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STUDY OF ASTRONAUT RESTRAINTS AND MOBILITY AIDS IN A WEIGHTLESS SHIRTSLEEVE ENVIRONMENT

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STUDY OF ASTRONAUT RESTRAINTS AND MOBILITY AIDS IN A WEIGHTLESS SHIRTSLEEVE ENVIRONMENT

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DRL No. T-764
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PREPARED FOR:

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FOREWORD

The following sections report a "Study of Astronaut Restraints and Mobility Aids in a Weightless Shirtsleeve Environment" conducted by the URS/ Matrix Company of the URS Systems Corporation under Contract NAS9-12574 to the National Aeronautics and Space Adminstration's Manned Spacecraft Center, Houston, Texas.

This contract was initially awarded to Environmental Research Associates (ERA) of Essex, Maryland. Subsequent to the award, the URS Systems Corporation of San Mateo, California, acquired certain assets from ERA, including this contract. At the date of this report, the novation of NAS9-12574 to the URS Systems Corporation has not been completed.

SUMMARY

This study was established to produce needed information about manual performance limits in intravehicular weightlessness, e.g., the motions induced by the astronaut's direct application of force against the body of the vehicle or an object to be moved. Using both conventional and water immersion techniques, it was possible to develop realistic time estimates for astronaut station-to-station translation in Skylab, to simulate and analyze specific Skylab tasks involving force application and motion dynamics, and to evaluate certain thresholds of force application in weightlessness.

The study was divided into three tasks. The first related to locomotion and verification or modification of present Skylab translation timelines. Velocity and acceleration for translation were measured to include the astronaut's acceleration from a full stop, "coasting", and deceleration to a full stop -- both burdened with package masses and unencumbered. In all cases, translation times were less than the Skylab timelines indicated.

The second task studied mass handling and transfer. Specifically, this involved measurement of the astronaut's ability to relocate the Skylab food lockers to stowage levels of three different heights and his ability to transfer the M509 PSS bottles between the OWS and the recharge station.

The third task helped define the physical limits of man's ability to perform Skylab translation tasks under weightless conditions. This yielded data which may be helpful in determining man's natural capability in handling

masses in weightlessness and in determining the optimum size of objects to be moved in such an environment.

In conjunction with the performance of these tasks, various restraints and motion aids were evaluated. These included portable foot restraints, magnetic shoes, isometric handholds, a grid-structured floor, and a water immersion version of the dutch shoe.

The study results indicate that the Skylab station-to-station timelines are overly conservative, making maximum efficiency in the conduct of planned operations and necessary planning for hazardous contingency operations (requiring knowledge of the fastest possible times) impossible. Also, there are potential problems in present Skylab mass handling tasks, which may lead to equipment damage due to translational subjection of the equipment to impacts above design tolerance. Resolution of these problems will depend on necessary redesign of certain equipment and on additonal testing in the weightless intravehicular environment to assure optimal man/machine interaction.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to several individuals. Among them are:

Mr. Robert L. Bond, NASA/MSC-EW, who served as the technical monitor for this contract and whose timely comments and criticisms enabled the conduct of tests which will impact both Skylab and future missions planning and crew/system interface design.

Mr. Kenneth M. Mallory of the URS/Matrix Company, who provided the statistical and experimental designs for the controlled testing reported herein.

Mr. Nelson E. Brown (URS/Matrix Co.), Mr. Edwin C. Pruett (URS/Matrix Co.), and Mr. George Hay (Consultant), who served as test subjects.

Mrs. Dana Ludewig (URS/Matrix Co.), who had the responsibility of editing the draft report and integrating all comments and changes into the final contract report.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES

URS MATRIX

LIST OF FIGURES (Cont'd)

LIST OF TABLES

STUDY OF ASTRONAUT RESTRAINTS AND MOBILITY AIDS IN A WEIGHTLESS SHIRTSLEEVE ENVIRONMENT

SECTION 1.0
INTRODUCTION

The purpose of this study was to investigate, analyze, and evaluate present Skylab restraints and mobility concepts by means of conventional and dynamic water immersion simulation techniques. The study used the results obtained from simulations of representative Skylab tasks to provide data for extrapolation to future requirements for astronaut restraints and mobility aids in weightless intravehicular environments. The technical effort under this contract was an expansion of the work reported in NASA CR-115436, "Hybrid Water Immersion Simulation of Manual IVA Performance in Weightlessness", released December 15, 1971.

The dynamic water immersion simulator (Cargo Transport Simulator - CTS) referred to throughout this report is described in NASA CR-115436. It is essentially a hybrid simulation technique which combines the best feature of conventional water immersion simulation--the total tractionlessness of a human subject--with force measuring devices to yield computer controlled relative motion. It is particularly useful for studies of astronaut translations with cargo masses under weightless conditions, since the CTS provides a realistic simulation of manually induced crewman motion.

The three primary objectives of this study were:

1. The development of information concerning Skylab timelines and the prediction of time estimates for station-to-station translation.

2. The simulation and analysis of specific Skylab tasks involving force application and motion dynamics.

3. The theoretical evaluation of certain thresholds of force application in weightlessness and simulation-measurement, where applicable.

The manual astronaut station-to-station translation times were investigated parametrically to determine the effect of the cargo mass and the distance travelled upon the total travel time and average velocities attained. The data have been reduced statistically and have been analytically applied to Skylab station-to-station timelines.

