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ABSTRACT

Future space operations will require transfers of a large variety of cargo under both intravehicular and extravehicular conditions. In order to determine the techniques, human factor considerations, assistive devices, package limitations, training procedures, and so forth related to the cargo transfer problem, extensive ground-based simulation is required.

To date, several zero- and reduced-gravity simulation techniques have been developed and utilized. All of these techniques have both limitations and definite areas of application. Two of these techniques, water-immersion and zero-g aircraft, are considered usable for cargo transfer simulation. However, the results being obtained using the techniques differ substantially. The reasons for disagreement are to be found in the limitations of the techniques and how they are considered.

The purpose of this paper is to provide a comparison of zero-g aircraft and water-immersion simulation, and to discuss various techniques which can be used to minimize the limitations associated with water immersion.

INTRODUCTION

Future space operations will require transfers of a large variety of cargo under both intravehicular and extravehicular conditions. In order to determine the techniques, human factor considerations, assistive devices, package limitations, training procedures, and so forth related to the cargo transfer problem, extensive ground-based simulation is required.

Many techniques are available, but two simulation techniques, water-immersion and zero-g aircraft, are being most widely used. Results being obtained, however, using these two techniques differ widely and, indeed, between simulators using the same technique. The reasons for disagreement are to be generally found in the limitations of the techniques and how they are considered.

This paper will address the problems associated with these two major simulation techniques and briefly describe a technique presently under evaluation which may offer an improvement in cargo transfer simulations.

CARGO TRANSFER BACKGROUND

In a pure weightless environment, the forces required for cargo transfer are those induced by the inertial properties of the man and cargo. Obviously, there is no theoretical limit to the mass of the cargo which can be transported. Limits arise only in light of practical constraints of time of transport and cargo acceleration limits, control characteristics induced by the cargo package size in conjunction with the physical point of attachment and vehicle geometry, and secondary constraints such as positioning accuracy. Currently there is disagreement over what are the practical limits of man's cargo handling capability. For example, initial efforts at the Manned Space Flight Center (refs. 1 and 2), both in-house and contractor-supported, have led to conclusions on package mass and moment of inertia limits for manual (one-man) cargo transfer. The test conditions and results for the study are presented in Figures 1 and 2, respectively, and represent studies using both neutral buoyancy and aircraft simulation techniques. Figure 2 indicates that as package moment of inertia increased, pilot rating on package maneuverability became less favorable, and that a moment of inertia of greater than 350 in. lb sec^2 is unacceptable. In addition, quoting from reference 1, the following conclusions were drawn concerning package mass limitations:

> Subjects suggested that approximately 90-100 pounds-mass (2.7-3.1 slugs) appears to be a reasonable maximum for one man to manually transfer, provided the package center of mass is not more than 14-16 inches from the handhold.

Subsequent to this effort, large mass packages, up to 10 slugs, were briefly evaluated at Environmental Research Associates (ERA) using a combined water-immersion/servo-drive simulation technique called a Cargo Transport Simulator (CTS). This system is described in reference 3. In addition, current studies at the Langley Research Center are investigating packages with masses up to 50 slugs and moment of inertias up to 10,000 in. lb sec^2 using conventional water-immersion techniques. In both of these studies, all masses and moments of inertias investigated could be satisfactorily handled and transferred using manual techniques.

The above apparent disagreement in simulation results is important when considered in light of a typical shuttle logistic mission. Figure 3 (taken from ref. 4) shows a representative shuttle resupply cargo profile. The figure divides the cargo into classes by weight and volume, and specifies the frequency (number of different packages falling within each class) for a composite cargo mission - composite in the sense that the cargo represents the total spectrum for all resupply missions.

Superimposed on this matrix, the rows of which are package weight and the columns of which are package volume, are indications of the currently accepted levels of cargo transfer capability. The white area inside the matrix represents cargo whose characteristics are generally accepted as within the range of manual cargo handling. In this region, the cargo could be manually transferred, and a required but unspecified number and location of transfer assists would be provided.

