Optimization of Space Vehicle Design with Respect to Artificial Gravity

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THE PURPOSE of this study is to derive some human-factors criteria which will be of value in the design of space vehicles which are rotated to create artificial gravity. Although no specific requirement for artificial gravity has yet been established, a straightforward attack on the problem is possible if it is assumed from the start, as it is in this paper, that artificial gravity is either highly desirable or absolutely necessary from a human-factors viewpoint. While very little direct evidence is available concerning man's ability to tolerate the peculiarities which exist in the artificial gravity environment of a rotating vehicle, sufficient information is available to justify an attempt to prescribe at least a rudimentary human-factors design envelope and some general design principles upon which an optimum vehicle configuration can be based.

For the purpose of this study an advanced state-of-the-art is assumed, i.e., the vehicle can be constructed in orbit if necessary and will remain permanently in orbit with provision made for resupply and exchange of crews at periodic intervals. Although these assumptions imply a projection into the future, the design principles derived herein are applicable to any space vehicle which is rotated to create artificial gravity.

The Artificial Gravity Environment: The peculiarities of the artificial gravity environment to which the crew member will be subjected stem from two sources: the dependence of "g"-level on radius of rotation, and the Coriolis forces which will be experienced due to motion with respect to the rotating vehicle.

That a "gravity gradient" will exist in the rotating vehicle is evident from the equation which describes the artificial gravity force, i.e.,

$$F_g = \frac{\omega^2 r}{32.2} \qquad (1)$$

where F_g = the magnitude of the artificial gravity force, in "g"s

ω = Omega, the magnitude of the angular velocity of rotation in radians/second

r = the perpendicular distance in feet from the axis of rotation to the mass on which the force acts.

The force always acts perpendicularly outward from the axis of rotation. It can be seen from the equation that the magnitude of the artificial gravity force is directly dependent on radius. Therefore, for a man standing in a rotating vehicle, as shown in Figure 1, there

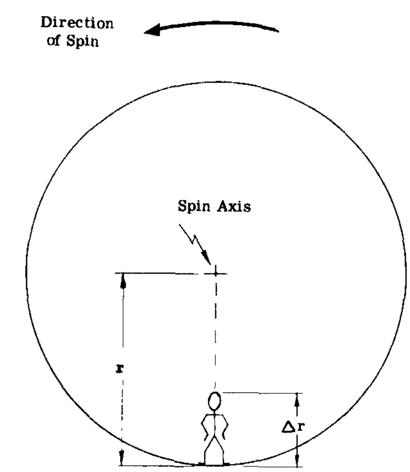

FIGURE 1. MAN STANDING IN ROTATING VEHICLE EXPERIENCING HEAD-TO-FOOT GRAVITY GRADIENT

exists a gravity gradient between head and feet equal in magnitude to $\omega^2 \Delta r/32.2$. This gradient will remain constant for the crew member regardless of the radius to the floor surface. For large values of r, the gradient will be negligibly small compared to floor-level gravity. For small-radius vehicles, however, the gradient will be relatively large. Depending on man's ability to tolerate this peculiarity, the gravity gradient becomes significant in design, particularly in small-radius vehicles.

The peculiarities introduced because of Coriolis forces are more complex. The direction in which the Coriolis force acts is not constant as it is for the artificial "g" force, but varies both in magnitude and direction depending on the geometric relationship between the spin axis and the velocity vector of the crew member relative to the vehicle, according to the vector equation

$$\bar{F}_c = -\frac{2\,\bar{\omega} \times \bar{v}}{32.2} \qquad (2)$$

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where $\overline{F}_c$ = the Coriolis force vector in "g"s
$\overline{\omega}$ = the vector quantity Omega in radians/sec.
$\overline{v}$ = the vector velocity of the crew member with respect to the rotating reference frame in ft./sec.

The Coriolis force environment can best be analyzed by considering motion in each of three orthogonal directions with respect to the spin axis of the vehicle: radial motion, tangential motion, and axial motion. The direction in which the Coriolis force acts for motion in each of these directions is illustrated in Figures 2, 3, and 4.

For radial motion (Figure 2) the Coriolis force acts to one side for motion toward the spin axis and to the other for motion away from the spin axis. The crew member moving radially with constant velocity would therefore experience a constant side force superimposed upon a varying gravity force. The resultant which he would experience would continually change both in direction and magnitude. It may be expected that such an experience could be perplexing to the crew member, particularly for radial motion near the axis of rotation, where the magnitude of the side force would be appreciable in comparison with the gravity force.

For tangential motion (Figure 3) the Coriolis force acts along the same line as the "g"-force, adding to it for motion in the direction of spin and subtracting from it for motion in the opposite direction. Thus, if the crew member remains stationary he will experience a constant "g"-level, if he walks "with" the spin he will feel "heavier," and if he walks "against" the spin, he will feel "lighter." This peculiarity of the environment could be troublesome depending on the magnitude of the change and man's ability to tolerate it.

For axial motion (Figure 4) in either direction, the Coriolis force is non-existent since the cross product of ω and v is zero. Therefore, except for minor side Coriolis forces induced by radial movement of the limbs or bobbing of the head while walking, the crew member would experience only a constant gravity force.

It is to be noted that the radial and tangential motion both take place in the plane of rotation, i.e., a plane perpendicular to the spin axis. Therefore, Coriolis forces are maximized, as is specified by the vector cross product. On the other hand, motion parallel to the spin axis produces no Coriolis forces. Since Coriolis forces significantly distort the artificial gravity environment, the above findings are highly significant in vehicle design from a human-factors viewpoint.

Human Tolerance to the Artificial Gravity Environment: Man maintains his spatial orientation through integration of information concerning the environment which is transmitted to his brain through his senses. The sensory mechanism, referred to as the "orientation