Selected Skylab tasks were performed according to scenarios adapted to the simulation technique employed. Sixteen millimeter motion picture film and 35 millimeter sequence films (at a rate of 2 fps) were made of selected tasks, facilitating analysis of the tasks and providing a preview of the data return for similar tasks from Skylab missions. In addition, dynamic force measurements were made to permit analysis of the tasks.

An overall study of thresholds and threshold forces, as they are applied in weightlessness, was beyond the scope of this study. However, one particilar threshold area has been investigated, and measurements have been made of task performance. The one area selected appears to be especially fruitful in its identification of the dynamic conditions related to man-machine integration in weightlessness. The information developed seems directly applicable to the engineering design of equipment involving manual operations.

This study report contains a description of the work performed, the analysis of the test data, and the conclusions, as they apply both to Skylab and to future manned spacecraft operations.

SECTION 2.0
TECHNICAL DISCUSSION

2.1 GENERAL

The increased internal volume afforded by Skylab and, implicitly, by future space station concepts, places particular emphasis on quantitative determination of the motions induced by the application of direct manual force in a weightless shirtsleeve environment. The increased volume not only affords more space within which the astronaut can maneuver, but it may also increase his strength and dexterity requirements, due to the complex complement of hardware on board.

Greater reliance should be placed on dynamic simulations to yield effective estimates of the limits of manual performance for two important reasons. The first is implicit in increasing the scope and duration of the astronaut's performance in that task performance and hardware optimization depend on proper allocation and design of the necessary restraint and mobility aids. The second reason is the optimization of human factors data return from each Skylab flight, thus maximizing the information carry-over to the next mission. This study effort was established to produce needed information concerning manual performance limits. The tasks into which the subject study was divided were broken down into three categories:

1. Locomotion--verification of the Skylab estimated translation time-lines.

2. Mass Handling and Transfer--relocation of the Skylab food lockers and transfer of the M509 PSS bottles between the OWS and the recharge station.

3. Generic Thresholds--definition of restraint - no restraint thresholds and local area retention.

Two additional tasks were also performed--evaluation of operational force limits of the Skylab trash disposal airlock and evaluation of the operational force limits of the sample extension rods for the T027/S073 experiment through the Scientific Airlock.

In conjunction with the above tasks, various restraints and motion aids were evaluated, as applicable. These included: portable foot restraints (triangular cleats), magnetic shoes (the Shuffler concept), isometric handholds, a grid structured floor, 3/8 in. diameter nylon rope, and a water immersion version of the dutch shoe concept.

2.2 LOCOMOTION--VERIFICATION OF THE SKYLAB ESTIMATED TRANSLATION TIMELINES

2.2.1 Background

The major simulation task performed during the study concerned the verification of the Skylab timeline matrix shown in Figure 2.1. In the previous contract report, "Hybrid Water Immersion Simulation of Manual IVA Performance in Weightlessness" (NASA CR-115436), a technique for the simulation of IVA manual linear point-to-point translations was utilized to provide a first-order evaluation of the Skylab estimated timelines.

The translation times were estimated from the acceleration/deceleration data resulting from an unlimited stroke maneuver with the subject's body

		H Waste Mgt. Compartment	W Wardroom	S Sleep Compartment	E Experiment Compartment	F Forward Compartment	D Forward Dome	A Airlock Module	ST Structural Transition Section	M Multiple Docking Adapter
Command Module	CM	2.8	2.8	2.8	2.6	2.3	1.8	1.2	.8	.6
Multiple Docking Adpater	M	2.2	2.2	2.2	2.0	1.7	1.2	.6	.2	
Structural Transition Section	ST	2.0	2.0	2.0	1.8	1.5	1.0	.4		
Airlock Module	A	1.6	1.6	1.6	1.4	1.1	.6			
Forward Dome	D	1.0	1.0	1.0	.8	.5				
Forward Compartment	F	.5	.5	.5	.3					
Experiment Compartment	E	.2	.2	.2						
Sleep Compartment	S	.2	.2							
Wardroom	W	.2								

NOTE:
Times are estimated and noted in minutes. These are unencumbered times, i.e., not suited and not carrying equipment. The time estimate applies for direct translation from Crew Station to Crew Station in either direction.

Figure 2.1: Estimated Translation Times

aligned along the motion aid. The body positions and representative forces experienced are shown in Figure 2.2. Maximum velocities were determined from the force-time profiles by noting the region where force direction instability occurred. It was noted that, as the subject reached maximum velocity, he was unable to maintain smooth force application.

The results of the simulation showed significant disagreement with the Skylab estimated timeline, as is shown in Figure 2.3. It was concluded that the Skylab timelines were overestimated, i.e., the average flight plan velocities between 0.4 and 0.5 fps were significantly below the simulation and analytic values of 1.0 - 1.25 fps. Further, since the original estimates did not consider the effect of additional cargo, an additional estimate of the timeline variation as a function of cargo mass was required. (The stations and nomenclature given in Figure 2.3 are related to the internal route designations of Figure 2.4.)

2.2.2 Simulation Requirements

While the information thus derived could have considerable impact on the overall timelines, particularly if the cargo and personnel transfer times were significant fractions of the total on-orbit time, several simulation artifacts required further evaluation. Principally, these were:

1. Application of multistroke maneuvers to the actual one- or two-stroke transfer maneuvers contemplated in Skylab.

2. Consideration of transfer modes other than the subject aligned with the motion aid.

3. Inclusion of neutrally buoyant cargo to provide information on handling characteristics. (The effective mass of the subject and cargo are provided by the analog computer.)

