chute diameter of 53 ft is optimum. These values are also near optimum for weight increases, as discussed. In addition, the following conclusions are reached. 1) Lifting entry and terminal phase system design performance may be optimized with respect to several performance parameters. 2) Criteria and results upon which optimization are based are usually compatible with little or no compromise in performance requirements. That is, the requirements of maximum entry corridor, maximum terrain height, and minimum terminal phase system weight are achieved within reasonable constraints and ground rules for the 1975 Mars lander. However, for a different set of constraints and ground rules, it might be possible that all requirements could not be mutually achieved. 3) Results of the optimization analysis depend on the constraints and requirements imposed by preliminary design results and other systems considerations.

References

[1] "Mars Engineering Model," M75-125-0, March 13, 1970; also April 22, 1970, NASA.

[2] Pritchard, E. B. and Harrison, E. F., "Lifting Entry ($L/D \leq 0.2$) for Unmanned Viking Class Mars Landers," TN D5828, June 1970, NASA.

MAY 1972 J. SPACECRAFT VOL. 9, NO. 5

Preliminary Results of Manned Cargo Transfer Studies under Simulated Zero-*g* Conditions

Amos A. Spady Jr.,* Gary P. Beasley,* and Kenneth R. Yenni†
NASA Langley Research Center, Hampton, Va.

A parametric investigation to determine man's capability to perform intravehicular cargo transfer tasks in simulated zero-*g* has been conducted in Langley Research Center's water-immersion facility. Packages with masses up to 51 slugs, volumes up to 142 ft^3, and moments of inertia about their center of mass of up to 285 slug-ft^2 were used. All tests were conducted using both one- and two-rail motion aids. All subjects were able to transfer satisfactorily all of the packages tested. Based on subject's comments, it was concluded that 1) the effects of package mass, size, and so forth, are minimal, therefore the maximum size package to be transferred will probably be determined by the restraints of the space vehicle, that is, tunnel size, hatch openings, and so forth, rather than man's capabilities; 2) even though the cargo could be handled using a one-rail motion aid, a two-rail motion aid is preferred, and 3) the use of a two-man team substantially reduces the task effort for large packages.

Nomenclature

I = moment of inertia, slug-ft^2
M = mass of the package, slugs
V = volume, ft^3
X,Y,Z = reference axis
$\Delta x, \Delta y, \Delta z$ = package dimensions

Subscript

c.m. = moment of inertia about center of mass

Introduction

THE transfer of large quantities of a wide range of cargo will be a requirement in future long-duration manned space missions. It is important to determine in the early planning stages of these missions the limits of astronaut participation in cargo transfer. Several preliminary studies have been conducted on various aspects of the problem using ground-based simulation. For example, one zero-*g* simulation study has indicated that man can control and transfer packages with masses up to a limit of 5 slugs.[1] In contrast, other studies[2,3] have indicated that man can handle packages up to approximately 10 slugs. Such studies have generally been limited in scope and the results obtained are difficult to correlate because of the differences in simulation and testing techniques used.

In an attempt to examine man's cargo transfer capabilities in a more comprehensive manner and to contribute information to the development of a set of guidelines, a series of studies has been conducted at the Langley Research Center. The over-all program is designed to investigate test subjects' ability to control and transfer cargo for both intravehicular (IVA) and extravehicular activities (EVA). The initial phase of the program discussed herein was a parametric study to determine the limits of IVA manual cargo transfer capability. The package parameters (mass, moment of inertia, etc.) were varied so that their criticality, with respect to the over-all transfer task, could be determined. Tests were carried out using the water-immersion technique for zero-*g* simulation. The results of this study should be useful in the determination of the IVA cargo transfer tasks which can be accomplished manually and those which require mechanical assistance.

Presented as Paper 71-851 at the AIAA/ASMA Weightlessness and Artificial Gravity Meeting, Williamsburg, Va., August 9–11, 1971; submitted August 23, 1971; revision received December 20, 1971.

Index categories: Manned Space Station Systems; Extra-Vehicular Activity.

* Aerospace Technologist, Flight Dynamics and Control Division Simulation and Human Factors Branch.

† Aerospace Technologist, Research Aircraft Flight Division, Pilots Section.