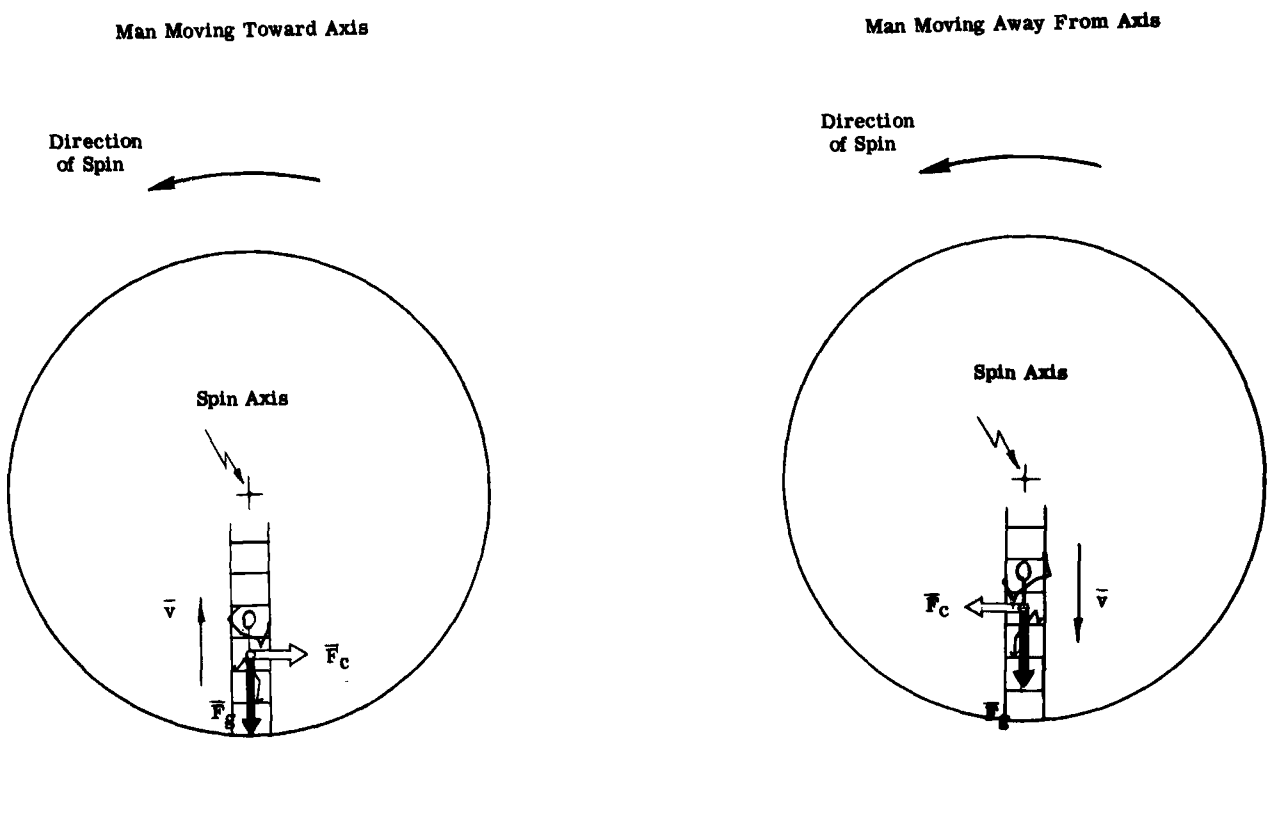

FIGURE 2. INERTIAL REACTION FORCES EXPERIENCED BY MAN MOVING IN RADIAL DIRECTION INSIDE ROTATING VEHICLE

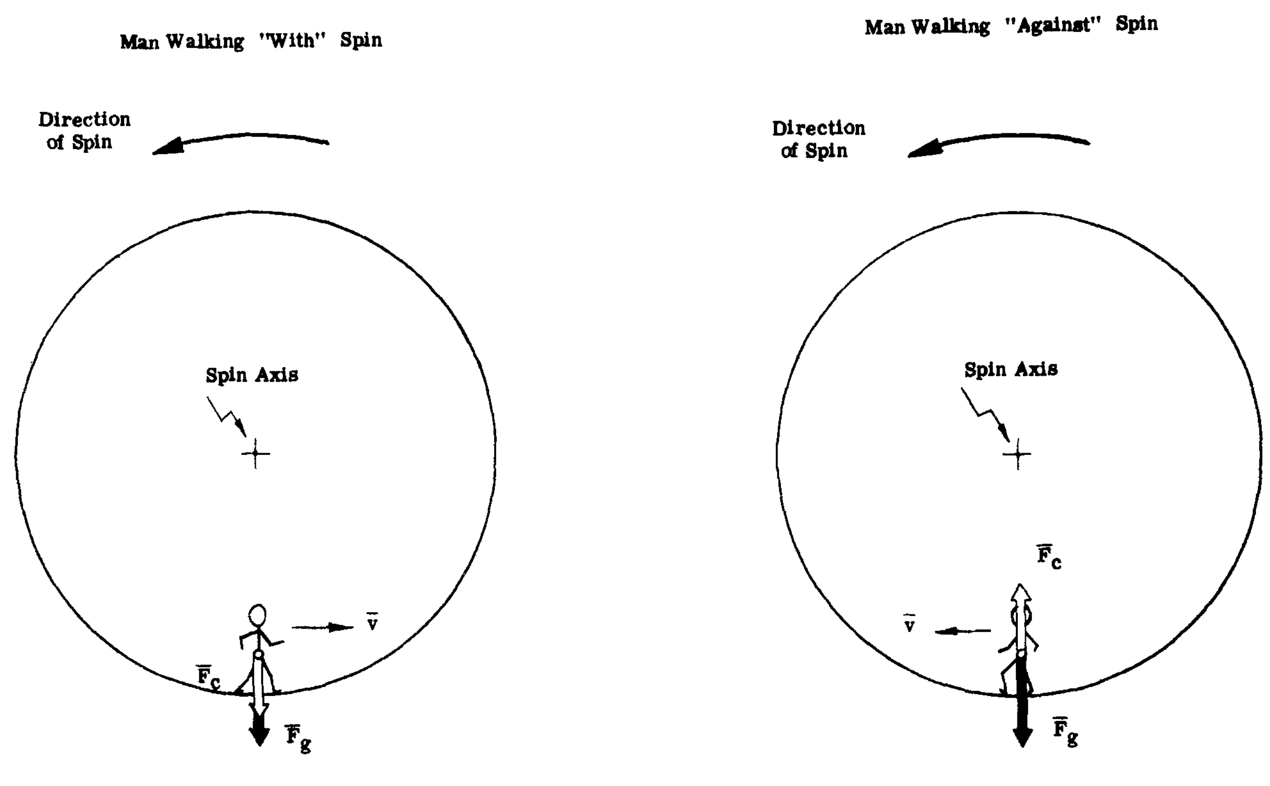

FIGURE 3. INERTIAL REACTION FORCES EXPERIENCED BY MAN MOVING IN TANGENTIAL DIRECTION INSIDE ROTATING VEHICLE

triad" by Campbell,[2] consists of the eyes, the vestibular organs located in the inner ear, consisting of the semicircular canals and the otoliths, and finally the mechano-

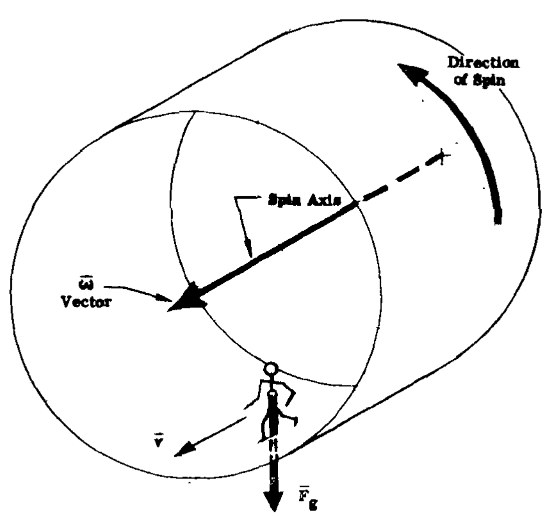

FIGURE 4. INERTIAL REACTION FORCES EXPERIENCED BY MAN MOVING IN AXIAL DIRECTION INSIDE ROTATING VEHICLE

receptors located in the muscles, tendons, and joints. Of particular significance is the fact that both the otoliths and the semicircular canals operate on inertial principles. The otoliths sense linear and gravitational accelerations while the semicircular canals sense angular accelerations. Therefore any accelerations (forces) which are applied to the organs act as stimuli. The impulses which result from the stimuli are sent to the brain, where they are integrated with impulses sent from the eyes and mechanoreceptors to provide man with spatial orientation and balance.