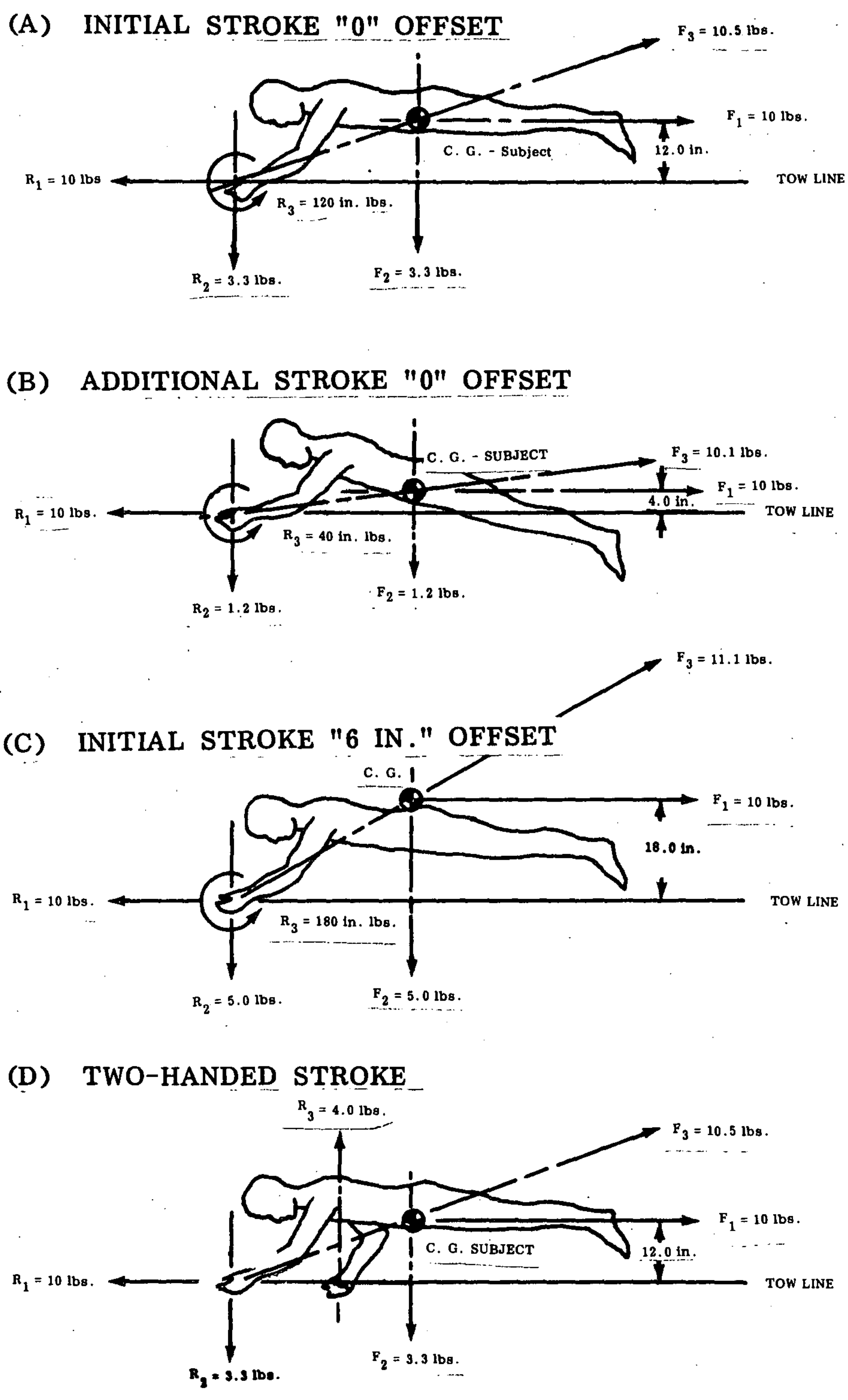
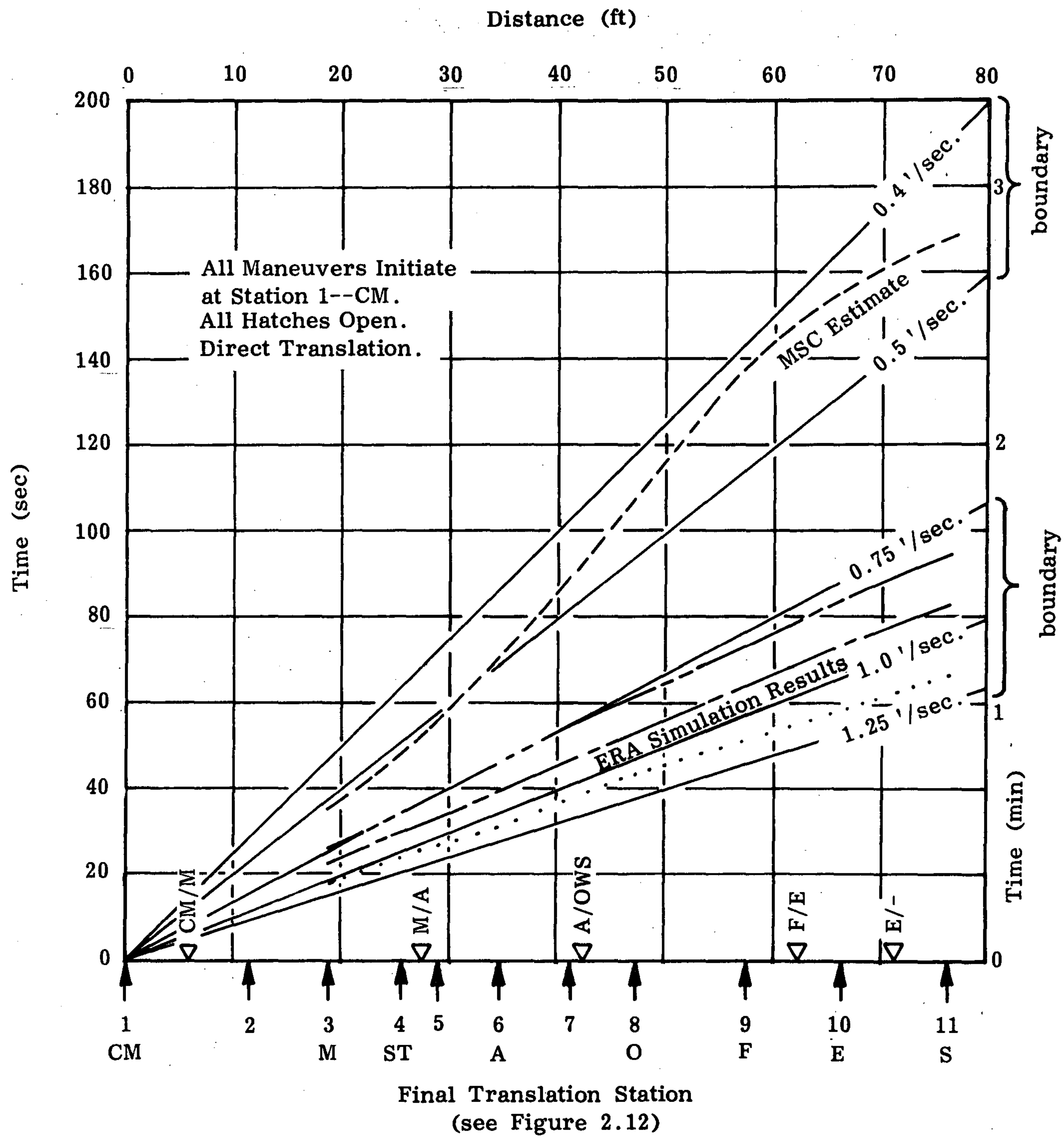