Equipment

All tests were conducted in Langley's water-immersion simulator facility (WIS). The WIS is 20 ft deep and 40 ft in diam. The facility has three large windows for observation and photographic purposes. It is equipped with three closed-circuit television cameras which can be remotely controlled to track the subject, thus allowing tests to be recorded on video tape for data purposes. In addition, for selected tests, motion pictures and still photographs were taken.

All simulated packages were constructed using styrofoam spheres for flotation, 1-in. galvanized pipe for shape, and lead for ballast. A typical package is shown in Fig. 1. A number of individual packages were constructed and tested (packages 1–5 of Table 1). These packages were then used as basic building blocks for larger packages. The mass, moment of inertia, and dimensions of the packages are presented in Table 1.

The sphere and pipe method of fabrication was chosen to provide minimum hydrodynamic drag as is discussed in Ref. 4. This method also provided a convenient means of attaching lead strips needed to balance the package to neutral buoyancy (Fig. 1). The packages were made neutrally buoyant in all axes. The subject was allowed to use as a hand hold any point on any of the pipes on the periphery of the package.

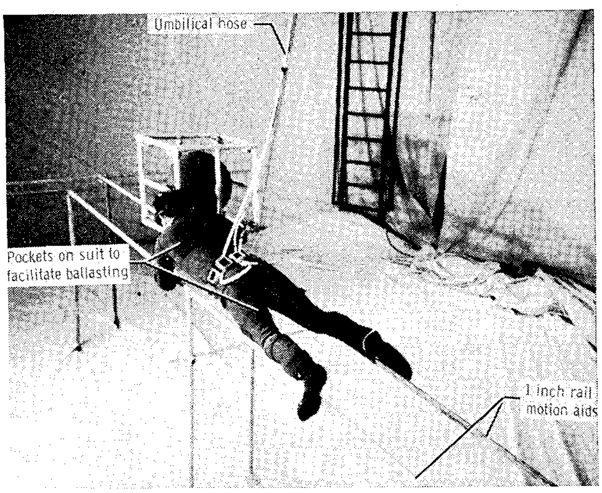

Fig. 1 View of subject transferring the reference package along the motion aid.

The motion aids provided were handrails made from 1-in. galvanized pipe spaced 1.5 ft apart and supported 5 ft above the floor of the WIS to assure that the subject would not inadvertently contact any other surface. The rails formed a rectangular course with inside dimensions of 10 ft by 20 ft, part of which can be seen in Fig. 1.

The subjects were dressed in custom-fitted wet suits equipped with a series of small pockets located on the suit at the chest, back, and upper and lower arms and legs (Fig. 1) to accommodate strips of sheet lead or styrofoam as needed to make the subject neutrally buoyant. The subjects wore a standard scuba weight belt and mask. Breathing air was supplied through an umbilical hose to eliminate the effects of the change in buoyancy of a scuba bottle as air is used. By exercising breath control, the subject was able to maintain his neutral state throughout the test.

Program Plan

The test series was organized so that each subject started with what was considered a nominal package which could be used as a standard for comparison (package 1, Table 1). The subjects were not allowed to handle any of the packages prior to the test program; therefore, their ratings and comments are based on their first attempts at transferring the various packages. Each subject was instructed to traverse around the rectangular course in a head-first, face-forward manner, keeping the trailing edge of the package forward of his shoulders. During the initial traverse for each package, a subject was limited to the use of a single pipe rail, and for the second traverse he was allowed to use both rails as desired. No other constraints were imposed on the subjects, such as velocity limitations, specific points of contact on the packages, or procedure for negotiating turns, and so forth. The subjects were instructed to pretend that the packages were solid; therefore, they made an effort to look around rather than through the packages.

After each traverse, the subjects were asked to evaluate the task and to give separate ratings for each of the following: translational and rotational maneuverability, visibility, and the over-all task effort. The ratings were based on a rating scale (Table 2) developed to fit the conditions of this study (a modified version of the standard pilot rating scale). Ratings from 1 to 6 were considered acceptable whereas a rating of 7 or above was considered unacceptable.