The lightly shaded area indicates areas in which there is significant current disagreement as to man's potential. The area with the densest shading is generally conceded as bordering on or lying outside the range of practical manual operations. It can be seen that extensions of man's capability into the lightly shaded areas would greatly benefit the missions. Extensions of manual operations to this region would significantly reduce the requirements for automated transfer mechanisms, internal to the spacecraft that are currently being considered.

Resolution of the current disagreements through continued simulation must be accomplished. These simulations, however, must consider the major simulator limitations and operational constraints in order for simulator results to be generally accepted. The limitations to be considered are covered in this paper.

ZERO-GRAVITY AIRCRAFT LIMITATIONS

Zero-g aircraft simulation has been used extensively in the past because it does provide true weightlessness, both physiologically and physically, and astronaut familiarization with true zero-g sensations is important. There are, however, limitations inherent in zero-g aircraft simulation which affect cargo transfer considerations or any astronaut performance study. The major limitations are: the short period of weightlessness (less than 30 sec), the lack of a stable reference (aircraft motions affect all things attached to it), and the effect of alternating zero-g and 2.5g on subject ability to participate. The alternating "g" forces have a generally subjective effect on results, and are not readily definable. The other two factors, however, are measurable or at least observable, and are areas which can be shown to affect test results.

For example, test subjects in the zero-g aircraft tend to conduct tasks at a rate much greater than comparable actual orbital operation. The effect of this factor on the study of cargo handling is readily seen. Typically, each cargo transfer task involves five steps: unstowing or acquisition of the cargo, stabilization of the cargo and subject before transfer begins, transfer (all the while maintaining package position), braking, and the final stowage or positioning. Because of the time available, and the prospect of being caught in the 2.5g pullout, all phases of the transfer task tend to be speeded up. With smaller packages (up to approximately the subject's mass), the time available allows the transfer task to be completed, and the relatively fast rates used and their effect on package stability and control can be handled satisfactorily by the subject. Package masses greater than around 150 pounds, however, require more initial time to orient and stabilize prior to transfer, more time to achieve desired transfer speeds, and more time to brake. All of this increased time is not available in the 30-second test period, and part task evaluation does not adequately evaluate the phenomena involved because of discontinuities in position, velocity, and so forth. Thus simulation of large package masses, moments of inertia, and so forth cannot be properly studied in the zero-g aircraft, and conclusions drawn about limits of manual cargo handling capabilities are subject to significant error.

Overlaid on the time limitation to cargo transfer studies in the zero-g aircraft is the lack of a stable reference for the simulation. This means that although the subject and cargo are in actual zero-g, when isolated from the aircraft, anytime the subject uses a maneuvering aid (handrail, rope, etc.) or mockup attached to the plane, he is subjected to aircraft motion. This motion generally consists of random motions of the aircraft because of vibrations, wind gusts, and so forth and controlled motions such as the continuous aircraft pitchover (rotating reference axis system) required to maintain the zero-g trajectory (90° in 30 sec). Figure 4 (taken from data reported in ref. 5) shows the results of a significant number of runs on the KC-135 zero-gravity research aircraft, and indicates the actual time limits associated with various gravity error ranges. The random motions, although relatively small, are sufficient to cause difficulty in package control and subject stabilization or maneuvering. Typical magnitudes of the random motions are found to be on the order of ±0.03g and range up to ±0.06g. These acceleration errors would provide undesired forces of approximately 5 to 10 pounds, respectively, on a five-slug package. These force levels are on the order or higher than those required to maneuver the package. The continuous pitchover motion effect, when considering cargo transfer, requires a continuous positioning of the subject relative to the maneuvering aid, and this, in turn, causes unrealistic motions between the subject and cargo. Both continuous and random motion effects are increased as the cargo masses and moments of inertia are increased. Representative results of cargo transfer simulation using this technique are presented in references 1 and 2.

Little improvement can be made to the zero-g aircraft simulation technique with present aircraft.