Figure 2.2: Instantaneous Forces on Subject During Transport Maneuver



· · · · · · · ·	ERA--0 Slug Cargo
—— — —	ERA--6 Slug Cargo
—— - - —	ERA--10 Slug Cargo
— — — —	MSC--0 Slug Cargo Estimate

Figure 2.3: Linearized Timeline Estimate

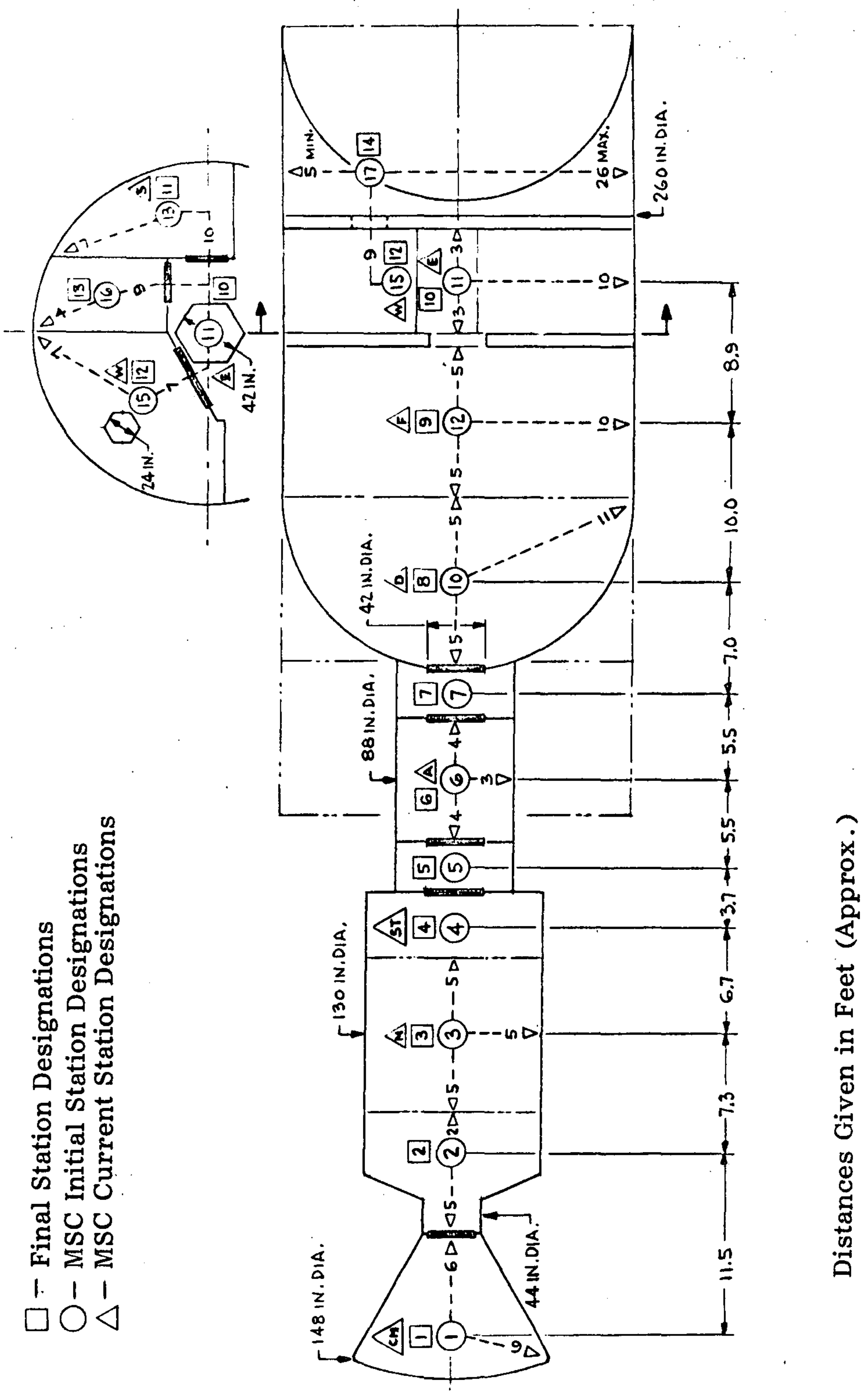


Figure 2.4: Distances--Internal Routes, Skylab Orbital Assembly

4. The effect of limited transfer distances, $\leq$ 20 ft, must be included.

To accommodate these factors, a new simulation program was instituted, and a reevaluation of the Skylab timeline was undertaken. The results of this simulation experiment program are described in the following section.

There are a number of considerations involved in the evaluation of station-to-station timelines. Since each of the cells or stations are actually volume areas, the translation time from the nearest point of Cell i to the nearest point of Cell j can be considerably different from the translation time from the farthest point of Cell i to the farthest point of Cell j. The information available for use during this study does not provide any detail as to the exact position within a cell to be considered the starting point. Therefore, cell-to-cell timelines are based on average distance to the approximate center of each cell.

Motion aids for translation are available when the astronaut is in contact with any surface, but specific motion aids are not widely distributed throughout Skylab. Generalized motion aids were, therefore, used for the experiment, since it is apparent that the astronaut will use available nearby structures and equipment. Our previous experiments have shown that translation forces are low (less than 20 pounds-force), making this technique optimum from a motion aid distribution standpoint. For example, the triangle floor sections can be considered as motion aids (distributed over a large area) because the astronaut can "walk" from triangle to triangle.

2.2.3 Simulation Description

Simulations were performed using various artifacts, including two versions of the portable foot restraints (triangle shoes), the magnetic shoes, and available handholds. Generally, handholds were preferred for both unencumbered translations and transfer of cargo up to and as large as the food locker.

Since the shortest point between two particular stations is often across a space having no intervening structure within reach, the astronaut will most likely soar, by providing a single acceleration impulse either with the hands or feet. To estimate this case, single impulse force profiles were measured, and the resulting velocities and times for transfer across a specified distance were used to evaluate the timelines. The position, or attitude, of the astronaut in relation to the surrounding structure at the end of a translation impulse is of particular interest. In general, man is incapable of providing a force directly through the combined man-package mass center, and, therefore, soaring may not only be inaccurate in direction, but may also comprise a tumbling motion such that the astronaut arrives at his end location in an inappropriate attitude. It further appears that any inaccuracies observed in single impulse thrust without cargo will be magnified during cargo transfer, since man is a relatively inaccurate judge of mass.