Under normal conditions on earth, maintenance of orientation and balance is a simple matter. The one-"g" force acting on the otoliths causes impulses to be sent to the brain which are in consonance with what man sees and feels. But under complex rotations, accelerations, and motions, which occur aboard ship in rough seas, for example, conflicting messages are sent to the brain. The results, some of which most people have experienced at one time or another, are dizziness, loss of orientation and balance, the appearance of visual illusions, nausea, and in severe cases even collapse.[1]

The manner in which the conflicting impulses interact with one another, and the influence of other psychosomatic disturbances such as anxiety, fear, and fatigue on these interactions to produce detrimental effects is not completely understood. Because overstimulation of the vestibular apparatus appears to be the primary factor involved, the term "canal sickness" has been used to describe these symptoms.[7]

Design Limitations Due to Canal Sickness: Man's response to the stimulus on the triad, and particularly on the inner ear, caused by the complex dynamic force environment peculiar to the rotating vehicle, is probably the most critical of all human factors in vehicle design.

The changing forces to which man's body is subject while moving inside the vehicle are also applied to the otoliths and semicircular canals. Changing gravity forces and Coriolis forces which come into play due to locomotion inside the vehicle or due to movement, rotation, or cocking of the head, all act on the vestibular mechanism. Such overstimulation is obviously conducive to canal sickness. Because of the deterioration in human performance and comfort which result, special attention must be given to vehicle design to prevent or minimize the possibility that Coriolis forces will produce canal sickness.

On the basis of a study involving a subject in a centrifuge, Clark and Hardy[3] have established an upper limit on angular velocity for the vehicle of 0.01 rad/sec. If the maximum limit on ω of 0.01 rad/sec. is to be observed, the radius to provide one "g," as calculated from equation (1), is an impractical 61 miles. To lessen the radius requires increasing ω above that which Clark and Hardy consider desirable from an environmental viewpoint, but there seems to be no other acceptable choice.

Experiments conducted in the slow-rotation room at Pensacola indicate that higher values of vehicle angular velocity may be permissible.[7] An upper limit of 0.4 radians per second, based on the Graybiel

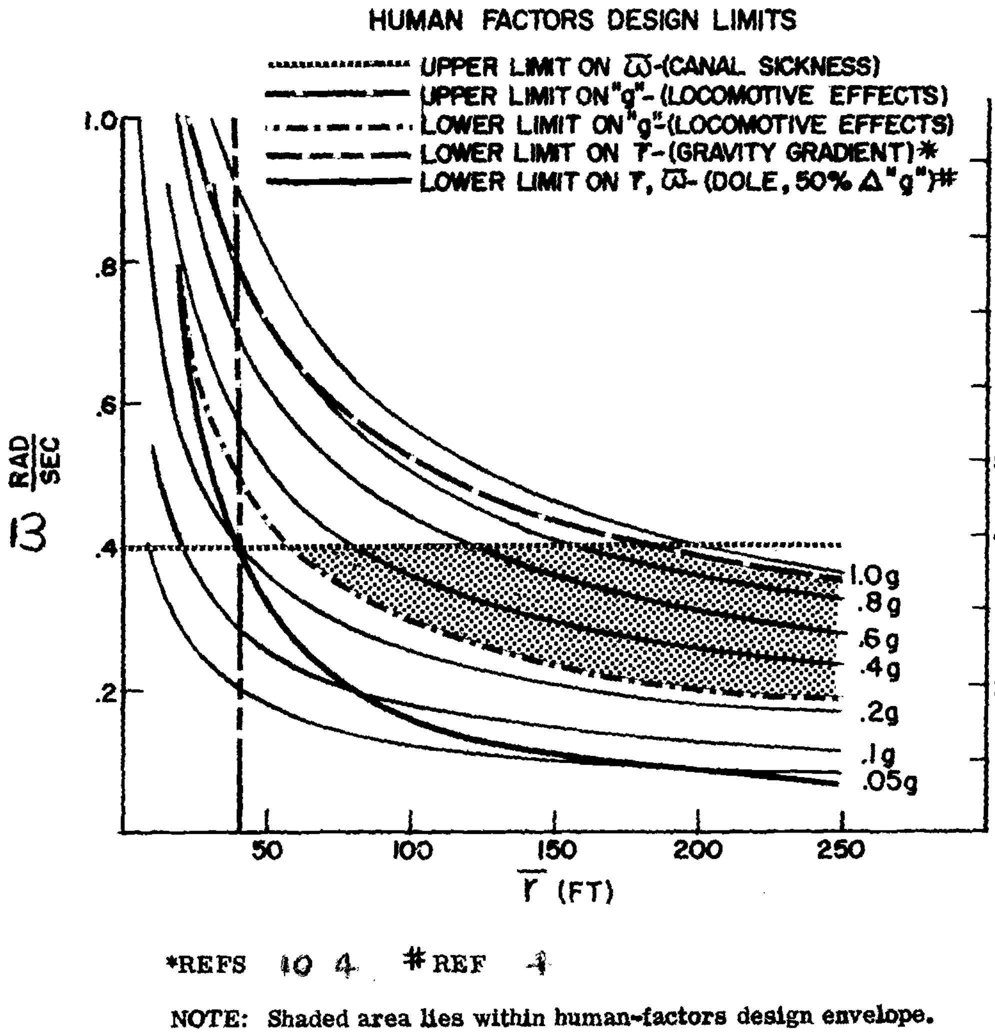

FIGURE 5. HUMAN-FACTORS STRESS LIMIT CURVES SUPERIMPOSED ON PLOT OF ANGULAR VELOCITY (ω) VERSUS RADIUS OF ROTATION (r̄) TO ACHIEVE VARIOUS LEVELS OF ARTIFICIAL GRAVITY IN MANNED ORBITAL SATELLITE VEHICLES

report and comments by Dole,[4] appears to be a realistic compromise between what is desirable from a human-factors viewpoint and what is at least practical from an engineering viewpoint. Accordingly, an upper limit of 0.4 radians/sec. is established for ω. The limit is indicated in Figure 5, superimposed upon a plot of angular velocity versus radius of rotation to achieve various levels of artificial gravity.

The degree to which the crew member will in fact be affected by canal sickness can be minimized through proper design. It is noted by Clark and Hardy, and corroborated by Graybiel, that if the head rotation takes place about an axis parallel to the spin axis, there is a minimum tendency for canal sickness to occur. From a design viewpoint, then, the crew station positions in the vehicle should be oriented so that the axis about which head rotation occurs most frequently, i.e., the head-to-toe axis, is parallel to the vehicle spin axis.

