likely that a carry-over effect was present.

A schedule of 7 consecutive hours of nightly sleep during one month has been compared with an experimental schedule of interrupted nightly sleep during the following month (173). On each night of the experimental month the subject slept 3 hours, remained awake 3 hours, and then slept 3 additional hours. No difference in performance was found between the two schedules; in those tests where learning was present, improvement continued at the same rates regardless of the alternation-of-sleep routine.

In another study two "capable and highly motivated" subjects were required to perform continuously without sleep for a period of 24 hours (120). The task situation was a complex one that required the constant attention of each subject. The tasks, enclosed in two "flight" simulators, were selected to measure eye-limb coordination, problem solving, estimation of closure rates, selection and manipulation of controls, and the noticing of environmental changes both inside and outside the simulator. As indicated by each of the seven specific measures used, performance followed a pattern of rising to a peak after 6 to 10 hours and then dropping off sharply to a low point reached during the final 2 or 3 hours of the test. Differences between the two subjects and among the several tasks used were also quite evident. End-spurt effects

were avoided by slowing the subjects' clocks so that after 24 hours had actually elapsed, the clocks indicated that the subjects still had about 3 hours to work.

The vigilance performances of subjects who had just returned from flying 15-hour sorties at night have been found to be surpassed by those of otherwise comparable subjects who had just flown the same sorties during the day (104). Although this decrement may be interpreted as being a function of the loss of sleep, it may also be interpreted as being the result of differences in the difficulty of day versus night flying.

Motivation, monotony, complexity of task, arousal factors, and many other variables control the degradation of performance of the sleep deprivation (39, 40, 68, 87, 118, 326, 347, 352, 362, 366). Specific periods of sleep are more sensitive than others to behavioral and other responses of deprivation (367). Sleep deprivation of different forms will alter performance when superimposed on individuals in the process of adapting, or even fully adapted, to altered WRS cycles. Preliminary studies are discussed above.

Induction of sleep by electrical means has received study in recent years (33, 175, 176, 177, 183, 374). The advantage over drug-induced sleep is reversibility. However, techniques are still in the preliminary stage of development. Under some emergency situations on long duration flights, such techniques may be of value. Anesthesia may also be induced electrically (175, 177, 180, 183, 198, 299, 300, 359). Learning and memory during natural sleep are under study (32).

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