The tests conducted during this contract were performed on a hybrid simulator designed to measure the input forces of the subject and to provide resulting weightless IVA motions in one-degree-of-freedom by means of water immersion simulation, but they were restrained from motion in the direction controlled by the simulator. While this does not give a completely accurate picture of the attitude of the test subject, it does give a clear picture of tendencies for motion, and it provides measurements of force impulses for both acceleration and deceleration. The results of the tests provide a numerical estimate of the force-acceleration profiles to be expected.

The work performed during the study does not provide an exact measurement for each cell-to-cell translation time. Rather, it provides the experimental and analytic basis for bounding the estimates of cell translation times, and it provides descriptions of the considerations involved in transfers between cells. The analytic treatment of the data relative to a mathematical model of the translation profile permits the estimate of the mean cell-to-cell transfer time.

To accomplish the desired objectives, a statistically optimum simulation-test program was developed. It is summarized in Table 2.1.

The experimental program, designed to evaluate and verify the Skylab estimated station-to-station translation timelines, has produced significant results. In general, the Skylab station-to-station timelines were found to be extremely conservative (the original timeline estimates are 2 - 4 times greater than the values found in this experiment).

The data from the simulation-experiment of the timelines are given in Table 2.2, which presents the combined results for each subject. The combined results represent 288 subject runs. The tests were factorialized as described in Table 2.1. Subsequent statistical analysis of variance showed that the

Table 2.1: Simulation/Test Plan
TITLE
Estimates of Nominal Times Required to Transport Selected Skylab Cargo
OBJECTIVE
To establish the gross times required by an astronaut to transport Skylab cargo packages over various distances. These data will be used to prepare accurate Skylab operational timelines.
METHOD
Time estimates will be developed through neutral buoyancy simulation using the Cargo Transport System (CTS) located at the URS/Matrix Company's Environmental Research Office in Essex, Maryland.
TEST DESIGN
Task Variables 1. Mass of Package (3 levels) • Subject only (1) • 3.4 slugs + subject • 6.3 slugs + subject 2. Transport Distance (4 levels) • 5 ft • 10 ft • 15 ft • 20 ft 3. Instructions • Set 1 - Subjects instructed to transport a package along the CTS and to come to a stop at a prescribed point with a minimum of overshoot/undershoot. • Set 2 - Subjects instructed to transport a package along the CTS and to come to a stop at a prescribed point. No mention made of overshoot/undershoot as a performance criterion.