Table 1 Packages used for cargo transfer studies

Package number	Approximate dimensions, ft Δx	Δy	Δz	Approx. volume, ft^3	Mass, slugs	Earth weight, lb	Moment of inertia, slug-ft^2 $X_{c.m.}$	$Y_{c.m.}$	$Z_{c.m.}$
1	2	2	2	8	3.35	108	5.3	5.3	5.3
2	2	2	2	8	6.25	210	9.5	9.5	9.5
3	3.5	3.5	3.5	42.8	5.0	163	14.5	14.5	14.5
4	3.5	3.5	3.5	42.8	9.32	300	37	37	37
5	4	2.5	2.5	24	16.75	540	30 to 47	17 to 78	30 to 75
6	4	2	2	16	6.7	216	10.6	16.8	17
7	4	2	2	16	9.88	318	15	23	23
8	4	2	2	16	13	470	19	31	31
9	7	3.5	3.5	86	14.4	463	51.5	84	84
10	4	4	2	32	19.7	636	47.8	46	64
11	4.5	4	2.5	41	23.5	756	33.8	63	69
12	4.5	4	2.5	41	29.8	960	48	82	92
13	6.5	4	2.5	57	36.5	1,116	65	143	160
14	7	6	4	143	51	1,640	215	285	368

After each test period, the subjects were questioned to determine the reason each package was given a particular rating and to ascertain the interrelation of the factors rated. It should be noted, however, that each rating is relative only to the factors being rated. Therefore, the numerical ratings given for one factor cannot be compared directly to another factor without taking the subject's comments into consideration.

Test Subject Qualifications

The results obtained from this study are based primarily on the subject rating data provided by three test subjects. Three other subjects have completed parts of the test program and their results are not included, but were in agreement with the data reported herein.

Test Subject 1 was a qualified NASA Langley engineering test pilot. Much of his simulation experience has involved testing of vehicles and methods of locomotion in a reduced-gravity environment. Test subject 2 was an NASA astronaut with Apollo flight experience. Test subject 3 was a practicing USAF Flight Surgeon with approximately 800 hr flight time.

All subjects were qualified in scuba diving procedures and had sufficient experience so that no psychological problems associated with the underwater environment should have been present.

Results and Discussion

As indicated in the program plan, the basic approach taken was to start with a package of moderate mass, volume, and moment of inertia as represented by package 1 of Table 1. This package was then used as a standard for comparison. In the remainder of the tests, the mass, volume, and moment of inertia parameters were varied in a random fashion for the purpose of determining a subjective limit (7 or higher on the pilot rating scale, Table 2) for at least one of the factors rated. However, the largest combination of packages used (Table 1) did not provide a 7 or higher rating. Therefore, a maximum mass, volume, or moment of inertia limit for man's capability to move cargo in a weightless environment was not defined.

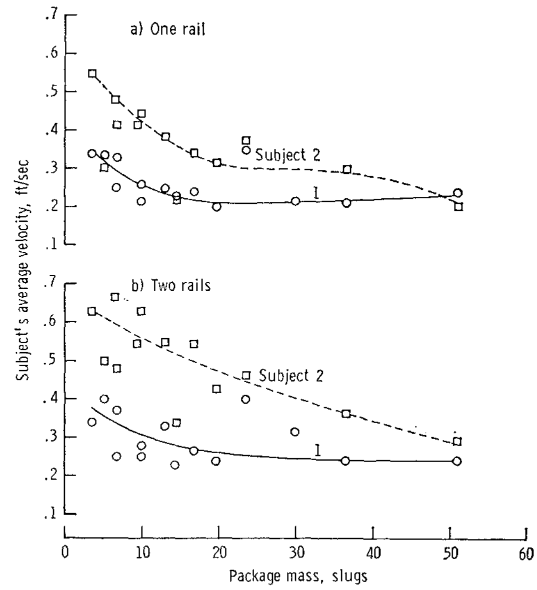

Fig. 2 Subject's average velocity as a function of package mass.

The discussion of the results obtained from this test series attempts to point out general trends and techniques based on the subject's ratings and comments. Where appropriate, the subject's ratings are presented in both test data form (actual ratings) and as normalized averages. The data were normalized by taking the difference between the rating given by a subject for the reference package and 1, which is the best possible rating (Table 2), then subtracting that difference from each of that subject's ratings. The normalized data for each package were then averaged.

