

**OPTIMIZATION OF MANNED ORBITAL SATELLITE VEHICLE  
DESIGN WITH RESPECT TO ARTIFICIAL GRAVITY**

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## FOREWORD

This report was prepared by Capt. Loret as a master's thesis in partial fulfillment of the requirements for the Master of Science Degree in Astronautics at the USAF Institute of Technology in 1961. The topic was selected from a list of requirements under the Behavioral Sciences Laboratory, Project No. 7184, "Human Performance in Advanced Systems," Task No. 718405, "Design Criteria for Crew Stations in Advanced Systems." Personnel of the Behavioral Science Laboratory and particularly of the Crew Stations Section provided consultation and background material to Capt. Loret.

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## ABSTRACT

A design envelope is established as the result of 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 radian/second to minimize the occurrence of "canal sickness"; a basic upper limit on artificial gravity of 1 g; and a basic lower limit on artificial gravity of 0.2 g as the lowest value of g at which man can walk unaided. Both g-limits are modified to compensate for Coriolis forces which cause variation in g-level for tangential walking inside the rotating vehicle. An upper limit on vehicle radius of 180 feet is established on the basis of engineering practicality.

The optimum vehicle configuration is established as a Modified Axially Expanded Dumbbell, characterized by a single, cylindrical, living-working compartment oriented parallel to the spin axis, counterbalanced by other vehicle components. The configuration is illustrated in the conceptual Pseudo-Geogravitational Vehicle, which has a radius of 180 feet and an operational angular velocity of 0.4 radian/second to produce 0.9 g in the living-working compartment.

## PUBLICATION REVIEW

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OPTIMIZATION OF MANNED ORBITAL SATELLITE VEHICLE  
DESIGN WITH RESPECT TO ARTIFICIAL GRAVITY

I. INTRODUCTION

The design of manned orbital satellite vehicles which are rotated to create artificial gravity is described. Human factors are given primary importance in the investigation but engineering and operational factors are also considered. The purpose of the study is to provide specific design criteria and an optimum configuration for vehicles of this type.

Background to the Problem

One of the most serious handicaps to the engineer who attempts to design a manned orbital satellite vehicle is his inability to obtain a definite answer to the question, "Will an artificial gravity environment be necessary for the efficiency and comfort of the crew, and if so, how much 'g' is necessary?" The answer to this question is unknown to the aeromedical specialists. To date the longest period of observed weightlessness experienced by man is a little over 1 day. Experimental data on long-term effects of zero gravity on man will not be available until human-orbit times of several days and weeks are available.

Until the data becomes available, the aeromedical specialists are extremely reluctant to make predictions concerning how much gravity is necessary, or whether any is necessary at all. They consider invalid any attempt to extrapolate from the data compiled from short-exposure, zero-g experiments, or from the longer-exposure experiments involving men and animals shot into short-time orbit.

Although the experts have attempted to refine their estimates, in the absence of a definite answer to the question, the design engineers have had no choice but to provide separate designs to meet either contingency. Design proposals to date have provided for either a weightless environment or a g-level for the vehicle based upon an educated guess at what the proper g-level should be.

Most satellite vehicles have been designed to optimize such parameters as mass ratios, thrust-weight ratios, booster engine performance, and other critical criteria. Very little appears to have been done to optimize design with respect to artificial gravity. Dole (ref. 9) makes note of this gap in his recent work on the subject for the Rand Corporation. The gap is only partly explained by the lack of definite information concerning the effects on man of sustained zero g. Another important reason is the fact that designing for artificial gravity is an activity that falls into the province of both the engineer and the aeromedical specialist. Neither individual, except in rare cases, is sufficiently qualified in both fields to undertake the job alone.

Because the optimization of design with respect to artificial gravity has not received so much attention to date as have other aspects of space-vehicle design, it is a fertile field for investigation.

### Scope of the Investigation

The question of whether artificial gravity is necessary will not be discussed in this paper. It is assumed from the beginning that artificial gravity is either desirable or absolutely necessary. The task then becomes one of optimizing the design with respect to this criterion.

As stated earlier, human factors are given primary importance; i. e., the criteria established are those which optimize vehicle design with respect to man, his efficiency, and his comfort, in an artificial gravity environment. The placement of emphasis on human factors is not meant to imply that other factors are ignored, but rather that their consideration is restricted to only those aspects relevant to the main topic.

Finally, it will be assumed that more than a minimal-capability vehicle can be placed in orbit. The assumptions are made that:

- (a) The vehicle can be constructed in orbit
- (b) The vehicle will be a permanent installation with provision made for resupply and exchange of crew every few weeks
- (c) The mission of the vehicle will require the presence of an inertially stable platform.

Although these assumptions imply a projection into the future, the principles derived in this investigation are applicable to the design of any manned orbital satellite vehicle which is rotated to create artificial gravity.

### Approach

The general approach is to identify the variables which affect the rotation, to analyze the interrelationships between the variables and the human factors in order to prescribe a human factors design envelope, and to select an optimum configuration for the vehicle based on human factors, engineering, and operational considerations.

In accordance with the general plan, Section II is devoted to an analysis of the artificial gravity environment. The variables are identified and their relationship to g-level established. Peculiarities of the artificial gravity environment in terms of static and dynamic forces are discussed. Some figures of merit are established.

Section III is concerned with man's ability to maintain his orientation, his equilibrium, and his efficiency in the artificial gravity environment. Where possible, experimental evidence is used to establish permissible stress levels. Reasonable assumptions are made to establish tolerance limits in those cases where no experimental evidence is available. The definition of maximum stress under which man can still operate comfortably and efficiently establishes a human factors design envelope and some human factors design principles.



Further limits on vehicle design are established in Section IV through consideration of engineering and operational requirements. A comparison of various possible vehicle configurations in the light of human, engineering, and operational factors permits the selection of an optimum design configuration in Section V. The use of the parameters for future design, illustrated in a description of a Pseudo - Geogravitational Vehicle, and some comments on mimal-capability design and current proposals serve to conclude the investigation.

Section VI contains a summary of the investigation, a statement of the conclusions derived therefrom, and some recommendations for future research.

II. THE ARTIFICIAL GRAVITY ENVIRONMENT

Creation of Artificial Gravity Through Rotation

In the weightless environment which exists in a satellite vehicle in orbit around the Earth, an artificial gravity force can be created by rotating the vehicle about some nearby axis or about some self-contained axis, as shown in figure 1. The rotating rim of the vehicle shown in the figure continually accelerates the man inward toward the spin axis. The rim force creating this acceleration is called centripetal force (shown by the white arrow). Centrifugal force (shown by the black arrow) is an equal and opposite inertial reaction force which is experienced by the man as "weight." The Newtonian expression  $\bar{F} = m \bar{a}$  is applicable and, for the case of rotation, the artificial gravity force is given in vectorial form as:

$$\bar{F}_g = - \frac{\bar{\omega} \times (\bar{\omega} \times \bar{r})}{g_c} \quad (1)$$

where

$\bar{F}_g$  = the artificial gravity force (centrifugal force),  $lb_f/lb_m$  (g's per unit mass)

$g_c$  = the gravitational constant,

$$32.2 \frac{lb_m ft}{lb_f sec^2}$$

$\bar{\omega} \times (\bar{\omega} \times \bar{r})$  = the centripetal acceleration\*,  $ft/sec^2$

in which  $\bar{\omega}$  = the angular velocity of rotation\*\*,  $rads/sec$

$r$  = the perpendicular distance from the axis of rotation to the object on which the force acts, feet

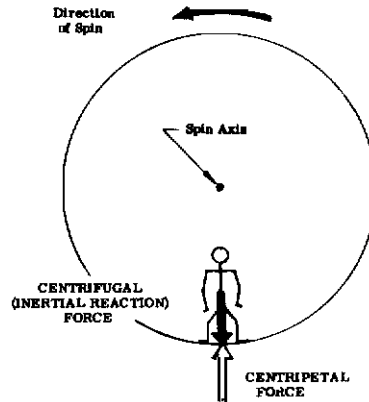


Figure 1. Creation of Artificial Gravity Through Use of Rotating Vehicle

\* The minus sign is introduced into the equation to account for the fact that the centrifugal force is an inertial reaction force which acts in a direction opposite to the centripetal acceleration.

\*\* In vector notation, the angular velocity vector is defined as a vector lying along the axis of spin, with its positive direction being that in which a right-hand screw would move if it were rotated in the direction specified, and with its length proportional to the scalar magnitude of the angular velocity. For basic vector analysis, the reader is referred to Wiley (ref. 4) or Constant (ref. 8).

The usual reference used in discussing artificial gravity is the 1-g value experienced by objects on the earth's surface, where the acceleration of 1 g, i. e., 32.2 ft/sec<sup>2</sup>, is used to express the equivalent force which will produce this value of acceleration. In this paper, the terms gravity, artificial gravity,  $\bar{F}$ , and g, are all used interchangeably to represent forces or their equivalent accelerations. Various levels of artificial gravity are expressed in terms of the standard gravity force on earth; i. e., 0.5 g is an artificial gravity force equivalent to an acceleration of 0.5 (32.2 ft/sec<sup>2</sup>), or 16.1 ft/sec<sup>2</sup>.

For rotation, the centrifugal force vector has a magnitude equal to  $(\omega^2 r)/g_c$  and is always directed outward from, and perpendicular to, the axis of rotation. The variables which influence the magnitude of artificial gravity force are the angular velocity ( $\bar{\omega}$ ) and the radius of rotation ( $\bar{r}$ ). The two may be regulated individually or together to achieve any desired level of gravity.

Figure 2 shows a plot of angular velocity versus radius to achieve various g-levels. For any constant angular velocity, the magnitude of gravity experienced by an object at a particular position inside the rotating vehicle varies directly as its radius from the axis of rotation. As a consequence, objects close to the axis of rotation experience a lower g-level than those further out. Objects at the axis of rotation will experience zero g; i. e., they will be weightless.

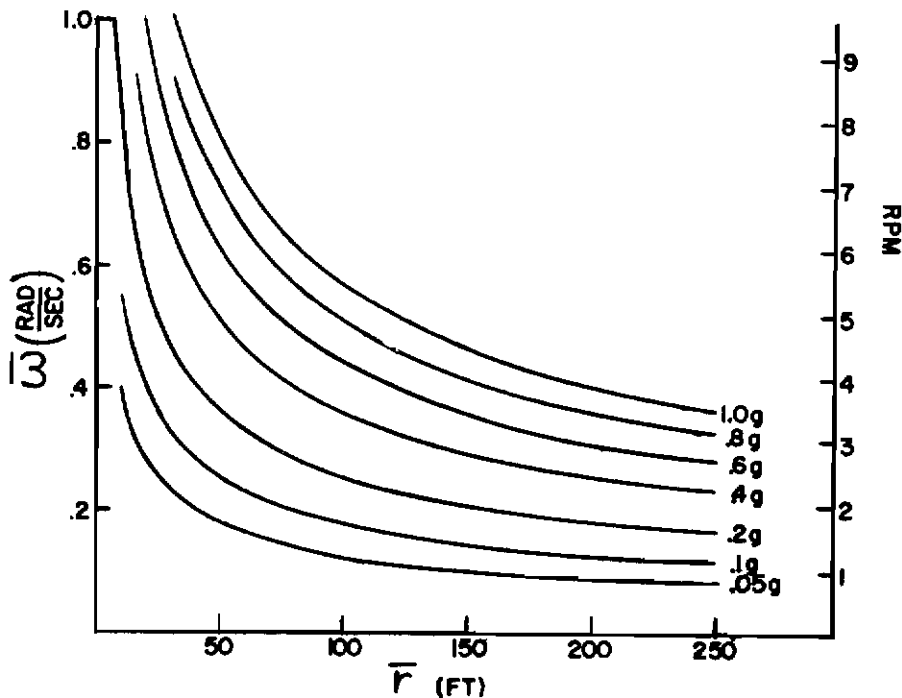


Figure 2. Angular Velocity ( $\bar{\omega}$ ) Versus Radius of Rotation ( $\bar{r}$ ) To Achieve Various Levels of Artificial Gravity in Manned Orbital Satellite Vehicles

Because of its significance in terms of human factors, this "gravity gradient" which exists inside the rotating vehicle is an important design consideration.

The Gravity Gradient

In a normal standing position on an inside rim of the rotating vehicle, a man will be oriented with his longitudinal axis perpendicular to the spin axis (figure 3). His head will be at a lesser radius than his feet, hence his head will feel "lighter" than his feet. For the reclining man (figure 4), this gravity differential will be negligible because his entire body lies at a constant radius.