WATER-IMMERSION SIMULATION LIMITATIONS

Water-immersion simulation studies have also been used extensively in the past few years to evaluate astronaut performance, to develop EVA tools, support equipment and techniques, and to train astronauts for orbital missions. This method of simulation also has limitations that must be considered when conducting zero-g simulations. The major limitations involved are neutral buoyancy ballasting accuracy, viscous drag, and hydrodynamic mass and moment of inertia effects. The effect of these limitations can be minimized, in most instances, with proper simulation design.

The potential problems associated with ballasting subjects or mockups can create major effects on the simulation results if not considered properly. The ballasting problem is minimal with inert, fixed mass and volume objects requiring only time and patience to obtain as accurate ballasting as desired for a specific operating depth. Changes in depth affect the balance of the packages due to changes in water density, compression of mockup materials, and so forth. Ballasting of the subject is much more difficult and varies considerably from the case of a scuba or hookah-equipped subject, which is very difficult because of the changing volume of the subject as he breathes, to the pressure-suited subject, which is essentially a constant volume case but which can require adding over 100 pounds of lead weight for ballast (for air-filled suit tests). Neutral buoyancy ballasting is still an art rather than a science, and is highly dependent on the support team and the subject's experience and basic knowledge of the problem. For example, the neutral buoyancy ballasting of a scuba or hookah-equipped subject depends on the subject using breath control to prevent large changes in lung volume. Failure to do this causes alternating up and down motions which can affect precision tasks significantly. This factor becomes less important in cargo handling as the package size increases and since the subject almost instinctively compensates for these motions using his maneuver aid. In addition to the above, when scuba is used, there is a constant decrease in total weight due to air usage. This creates an increasing positive (up) buoyancy bias on the subject. Use of hookah equipment eliminates the problem.

Ballasting of pressure-suited subjects, although simpler because of the essentially constant volume, does still require some thought and does affect results obtained from cargo handling studies. The prime effect is due to the increased inertia resulting from adding ballasting weights. This added weight requires increased effort during acceleration/deceleration, and so forth, and tends to make any result obtained conservative, especially in matters of time to achieve transfer velocity and braking, ease of acceleration, and so forth. This problem can be reduced through use of one other means of suit pressurization used by some researchers. This is the water-filled suit. In this situation the ballast requirements are almost eliminated, since only the man has to be ballasted. The mass of the suit, water, and man is still relatively high and answers obtained are generally conservative. Use of this technique does create some additional operational problems. Ballasting of scuba or pressure-suited subject is also based on particular working depth.

The other two major limitations - viscous drag, and hydrodynamic mass and moment of inertia - are dynamic effects on the subject and cargo. The effects due to viscous drag are proportional to their velocity squared and hydrodynamic mass and moment of inertia effects are proportional to the body's acceleration. Both effects are functions of subject's and cargo's shapes. Drag forces are the most commonly recognized effects occurring in water-immersion studies, and are due primarily to the high viscosity of the water. The drag effects can be minimized by proper equipment and experiment design, but cannot be eliminated. For example, use of spheres in mockups to provide buoyancy gives the same drag force in all directions and eliminates hydrodynamic lift effects. This, in conjunction with thin pipe construction of cargo mockups, provides minimum drag configuration when considering all areas. Figure 5 illustrates this technique.

However, drag effects do become significant for velocities greater than 1 ft/sec as shown in Figure 6. This figure gives drag forces versus velocity for various orientations of a pressure-suited subject. The velocity of subject and cargo is, of course, task dependent, but experience in space and results of LRC-sponsored research have shown that slow deliberate motions are generally used in zero "g". For example, cargo transfer studies being conducted now at Langley have found cargo transfer velocities to be less than 0.7 fps for packages ranging between 3 and 50 slugs. It is important, however, to determine what effects drag does have on the total simulation even at relatively low velocities.