Although it is impossible to position man inside the rotating vehicle so that he can sit or stand normally and meet the requirement above, an advantage may be gained by orienting the crew station position so that when the crew member is in his normal position, his lateral axis, i.e., an axis through both his ears, will be parallel to the spin axis. This arrangement will permit maximum up-down rotation of the head with minimum Coriolis effects on the canals. In observance of this principle, it follows that the instrument display console at the crew-duty station should have an up-down rather than a left-right orientation. The console and controls should be designed so that in performance of duty-station tasks a minimum of left-right head movement is required. Similarly, assuming that most head rotation while in bed would occur about man's longitudinal axis, the crew bunks should be oriented axially. Figure 6 shows the geometric relationship which should exist between the designated axis of the crew member and the spin axis of the vehicle for both on-duty and off-duty stations.

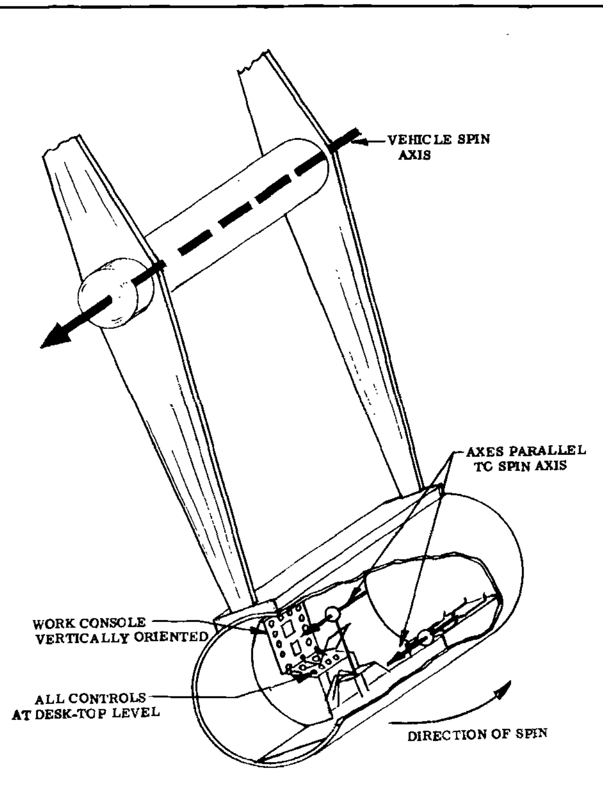

FIGURE 6. LIVING-WORKING COMPARTMENT DESIGN FEATURES TO MINIMIZE ADVERSE EFFECTS OF CORIOLIS FORCES ON CREW MEMBERS INSIDE ROTATING VEHICLE

The Upper Limit for Artificial Gravity: A requirement for a level of artificial gravity in excess of one "g" would appear to be necessary only for the purpose of pre-adapting a space crew prior to landing on a planet or other celestial body whose surface gravity level is greater than that on earth. Since at best this requirement lies in the remote future, it appears reasonable to select an upper limit of one "g." The upper limit is therefore prescribed by the requirement that at no time or position in the vehicle should the crew member experience more than one "g."

This basic limitation has further design implications because additional forces act when motion takes place tangentially in the direction of spin. Since the "g"-force increases due to this motion, it would be possible for the crew member in a vehicle rotated to provide one "g" to experience more than one "g" if he were to walk tangentially in the direction of spin. In order to permit him to walk tangentially with the spin without exceeding the basic one-"g" limit, the ambient "g"-level for the vehicle must be lower. This lower value sets the upper limit on artificial gravity.

For an assumed walking velocity of 4 ft./sec. and for any given radius of rotation, the upper limit on "g" may be calculated. For a vehicle with a radius of 80 ft., the maximum permissible value for ω is calculated to be 0.585 rad/sec. which results in an ambient "g"-level of 0.85 g. A crew member in this vehicle could move tangentially in the direction of spin at normal walking speed without exceeding the one-"g" limit. The upper "g"-limit curve showing limiting values of "g" for all values of r is shown on the graph of Figure 5. As might be expected, the curve diverges from the one-"g" curve at small values of radius, where the high values of ω cause significant Coriolis effects, and approaches the one-"g" curve at large values of radius, where the Coriolis effects are comparatively negligible.

The Lower Limit for Artificial Gravity: Recent in-flight experiments have been conducted by Aerospace Medical Laboratory personnel at Wright-Patterson Air Force Base, Ohio, which indicate that from a human-factors viewpoint a lower limit of 0.2 g should be established. The experiments involved an evaluation of the ability of a man to walk unaided under various levels of sub-gravity. The sub-gravity levels were obtained by flying a C-131 aircraft through Keplarian trajectories. Although the experiment was crude in nature, due to lack of precise instrumentation for maintaining constant sub-gravity levels close to the zero-gravity value, the results conclusively indicate that man is able to walk unaided at 0.2 g.

From a human-factors viewpoint, that "g"-level at which man can walk unaided appears to be a logical choice for the lower "g"-limit. Any lower value would probably provide more an environment of convenience than one which meets the psychophysiological requirements of man. Therefore a 0.2 g level is established as the lower limit for artificial gravity.

Following the same reasoning applied to the basic upper limit of one "g," the Coriolis effect for the crew member walking tangentially against the spin establishes a lower limit which is something greater than the basic 0.2 g limit. For the 80-ft.-radius vehicle, the lower limit is calculated to be 0.277 g. The curve showing the lower limit for all values of radius is shown in Figure 5. As in the case of the upper limit, the modification is more significant at small values of radius.

Limitation Due to Gravity Gradient: There is no experimental evidence available on the effect of a gravity gradient on man, nor is there any non-orbital experiment which can be performed to determine man's tolerance to a gravity gradient at "g"-levels less than one. As a result, it is necessary to assume some maximum permissible percentage of head-to-foot gravity gradient to floor-level gravity. Payne,[10] and Dole,[4] among others, select an arbitrary maximum percentage of 15 per cent, i.e., no value of radius will be used for which the gravity gradient between head and feet is more than 15 per cent of floor-level gravity. Selection of this figure places a minimum value on vehicle radius at 40 ft., as shown in Figure 5.

Other Limitations Due to Coriolis Effects on Locomotion: For radial motion in the vicinity of the axis of rotation, the distortion of the environment due to change in resultant force both in magnitude and direction would probably cause the onset of illusions[6] and mental confusion. Radial transport across the axis of rotation would be particularly stressful since the direction of "down" would reverse. The 180-degree change in body position would have to be performed in the vicinity of the axis. Because of the myriad of rapidly changing stimuli to the vestibular apparatus which would accompany this maneuver, it is clear that radial transport across the axis of rotation, or even stationary activity at the rotating axis, could probably not be tolerated unless the "hub" of the vehicle were non-rotating, with provision made for transfer from moving "spoke" to non-rotating hub at some minimum radius, say 6-10 ft.

From a design viewpoint, the minimization of the adverse effects of radial motion can be affected by conducting all normal activity as far away from the axis of rotation as possible (since large radius minimizes the effect), by keeping radial traffic to a minimum, by precluding transport across the axis, or activity at the axis, unless the hub of the vehicle is non-rotating, and finally, by minimizing radial movement of hands, arms, legs, and feet at the crew duty-stations.