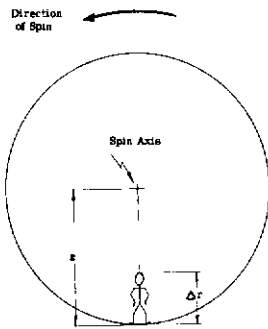


Figure 3. Man Standing in Rotating Vehicle Experiencing Head-to-Foot Gravity Gradient

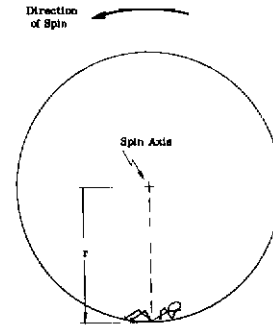


Figure 4. Man Reclining in Rotating Vehicle Experiencing Uniform Gravity

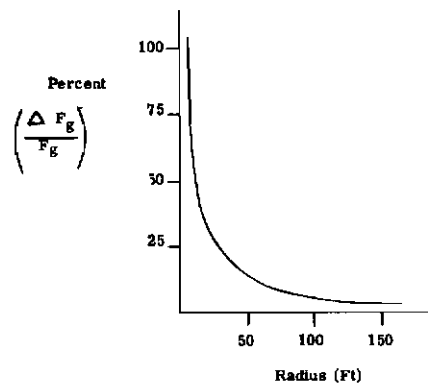
The percentage expressed as the gravity gradient between head and feet to the gravity at "floor" level varies with radius. For any radius of the floor and with the assumption of the man's height as 6 feet, the percentage can be expressed as:

$$\frac{\Delta F_g}{F_g} = \frac{\omega^2 (6)}{\omega^2 r} (100\%) = \frac{600}{r} \% \quad \text{for } r \geq 6 \quad (2)$$

The restriction is placed on  $\bar{r}$  because, for values of  $\bar{r}$  of less than 6 feet, the axis of rotation will pass through the man's body, with the result that the portion "above" the axis of rotation will experience slight negative g, while the portion at the axis experiences weightlessness. Such a situation is obviously unacceptable.

A plot of percentage versus radius is shown in figure 5. A glance at the curve shows that, at radii larger than 40 feet, the percentage drops to less than 15 percent.

Figure 5. Gravity Gradient (Head-to-Foot) Experienced by a 6-ft. Man in Rotating Vehicle, Expressed as Percentage of Gravity at Floor Level, for Various Values of Floor Radius



## Coriolis Effects

In addition to the artificial gravity force discussed above, a man on or inside the rotating vehicle who moves with respect to the vehicle will experience inertial reaction forces known as Coriolis forces. The Coriolis force vector is given by the expression:

$$\bar{F}_c = - \frac{2 \bar{\omega} \times \bar{v}}{g_c} \quad (3)$$

where  $\bar{F}_c$  = the Coriolis force,  $\text{lb}_f/\text{lb}_m$  (g's per unit mass)

and  $\bar{v}$  = the velocity of the man with respect to the rotating reference frame, ft/sec

The magnitude of the Coriolis force, expressed in g's per unit mass, is:

$$F_c = \frac{2 \omega v \sin \theta}{g_c}$$

where

$\theta$  = The angle between the  $\bar{\omega}$  vector and the  $\bar{v}$  vector, in degrees or radians

The direction in which the Coriolis force acts is given by the normal rule for vector cross products. \*

It can be seen that the Coriolis force is proportional to the magnitudes of the variables  $\bar{\omega}$ ,  $v$ , and  $\theta$ , but is independent of  $\bar{r}$ . The introduction of the variable  $\theta$  causes the phenomenon of Coriolis force to differ from that of centrifugal force in that, while the centrifugal force is always directed perpendicularly outward (i. e., radially) from the spin axis, the Coriolis force direction and magnitude depend upon the geometric relationship between the spin axis and the relative velocity vector

Coriolis forces will have maximum value when  $\theta$  equals  $90^\circ$ ; i. e., when the velocity vector lies in the plane of rotation (any plane perpendicular to the spin axis). Any motion in the plane of rotation can be resolved into radial and tangential components.

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\* The direction of a vector cross product is given by the "righthand rule"; i. e., if the fingers of the right hand are pointed in the direction of the  $\bar{\omega}$  vector and the hand is then rotated fingers toward palm (through the shortest angle) so that the fingers point in a direction parallel to the  $\bar{v}$  vector, the right thumb will point in the direction of the vector cross product. The minus sign on the right side of equation 3 indicates that the Coriolis inertial reaction force acts in a direction opposite that indicated by the vector cross product ( $\bar{\omega} \times \bar{v}$ ).

For radial motion, the Coriolis force will act perpendicular to the gravitational force as shown in figure 6. This peculiarity results because each rung of the ladder has a higher inertial tangential velocity than the one above it, the magnitude of the velocity for each rung being equal to the product of  $\omega$  and the radius to the rung. Therefore, the man climbing the ladder (figure 6, left) must decelerate to the left to match his tangential velocity to the tangential velocity of the next higher rung. He does this by pulling himself to the left as he climbs. The deceleration gives rise to an inertial reaction force, the Coriolis force, which acts to the right as shown. The converse analysis is applicable for descent from the spin axis (figure 6, right).

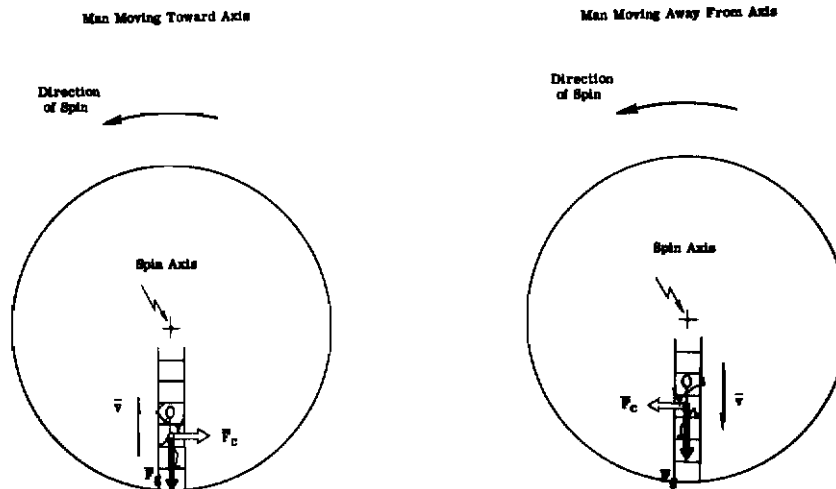


Figure 6. Inertial Reaction Forces Experienced by Man Moving in Radial Direction Inside Rotating Vehicle

For tangential motion, the Coriolis force will act parallel to the centrifugal force, adding to it if the direction of motion is "with" the spin, and opposing it if the direction of motion is "against" the spin (figure 7). Thus, a man walking tangentially with the spin will feel "heavier," while a man walking in the opposite direction will feel "lighter." In effect, a tangential velocity acts to increase or decrease the effective (inertial) angular velocity. Hence, a man walking tangentially can be considered to be subject to an artificial gravity force equal to  $(\omega_{\text{effective}})^2 r / g_c$ , where  $\omega_{\text{effective}} = (\omega \pm \frac{v}{r})$ . An expansion of the squared term gives rise to the artificial gravity force consisting of two positive terms—the normal artificial gravity force,  $+ \omega^2 r / g_c$ , due to vehicle rotation, and an additional artificial gravity force,  $+ v^2 / r g_c$ , due to the relative velocity of the man around the inside rim of the vehicle—with respect to the vehicle—and to the Coriolis force,  $\pm 2\omega v / g_c$ , the sign of which depends on whether the direction of walk is with or against the spin.

No Coriolis forces will exist when  $\theta = 0^\circ$  or  $\theta = 180^\circ$ ; i.e., when the velocity vector is parallel to the spin axis.\* A man walking parallel to the spin axis with constant velocity will therefore, in general, experience only the local gravity force (figure 8).\*\*

\* The only other condition for which Coriolis forces will be nonexistent in the rotating vehicle will be for stationary objects, i.e.,  $v = 0$ .

\*\* The minor Coriolis forces which will act on various parts of the body—i.e., the limbs, due to their radial motion while walking in an axial direction—are discussed in section III.

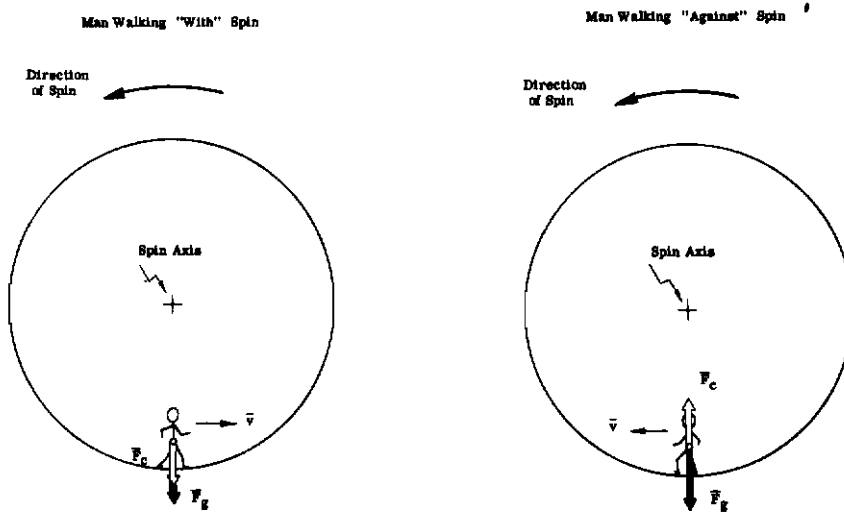


Figure 7. Inertial Reaction Forces Experienced by Man Moving in Tangential Direction Inside Rotating Vehicle

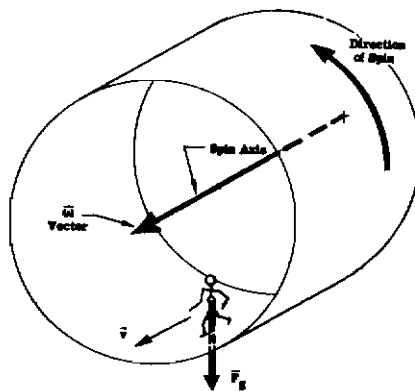


Figure 8. Inertial Reaction Forces Experienced by Man Moving in Axial Direction Inside Rotating Vehicle

The Coriolis force experienced by a man moving along any random path inside the rotating vehicle can be calculated through resolution of the motion along the orthogonal system formed by the radial, tangential, and spin axes. The superposition of the calculated effects along each axis will provide a net resultant Coriolis force. The contributions of Coriolis forces due to the radial and tangential components of velocity added to the local centrifugal force will give the total resultant force on the man due to rotation and movement. As seen above, the component of velocity along the axis of rotation causes no contribution to the net total force experienced.

The path followed by any object thrown, tossed, or "dropped" inside the rotating vehicle can be calculated with respect to any desired reference frame by use of analytical dynamics (ref. 26).

Combined Effects of Coriolis Forces Plus Artificial Gravity

The force environment to which man is subject inside the rotating vehicle may differ significantly from the gravitational environment to which he is subject on earth, depending on the values selected for the variables which influence the artificial gravity environment, i. e.,  $\omega$  and  $\bar{r}$ .

Radial motion, which superimposes side forces upon the artificial gravity force, is one peculiarity man will experience in the rotating vehicle. With respect to this peculiarity, a figure of merit which is used in vehicle design is the ratio of the side force to the artificial g-force for varying radius (ref. 23).

For a man climbing radially toward the axis of rotation with constant velocity relative to the rotating frame, the side force will remain constant while the artificial gravity force decreases. The ratio of the side force to the artificial gravity force is given by the following equation:

$$\frac{F_c}{F_g} = \frac{2 \omega v}{\omega^2 r} = \frac{2 v}{\omega r} \quad (4)$$

Since, for constant  $\bar{\omega}$ , the ratio varies inversely as the radius, the effect is most significant in the vicinity of the spin axis. An appreciation of the magnitude of this effect can be gained by considering a specific case. Assuming that an angular velocity of 0.8 rad/sec is specified to provide a 1-g environment at a vehicle radius of 50.3 feet, and assuming a radial transport velocity for a man of 2 ft/sec, the radius at which the man experiences a side force equal to one half the local gravity force as he approaches the spin axis is calculated to be 10 feet. At this radius he will be subject to a local gravity force of about 0.2 g and a side force of 0.1 g.

The direction of the resultant force vector can vary significantly for radial motion near the spin axis and is therefore an important consideration in human factors design. The importance of this ratio will depend on the value of  $\bar{\omega}$  and the configuration of the vehicle, which in turn will both be influenced by man's ability to tolerate this particular stress.