One factor which must be considered in any water-immersion study is the effect of hydrodynamic drag. Drag is a function of both package frontal area and velocity. The

Table 2 Subject rating scale

ABILITY TO PERFORM TASK	PACKAGE CHARACTERISTICS	DEMANDS ON THE SUBJECT FOR SELECTED TASK	SUBJECT RATING
Satisfactory	Excellent Highly desirable	Subject compensation* not a factor for desired performance	1
	Good Negligible deficiencies	Subject compensation not a factor for desired performance	2
	Fair - Some mildly unpleasant deficiencies	Minimal subject compensation required for desired performance	3
Moderately satisfactory	Minor but annoying deficiencies	Desired performance required moderate subject compensation	4
	Moderately objectionable deficiencies	Adequate performance requires considerable subject compensation	5
	Very objectionable but tolerable deficiencies	Adequate performance requires extensive subject compensation	6
Unsatisfactory	Major deficiencies	Adequate performance not attainable with maximum tolerable subject compensation Controllability not in question	7
	Major deficiencies	Considerable subject compensation is required for control	8
	Major deficiencies	Intense subject compensation is required to retain control	9
	Major deficiencies	Control will be lost during some portion of required operation	10
Subject decisions			

*Compensation is defined as concentration and/or physical strength.

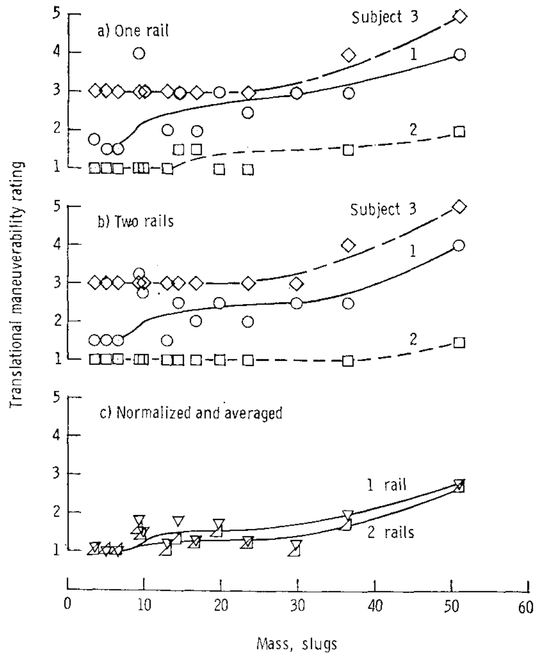

Fig. 3 Subject's translational maneuverability ratings as a function of package mass.

method used for package construction (pipes and spheres) was chosen to minimize the package frontal area in all attitudes. The average velocity used by the subjects was less than 0.7 fps for the small package and decreased to approximately 0.2 fps for the larger packages as can be seen on Fig. 2. Figure 2 gives subjects 1 and 2 average velocities vs package mass for both the one- and two-rail cases (average velocities for subject 3 were not obtained because of equipment malfunction). Although the package drag was not eliminated, it was considered to be small enough that it should not have appreciably affected the trends noted in the results.

Translational Maneuverability

The translational maneuverability rating data presented are based on the subject's ability to start and stop linear motion. Figure 3 shows subjects' ratings for one and two rails and the normalized averages for one and two rails vs package mass.

As indicated by the normalized average curves and verified by subjects' comments, the effect of mass on translational maneuverability was relatively minor. The subjects commented that they preferred using two rails to one rail; however, the number of rails used did not appreciably affect the ratings given. Consequently, it is concluded that package mass, for the range tested, is not a limiting factor in terms of translational maneuverability.

Visibility

The subjects were instructed to pretend that the boxes were solid; consequently, the only method available to the test subjects for determining where they were maneuvering the package was to look at the relationship between a side and the bottom of the package and the motion aids (rails). The larger size boxes required the subject to change his position on the motion aids periodically in order to observe his progress, particularly at the corners. This frequent body positioning caused an increase in the over-all workload and resulted in a degrading of the visibility rating as package size increased. This is shown in Fig. 4 which shows the subject's visibility ratings vs package volume for all the packages tested.

The normalized average curves given on Fig. 4 indicate that the subjects' ratings were not influenced appreciably by two