Tangential motion has previously been discussed in establishing upper and lower artificial gravity limits. The change in gravity experienced by the crew member walking tangentially poses a problem in that there is no experimental evidence to indicate the ability of man to discriminate between small gradations of gravity or on the maximum permissible deviation from local "g"-level which can be tolerated without adverse psychophysiological or locomotive effects. Dole[4] places a maximum permissible limit of 50 per cent variation between tangential walking and stationary gravity levels. The curve labeled "Dole, 50 per cent $\triangle$ g" in Figure 5 indicates the lower limits for ω and τ corresponding to this requirement for a walking velocity of 4 ft./sec.

For axial walking, the only peculiarity to be observed is the fact that the radial components of limb velocity will result in the application of side Coriolis forces to the limbs. But because the radial velocity components of the arms and legs will be small, and because the radial motion will be reciprocating in nature, the disturbance will probably be of the form of minor perturbations of the limbs accompanying rather than hindering locomotion. As a foot is raised, for example, it will be deflected sideways by a small Coriolis force. As it is planted, the force will act in the opposite direction with the result that the foot will more or less be planted in line with the intended direction of walk. There will be some effect on the vestibular apparatus due to Coriolis forces which result from radial bobbing of the head while walking (which will also occur when walking tangentially), but in general the effects will not be as critical as those others which accompany radial and tangential locomotion.

Because axial motion results in the least distortion of the artificial gravity environment, it would appear that the vehicle should be designed so as to take advantage of this fact, i.e., the major dimension of the crew compartment should be placed parallel to the vehicle spin axis.

The Human-Factors Design Envelope: An examination of the tolerance limit curves superimposed on the basic ω versus τ graph of Figure 5 indicates that the human-factors design envelope is prescribed on three sides by the upper "g"-limit, the lower "g"-limit, and the upper limit on ω of 0.4 rad/sec. Since the other stress-limit curves lie outside the envelope, the stress limits they represent will not normally be exceeded in the crew compartment for any operating point of ω and τ which lies within the envelope.

Human-Factors Design Principles: The general principles to be observed in vehicle design may be briefly summarized:

1. Radial traffic should be kept to a minimum.
2. Transport across the spin axis and human activity at the spin axis should be prohibited unless the hub is non-rotating.
3. The crew compartment should be located as far as possible from the axis of rotation.
4. The compartment should be oriented so that the direction of traffic, i.e., the major dimension of the compartment, is parallel to the spin axis.
5. Crew duty-station positions should be oriented so that during normal activity, the lateral axis through the crew member's ears is parallel to the spin axis. In conjunction with this requirement, the work console instruments and controls should be designed so that left-right head rotations and up-down arm motions are minimized (Figure 6).
6. Sleeping bunks should be oriented with their long axis parallel to the vehicle spin axis (Figure 6)
7. The presence of confusing visual stimuli should be minimized. For example, the apparent convergence of the vertical from any two points separated tangential-

ly should be played down by proper interior decoration, and except for necessary observation ports, which should be covered when not in use, the crew compartment should be windowless.[10]

While not directly related to vehicle design, it is worth noting parenthetically that proper crew selection and training can minimize those environmental deficiencies which cannot be eliminated. Graybiel's findings indicate that susceptibility to canal sickness should be included as a screening device for selection of astronauts, and that insofar as earth-bound facilities permit, the astronauts should be pre-adapted to a rotating-vehicle environment.

Selection of an Optimum Vehicle Configuration: While many vehicle configurations are possible, there are essentially only three basic configurations, all stemming from the simple dumbbell as a prototype. The first is the dumbbell itself. The second is the torus, which is a figure of revolution obtained by rotating a symmetrical dumbbell about its major axis of inertia. The third may be described as an axially-expanded dumbbell. This configuration is obtained by using parallel cylinders rather than spheres and by using one or more connecting shafts.

The Dumbbell: This configuration is characterized by a crew compartment and useful or deadweight countermass, connected by a rigid shaft.* Rocket boosters presently in use are particularly adaptable to this configuration. Because of its elongated, cylindrical shape, the booster can serve as the rigid connecting structure, with a crew compartment at one end and, as in a proposal by Ehricke,[5] a nuclear power source as countermass at the other (Figure 7).

The primary advantage to be gained through use of this configuration is the early achievement of an orbiting vehicle which will provide an artificial gravity environment.

The primary disadvantage connected with use of this configuration is the limitation in the lateral dimensions of the crew compartment. This limitation can be minimized through use of several "floors," each at a different radius with a different "g"-level. Radial expansion of the crew compartment is more or less dictated by necessity when the booster itself is used as the dumbbell structure.

Because of the disadvantages which result from a human-factors viewpoint, i.e., the existence of several different "g"-levels and the excessive radial traffic which becomes necessary in a radially-oriented compartment,

* Use of a flexible shaft, i.e., a steel cable, to connect the crew compartment with the countermass is treated in some detail in Reference 9.