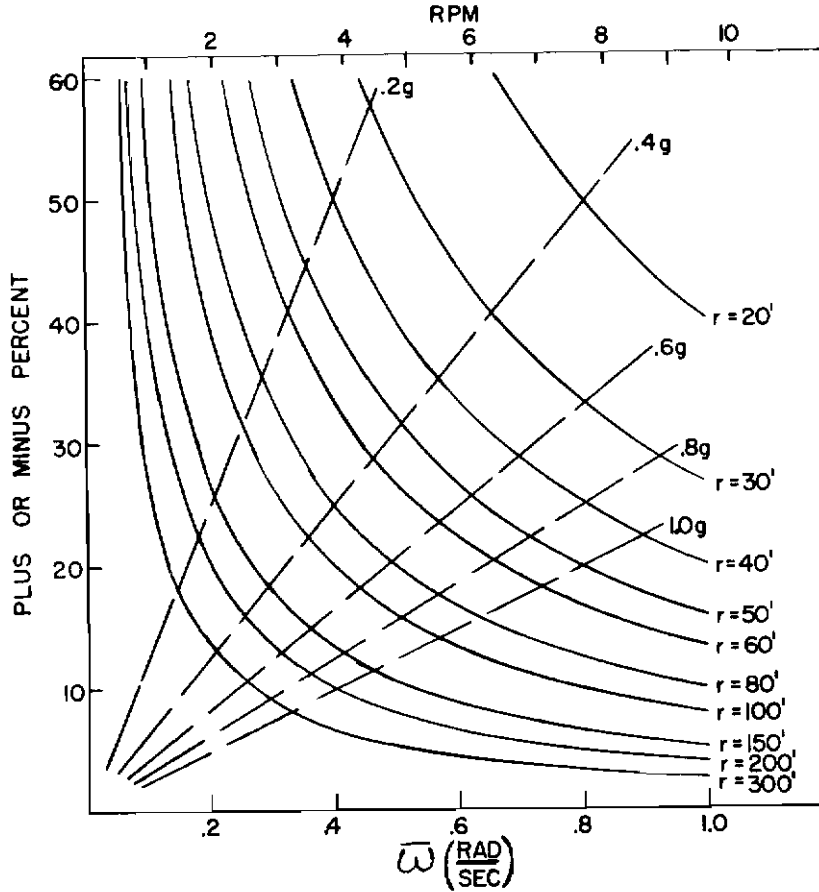
The variation in artificial gravity as man walks tangentially in the plane of rotation is a second peculiarity of the artificial gravity environment. A figure of merit which reflects this stress is the percentage of change in total force experienced by the walking man from that experienced by the stationary man (refs. 9, 25). The formula is similar to that used for radial motion except that an indoor walking velocity of 4 ft/sec is assumed and the ratio is given as a percentage; i. e.:

$$\frac{\Delta F_g}{F_g} \left[ \pm \frac{2 \omega (4)}{\omega^2 r} + \frac{(4)^2}{\omega^2 r^2} \right] 100\% = \left[ \pm \frac{800}{\omega r} + \frac{1600}{(\omega r)^2} \right] \% \quad (5)$$

where the plus or minus reflects the direction of walk.

The effect is seen to be inversely proportional to the first and second powers of the quantity  $(\omega r)$ ; i. e., the linear tangential velocity of the floor on which the man walks. The graph of figure 9 shows the approximate percent variation in gravity versus angular velocity for various values of floor-level radius, assuming a walking velocity of 4 ft/sec. For convenience, g-levels corresponding to the various values of radius and angular velocity for the stationary man are superimposed on the basic graph.





NOTE: For walk in direction of spin (+ %), indicated value is slightly low.  
 For walk in direction opposite spin (- %), indicated value is slightly high.

Figure 9. Approximate Percent Change in Artificial Gravity Experienced by Man Walking With Tangential Velocity of 4 ft/sec Inside Rotating Vehicle Versus Angular Velocity ( $\bar{\omega}$ ) of Vehicle, for Various Values of Floor-Level Radius ( $\bar{r}$ ).

Artificial Gravity Levels Corresponding to Angular Velocity and Floor-Level Radius for Stationary Man Are Shown by Dashed Lines.

For simplicity of presentation, the second term of equation 5 is not included in figure 9. Since the contribution from the second term is relatively small (particularly for large values of  $\omega r$ ), the graph has sufficient accuracy to be of value in obtaining the change in artificial gravity for tangential walking in any given vehicle. The precise percentage change may be obtained by algebraically adding the increment  $1600\% / (\omega r)^2$  to the plus or minus value obtained from the graph.

The use of the graph and its accuracy may be illustrated by an example. With the same data used previously—i. e., for an angular velocity of 0.8 rad/sec and a radius of 50.3 ft—the percentage variation in gravity for tangential walking is found from the graph to be about 20 percent. The value of local gravity can also be taken from the graph as being 1 g. Therefore, the man will experience  $(100 + 20)\%$  of 1 g, or 1.2 g's when he walks in the direction of spin, and  $(100 - 20)\%$  of 1 g, or 0.8 g when he walks against the spin. The exact values are calculated to be -20.8% or 1.208 g, and -18.8% or 0.812 g, respectively.

Establishing tolerance limits of man to this variation in artificial gravity as well as to the other peculiarities of the rotating-vehicle environment will permit the establishment of a design envelope within which the variables  $\bar{\omega}$  and  $\bar{r}$  must lie.

### III. THE INFLUENCE OF HUMAN FACTORS ON DESIGN

In his terrestrial environment, man is subject to a 1-g force which always acts perpendicular to the earth's surface. While he is subject to minute variations in gravity from place to place, and to Coriolis forces due to the earth's rotation, these variations are so minute that they are below the threshold of man's senses.\* Such is not the case inside the rotating vehicle where variation in artificial gravity and Coriolis forces may be of sufficient magnitude not only to disturb man but also to incapacitate him.

At what values these variations become significant or intolerable is largely conjecture. Since it is difficult, if not impossible, to create on earth the conditions which exist in a rotating space vehicle, only a bare minimum of experimental evidence is available upon which tolerance limits can be based. The best that can be done presently is to evaluate man's tolerance on the basis of this meager evidence. In some cases, where evidence of man's tolerance to a particular combination of stresses is not available, an attempt at extrapolation of data from related experiments may be made, but only with full knowledge that the results may not be precise. In other cases, where no evidence at all is available, assumptions must be postulated.

That the derived design criteria may not be exact should not bar an attempt to prescribe at least a rudimentary human factors design envelope and some general principles upon which vehicle design can be based.

#### General Considerations

As far as man is concerned, the ideal vehicle environment is one which would duplicate that on earth. Such an environment could be closely approximated using a vehicle with an extremely small value for angular velocity and the correspondingly large radius necessary to produce 1 g. But a glance at figure 2 shows that, as  $\bar{\omega}$  approaches zero, the radius required to achieve any g-level approaches infinity. As an example, for an  $\bar{\omega}$  of 0.01 rad/sec, the radius required to provide 1 g is 61 miles. The construction of such a vehicle is clearly impractical.

Practicality dictates the use of a smaller radius of rotation, which necessitates the use of higher values of  $\bar{\omega}$ . But at some upper limit of  $\bar{\omega}$ , Coriolis forces would be of sufficient magnitude to produce noticeable effects. Hence, the environment would be something less than ideal.

The designer is thus confronted with a dilemma. On the one hand, practicality dictates the use of as small a radius as possible. On the other, the corresponding increase in  $\bar{\omega}$  acts to distort the desired ideal environment. The degree to which the environment may be distorted and still be acceptable to a human is the crux of the design problem.

Because it is the decrease in radius and the increase in angular velocity which distort the gravitational environment, the inner limit of  $\bar{r}$  and the upper limit of  $\bar{\omega}$  at which man can operate efficiently become parameters of interest. Since the artificial gravity level is intimately connected to these variables, the maximum and minimum permissible values of artificial gravity are additional parameters of interest. Thus, the human factors design envelope will be an open figure prescribed by: minimum permissible  $\bar{r}$ , maximum permissible  $\bar{\omega}$ , and the upper and lower limits on g. The figure will be an open one because there is no maximum permissible value of  $\bar{r}$  or minimum permissible value of  $\bar{\omega}$ , the only limit being one of practicality.

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\*The angular velocity of the earth about its axis is  $7.29 \times 10^{-5}$  rads/sec. Maximum variation in gravity value over the earth's surface is less than 1 percent from standard value.

In the process of establishing the human factors design envelope, general principles may also be derived which, if observed in engineering design, will result in a vehicle gravitational environment which more nearly simulates the terrestrial one.

### The Human Mechanism for Spatial Orientation

Man maintains his spatial orientation through integration of information concerning the environment which is transmitted to his brain through his senses. Some discussion of the mechanism by which man senses his environment will assist in establishing his tolerance limits to the unusual effects of the rotating-vehicle environment.

The sensory mechanism, referred to by Campbell (ref. 5) as the "orientation triad," consists of the eyes, the vestibular organs located in the inner ear (the semicircular canals and the otoliths), and finally the mechanoreceptors located in the muscles, tendons, and joints. Of these, the eyes are the primary sensors and, in the absence of any other stimuli, as in weightlessness, they provide sufficient information to permit orientation.

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 the mechanoreceptors to provide man with spatial orientation and balance.

Under normal conditions on earth, maintenance of orientation and balance is a simple matter. The 1-g force acting on the otoliths causes impulses to be sent to the brain which are congruent 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 (ref. 4).

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, as is evidenced by the writings of authorities on the subject (refs. 6, 13-16, 19-21, 32, 35-37, 39). Because overstimulation of the vestibular apparatus appears to be the primary factor involved, the term "canal sickness" has been used to describe these symptoms (ref. 18).

### 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 subjected while moving in the vehicle are also applied to the otoliths and semicircular canals. The changing gravity forces and Coriolis forces, which result from locomotion inside the vehicle or due to movement, rotation, or cocking of the head, 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.

The results of some experimental studies may be used to obtain stress limits. While the experiments did not create the exact conditions which would exist in the rotating vehicle, they did provide some conclusions upon which stress tolerances may be estimated.

In the experiments performed by Graybiel, Clark, and Zarriello (ref. 18) at the U.S. Naval School of Aviation Medicine at Pensacola, Florida, subjects were placed in a 15-foot-diameter, 7-foot-high room centered on a centrifuge. The room was rotated at constant angular velocity for 48 hours during which time the subjects were observed not only while they performed various tasks but also during "off-duty" hours. Separate runs were made at 1.71, 2.22, 3.82, 5.44, and 10.00 rpm to provide experimental data for a range of rotation rates. Since the subjects were within 8 feet of the axis of rotation, the sideward centrifugal force to which they were subjected, compared to the normal 1 g they experienced vertically, was not considered significant. Therefore, the primary stimuli were considered to be the Coriolis forces which acted on the canals during the experiment.

The general findings of the experiment may be summarized as follows (ref. 18):

(a) Head motion parallel to the axis of rotation or head rotation about that axis produced no ill effects. (This was to be expected since practically no Coriolis forces would act on the canals for this type of motion.)

(b) Head motion in any other direction or head rotation about any other axis caused the canals to be stimulated. Maximum stimulation occurred when the head was rotated about an axis perpendicular to the spin axis. (Maximum Coriolis forces act on the canals for this type of motion.)

(c) Illusions and symptoms of canal sickness such as malaise, apathy, nausea, and incapacity to perform assigned tasks were experienced by various subjects at various times during each run.

(d) There were marked differences in susceptibility to canal sickness among the subjects but even the subjects least susceptible to canal sickness became ill and were unable to carry out tasks at 10.00 rpm. The control subject, whose vestibular apparatus was permanently inoperative due to previous ear illnesses, experienced none of the symptoms of canal sickness.

(e) There was some adaptation to the environment after different periods of time for different subjects.

In a report on gravity problems in manned space stations, Clark and Hardy (ref. 7) comment on an experiment performed on the centrifuge at the Naval Aviation Medical Acceleration Laboratory at Johnsville, Pennsylvania, which provides numerical data on stress limits for canal sickness.

When a subject was rotated in a centrifuge for 24 hours at 2 g's with an angular velocity of 1 rad/sec, head rotation of 0.06 rad/sec about an axis perpendicular to the spin axis resulted in the onset of visual illusions. Any such head rotation at 0.6 rad/sec resulted in nausea.

Although the effect of the 2-g environment on these figures could not be determined, and although the figures are based on only one subject, Clark and Hardy tentatively conclude that the maximum permissible magnitude of the vector cross product of head angular velocity with vehicle angular velocity, if illusions are to be avoided, is less than  $0.06 \text{ rad}^2/\text{sec}^2$ ; i. e.,  $|\bar{\omega}_{\text{head}} \times \bar{\omega}| < 0.06 \text{ rad}^2/\text{sec}^2$ . Pursuing the analysis a step further, Clark and Hardy indicate that, to permit normal head rotation in a rotating vehicle for which head rotation rates might be as high as 5 rads/sec, the maximum permissible angular velocity for the vehicle should be 0.01 rad/sec. To permit the use of any higher  $\bar{\omega}$  for the vehicle, they propose that prisms, mirrors, or restraining devices be used to keep head rotation rates at low values.

If the maximum limit for  $\bar{\omega}$  of 0.01 rad/sec is to be observed, the required radius to provide 1 g, as seen earlier, is an impractical 61 miles. To lessen the radius would require increasing  $\bar{\omega}$  above that which is desirable from an environmental viewpoint, but there seems to be no other acceptable choice.

Dole (ref. 9) selects a limit of "less than about 4 rpm" as an upper limit for  $\bar{\omega}$  based primarily on Graybiel's study (ref. 18). An upper limit on  $\bar{\omega}$  in the range of 4 rpm appears to be a realistic compromise between what is desirable from a human factors view point and what is at least practical from an engineering viewpoint. Accordingly, an upper limit of 0.4 rad/sec is established for  $\bar{\omega}$ . The limit is superimposed on the basic  $\bar{\omega}$  versus  $\bar{r}$  plot of figure 10.