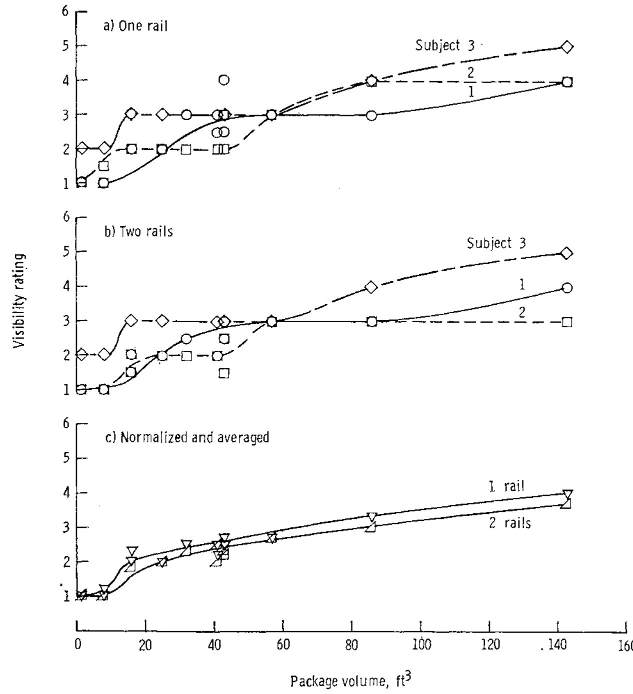

Fig. 4 Subject's visibility ratings as a function of package volume.

rails vs one rail. Although the subjects stated they preferred the two-rail system, they felt that their method of coping with the visibility problem was basically the same for both cases. Consequently, from a "visibility" standpoint the number of rails used was not considered important.

Rotational Maneuverability

The rotational maneuverability is the subject's ability to control package angular motions. The subject's rotational maneuverability ratings are shown in Fig. 5 for one rail and

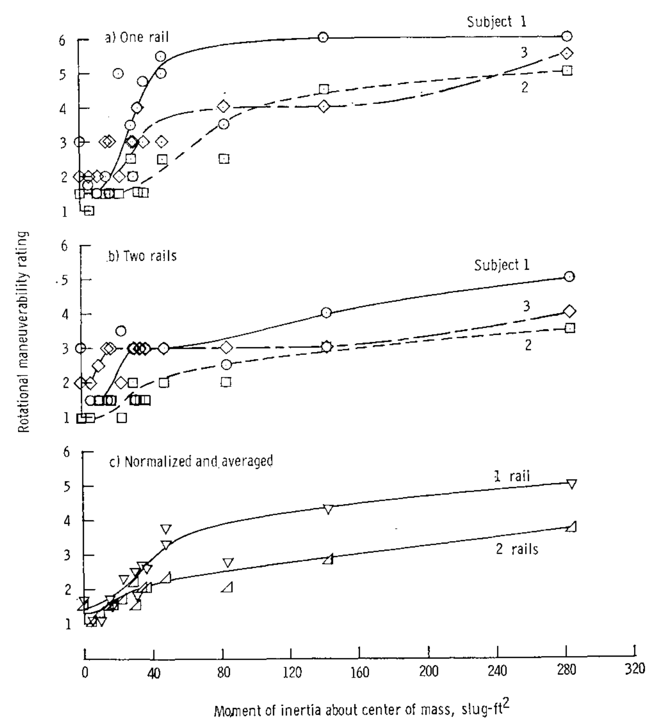

Fig. 5 Subject's rotational maneuverability ratings as a function of package moment of inertia about its center of mass.

two rails and the normalized averages for one and two rails vs package moment of inertia about its center of mass. The curves can basically be broken into three fairly distinct areas.

The three areas can be explained as a function of the technique used to control the package. For the packages with small moments, the subjects tended to handle the package as if it were an extension of their arm, feeling that no special attention to package control was required. In the range of 15–50 slug-ft^2 two items of interest were noted. First, the forces required to control the packages caused a change in technique (the packages became a separate entity), and inputs were applied so that the package tended to rotate about its own center of mass. Second, this range of moments of inertia encompasses the region where, when a subject attempted to apply an input, he would move as much as or more than the package, unless he was securely and properly anchored. For the packages with moments of inertia greater than 50 slug-ft^2, the transition in technique and stability required had been completed; consequently, little effect was noted as a result with further increases in moments of inertia.

The normalized average curves (Fig. 5) show clearly that the use of two rails was preferred to one rail and that the subject ratings for package with moments of inertia greater than 50 slug-ft^2 was not directly proportional to package moments of inertia.

Task Effort

The task effort parameter was used as a means of determining the test subjects' opinions concerning the degree of difficulty of the transfer task considering all factors. Each of the subjects stated that the task effort required was primarily a function of package moment of inertia, with mass and volume relegated to secondary roles. The task effort ratings were therefore basically equivalent to those given as a function of rotational maneuverability.