A technique to permit this determination for cargo mockups and subjects is being developed at Langley. This device will be used to conduct pretest determination of water effect on mockups and subjects over a range of dynamic conditions. This information will permit post-test accounting for drag effects occurring during tests, when used in conjunction with a velocity measuring system. At best, this is an empirical technique and does not determine accumulative forces and motions developing from continuous drag effects. Thus drag effects are still the most limiting restriction of water-immersion studies involving translations.

Less commonly considered dynamic effects experienced in water-immersion simulation are those of hydrodynamic mass and moments of inertia. These occur when a body is moved through a fluid (water) which is at rest far from the body. There is kinetic energy associated with the motion of the water as well as with the motion of the object. If the body (the cargo package-mass combination) is moved with varying velocity, there is a corresponding change in the kinetic energy of the surrounding water. The kinetic energy increases as the body does work on the water and decreases when the water does work on the body. This results in the additional forces on the accelerating body, and since the water does work on the decelerating body, a negative force is exerted on the body during deceleration in the direction of motion.

The water in opposing the changes in the body's velocity acts as if the body has an additional inertia (hydrodynamic mass) corresponding to an increased body mass. Because of the highly unsymmetric and variable character of the human subject-package combination, precise analytic determination of the effective instantaneous inertia is impractical. These are acceleration-dependent forces and, when using spheres as the means of buoyancy, increase apparent mass of the package by 50 percent according to analysis reported in reference 6.

Hydrodynamic moments of inertia are largely eliminated when a sphere is used. Thus spheres again offer best choices for mockup construction. Hydrodynamic mass effects can be significant, and thus must be either eliminated or compensated for. As mentioned earlier, these effects are also highly dependent on body shape and mass and as high as possible mass to area ratio should be maintained. In the study of cargo transfer, the hydrodynamic mass effects are present during the initial acceleration to a constant transfer velocity and during braking. These effects, as with viscous drag, can be determined during tests by proper instrumentation and pretest determination of hydrodynamic forces at different accelerations. A detailed discussion of hydrodynamic mass and moment of inertia effects are presented in reference 6.

One thing not specifically covered in the above discussion is the effects of drag and hydrodynamic forces on the irregular and variable shape of the subject. This area is the least defined of all in water-immersion studies, and can be approached only in an empirical fashion, with similar pretest evaluation of the forces and motions involved at different velocities and accelerations for different subject orientations and post-test application of these results to test data. A study of the water's effects on a subject under dynamic conditions is also planned at LRC using the drag measurement device mentioned earlier. This study will permit some insight into dynamic effects on simulation results.

The LRC study mentioned earlier using conventional water-immersion techniques is part of a parametric evaluation of manual cargo transfer. This study includes packages with masses from 3 to 50 slugs with volumes of from 1.5 cu ft to around 140 cu ft. The package moment of inertias being studied range from 42 to 10,000 in. lb sec^2. Preliminary results indicate little if any difficulty in manually maneuvering any of these packages using either one or two handrails for maneuvering. Results of these studies, to date, show that all transfers were accomplished with average velocities less than 0.7 fps. Velocities varied from 0.7 fps for the smallest package down to 0.3 fps for the 50-slug package. The subjects were told that speed was not an important test parameter but were asked only to maintain a velocity that was comfortable and allowed positive control of their package at all times. There is some question as to whether the velocities obtained are influenced significantly by water effects and whether subjects could realistically move faster while controlling the package. Results from a study (ref. 3), indicate an upper limit to the amount of velocity a man can put in, using handrails, which is substantially different from those found in LRC simulations. The wide difference between velocities experienced in the LRC simulation and those which can be achieved offers a potential means of considerably affecting manual cargo transfer times and utlimately affects the question of whether automated systems are required because of time constraints. Conventional water-immersion techniques do not provide an adequate means of studying these particular considerations. To answer these questions, other methods must be used.