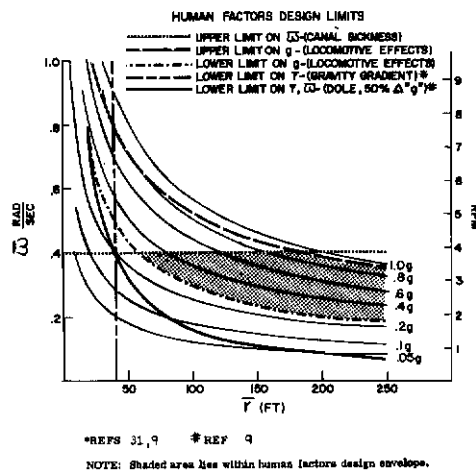


Figure 10. Human Factors Stress Limit Curves Superimposed on Plot of Angular Velocity ( $\bar{\omega}$ ) Versus Radius of Rotation ( $\bar{r}$ ) to Achieve Various Levels of Artificial Gravity in Manned Orbital Satellite Vehicles

If the formula established by Clark and Hardy is valid, an  $\bar{\omega}$  of 0.4 rad/sec would permit a maximum rate of rotation of the head about an axis perpendicular to the  $\bar{\omega}$  axis of about 0.15 rad/sec. This restriction seems severe when compared to normal head rotation rates of up to 5 rads/sec. But the evidence upon which the 0.01 rad/sec limit is based is not conclusive. There is some justification to accept the figure as being conservative since the experiment was not conducted under ideal conditions; i. e., the subject was under a 2-g linear stress during the experiment. Further, the Graybiel findings indicate that, through proper selection of crew members and due to the fact that adaptation to the rotating environment does occur, the limit of 0.01 rad/sec might be revised upward. These factors support the conclusion that, while the selected upper limit of 0.4 rad/sec for  $\bar{\omega}$  is not ideal, the difference between this limit and that set by Clark and Hardy is not so extreme as it appears.



The degree to which the crew member will in fact be affected by canal sickness can be minimized through proper design. As noted above, the cross product of head  $\bar{\omega}$  and vehicle  $\bar{\omega}$  is involved. Clark and Hardy noted and Graybiel corroborated that, if the head rotation takes place about an axis parallel to the spin axis, the vector cross product is zero. Hence, there is 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 would occur most frequently is parallel to the vehicle spin axis.

Because he lives in a "flat" environment man most frequently rotates his head about his longitudinal axis, i. e., left-right. Unfortunately, as a glance at figure 1 will show, any standing or sitting position in the rotating vehicle places man's longitudinal axis perpendicular to the spin axis. This situation cannot be avoided. Thus, the head rotation normally used most by man on earth is the rotation which must be minimized in the vehicle. Man will have to learn to restrict the velocities at which he turns his head in the left-right direction and substitute as much left-right eye movement as possible. In fact, the substitution of eye movement for head rotation was precisely what the subjects in the rotating-room experiments unconsciously learned (ref. 18).

Although man cannot be oriented inside the rotating vehicle so that he can sit or stand normally and make normal left-right head movements, an advantage may be gained by orienting the crew station position so that, when man is in his normal position, his lateral axis—i. e., an axis through both his ears—will be parallel to the spin axis. This will permit maximum up-down rotation of the head with minimum Coriolis effects on the canals. It follows that the instrument display console at which the man works should have an up-down rather than a left-right orientation. The console and controls should be designed so that a minimum of left-right head movement is required in performance of duty-station tasks. Similarly, assuming that most head rotation while in bed would occur about man's longitudinal axis, the crew bunks should be oriented axially. Figure 11 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.

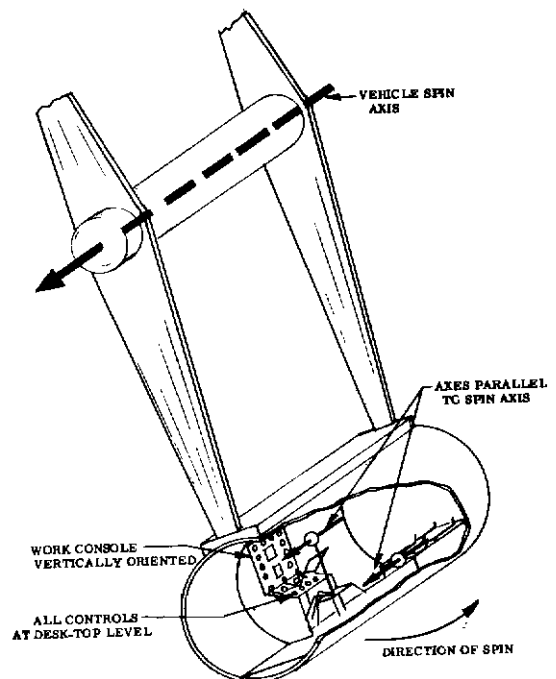


Figure 11. Living-Working Compartment Design Features to Minimize Adverse Effects of Coriolis Forces on Crew Members Inside Rotating Vehicle

No crew duty stations should be oriented so that the lateral axis lies along a tangential axis; for under this orientation both up-down and left-right head rotations would result in stimulation of the vestibular apparatus by Coriolis forces.

### Establishment of the Upper Limit for Artificial Gravity

Some writers have considered values for the upper limit in excess of 1 g. Dole (ref. 9) includes 1.5 g's as the upper g-limit. Kramer and Byers (ref. 23) also mention the possibility of a requirement for a level higher than 1 g. This requirement seems necessary only for preconditioning a space crew prior to landing on a planet or other celestial body whose surface gravity level is greater than that on earth. Since this requirement lies in the remote future, it appears reasonable to select an upper limit of 1 g. The upper limit is therefore prescribed by the requirement that at no time at any position in the vehicle should the crew member experience more than 1 g (see figure 10).

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 a man in a vehicle rotated to provide 1 g to experience more than 1 g if he were to walk tangentially in the direction of spin. To permit him to walk tangentially in the direction of spin without exceeding the basic 1-g limit, the ambient g-level of 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. Assuming an 80-foot radius vehicle and a maximum permissible g-level of 1 for the walking man, the magnitude of  $\bar{\omega}$  effective can be computed as:

$$\omega = \sqrt{\frac{g_c}{r}} = \sqrt{\frac{32.2}{80}} = 0.635 \text{ rad/sec}$$

The corresponding linear velocity at floor level is:

$$\omega r = 0.635 (80) = 50.80 \text{ ft/sec}$$

The maximum permissible linear velocity at floor level for the vehicle will equal the effective linear velocity for 1 g less the walking velocity of the man; i. e.:

$$(\omega r)_{\text{permissible for vehicle}} = (\omega r)_{\text{effective}} - v_{\text{man}} = 50.80 - 4.0 = 46.80 \text{ ft/sec}$$

The corresponding value of vehicle  $\bar{\omega}$  is:

$$\omega = \frac{\omega r}{r} = \frac{46.80}{80} = 0.585 \text{ rad/sec}$$

and the maximum permissible g-level for the vehicle is:

$$F_g = \frac{\omega^2 r}{g_c} = \frac{(0.585)^2 80}{32.2} = 0.85 \text{ g}$$

Thus, a crew member in this vehicle could move tangentially in the direction of spin at normal walking speed without exceeding the 1-g limit. He would experience 0.85 g when stationary.



The upper g-limit curve showing limiting values of g for all values of  $\bar{r}$  is shown on the graph of figure 10. The curve diverges from the 1-g curve at small values of radius, where the high values of  $\bar{\omega}$  cause significant Coriolis effects, and approaches the 1-g curve at large values of radius, where the Coriolis effects are comparatively negligible.

The basis for the establishment of the 1-g limit is sound. The lowering of the limit due to Coriolis effects is to some extent arbitrary. It might well be argued that, once the man becomes accustomed to the ambient g-level, the increase in g-level experienced when walking tangentially in the direction of spin will be an added burden regardless of whether or not the total exceeds 1 g. But since from a human factors viewpoint the difference between the two limits, except at very small r, is probably negligible, and since engineering practicality favors its selection, the lower value is a useful limit.

### Establishment of the Lower Limit for Artificial Gravity

Many design proposals have specified quite low values of artificial gravity. The low levels selected reflect one or more of the following considerations:

- (a) Belief that small values of artificial gravity are sufficient from a human factors viewpoint
- (b) A requirement for practicality and simplicity, particularly for the minimal-capability vehicles of the immediate future
- (c) Desire for a low level of g for convenience—i.e., to keep objects in place, to permit use of conventional plumbing, to make use of natural convection, etc.

Recent in-flight experiments conducted by the Aerospace Medical Laboratory personnel at Wright-Patterson Air Force Base, Ohio, indicate that from a human factors viewpoint a lower limit of 0.2 g should be established. The experiment involved an evaluation of the ability of a man to walk unaided under various levels of fractional gravity (less than 1 g and more than 0 g). The fractional gravity levels were obtained by flying a C-131 aircraft through Keplerian trajectories. Although the experiment was crude due to the lack of precise instrumentation for maintaining constant fractional gravity levels close to the zero gravity value, the results conclusively indicate that man is able to walk unaided at 0.2 g.

Mr. Earl Sharp of the Behavioral Sciences Laboratory, Aerospace Medical Laboratory, who conducted the experiment, suggested that the value of 0.2 g might possibly be too high, but that downward refinement of the figure cannot be made until more precise instrumentation of the figure becomes available. Mr. Sharp said that man can walk at zero g, but only with the assistance of some mechanical or magnetic device.

From a human factors viewpoint, the 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 an environment of convenience more than one which reflects the psychophysiological requirements of man.

Following the same reasoning applied to the basic upper limit of 1 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-foot-radius vehicle, the lower limit is calculated to be 0.277 g. The curve in figure 10 shows the lower limit for all values of radius. As in the case of the upper limit, the modification is more significant at smaller values of radius.

If the basic lower limit is assumed to be that minimum level of g at which man can walk unaided, the modification of the basic lower limit due to Coriolis effects is easily justified, for under no circumstances would it be desirable for the walking man to experience a g-level at which he could not walk unaided.

Limitation Due to Gravity Gradient

There is no experimental evidence available on the effect of a gravity gradient on man, nor is there any nonorbital experiment which can be performed to determine man's tolerance to a gravity gradient at levels of less than 1 g. As a result, it has been necessary to assume some maximum permissible percentage of head-to-foot gravity gradient to floor-level gravity. Payne (ref. 31) and Dole (ref. 9) select an arbitrary maximum 15 percent; i. e., no value of radius will be used for which the gravity gradient between head and feet is more than 15 percent of floor-level gravity. Using equation 2 the excluded values of radius are calculated to be those less than:

$$r = \frac{600\%}{15\%} = 40 \text{ ft}$$

This assumption thus places a lower limit on  $\bar{r}$  of 40 ft, as shown in figure 10.

Other Limitations Due to Coriolis Effects on Locomotion

A consideration of Coriolis effects on locomotion from a human factors viewpoint can best be analyzed by considering the effects for each of the three components of motion: radial, tangential, and axial, as was done in section II.

For radial motion in the vicinity of the axis of rotation, the distortion of the gravitational environment due to the change in resultant force both in magnitude and direction, as discussed in section II, would probably cause the onset of illusions (ref. 17) 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 changing stimuli to the vestibular apparatus which would accompany this maneuver, 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 nonrotating, with provision made for transfer from moving "spoke" to nonrotating hub at some minimum radius, as from 6 to 10 feet.

From a design viewpoint, the minimization of the adverse effects on man of radial motion can be effected by conducting all normal activity as far away from the axis of rotation as possible (since a large radius minimizes the effect, as seen in equation 4), 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 nonrotating, 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 (ref. 9) places a maximum permissible limit of 50 percent variation between tangential walking and stationary gravity levels. Dole's curve in figure 10 indicates the lower limits for  $\bar{\omega}$  and  $\bar{r}$  corresponding to this requirement for a walking velocity of 4 feet/second.

For axial walking, the only peculiarity to be observed is that the radial components of limb velocity will result in applying side Coriolis forces to the limbs. But because the radial velocity component of the arms and legs will be small, and because the radial motion will be reciprocating in nature, the disturbance will probably be 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 so critical as those which accompany radial and tangential motion.

Because axial motion results in the least distortion of the artificial gravity environment, the vehicle should probably be designed to take advantage of this fact; i. e., the major dimension of the living-working compartment should be placed parallel to the vehicle spin axis.

### Results of Human Factors Analysis

#### The Human Factors Design Envelope:

An examination of the tolerance limit curves superimposed on the basic  $\bar{\omega}$  versus  $\bar{r}$  graph of figure 10 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  $\bar{\omega}$  of 0.4 rad/sec. Since the other human factors stress-limit curves lie outside the envelope, the stress limits they represent will not normally be exceeded in the living-working compartment for any operating point of  $\bar{\omega}$  and  $\bar{r}$  which lies within the envelope.

#### Human Factors Design Principles:

In addition to the design envelope, the general principles to be observed in vehicle design are:

- (a) Radial traffic should be kept to a minimum.
- (b) Transport across the spin axis and human activity at the spin axis should be prohibited unless the hub is nonrotating.
- (c) The living-working compartment should be located as far as possible from the axis of rotation.
- (d) The compartment should be oriented so that the direction of traffic—i. e., the major dimension of the compartment—is parallel to the vehicle spin axis.
- (e) 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 11).
- (f) Sleeping bunks should be oriented with their long axes parallel to the vehicle spin axis.