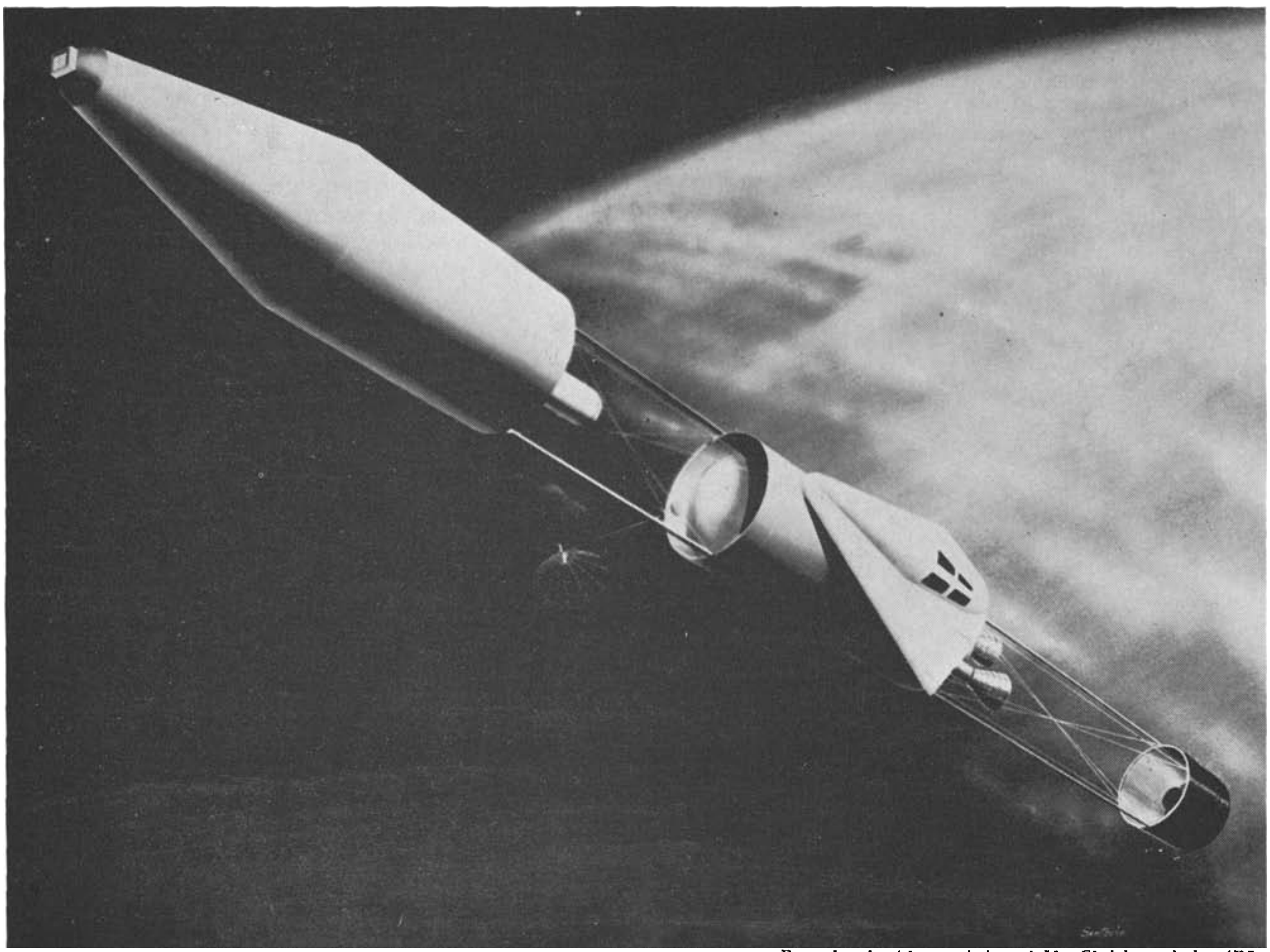

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Fig. 7. Illustration of use of dumbbell configuration in design proposal by Ehricke.

the configuration is not considered to be optimum.

The Torus: The limitation in the lateral dimensions of the crew compartment of the dumbbell can be alleviated by extending the compartment in the tangential or axial direction. The torus configuration is obtained by extension of the compartment in the tangential direction. The configuration was made famous by Von Braun with his celebrated "space wheel" proposal in 1952.[12] Among the advantages enumerated for the torus configuration by Schnitzer are: (1) the spinning torus can easily be stabilized since the torus is rotated about its major axis of inertia, and (2) there is an equal gravity level everywhere along the outer wall, i.e., the "floor," of the torus.[11] To these advantages of the torus configuration may be added the ease with which the "inner-tube" configuration lends itself to the use of an inflatable material as the primary vehicle structure.

There are several disadvantages which accompany use of this configuration. They stem primarily from the fact that the plane in which the torus lies is the plane of rotation, i.e., the plane in which motion produces maximum Coriolis forces. The disadvantages are:

1. The major axis of traffic is tangential. Therefore, crew members would be subject to continual variations in gravity-level while moving back and forth.

2. Orientation of bunks and control consoles to minimize incidence of canal sickness would require that they be placed perpendicular to the "aisle" rather than along it. This arrangement would probably result in inefficient utilization of space.

3. Visual conflict would be prevalent unless special precautions were taken in interior design.

a. The change in apparent vertical from one point to another down the aisle would be obvious and disconcerting.

b. The curvature of the floor in the direction of the aisle would be apparent. The crew member would always be in a "valley."

c. It would always appear to the crew member walking along the aisle that he were walking "uphill." At the same time, while walking against the spin, he would feel "lighter," i.e., he would feel as though he were walking "downhill." It may be expected that the resulting conflict would be particularly stressful.

These phenomena would be emphasized in smaller-radius vehicles and less apparent for vehicles of large radius. While compartmentalization of the torus would help to minimize some of the visual conflict, it could not be completely eliminated.

4. The torus cannot very well be optimized for size. Once a radius for the floor of the crew compartment is selected from the design envelope, the size of the torus

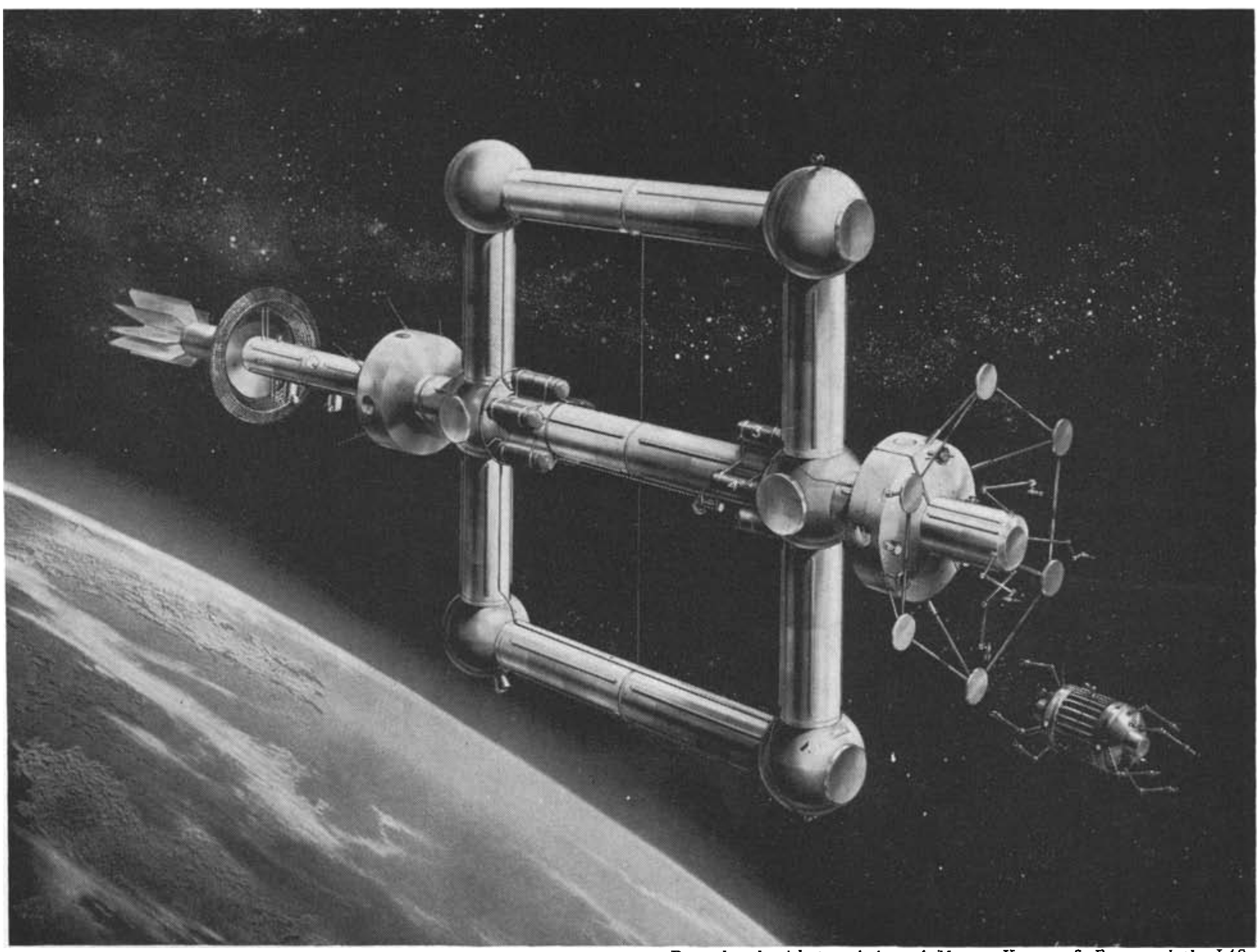

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Fig. 8. Illustration of use of axially-expanded configuration in design proposal by Kramer and Byers.

is automatically established with a circumference of $2\pi r$, regardless of whether or not the resulting space provided is optimum. The location of most of the vehicle components at the radius of the torus compartment to make maximum use of space within the torus would involve unnecessary structural penalties.