The subjects' task effort ratings for one rail, two rails, and the normalized averages for one and two rails vs the moment of inertia about the package's center of mass are given in Fig. 6. The curves show the same trends at the rotational maneuverability curves presented in Fig. 5.

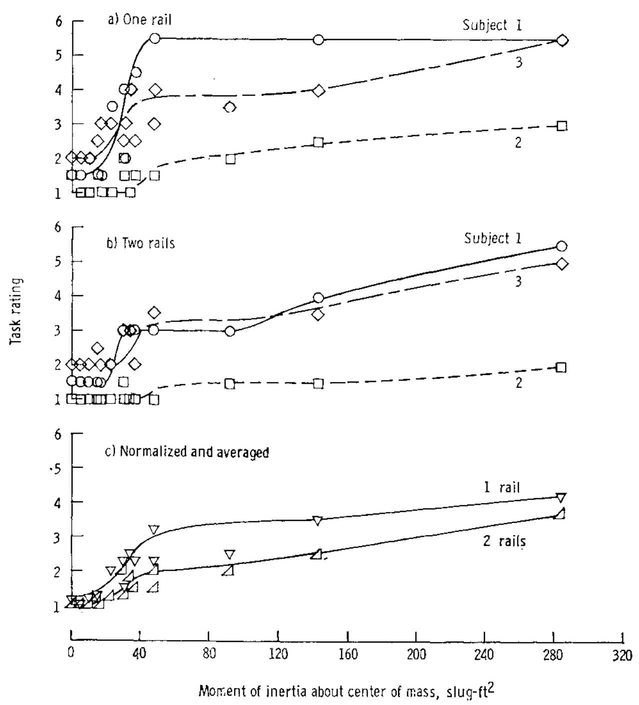

Fig. 6 Subject's task effort ratings as a function of package moment of inertia about its center of mass.

The task effort for performing cargo transfer did not increase in direct proportion to increase in moment of inertia, mass, and/or volume, as might be expected. This can be attributed to the fact that the subjects were able to alter their technique for both package and body control as a function of package moment of inertia (see section on rotational maneuverability) and motion aid utilization. Each subject was encouraged to develop his own techniques with respect to the use of the motion aids. The techniques developed can generally be placed in three basic categories.

The technique used for packages with moments of inertia about their center of mass of less than about 15 slug-ft^2 (Fig. 6) resulted in the subjects' assuming an essentially prone position on the rail(s). The utilization of the legs and feet was a matter of convenience and comfort, rather than necessity. The feet, when used, provided a drag force by squeezing the rails, allowing the subjects to better control their translation velocity.

For packages with moments of inertia in the range of about 15-50 slug-ft^2, two rails were preferred and the techniques used resembled a crawl. Here, the subject placed his instep and calf on the outside of the rails and one hand on the rail. He applied forces so that his legs "squeezed" the rails, and by alternating his grip between his legs and hand he could, in effect, crawl. When he was required to exert precise control over the package, he could anchor himself securely with his legs thus allowing both hands to be used.

The packages with moments of inertia in the range above 50 slug-ft^2 allowed the subject to use a "walking" technique. In this case, the subject squeezed the rails with his insteps and gripped the package with both hands. The moments of inertia of the packages were sufficient so that they, in effect, could be used as an anchor point or third rail. By alternating the forces applied between the rails and the package, the subject could proceed along the motion aids in an almost upright position. When additional body control was required (at the corners), the subject would automatically assume the crawl position.

Each subject was asked, in the case of the large packages, if given the choice would he prefer to break the package into smaller components before transferring them or if they would move the package "as is." In all cases, the subjects stated that they would move the complete package. The difference in effort required between the smaller packages and the large packages was not sufficient to warrant the effort required to disassemble the unit into its component parts and the multiple transfers required. This is emphasized by the fact that the largest package tested was rated by each of the subjects as being within the limits of the subject's manual transfer capabilities.

Two-Man Team Effort

A brief evaluation of a two-man team effort was conducted. The subjects (1 and 2) experienced no difficulty transferring the largest package tested (51 slugs). They both felt the task was extremely easy, requiring only about one-fourth of the effort required to handle the package alone. In addition, both subjects agreed that they could anticipate each other's actions with only hand motions for communications. Since the subjects could, without prior briefing and training, maneuver the largest available package with minimal effort, no additional two-man tests were conducted.