Table 2.1: Simulation/Test Plan (Cont'd)

4. Subjects

- George Hay (Environmental Research Office) (1)
- Edwin Pruett (Man/Systems Division) (2)
- Nelson Brown (Man/Systems Division) (3)

5. Measures

- Transport velocity as a function of time
- Gross transport time
- Transport endpoint miss-distance (for Instruction Set 1)

6. Statistical Design

- Complete factorial (4 replications per cell).
  Mass (3 levels) x transport distance (4 levels)
  x instructions (2 levels) x subjects (3 levels)
  = 72 test conditions x 4 replications
  = 288 trials.

- Latin Square counterbalancing of the order of presentation of trial conditions: (mass x transport distance) x (subjects x replications). No trial condition follows another trial condition more than once.

- Partial counterbalancing of instruction set x subject x session (morning and afternoon) x trial block per session (12 trials per trial block).

7. Subject Running Order

	Day 1	Day 2
Morning	1, 2, 3	2, 3, 1
Afternoon	1, 2, 3	2, 3, 1

TIME BETWEEN MORNING AND AFTERNOON SESSIONS

MUST BE EQUAL FOR ALL TEST SUBJECTS

Table 2.1: Simulation/Test Plan (Cont'd)

8. Instruction Set Running Order

		Day 1		Day 2	
		Morning	Afternoon	Morning	Afternoon
Subject 1	Block 1	Set 1	Set 2	Set 2	Set 1
	Block 2	Set 2	Set 1	Set 1	Set 2
Subject 2	Block 1	Set 2	Set 1	Set 1	Set 2
	Block 2	Set 1	Set 2	Set 2	Set 1
Subject 3	Block 1	Set 1	Set 1	Set 2	Set 2
	Block 2	Set 2	Set 2	Set 1	Set 1

9. Instruction Sets*

10. Briefing/Debriefings

- All subjects will be thoroughly briefed on the purpose of the test, the CTS, the test procedure, and the difference in the instruction sets.
- Each subject will be debriefed after each session with respect to his physical condition and any anomaly in CTS operation.

*Instruction Set 1 - Precision Stopping--During the following trail, you are to transport the provided cargo package for a distance of X ft† along the CTS. At the end of this transport, you are to attempt to stop with your hand as close to the end point as possible.

Instruction Set 2 - General Transport--During the following trial, you are to transport the provided cargo package for a distance of X ft along the CTS.

†Distance obtained by safety diver from Test Conductor between trials.

Table 2.2: Combined Data Summary for the Timeline Verification Simulations

SUBJ/ NAME	MASS CARGO	MASS TOTAL	DIST.	COND. I Σ	COND. I AVG	COND. II Σ	COND. II AVG	COMBINED Σ	COMBINED AVG
HAY (1)	0	4.8	5	16.1	4.0	15.1	3.8	31.2	3.9
			10	20.4	5.1	21.9	5.5	42.3	5.3
			15	25.2	6.3	27.0	6.8	52.2	6.5
			20	31.3	7.8	31.1	7.8	62.4	7.8
	3.4	8.2	5	15.7	3.9	16.5	4.1	32.2	4.0
			10	22.7	5.7	24.2	6.1	46.9	5.9
			15	28.8	7.2	33.5	8.4	62.3	7.8
			20	35.0	8.8	37.8	9.5	72.8	9.1
	6.3	11.1	5	16.7	4.2	19.2	4.8	35.9	4.5
			10	27.9	7.0	27.0	6.8	54.9	6.9
			15	32.9	8.2	33.4	8.4	66.3	8.3
			20	39.6	9.9	40.4	10.1	80.0	10.0
PRUETT (2)	0	5.4	5	13.6	3.4	14.6	3.7	28.2	3.5
			10	19.4	4.9	22.4	5.6	41.8	5.2
			15	23.2	5.8	24.2	6.1	47.4	5.9
			20	32.7	8.2	27.6	6.9	60.3	7.5
	3.4	8.8	5	21.4	5.4	14.9	3.7	36.3	4.5
			10	20.6	5.2	22.1	5.5	42.7	5.3
			15	34.1	8.5	32.6	8.2	66.7	8.3
			20	43.1	10.8	35.8	9.0	78.9	9.9
	6.3	11.7	5	20.9	5.2	21.4	5.4	42.3	5.3
			10	26.5	6.6	25.5	6.4	52.0	6.5
			15	35.2	8.8	31.7	7.9	66.9	8.4
			20	41.5	10.4	38.1	9.5	79.6	10.0

Table 2.2: Combined Data Summary for the Timeline Verification Simulations (Cont'd)

SUBJ/ NAME	MASS		DIST.	COND. I		COND. II		COMBINED	
	CARGO	TOTAL		Σ	AVG	Σ	AVG	Σ	AVG
BROWN (3)	0	13.4	5	13.4	3.4	13.3	3.3	26.7	3.3
			10	19.0	4.8	17.0	4.3	36.0	4.5
			15	26.8	6.7	24.0	6.0	50.8	6.4
			20	28.8	7.2	28.0	7.0	56.8	7.1
	3.4	8.2	5	17.7	4.4	14.8	3.7	32.5	4.1
			10	21.7	5.4	21.2	5.3	42.9	5.4
			15	28.5	7.1	29.6	7.4	58.1	7.3
			20	35.6	8.9	35.1	8.8	70.7	8.8
	6.3	11.1	5	17.3	4.3	17.4	4.4	34.7	4.3
			10	24.5	6.1	24.9	6.2	49.4	6.2
			15	34.5	8.6	31.8	8.0	66.3	8.3
			20	38.9	9.7	40.8	10.2	79.7	10.0

condition of measuring the miss distance and subject variation did not exhibit a significant effect; therefore, complete pooling of the data was permissible.