(g) The presence of confusing visual stimuli should be minimized. For example, the apparent convergence of the vertical from any two points separated tangentially should be played down by proper interior decoration and, except for necessary observation ports, which should be covered when not in use, the living-working compartment should be windowless (ref. 31).

While not directly related to vehicle design, proper crew selection and training can minimize the environmental deficiencies which cannot be eliminated Graybiel's findings (ref. 18) and studies made by Kraus (ref. 24) and Johnson (ref. 22) indicate that susceptibility to canal sickness should be included as a screening device for selection of astronauts, and that, insofar as earthbound facilities permit, the astronauts should be preconditioned to a rotating-vehicle environment.

Establishing human factors design parameters provides basic criteria for selecting an optimum vehicle configuration.

## IV. THE INFLUENCE OF ENGINEERING AND OPERATIONAL FACTORS ON DESIGN

The derived human factors parameters and principles form the basic criteria to be used in selecting an optimum vehicle configuration. But while adherence to human factors criteria will provide for a satisfactory artificial gravity environment, the criteria alone will not permit selecting a configuration which will be both practical and operationally suitable. To establish design criteria which will permit selection of a practical and operationally suitable vehicle, other factors must be considered.

Of primary importance are the factors which may be categorized as engineering and operational. An analysis of these additional factors is a prerequisite to the establishment of comprehensive criteria which will permit selecting an optimum vehicle configuration.

### Engineering Factors

Two of the most important considerations in the overall engineering design of the vehicle are those involving structural economy and rotational stability. Both can best be analyzed through use of a simple, idealized model of a rotating vehicle, a dumbbell. The engineering principles which can thus be illustrated will be applicable to any rotating vehicle regardless of the complexity of its configuration.

#### Analysis of a Rotating Dumbbell:

The model vehicle to be used is the idealized dumbbell shown in figure 12. The dumbbell consists of two spheres connected by a rigid rod of negligible mass. Sphere 1, which may be considered to be the living-working compartment, the g-level for which is to be specified, is of mass  $m_1$ . Mass  $m_1$ , for simplicity, is considered to be a point mass acting at the center of the sphere. Similarly, sphere 2, which may be considered to be the counter-mass, is of mass  $m_2$ . The vehicle is to be rotated about an axis perpendicular to the rod through point 0. Point 0 is selected a distance  $r_1$  from the center of sphere 1 so that the desired artificial gravity level will exist at sphere 1 when the vehicle is rotated at some specified value of  $\bar{\omega}$ . The distance  $r_2$  from the center of sphere 2 to point 0 is adjustable.

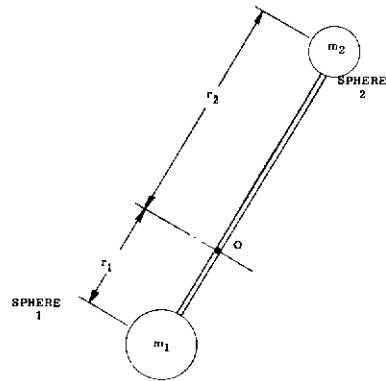


Figure 12. The Idealized Dumbbell as a Simple Model of a Rotating Vehicle

The total centrifugal force experienced by sphere 1 is calculated to be  $F_{g1} = m_1 r_1 \omega^2 / g_c$ , which equals the tension in the rod. To maintain this tension, an equal and opposite force must act at point 0. This equivalent force is obtained as the centrifugal force acting on sphere 2 due to its rotation about point 0; i.e.,  $F_{g2} = m_2 r_2 \omega^2 / g_c$ . If, as in this case,  $r_1$ ,  $m_1$ , and  $m_2$  are specified, then the distance  $r_2$  must be such that  $F_{g2} = F_{g1}$ ; i.e.,  $m_2 r_2 = m_1 r_1$ . This equality has important implications in vehicle structural design and rotational stability.

**Distribution of Vehicle Mass for Structural Economy:**

In the ideal model, the connecting structure (the rod) has been assumed to be massless and of infinite strength. But the connecting structure of an actual vehicle will have not only mass but finite strength. The mass and strength of the connecting structure must obviously be taken into account in design.

In the actual vehicle, the mass of the connecting structure will also be subjected to centrifugal force, which will differ at each point along the structure depending on radius. The total force acting along the massless rod was constant. In the actual case the tensile force acting at each point of the structure will vary. At any point the total force will equal the centrifugal force acting on the sphere plus the centrifugal force which acts on the mass of that part of the structure outboard from the point in question. The tension in the connecting structure is thus seen to vary inversely with radius, with maximum tensile force acting at point 0, where it is equal to the centrifugal force acting both on sphere 1 and the entire length  $r_1$  of the connecting structure. This same analysis is applicable to the counter mass and its connecting structure.

Radial distribution of mass in the vehicle is extremely important in design for structural economy. Because centrifugal force varies directly as radius, vehicle mass should be kept as close to the axis as possible. A structural penalty is involved any time a pound of mass is placed any further from the axis of rotation than is necessary. The penalty is severe in that each pound of mass placed at extreme radius (added to sphere 1), for example, increases the force acting on the connecting structure by the increment  $\omega^2 r_1$ . The penalty which is exacted involves not only an increase in counter mass but also an increase in the mass of the connecting structures  $r_1$  and  $r_2$ . In contrast, a pound of mass placed at the axis of rotation, where it is weightless, requires a bare minimum of structure to keep it in place.

Therefore, minimum mass must be placed at points other than the axis of rotation if structural economy is to be observed. It naturally follows that the radius of the vehicle should be kept as small as possible.

**Structural Design Principles:**

A glance at the human factors design envelope, figure 10, shows that the radius to the living-working compartment must be a minimum of about 60 feet for an artificial gravity level of about 0.3 g. The minimum radius which will provide for maximum permissible g (about 0.9 g) is about 180 feet. The radius of the vehicle is thus fixed by human factors requirements to lie somewhere between an absolute minimum of 60 feet and a probable maximum of 180 feet. With the vehicle radius restricted by this requirement, the task becomes one of the determination of design principles which will result in the most economical structure. Several such principles may be delineated.

The living-working compartment, which will be placed at the outermost radius of the vehicle, should be as "light" as possible; i. e., the compartment should consist of minimum mass. All components which must not of necessity be located within the compartment should be placed nearer to the spin axis. A decision must be made as to which items must be readily accessible to the crew and which may be remotely located. The decision is not an easy one. Factors to be considered are:



reliability of components, accessibility of critical equipment, the additional mass of ducting, power transmission circuitry, and perhaps shielding, which must be introduced when components are remotely located, and others. Some obvious cases of components which can definitely be remotely located are such massive items as storage batteries, power machinery, and storage tanks. The decision will require an optimization by trade-off between structural mass saved by remote location of each component versus the increased reliability required for remote operation and the additional mass and complexity of controls and ducting involved. Because a severe structural penalty is involved in locating mass at the extreme radius of the compartment, however, the general principle to be observed is to locate all major components remotely and to restrict the living-working compartment mass to only those essential items required for display, control, and crew safety and comfort.

In design of the counter-mass the most important principle to be observed is to have the counter-mass consist of useful mass rather than dead mass which serves merely as ballast. Various options are possible. The counter-mass may consist of a second living-working compartment, located at an appropriate radius, although such an arrangement would lead to an undesirable increase in radial traffic by crew members and complicate the design of the closed ecological system. A more optimum arrangement would be the use of the remotely located components as counter-mass. The more massive the components the better, since the radius of connecting structure to the counter-mass could correspondingly be minimized. A nuclear power source would be an ideal item to make up part of the counter-mass as would the other massive items previously mentioned.

In essence, the primary principle to be observed for structural economy is to minimize overall vehicle mass. Once the parameters  $\bar{r}$  and  $\bar{\omega}$  for the living-working compartment are selected, the design procedure which should be followed to minimize overall vehicle mass may be summarized:

(a) The living-working compartment should consist of only the components and equipment which need to be readily accessible for mission accomplishment (i. e., display and control) and for crew safety and comfort.

(b) All remaining components which are not required to be located at the living-working compartment, at the axis of rotation, or at some other location to provide stability should be used as counter-mass to minimize counter-mass radius.

(1) If a nuclear reactor is to be used as counter-mass, it should be located at the extreme radius of the counter-mass-connecting structure with adequate shielding and separation provided between it and other counter-mass components.

(2) If the total useful mass is much less than the living-working compartment mass, so that an extremely long connecting structure is required, it may be more economical to use some deadweight counter-mass to keep counter-mass radius small. Some of the variables involved in the tradeoff would be: the relative masses of the living-working compartment, the counter-mass, and the mass-per-unit-length of the connecting structure; nuclear shielding mass and separation distance to other components; bending loads to which the vehicle would be subject; and complexity and mass of ducting and circuitry involved in remote location of components.

Rotational Stability Requirements:

Once a particular radius of rotation for the living-working compartment is selected, that radius must remain constant if a constant g-level is to be maintained in the compartment. The requirement may be illustrated through consideration of the idealized dumbbell.

If, for example, the value of  $r_2$  were selected so that  $m_2 r_2 \neq m_1 r_1$ , the vehicle would not rotate about point O, but would rotate about the actual center of mass of the system, in accordance with the laws of mechanics. Assuming constant  $\bar{\omega}$ , this shift in the axis of rotation would result in a change in the gravity level at sphere 1 and at every other point in the vehicle.

Any change in mass distribution along the rod of the dumbbell could cause a similar effect. Thus, in an actual vehicle in which mass distribution could be expected to change frequently due to movement of personnel, flow of fluid mass, motion of the moving parts of machinery, addition or loss of mass, etc., the continual redistribution of mass which would take place would cause the continual shift of the center of mass of the vehicle with an accompanying variation in g-level at every point in the vehicle. While minor shifts in mass could be tolerated, any major shifts in mass, if uncompensated, could result in an unstable rotation which would make the vehicle unsatisfactory from both human factors and engineering viewpoints.

For stable rotation, provision must be made to maintain a constant center of mass and a constant  $\bar{\omega}$  regardless of transient changes in mass distribution within the vehicle. Two provisions must be made in the design of the vehicle to provide rotational stability. Provision must first be made for including an automatic stabilizing system in the vehicle. Provision for inherent vehicle stability must also be made, not only to minimize the performance requirements of the automatic system, but also, as mentioned by Schnitzer (ref. 34), to provide backup stability in the event of failure of the automatic system.

The function of the primary stabilization system is to maintain constant  $\bar{\omega}$  and a constant vehicle center of mass through compensatory shift of mass or application of corrective torques, the entire process to be performed automatically.

Inherent stability of a rigid vehicle can be provided by rotating the vehicle about either the major or minor axis of inertia, any other axis being inherently unstable (ref. 4). For a perfectly rigid vehicle, choice of major or minor axis is arbitrary since rotation will be stable about either axis. But for a nonrigid vehicle or a vehicle in which internal damping due to mass shifts, sloshing fluids, etc., will result in dissipation of rotational energy, the minor axis of inertia is an unstable axis (ref. 27). Since some dissipation of rotational energy due to mass shifts and flexure of the structural members is probable in the vehicle under consideration, the logical choice seems to be to rotate the vehicle about its major axis of inertia to maximize rotational stability.

The problems involved in vehicle stability are extremely complex and are among the most difficult encountered in engineering design. Treatment of some of the problems of stability can be found in refs. 23, 28, and 29 .

Rotational Stability Design Principles:

For selecting an optimum configuration, the vehicle configuration should be one in which the intended axis of rotation coincides with the major axis of inertia of the vehicle.

A particular design conflict which involves stability versus structural economy should also be noted. Placement of mass at the axis of rotation involves minimum structural penalty. In view of stability requirements, however, there is a limit to the amount of mass which may be strung out along the axis of rotation, the limit being prescribed by the requirement that the major axis of inertia of the vehicle be coincident with the vehicle spin axis. This requirement must be met at the expense of structural economy if necessary.



## Operational Factors

Operational factors intimately related to engineering factors and overall vehicle design are those involving mission requirements, resupply operation, maintenance, and emergency escape.

### Mission Requirements:

For performing of some of the many operational activities in which the orbiting space station will be engaged (refs. 1, 3), such as earth surface and celestial observation, there will undoubtedly be a requirement for an inertially stable platform. While it would be convenient to locate this platform at the living-working compartment, the advantages to be gained in structural economy and simplicity by locating the platform on a nonrotating hub at the axis of rotation would probably outweigh any disadvantages involved in the remote readout of data and operation of platform equipment such as telescopes, cameras, radar, and infrared scanners. The advantages to be accrued from a stable platform located at the spin axis of the vehicle appear to make it mandatory that the vehicle design include a nonrotating compartment at the axis.

Zero-gravity experiments will have to be conducted at the axis of rotation. The zero-g experimental compartment can be included in the hub along with the stable platform.