Transfer Velocity

The transfer velocity was not a parameter in these tests. However, several items of interest were noted with respect to the subject's average speed. Figure 2 shows average speed vs package mass, for subjects 1 and 2. Subject 1 set himself the challenge of keeping very tight control of the package at all times including stopping at the corners and turning the packages using the minimum possible volume (simulating a 90° corner in a tunnel). This resulted in relatively low average velocities. Subject 2 maintained positive control of the package but did not slow down for the corner as he felt this required additional effort. This approach resulted in higher average rates. All the subjects felt that the speed used was primarily a function of the task rather than any limitation imposed by the underwater environment.

The subjects' general feeling was that a primary factor associated with cargo transfer is, as stated by subject 3, ". . . discipline or, more specifically, patience obtained as a result of training and experience. In a weightless condition a slow gentle force applied over a longer period of time is necessary, whereas here on Earth we apply force more strongly and expect a quicker reaction. Thus, psychologically, work in a weightless state can lead to frustration, and frustration to wasted effort." It can be noted from the curves in Fig. 2 (subjects' average velocity vs mass) that, in general, as mass increases the subjects' average velocity decreases due, apparently, to the need for more precise and patient control inputs and slower accelerations. It can also be noted that on the average the subjects' velocity is faster for the two-rail cases than for the one-rail. The subjects commented that this could be attributed to the improved body control obtainable using a two-rail motion aid.

Handholds

The pipe construction of the packages, as seen in Fig. 1, provided a variety of possible handholds and the subjects were allowed to use any of the pipes needed. (They were not, however, permitted to reach into the interior of the package.) For the small moment of inertia packages, less than approximately 15 slug-ft^2, precise control could be maintained regardless of hand position, and normally only one hand was used. For the range of moment of inertia between 15 and 50 slug-ft^2, the subjects began to utilize a variety of handholds dependent upon the control input required and package moment of inertia. The majority of these inputs, when a two-rail mobility aid was used, could have been accomplished even if no handhold was present. That is, the use of both hands allowed the subject to squeeze the sides of the package to obtain an adequate grip.

Additional research is desirable to determine optimum handhold placement. However, for large mass and moment of inertia packages it may (especially if standardized cargo containers are to be utilized) be advantageous to place lightweight railings around the edges of the packages (in the same manner as the mockups used). The railing, properly designed, could be utilized for package transfer, tiedown, and as a bumper or energy absorber in cases of inadvertent impacts with the vehicle's interior during transfer operations.

Conclusions

Based on the subjects' ratings and comments obtained from the study conducted to define man's capability to perform intravehicular manual cargo transfer, the following observations can be made.

1) The largest package tested, with a mass of 51 slugs, a moment of inertia about its center of mass of 285 slug-ft^2, and a volume of 142 ft^3 was well within the subjects' cargo transfer capability, therefore no manual cargo transfer limits were established.

2) The subjects could control and transfer all of the packages tested using only a one-rail motion aid. However, a two-rail motion aid was definitely preferred for packages with moments of inertia about their c.m. greater than approximately 15 slug-ft^2.

3) The subjects commented that the package rotational maneuverability was the prime factor involved in the overall task effort with visibility and translational maneuverability relegated to secondary roles.

4) The maximum size (mass, moment of inertia, and volume) package a man can transport in an intravehicular situation will probably be determined by the restraints of the space station; that is, tunnel size, hatch opening, and so forth, rather than by man's capabilities. However, additional studies using mockups of spacecraft will be needed to verify this point.

5) Two-man operation substantially reduces individual effort required for transferring large packages.

References

[1] Nelson, Charles B., "Simulation of Package Transfer Concepts for Saturn I Orbital Workshop," TN D-5111, March 1969, NASA.

[2] Wortz, E. C., Schreck, W., Robertson, W., Lamb, G., and Browne, L., "A Study of Astronauts' Extravehicular Work Capabilities in Weightless Conditions," CR-1334, May 1969, NASA.

[3] Loats, Harry L., Jr., and Mattingly, G. Samuel, "Study of the Astronaut's Capabilities to Maintain Life Support Systems and Cabin Habitability in Weightless Conditions—Mod. 3. A New Technique for Investigating Cargo Transfer in Simulated Weightless Environments," CR-66,708, 1968, NASA.

[4] Goldstein, S. E. and Alvarado, U. R., "High-Fidelity Underwater Simulation of Manned Space Activities," *Journal of Spacecraft and Rockets*, Vol. 5, No. 5, May 1968, pp. 595–599.