CARGO TRANSPORT SIMULATOR DESIGN

One new technique which may offer a means of answering the question raised above, as well as providing a method of reducing water effects in water-immersion cargo transfer studies, is presently being evaluated. This technique, the Cargo Transport Simulator, was originated by Environmental Research Associates, and is being developed by them under contract to the NASA Langley Research Center. This concept operates on the equivalence principle. Instead of the test subject and cargo moving along some form of transfer aid, the subject and cargo remain quasi-stationary and the transfer aid is moved. It is moved by a servosystem which responds to the forces applied by the test subject. A schematic of the system is shown in Figure 7. Since the subject and cargo remain essentially fixed, viscous and hydrodynamic forces are reduced significantly, yet the simulator retains the prime advantages of water immersion (simulated weightlessness, and a full six degrees of freedom).

A preliminary study using the CTS has been conducted and is reported in reference 3. This reference describes in more detail the CTS concept and potential applications. As mentioned previously, one result obtained in the preliminary study was a determination that when using a handrail for transfer there is a limiting velocity at which one can propel himself. This is due to the finite time required for the subject to extend arm, engage handrail, exert a force and release aid and, of course, is subject dependent.

CONCLUDING REMARKS

The transfer of large quantities of a wide range of cargo will be a requirement in future manned space missions. It is important to determine in the early planning stages of these missions the limits of astronaut participation in cargo transfer and the requirements, if any, for automated transfer system. Simulation efforts to determine man's capabilities and to develop aids and techniques are presently underway. The results to date are conflicting and further, more complete, research considering all aspects of the problem must be accomplished. These further data will provide a basis for general acceptance of limits of manual transfer and areas where automated systems are needed.

In order to accomplish these research goals, it is necessary to provide means of obtaining quantitative measurements in simulations. This is being done primarily in aircraft and conventional water-immersion studies. Future studies may also use a Cargo Transport Simulator which is presently being evaluated and which may offer advantages over present techniques.

The results being obtained from these studies, in addition to answering specific cargo transport questions, will be applicable to general orbital operation including tasks such as handling satellites and assembling large structures including the modular space station.

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PKG. SIZE	PKG. WT. \ HANDLE LGT.	PACKAGE MOMENT OF INERTIA (in.-lb-sec^2)				
		3"	6"	10"	16"	24"
10" × 10" × 20"	70 lb	35	51	77	127	214
10" × 10" × 30"	110 lb	130	162	215	311	470
10" × 10" × 40"	140 lb	266	318	400	545	775

$$\text{MOI} = I_0 + \frac{MK^2}{12g} \qquad I_0 \text{ DETERMINED EMPIRICALLY ON AIR BEARING TABLE}$$

Figure 1.- MSFC cargo transfer test conditions (ref. 1).

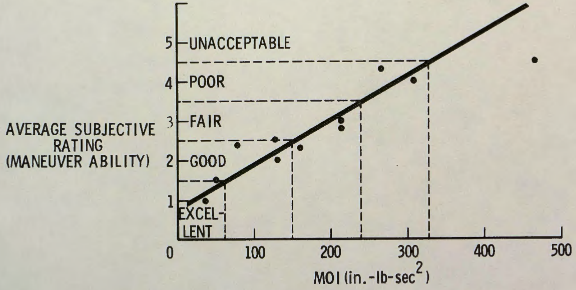
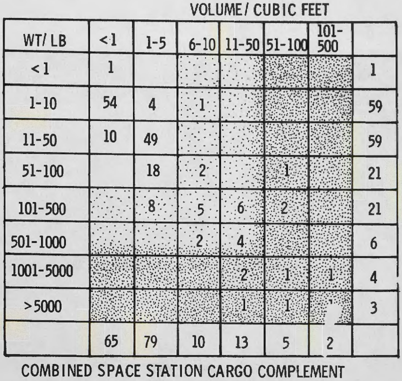


Figure 2.- Subjective rating vs moment of inertia (reported in ref. 1).



VOLUME/ CUBIC FEET

WT/ LB	<1	1-5	6-10	11-50	51-100	101-500	
<1	1						1
1-10	54	4	1				59
11-50	10	49					59
51-100		18	2		1		21
101-500		8	5	6	2		21
501-1000			2	4			6
1001-5000				2	1	1	4
>5000				1	1	1	3
	65	79	10	13	5	2	

COMBINED SPACE STATION CARGO COMPLEMENT

Figure 3.- Human performance - package density interface.