### The Resupply Operation:

Analysis of the problems involved in rendezvous and docking of the resupply vehicle with the orbiting satellite favor a decision for the docking to take place at the axis of rotation of the vehicle rather than at the living-working compartment. The reasons for this choice are:

- (a) A docking facility at the spin axis simplifies the terminal guidance problem for the resupply vehicle.
- (b) Docking facility mass can be located at the spin axis.
- (c) Vehicle stability will be relatively undisturbed during the resupply operation.

The disadvantages involved in docking at the living-working compartment can be minimized by cessation of vehicle rotation during the resupply operation; but the addition of docking facility mass to the compartment would sacrifice structural economy. In addition, rerotation of the vehicle could not occur if departure of the resupply vehicle were delayed without seriously overtaxing the automatic stabilizing system of the vehicle. Thus, the resupply vehicle should be docked at the hub of the vehicle.

Consideration must be given to the advisability of stopping vehicle rotation during the resupply operation, even for docking at the axis of rotation. Some advantages are:

- (a) A nonrotating docking hub would not be necessary.
- (b) The complex facility necessary for transfer of personnel and supplies from the nonrotating hub to rotating compartment could also be eliminated. The mechanism involved in such a facility has been discussed by Ross (ref. 33) and Ley (ref. 28).
- (c) Radial traffic of personnel, which would be maximized during the resupply operation, would occur under weightless conditions rather than under the stressful conditions characterized by the combination of Coriolis and centrifugal forces which accompany radial motion during rotation.

The disadvantages are:

(a) The living-working compartment would have to be designed for operation under both weightless and artificial gravity environments, although this requirement would probably have to be met anyway, for initial use of the compartment as a nonrotating vehicle during in-orbit construction of the finished space station.

(b) All crew members would be subject to weightlessness during the resupply operation. This is not an appreciable disadvantage. It is fairly certain that weightlessness over a period of a few hours has no detrimental effects. Further, the change would probably be a welcome diversion from the monotonous routine of normal activity. Finally, the weightlessness would not be so stressful as radial motion during rotation.

(c) Crew members would probably experience illusions during the rotational accelerations involved in slowdown or speedup of the vehicle. The occurrence of illusions could be minimized, however, by low acceleration rates and by motionless positioning of crew members during these intervals.

(d) Energy would have to be expended each time rotation is stopped or started. The mass of the propellants required to produce the necessary torque would involve considerable mass (ref. 23). Over a long period of time the mass penalty would more than overcome the initial mass savings realized in eliminating the requirement for a completely nonrotating hub and the transfer mechanism.

Although it would be advantageous from a human factors viewpoint to stop vehicle rotation during the resupply operation, the long-term mass penalty involved would be prohibitive. If some practical system could be devised which would minimize the energy (mass) penalty involved in starting and stopping rotation, the decision to stop vehicle rotation for resupply and other operations would be preferable. Two possibilities for such a system might be feasible, both involving the use of a counter-rotating flywheel:

(a) Transfer of angular momentum of the rotating vehicle to the nonrotating flywheel during deceleration of the vehicle, with reverse transfer of the momentum back to the vehicle during acceleration to normal rotating speed. The energy lost in the process would be supplied by spin rockets.

(b) Use of electrical energy from the nuclear power source to rotate the vehicle in one direction against the inertia of the flywheel in the other, both for starting and stopping vehicle rotation.

The feasibility of both these devices would be enhanced if flywheel mass could be made to consist of useful mass.

Until an efficient system either for storing and recovering energy or for producing it inexpensively is proved feasible, the evidence appears to indicate conclusively that the vehicle should rotate continuously with provision made for a completely nonrotating hub and the accompanying transfer mechanism. The nonrotating hub might thus consist of a large zero-g experimental compartment, the docking facility, the transfer mechanism, and the stable platform, all perhaps enclosed in a shirt-sleeve environment, although this latter provision might be considered an unnecessary luxury.

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## Maintenance:

Maintenance of the vehicle and its components at locations other than the nonrotating hub and in the living-working compartment would probably best be performed at times when the vehicle is not rotating, to preclude the occurrence of canal sickness to which crew members would be susceptible while moving and working at external points on the rotating vehicle structure. Since economy forces the choice of a continuously rotating vehicle, however, external vehicle maintenance will have to be performed while the vehicle is rotating.

The adverse human factors effects can be minimized through:

- (a) Reliability and redundancy of components, particularly those remotely located
- (b) Low-velocity transport mechanisms along the connecting structure which would permit passive transport of crew members as well as transport of equipment
- (c) Arrangement of external vehicle components so that maintenance can be performed from fixed-station positions with the preferred body orientation, i. e., crew member lateral axis parallel to vehicle spin axis

## Emergency Crew Escape:

While provision cannot be made to insure crew protection against catastrophe, a requirement for emergency escape from the vehicle will exist. Escape capability can most economically be provided by one-way re-entry capsules or gliders anchored to the satellite vehicle. Structural economy can be observed by locating these "lifeboats," as they are referred to by Ehrlicke (ref. 10), remotely from the living-working compartment, under the assumption that sufficient time will be available in any probable emergency to permit the crew to reach the lifeboats and escape. The lifeboats could thus be located at the spin axis or to provide counter-mass or stability to the vehicle. For the latter two choices,

- (a) The lifeboats would be considered as somewhat permanent ballast, to be used only for abandonment of the vehicle.
- (b) If the space station were to be abandoned, launching of the lifeboats would be facilitated by stopping vehicle rotation prior to launch. No additional mass penalty would be involved in stopping vehicle rotation since the propellant would be on board the vehicle at all times anyway, to permit one or two stop-start-rotation cycles if necessary in the course of normal operation.

## Summary of Engineering and Operational Design Principles

The design principles which have been derived from an investigation of engineering and operational factors may be briefly summarized:

- (a) The living-working compartment should be placed at the outermost radius of the vehicle.
- (b) The compartment should consist of minimum mass. Only those items essential to mission accomplishment (display and control equipment) and to crew safety and comfort should be located in the living-working compartment.
- (c) All remaining components with the exception of the components discussed below should be used as counter-mass to minimize counter-mass radius or to satisfy stability requirements.

(d) The stable platform, the zero-gravity experimental compartment, and the docking facility for the resupply vehicle should all be located at the axis of rotation in a nonrotating compartment.

(e) The vehicle should rotate continuously, with provision for transfer between the rotating structure and the nonrotating hub through use of a transfer mechanism.

(1) Maximum remote operation capability should be built into the vehicle to minimize human traffic in the radial direction and in the nonrotating compartment.

(2) Low-velocity transport mechanisms should be provided for passive radial transport of personnel and for transport of supplies and equipment.

(3) Maintenance duty station on the external vehicle structure should be designed to permit preferred body orientation of crew members while performing maintenance.

(f) The vehicle must have rotational stability.

(1) An automatic stabilization system must be provided.

(2) The major axis of inertia of the vehicle should coincide with the intended axis of rotation to provide inherent stability.

(g) Emergency one-way escape vehicles should be located at the axis of rotation or positioned to satisfy counter-mass or stability requirements.

The principles listed above are not all to be taken as rigid, inflexible rules but as basic parameters which can be used in making any tradeoffs necessary to achieve optimum vehicle design.

These principles and those developed in the previous section provide sufficient criteria to permit selecting an optimum configuration for the vehicle.

V. THE OPTIMUM VEHICLE CONFIGURATION

With the human, engineering, and operational factors as parameters against which various possible vehicle configurations may be compared, it is possible to select a configuration which is optimum from an artificial gravity viewpoint. The integrated application of the principles derived from the investigation may be illustrated in the conceptual design of an actual vehicle. Minimal capability design and some current design proposals are discussed below.

Analysis of Various Possible Vehicle Configurations

While many vehicle configurations are possible, there are essentially only three basic configurations, all stemming from the prototype idealized dumbbell. The first is the dumbbell itself, with either a rigid or flexible shaft. The second is the torus, a figure of revolution obtained by rotating a symmetrical dumbbell about its major axis of inertia. The third is 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 with Flexible Shaft:

This configuration, characterized by a living-working compartment and a useful or dead-weight counter-mass, connected by a long, steel cable, is the only one which approaches practicality for vehicles of extremely large radius (figure 13). The design of such a vehicle, using a tapered cable length of about 5 miles, is discussed in detail by Oberth (ref. 30). Using flexible cable, which provides the highest possible strength-to-mass ratio, is feasible because, under a constant rate of rotation, tensile force is the only force acting on the connecting structure, i. e., the cable. The advantage to be gained through this configuration is the extremely low value of angular velocity which can be used to provide artificial gravity. From a human factors viewpoint this advantage is important, since  $\bar{\omega}$  is intimately connected with the source of most of the human factors difficulties, i. e., Coriolis forces. In fact, if human factors alone were to be considered, this configuration would be ideal. For the vehicle under consideration in this study, however, the design has too many disadvantages to be of value:

(a) For extremely large  $\bar{r}$ , the counter-mass would be too remote to be useful mass, unless it were a second, completely independent vehicle with its own crew.

(b) For cable lengths greater than about 5-1/2 miles, tidal forces would become unpleasant (ref. 30).

(c) Because flexible cable cannot support a bending moment, acceleration of the vehicle (or vehicles) to rotational speed or deceleration to zero angular velocity would be a difficult maneuver.

(d) On cessation of rotation, the relaxation of the taut cable would tend to pull the living-working compartment and the counter-mass toward each other with erratic motion and possibility of collision. The danger would be heightened if the counter-mass on a small-radius vehicle were to consist of a nuclear auxiliary power source. In this situation, as pointed out by Ehricke (ref. 11), unless the reactor were completely encased in shielding (at large expense in mass), there would be a radiation danger to the crew members.

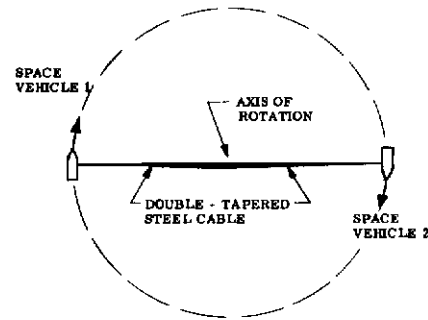


Figure 13. Illustration of Use of Dumbbell-With-Flexible-Shaft Configuration to Create Artificial Gravity in Space Vehicle

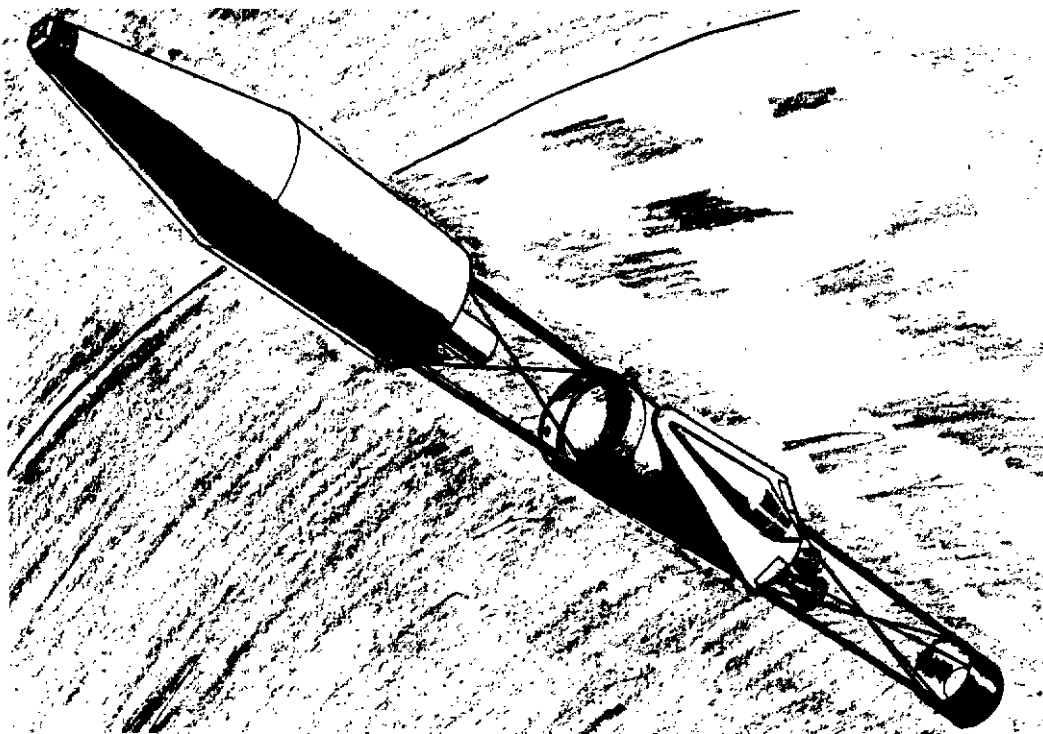
(e) All facilities would have to be placed in the living-working compartment at the expense of structural economy and of stability during the resupply operation.

A vehicle of this configuration would have usefulness only as a minimal-capability vehicle, for which empty tankage or other booster debris on a relatively short length of cable, or mere cable-length alone, could serve as counter-mass to a small, manned compartment designed for a short-duration mission. The configuration does not appear to be a favorable one for a large, permanent space station.