2.2.4 Simulation Results

The results of the combined pooling are given in Figure 2.5, which shows the average time to traverse a specified distance for a subject oriented perpendicular to the translation aid during manual IVA translation. The data were subjected to a multivariate linear regression analysis, and the results are given in Equation (1).

$$\hat{T} \doteq .337D + .319M - .16 \qquad (1)$$

where T is the estimated total time required in seconds.

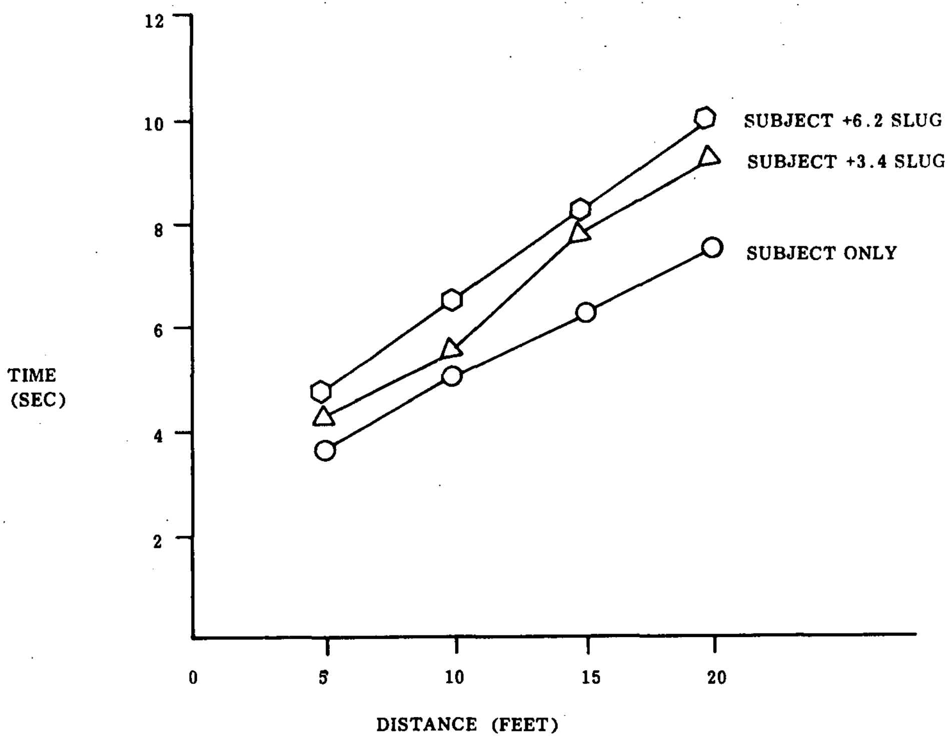
D is the distance to be traveled in feet.

M is the total mass in slugs.

It should be noted that the expression holds strictly for $5 \text{ ft} \leq D \leq 20 \text{ ft}$.

Figure 2.6 shows the corresponding average velocities to traverse specific distances. It includes acceleration from full stop, "coasting", and deceleration to full stop. The minimum distance traversed was 5 ft, and the average velocity for that distance was on the order of 1.3 ft/sec for the zero cargo case. As the distance increased, the average velocity also increased to a maximum, for the 20 ft distance with zero cargo, of 2.7 ft/sec. It is interesting to note that the rate of velocity increase diminishes with increases in distance, which indicates that a maximum average velocity would be reached if the curve were extended to perhaps 40 ft and 4 ft/sec. These data show that an astronaut moving around in a restricted compartment, such as the galley, would have an average velocity of less than 1.5 ft/sec. This is

- TIMES ARE POOLED ACROSS SUBJECTS & INSTRUCTION SETS -



LINEAR TIME ESTIMATOR: $\hat{T} \doteq .337D + .319M - .16 \; ; \; 5 \leq D \leq 20$