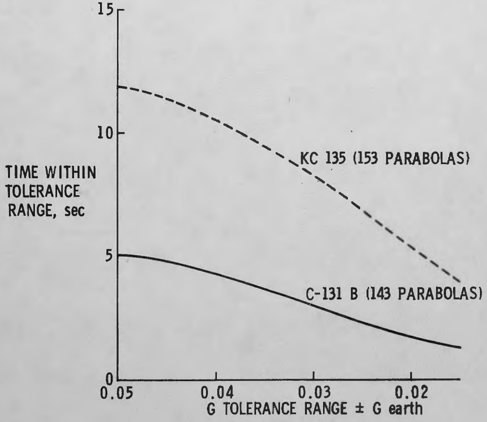


Figure 4.- Attainable "G" tolerance times, zero gravity research aircraft (data reported in ref. 5).

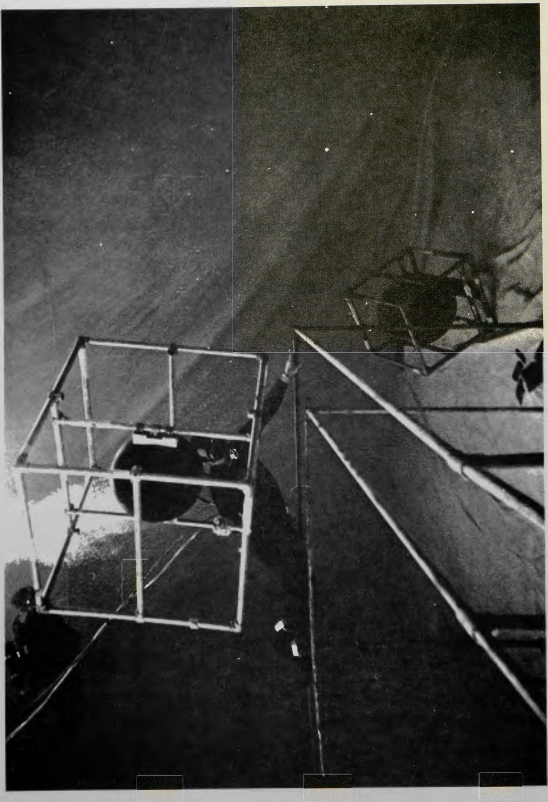


Figure 5.- Typical water immersion cargo mockup.

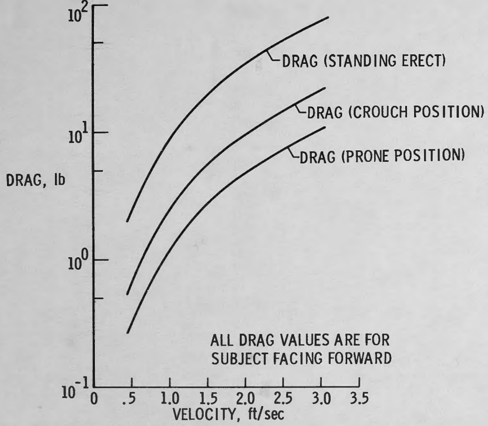


Figure 6.- Variation of calculated drag with velocity for water immersion tests. (data for pressure-suited subject at 3.5 psig).

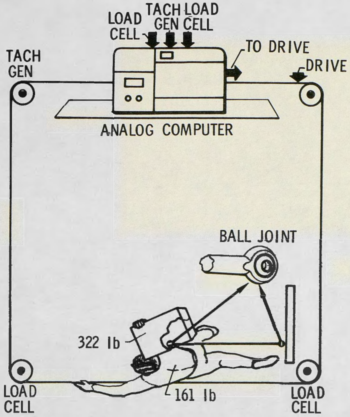


Figure 7.- Cargo transport simulator schematic.