#### The Dumbbell with Rigid Shaft:

This configuration has an advantage over that above in that it can withstand bending moments and any relaxation-compression which might accompany cessation of rotation. Thus, a nuclear reactor used as counter-mass would require only unidirectional, shadow-type shielding with corresponding savings in overall mass. However, the radius of the rigid dumbbell would be restricted to much shorter lengths because a long connecting structure would have to be massive to resist bending moments. Shorter values of radius would naturally require larger values of  $\bar{\omega}$  with an accompanying increase in Coriolis forces.

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 living-working compartment at one end and, as proposed by Ehricke (ref. 10), a nuclear power source as counter-mass at the other, as shown in figure 14.



(Reproduced with permission of Mr. Ehricke and the ARS.)

Figure 14. Illustration of Use of Dumbbell-With-Rigid-Shaft Configuration in Design Proposal by Ehricke (ref. 10)



The primary disadvantage connected with this configuration is the limitation in the lateral dimensions of the living-working compartment. This limitation can be minimized by using several "floors," each at a different radius with a different g-level. Radial expansion of the living-working 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 radial traffic which becomes necessary in a radially oriented compartment, the configuration is not considered optimum.

#### The Torus:

The limitation in the lateral dimensions of the living-working compartment of the dumbbell can be alleviated by extending the compartment in the tangential or axial directions. The torus configuration is obtained by extension of the compartment in the tangential direction, i. e., the torus is a body of revolution formed by a rotation of a symmetrical dumbbell about its major axis of inertia. The torus configuration has been popularized as a "Space Wheel" because of its obvious resemblance to an inflated innertube with radial spokes leading to a central hub, as is shown in figure 15. The configuration was made famous by von Braun (ref. 38) with his proposal in 1952, although essentially the same configuration was proposed earlier by Ross and Smith (ref. 33). It has been favored by Ley (ref. 28), and more recently by Schnitzer (ref. 34), among others.

Schnitzer, in his proposal for a minimal-capability experimental torus, has listed some advantages of the torus configuration:

- (a) The configuration is compatible with a large parabolic solar collector which can be placed in the center of the wheel.
- (b) The spinning torus can easily be stabilized since the torus is rotated about its major axis of inertia.
- (c) There is an equal gravity level everywhere along the outer wall, i. e., the "floor," of the torus.

To these advantages of the torus configuration, of which the last is the most important from a human factors viewpoint, 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 this configuration. They stem primarily from the fact that the plane of the torus lies in the plane of rotation, i. e., the plane in which motion produces maximum Coriolis forces, as was determined in section II.

The disadvantages are:

- (a) The major axis of traffic is tangential. Therefore, crew members would be subject to continual variations in gravity level while moving back and forth.
- (b) Orientation of bunks and control consoles to minimize the 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 use of space.

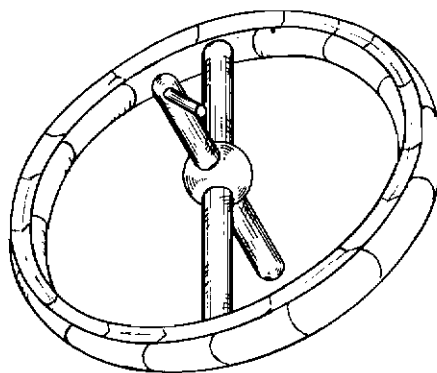


Figure 15. Illustration of Use of Torus Configuration in Design Proposal by von Braun (ref. 39)

(c) Visual conflict would be prevalent unless special precautions were taken in interior design.

(1) The change in apparent vertical from one point to another further down the aisle would be obvious and disconcerting.

(2) The crew member walking along the aisle would feel that he were walking against the spin, he would feel "lighter"; i. e., he would feel as though he were walking "downhill." The resulting conflict would probably be particularly stressful.

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

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

(d) The torus cannot very well be optimized for size. Once a radius for the floor of the living-working compartment is selected from the design envelope, the size of the torus is automatically established with a circumference of  $2 \pi r$ , regardless of whether or not the resulting space provided is optimum. To locate most of the vehicle components at the radius of the torus compartment to make maximum utilization of space within the torus would involve unnecessary structural penalties.

This disadvantage could 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. However, this modification would result in extensive radial traffic if more than one of the segments were to be occupied. If not, the configuration would essentially degenerate into a dumbbell with all of the above disadvantages still present.

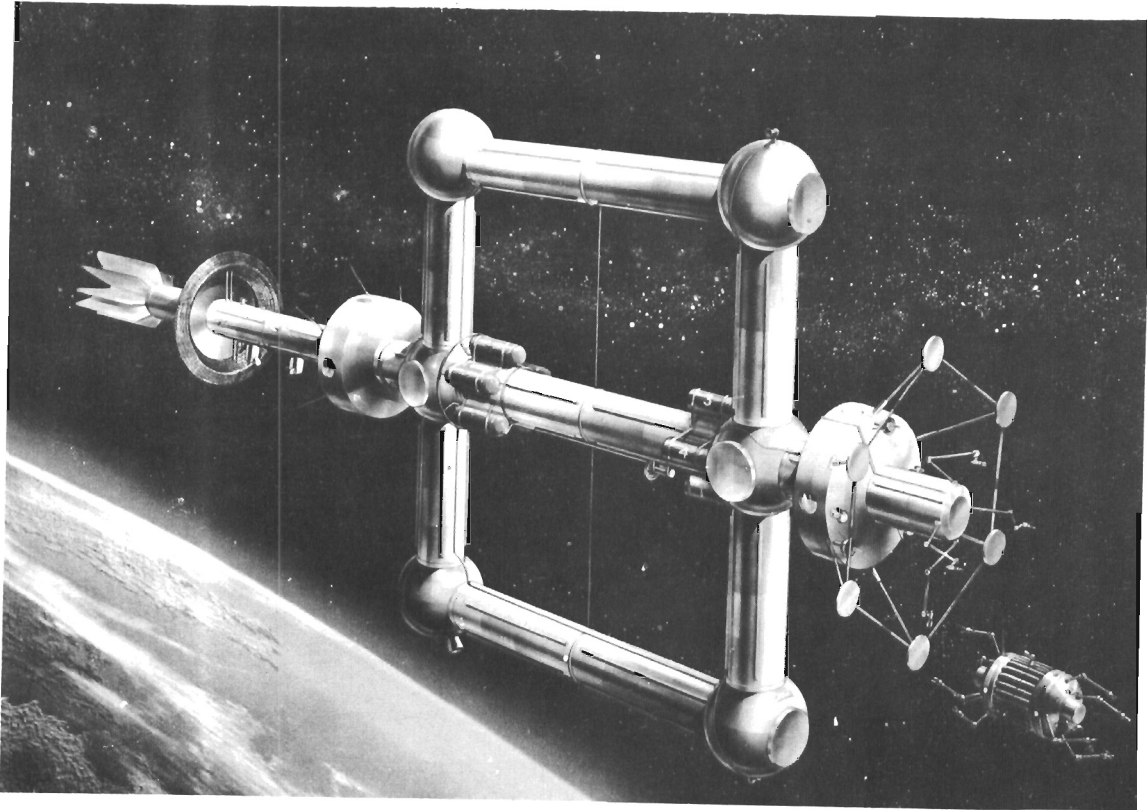
An expansion of the living-working compartment of the dumbbell in the tangential direction would result in a magnification of the inadequacies inherent in the artificial gravity environment, and in inefficient economy of structure. Because the torus is admirably suited to the use of an inflatable material as 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 living-working 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 (ref. 23), although the basic configuration is evident in an earlier proposal by Ehrlicke (ref. 12). The Kramer and Byers vehicle, shown in figure 16, provides for two symmetrically opposed living-working compartments and two radial shafts (plus a third compartment along the spin axis).

The axially expanded dumbbell configuration has inherent advantages which accrue as a natural consequence of the orientation of the major dimension of the living-working 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:





(Reproduced with permission of Messrs. Kramer & Byers and the IAS.)

Figure 16. Illustration of Use of Axially Expanded Dumbbell Configuration in Design Proposal by Kramer and Byers (ref. 23).

(a) The major axis of traffic is axial. Therefore, crew members would experience a constant gravity level while moving back and forth along the living-working compartment. Increase and decrease in  $g$ -level accompanying tangential motion would be minimized because such movement would occur across the relatively narrow dimension of the compartment. Such movement would probably occur at velocities less than the assumed indoor walking velocity of 4 feet per second. Hence, the effect would be further minimized if not practically eliminated.

(b) 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.

(c) Visual conflict would be minimized.

(1) 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. For a large-radius vehicle the change would probably be imperceptible. Assuming a 10-foot floor width across the aisle, the total change in the angle of the vertical across the compartment would be  $10^\circ$  for a minimum permissible vehicle radius of 60 feet, and less than  $4^\circ$  for a design radius of 180 feet.

(2) 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 in for small-radius vehicles. For large-radius vehicles the floor could be made perfectly flat.

(d) The axially expanded dumbbell can more easily be optimized with respect to size. The relationship between the radius selected for the vehicle and the length of the living-working 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.

(e) The cylindrical shape of the living-working compartment would simplify the boost problem, since the shape would be compatible with the cylindrical shape of the booster.

The disadvantages are:

(a) The configuration has inherent disadvantages which result from the use of a second living-working compartment as counter-mass to the first.

(1) Essentially two separate closed ecological systems or one large, complex one would be required.

(2) Radial traffic would be extensive.

(b) Design for inherent stability would be more critical for this configuration than it would be for the torus. The configuration would have less inherent stability because the stretching out of dumbbell mass in the axial direction would tend to increase the moment of inertia about an axis perpendicular to the axis of rotation.

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 living-working compartment. Useful counter-mass, consisting of vehicle components, is used in place of the second compartment. This modification results in eliminating 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 versus engineering viewpoint, without sacrificing operational suitability.

The optimum configuration is reflected in the vehicle illustrated in figure 17. A description of the vehicle, referred to as the Pseudo-Geogravitational Vehicle (PGV) because it provides an artificial gravity environment which approximates that on earth, will serve to illustrate the application of the design principles derived in this study.

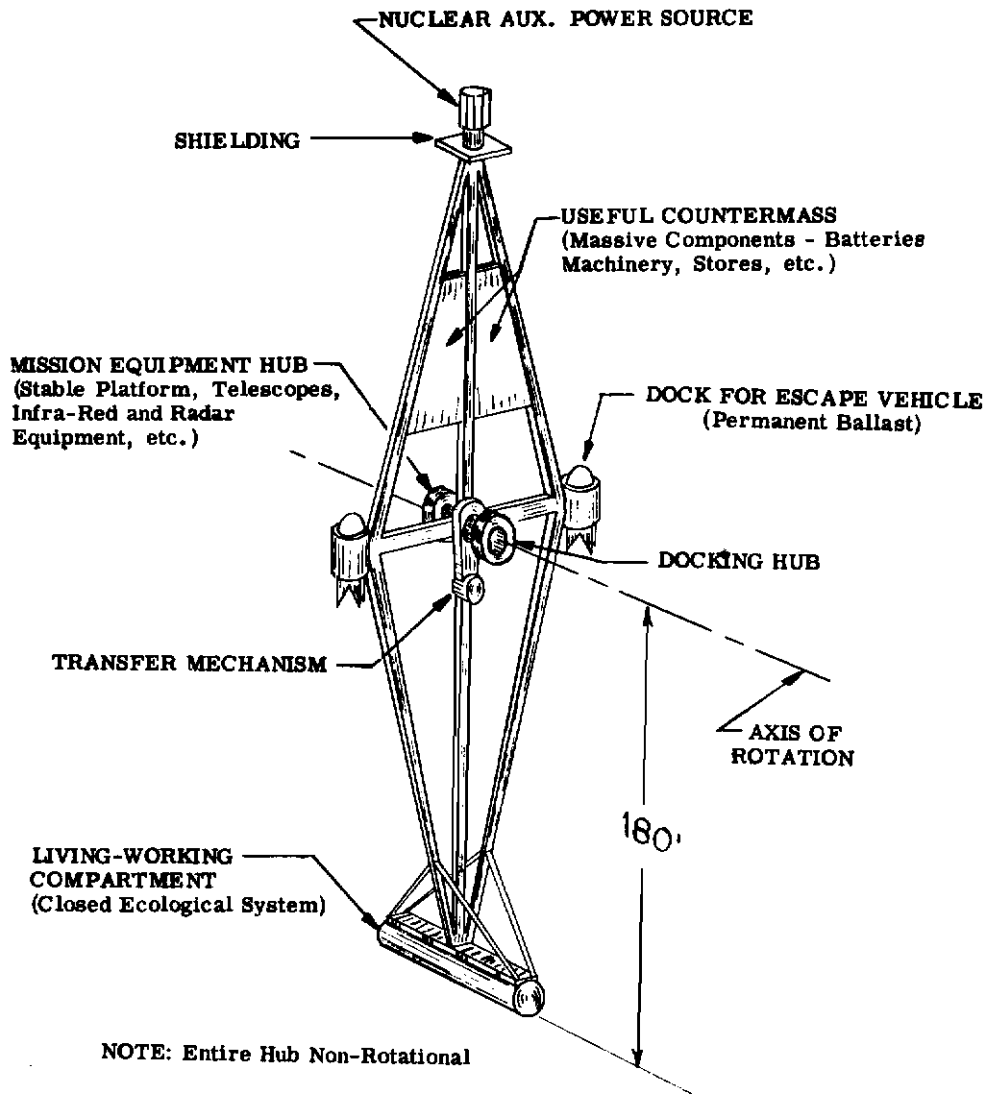


Figure 17. Illustration of Use of the Modified Axially Expanded Dumbbell Configuration in the Conceptual Design of a Manned Orbital Satellite Vehicle

The Pseudo-Geogravitational Vehicle (PGV)

The selected values for the rotational variables  $\bar{\omega}$  and  $\bar{r}$  are indicated on the human factors design envelope of figure 18 by the point labeled PGV. This 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:

- (a) 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 manned orbital satellite vehicles.