This disadvantage can be minimized by using an interrupted torus, in which only segments of the torus would be used, with each segment connected to the hub by one or more spokes, but this modification would result in extensive radial traffic if more than one of the segments were occupied. If not, the configuration would essentially degenerate into a dumbbell with most of the above disadvantages still present.

It may be concluded that an expansion of the crew compartment of the dumbbell in the tangential direction would result in a magnification of the inadequacies inherent in the artificial gravity environment, and in inefficient economy of structure. Because the torus is admirably suited to use of an inflatable material for its basic structure, the configuration has some value as a minimal-capability, experimental vehicle. But its inherent disadvantages bar its selection as an optimum configuration.

The Axially-Expanded Dumbbell: The alternate direction in which the crew compartment of the dumbbell may be extended is the axial direction. This configuration is obtained by merely expanding the dumbbell along the spin axis. The most prominent example of the use of this configuration is in a proposal by Kramer and Byers.[8] The Kramer and Byers vehicle (Figure 8) provides for two symmetrically-opposed crew compartments and two radial shafts (plus a third compartment along the spin axis).

The axially-expanded dumbbell has the inherent advantages which accrue as a natural consequence of the orientation of the major dimension of the crew compartment parallel to the axis of rotation. The design minimizes the detrimental effects of the artificial gravity environment caused by Coriolis forces. The advantages are:

1. The major axis of traffic is axial. Therefore, crew members would experience a constant gravity-level while moving back and forth along the crew compartment. Increase and decrease in "g"-level accompanying tangential movement would be minimized because this movement would occur across the relatively narrow dimension of the compartment. Such movement would probably be at velocities less than the assumed 4 ft./sec. indoor walking velocity; hence the effect would be further minimized if not practically eliminated.

2. Orientation of crew bunks and control consoles parallel to the aisle and against the walls would be ideally compatible with the axial orientation of the aisle.

3. Visual conflict would be minimized.

a. There would be no change in apparent vertical anywhere along the center of the aisle. Change in apparent vertical across the aisle would be minimized due to the narrow dimension in the tangential direction, and for a large-radius vehicle the change would probably be imperceptible.

b. The floor would be perfectly flat along the length of the compartment. The crew member walking back and forth along the aisle would experience a constant "g"-level compatible with what his eyes would see as a flat, level surface. To compensate for the slight variation in vertical across the compartment, a slight lateral curvature could be built into the floor for small-radius vehicles. For large-radius vehicles the floor could be made perfectly flat.

4. The axially-expanded dumbbell can be optimized with respect to size. The relationship between the radius selected for the vehicle and the length of the crew compartment would not be fixed, as it is for the torus. The only limit on compartment length would be that imposed by the requirement for inherent vehicle stability.

5. The cylindrical shape of the crew compartment would simplify the boost problem, since the shape would be compatible with the cylindrical shape of the booster.

The disadvantages are:

1. The configuration has the inherent disadvantages which result from the use of a second crew compartment as countermass to the first.

a. Essentially two separate closed-ecological-systems or one large, complex one would be required.

b. Radial traffic would be extensive.

2. Design for inherent stability would be more critical for this configuration than it would be for the dumbbell or the torus.

In summary, of all the configurations considered, the axially-expanded dumbbell is unique in that it minimizes the undesirable effects of the artificial gravity environment. Its disadvantages can be eliminated or compensated for through slight modification and proper design.

The Optimum Configuration: The optimum configuration is a Modified Axially-Expanded Dumbbell in which only one of the two cylinders is used as a crew compartment. Useful countermass, consisting of vehicle components, is used in place of the second compartment. This modification results in the elimination of the requirement for a complex closed-ecological-system, and minimizes radial traffic and its detrimental effects, thus making the configuration optimum from a human-factors viewpoint without sacrificing engineering practicality or operational suitability.

The optimum configuration is reflected in the vehicle conceptually illustrated in Figure 9. The vehicle is referred to as the Pseudo-Geogravitational Vehicle because it provides an artificial gravity environment which approximates that on earth (about 0.9 g). The selected values for the rotational variables ω and r are indicated on the human-factors design envelope of Figure 10 by the point labeled P.G.V. Operating points for some current proposals are also indicated on the figure.

It is seen that the P.G.V. operating point lies at the upper border of the envelope at the minimum possible radius which permits achievement of the upper "g"-limit. The designated operating point is significant because:

1. Of all the operating points which lie within the design envelope, it is an optimum operating point which reflects considerations of practicality at the same time

that it provides a nearly earthlike artificial gravity environment. As such, it represents the upper limit of difficulty of the engineering design problems connected with artificial gravity in space vehicles.

2. It establishes a practical upper limit on τ, since the range of τ values between 60 ft. and 180 ft. permit the selection of the entire range of permissible "g"-values. The upper limit on τ, indicated by the vertical