(b) It establishes a practical upper limit on  $\bar{r}$ , since the range of  $\bar{r}$  values between 60 feet and 180 feet permits the selection of the entire range of permissible g-values. The upper limit, indicated on the design envelope by the vertical dashed line, narrows the region of interest for future design. Therefore, the design of future vehicles should be based on operating points which lie within the shaded area.

The PGV Artificial Gravity Environment:

The selected operating point corresponds to a value of 0.4 rad/sec for  $\bar{\omega}$ , and a value of 180 feet for  $\bar{r}$ . Thus, the floor of the living-working compartment of the illustrated vehicle is located 180 feet from the axis of rotation. The corresponding g-level is about 0.9 g (figure 18). This g-level will be experienced by crew members both when stationary and when walking along the length of the compartment. The gravity gradient as a percentage of floor-level g is a negligible 3.3 percent. The percent change in gravity experienced by crew members walking across the aisle of the compartment, obtained directly from figure 9, will be about 11 percent. This figure is conservative since it is based on normal walking velocity. Movement across the narrow dimension of the compartment will probably be at lower-than-normal walking velocities. The possibility that some canal sickness symptoms will be experienced cannot be eliminated, but any inadequacy of the environment in this respect can be minimized through careful crew selection, crew training, and proper design of the vehicle.

The Living-Working Compartment:

The single living-working compartment at the lower end of the figure consists of a closed ecological system which provides for a shirt-sleeve environment. All human activity outside the compartment is conducted essentially in the space environment. The compartment itself contains only the minimum components required for display and control and life support. One or more air locks are provided in the roof of the compartment for entry and exit. The compartment is designed to operate under zero gravity as a self-sustained unit during in-orbit construction of the vehicle.

Control consoles are located against the walls of the compartment and are vertically oriented. Bunks in the off-duty section of the compartment are placed on both sides of the aisle and are axially oriented. (The orientation of both these components is as illustrated in figure 11.) The floor is perfectly flat. The interior decoration emphasizes spaciousness and the normal vertical-horizontal orientation which exists in earthbound facilities. With the exception of viewing ports located in the roof, the compartment is windowless.

The more massive components of the compartment are located in the roof to minimize the requirement for counter-mass. Provision for housing these components is indicated in the illustration by the boxlike structure which caps the compartment.

Engineering Design Features:

The living-working compartment is counterbalanced by vehicle components and a nuclear auxiliary power source. Figure 17 merely illustrates the relative positioning of the vehicle components. No attempt has been made to indicate the relative size or the radius to each of the components, nor should any conclusions be drawn concerning these parameters from the scale of the drawing.

Inherent stability about the designated spin axis is achieved primarily through counterbalancing two permanent-ballast, one-way escape vehicles in the plane of rotation, as shown. Axial distribution of mass is minimized by concentrating the more massive components of the living-working compartment toward the center of the compartment and by locating the least massive items at the extremities.

The nonrotating hub consists essentially of a hollow, cylindrically shaped compartment located at the vehicle spin axis, with the stable platform containing mission equipment (telescopes, cameras, etc.) at one end and the docking hub at the other. Ample space is provided for zero-g experiments.

#### Vehicle Operation:

Since mission equipment located in the nonrotating hub is remotely monitored and operated, crew members will remain, for the most part, in the shirt-sleeve environment of the living-working compartment during normal operation. The normal activities which require crew members to leave the shirt-sleeve environment are few, infrequent, and for the most part involve short-time exposure to the fractional gravity space environment, such as:

- (a) Transfer of personnel, supplies, and equipment during the resupply operation
- (b) Performance of external vehicle maintenance
- (c) Conduct of those zero-g experiments which require participation or presence of crew members in the nonrotating compartment

#### Minimal-Capability Design

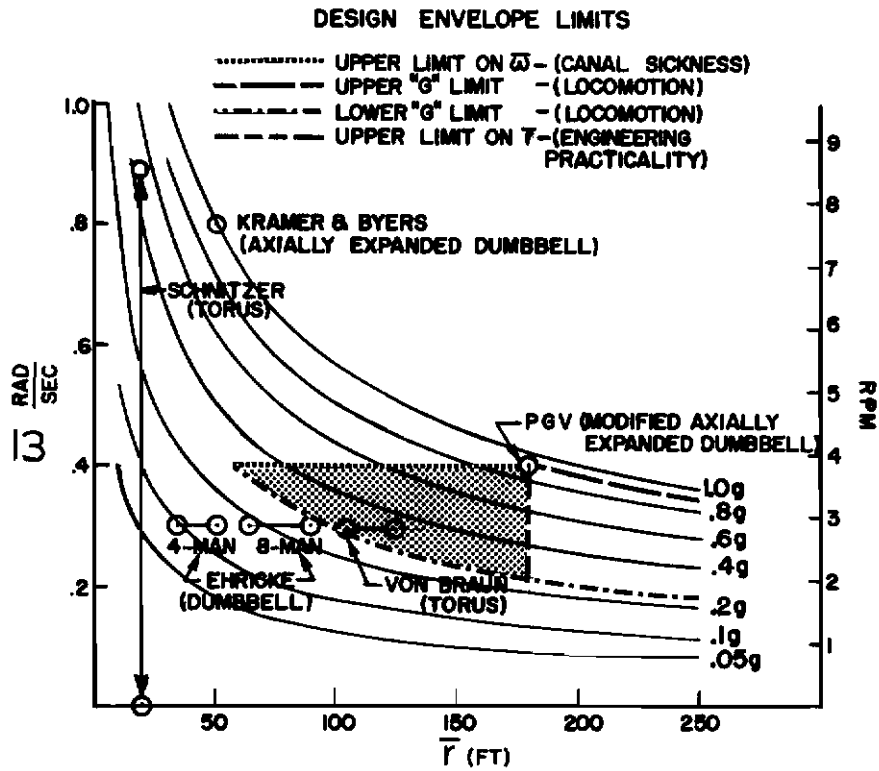
The operating point for the minimal-capability vehicle should obviously be chosen at the smallest permissible value of radius within the design envelope, i. e., 60 feet. The problems involved in the engineering design of the 60-foot-radius vehicle will be appreciably simplified, which should facilitate the realization of an experimental vehicle in the near future using present state-of-the-art components. Such a vehicle would be an invaluable forerunner to the fully operational PGV.

#### Current Design Proposals

The relationship to the design envelope of the operating points for some well-known design proposals are indicated in figure 18.

Those which may be considered to be minimal-capability vehicles are the Schnitzer torus (ref. 34), which is an experimental vehicle of 20-foot radius designed to provide from 0.0 to 0.5 g through variation of  $\bar{\omega}$ , and the Ehricke 4-man rigid dumbbell (ref. 10), which is to operate at a fixed value of  $\bar{\omega}$  but with several floor levels, each located at a different radius with a different g-level.

Those which are advanced-capability vehicles are the von Braun torus (ref. 38), which is to operate at constant  $\bar{\omega}$  but with different g-levels for each of three radially separated floors, the Ehricke 8-man rigid dumbbell (ref. 10), which is an advanced version of the 4-man vehicle, and the Kramer and Byers axially expanded dumbbell (ref. 23), which provides for 1-g environment at the floor level of each of the two outer compartments.



NOTE: Shaded area is design area of interest.

Figure 18. Human Factors Design Envelope Superimposed on Plot of Angular Velocity ( $\bar{\omega}$ ) Versus Radius of Rotation ( $\bar{r}$ ) to Achieve Various Levels of Artificial Gravity. Operating Points for Pseudo-Geogravitational Vehicle (PGV) and Other Current Design Proposals Are Indicated.



## VI. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The objective of the investigation has been the synthesis of design criteria which optimize manned orbital satellite vehicle design with respect to artificial gravity. Human factors have been given paramount consideration.

The first step in the investigation has involved an analysis of the artificial gravity environment and its peculiarities in terms of the rotational parameters  $\omega$  and  $r$ . An analysis of human factors based in part on experimental evidence and in part on assumptions has led to the establishment of a human factors design envelope and some human factors design principles. An analysis of engineering and operational factors has provided design criteria which, in conjunction with the basic human factors design criteria, have led to the selection of an optimum configuration for the vehicle.

Application of the derived criteria has been illustrated in the conceptual design of a vehicle rotated to provide a nearly earthlike artificial gravity environment.

Conclusions

## The Human Factors Design Envelope:

The design envelope is prescribed in figure 18. The limits are prescribed as follows:

- (a) The Upper Limit on Vehicle Angular Velocity ( $\bar{\omega}$ ) - established at 0.4 rad/sec, to minimize the occurrence of "canal sickness"
- (b) The Upper Limit on Artificial Gravity - established as a 1-g maximum, modified to compensate for Coriolis effects for tangential walking in the direction of spin
- (c) The Lower Limit on Artificial Gravity - established as 0.2 g minimum on the assumption that the lowest value of artificial gravity to be permitted is that minimum value (0.2 g) at which man can walk unaided, the minimum limit modified to compensate for Coriolis effects for tangential walking against the spin
- (d) The Practical Upper Limit on Vehicle Radius ( $\bar{r}$ ) - established at 180 feet based on engineering considerations

## Human Factors Design Principles:

- (a) Radial traffic should be kept to a minimum.
- (b) Transport across the spin axis and human activity at the spin axis should be prohibited unless the hub is nonrotating.
- (c) The living-working compartment should be located as far as possible from the spin axis.
- (d) The compartment should be oriented so that its major dimension is parallel to the vehicle spin axis.
- (e) Crew duty-station positions should be oriented to provide the preferred orientation of the crew member's lateral axis.
- (f) Sleeping bunks should be oriented with their long axis parallel to the vehicle spin axis.



- (g) The presence of confusing visual stimuli should be minimized.

#### Engineering and Operational Design Principles:

- (a) The living-working compartment should be placed at the outermost radius of the vehicle.
- (b) The compartment should consist of minimum mass, i. e., those items essential to mission accomplishment and to crew safety and comfort.
- (c) All remaining components, with the exception of those listed below, should be used as countermass or to meet stability requirements.
- (d) The stable platform, the zero-gravity experimental compartment, and the docking facility for the supply vehicle should all be located at the axis of rotation in nonrotating compartment.
- (e) The vehicle should rotate continuously, with provision made for transfer from the rotating structure to the nonrotating hub through use of a transfer mechanism.
- (f) The vehicle must have rotational stability.
- (g) Emergency one-way escape vehicles should be located at the axis of rotation or positioned to meet countermass or stability requirements.

#### The Optimum Vehicle Configuration:

The optimum configuration is a modified axially expanded dumbbell. Its features are illustrated in the conceptual configuration shown in figure 17.

#### Selection and Training of Crew Members:

Because canal sickness is the most critical of human factors connected with the artificial gravity environment, screening of astronaut candidates should include an evaluation of susceptibility to canal sickness. Effort should be devoted to the design of the test device and test procedure.

Astronauts in training for duty in the artificial gravity environment should be exposed to the peculiarities of a rotating-vehicle environment to the extent that earthbound facilities will permit. Effort should be devoted to development of a training facility which will most nearly simulate the rotating-vehicle environment.

#### Recommendations for Future Research

##### Human Factors:

More conclusive and precise experimental data must be obtained on human factors stress limits, particularly those pertaining to canal sickness and the lower limit on artificial gravity.

The upper limit on vehicle angular velocity established in this investigation represents a compromise between practicality and inconclusive experimental evidence. It should be possible to define this upper limit with a greater degree of precision through further experimentation in rotating-room environments involving a large number of test subjects.

The validity of the assumption that the lowest value of fractional gravity at which man can walk unaided cannot be established until long-period, human-orbit times can be achieved. But a more precise value of the minimum g-level for unaided walking can be established, and will be forthcoming in the near future as a result of experiments to be conducted by the Aerospace Medical Laboratory personnel at Wright-Patterson Air Force Base.

Since the upper limit on  $\bar{\omega}$  and the lower g-limit are critical parameters of the human factors design envelope, a refinement of these limits based on further experiments, which are within present capability, will enhance the usefulness of the design envelope established herein.

#### Engineering Design:

Other than to consider those factors which are relevant to the selection of an optimum configuration and to insure practicality, the subject of engineering design has been subordinated in this investigation. There are many engineering problems which will bear further investigation in the light of the conclusions reached in this study. Some of the problem areas which merit detailed investigation are those involving distribution of vehicle mass, rotational stability and control, living-working compartment design, shielding of vehicle components and crew members from the radiation environment of space and of the nuclear reactor, etc.

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