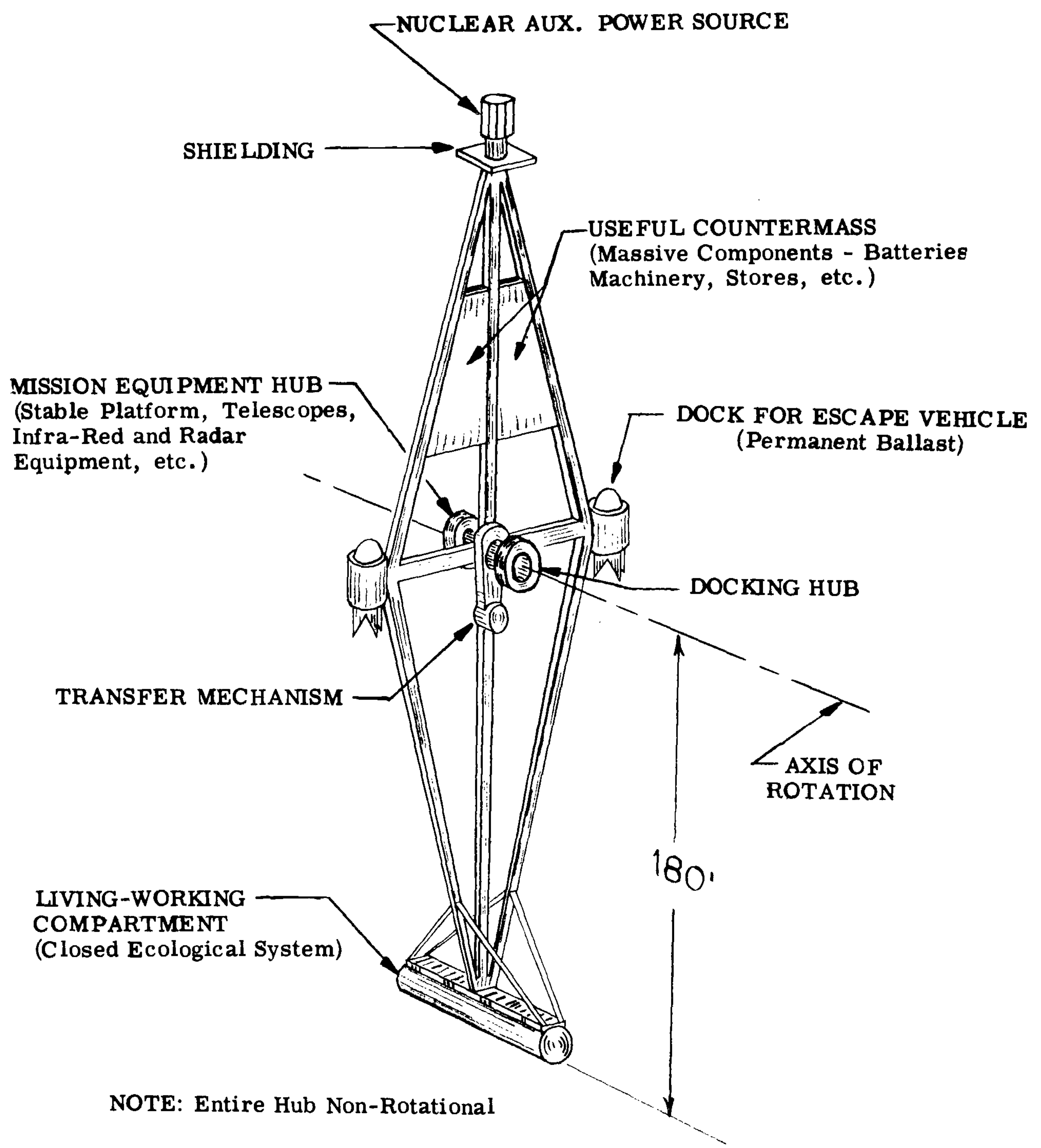

FIGURE 9. ILLUSTRATION OF USE OF THE MODIFIED AXIALLY-EXPANDED DUMBBELL CONFIGURATION IN THE CONCEPTUAL DESIGN OF A MANNED ORBITAL SATELLITE VEHICLE

dashed line, serves to narrow the region of interest for future design.

It may therefore be concluded that the design of future vehicles should be based on operating points which lie within the shaded area of Figure 10 and on the principles embodied in the conceptual configuration shown in Figure 9.

SUMMARY

A design envelope and the optimum vehicle configuration are established through a human-factors analysis of the artificial gravity environment peculiar to rotating space vehicles. The envelope is prescribed by: an upper limit on vehicle angular velocity of 0.4 radians/sec. to minimize occurrence of "canal sickness"; an upper limit of one "g," and a lower limit of 0.2 g to permit unaided walking, both limits modified to compensate for Coriolis effects; and a practical upper limit on vehicle radius of 180 feet. The optimum configuration is characterized by a single cylindrical crew compartment oriented parallel to the spin axis, counterbalanced by other vehicle components. The configuration is illustrated in the conceptual Pseudo-Geogravitational Vehicle of 180-foot radius, rotated at 0.4 radians/sec. to produce 0.9 g in the crew compartment.

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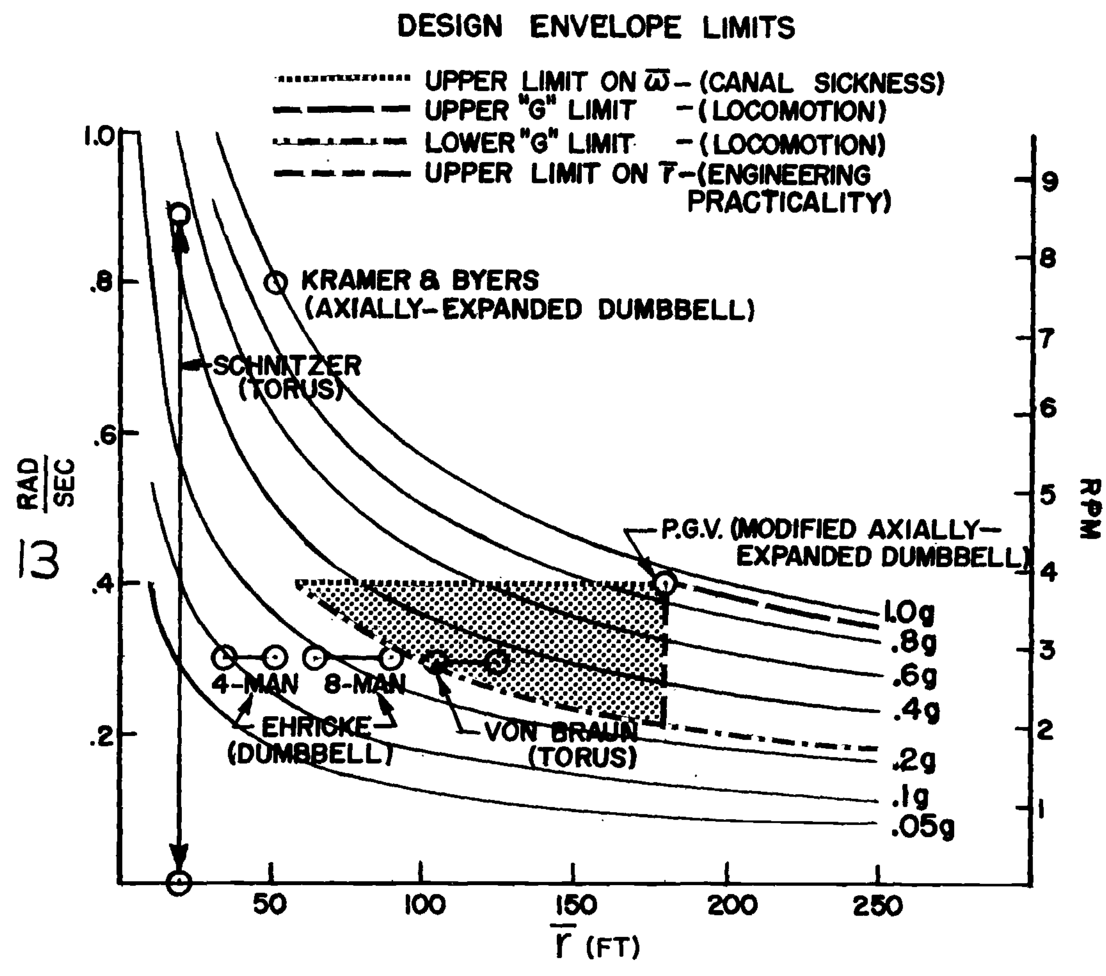

NOTE: Shaded area is design area of interest.

FIGURE 10. HUMAN-FACTORS DESIGN ENVELOPE SUPERIMPOSED ON PLOT OF ANGULAR VELOCITY (ω̄) VERSUS RADIUS OF ROTATION (r̄) TO ACHIEVE VARIOUS LEVELS OF ARTIFICIAL GRAVITY. OPERATING POINTS FOR PSEUDO-GEOGRAVITATIONAL VEHICLE (P.G.V.) AND OTHER CURRENT DESIGN PROPOSALS ARE INDICATED

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