Figure 2.5: Summary of Test Results

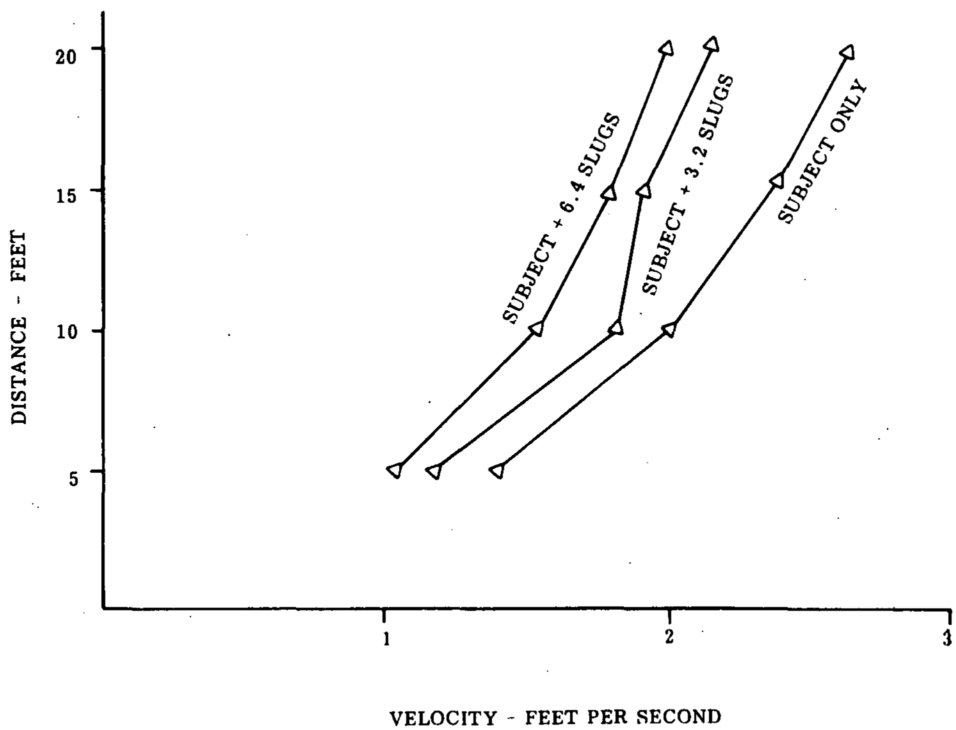


Figure 2.6: Average Velocity vs Distance

not to say that he could not move faster if he were required to do so. The subject is quickly aware, however, that any impulsive force for acceleration must be followed by a matching decelerating force, and he instinctively controls his velocity relative to task requirements. This is consistent with human performance in most activities.

As would be expected, subjects carrying additional mass moved at lower average velocities than they did when unencumbered. Table 2.3 lists the neutrally buoyant packages (supplied by NASA Langley Research Center) used during the study. The maximum mass handled during this test series was 6.4 slugs (approximately 200 lbs and representative of the Skylab food containers). Each mass was configured so it could be held in one hand while using the other for acceleration and attitude control. No significant difficulty was experienced in handling even the heaviest of the cargo masses. An interesting anomaly occurred, however, when the subject handled a mass of 3.4 slugs. The average values of the velocity did not follow the smooth curve exhibited for the other masses investigated. It has been reported by the Langley Research Center* that the difficulty in handling cargo was greatest near the point where the mass of the object and the mass of the subject were equal. Since this anomaly was exhibited in the data from this study and also from the LRC work, which was carried out under entirely different simulation conditions, it warrants closer scrutiny to determine: (1) that it does really exist, and (2) whether or not it is important enough to make recommendations concerning the size of masses to be handled in future missions.

*Spady, A. A., Jr., and G. P. Beasley. "Zero-g Manual Cargo Handling", 6th IES/AIAA/ASTM Space Simulation Conference, New York, N.Y., May 4, 1972.

Table 2.3: Neutrally Buoyant Packages

Package No.	1	2	6
Shape	Cubical	Cubical	Spherical
Approximate dimensions (ft)			
Δ x	2	2	1.4 ϕ
Δ y	2	2	---
Δ z	2	2	---
Approximate volume (cu. ft)	8	8	1.5
Mass (slugs)	3.4	6.3	3.1
Earth weight (lbs)	108	210	101
Moment of Inertia (slug-ft^2)			
x cm	5.3	9.5	0.2
x face center	8.4	15.1	---
x edge	11.5	21.0	---
x handle	---	---	3.5

While this study did not address those problems specifically in enough depth to provide supportable conclusions, it did recognize that the mode of operation changes in mass transfer as the mass approaches that of the subject. An unencumbered subject is concerned only with his body position as he accelerates and decelerates. Carrying small masses, his mode is unaffected. When carrying large masses, however, the subject's mode changes, since his major concern becomes control of the added mass and he is only marginally aware of his body control. Obviously, at some point or in some range, his mode is shifting. This is probably due to the subject's sensing of an incremental shift in the combined mass center of subject/cargo mass ratios of less than 1. Below unity mass ratios, the effects of subject inertia changes due to inconstant human body configurations are amplified, causing subjective difficulty in applying the proper force vector required for control. In this range, then, human performance becomes irregular and, as Spady and Beasley reported, more difficult. A specific test program addressing this problem should be performed in order to produce quantitative assessment of optimum package masses.

In a previous study, a discretized algorithm was required to produce the timeline estimates. This algorithm consisted of using a one-stroke approximation deduced from the accelerations/decelerations determined as a function of cargo mass. The resulting velocities were used by breaking any transfer into a series of linear elements and summing over the elements. The maximum free distance in Skylab is approximately 20 ft, and the majority of transfer maneuvers preclude free passage through more than one section at a time due to limited ability to change direction in mid-soar. The station-to-station times were derived directly by using time as a function of distance and mass. The same breakdown of the paths into linear segments was performed, and the results of the analysis are shown in Table 2.4. The data exhibit significant difference from the Skylab timeline given in Figure 2.1.

Prediction of the forces required for transfer without cargo agrees with the subjective comments of the simulation subjects concerning the level of forces exerted. Initial Skylab timeline data, indicating average velocities of 0.5 ft/sec in crossing the OWS open area, would require more than 40 sec before contact was made with the far wall. The acceleration force required to accomplish this is less than 1 lb (assuming a 1 ft stroke). Both the subjective and test data of this study, however, indicate that it is more realistic to consider that the astronaut would apply forces on the order of 20 lbs for the 1 ft stroke and would cross the breadth of the OWS in somewhat less than 10 sec. Figure 2.7 shows the expected range of velocities and forces relative to unencumbered transfer.

One of the objectives of this study was to verify or modify the existing Skylab timeline estimates. It is unnecessary to emphasize the importance of accurate timelines for mission planning purposes, since it is obvious that the economics of maximum effective utilization of available time on orbit is essential to the Skylab program, and, indeed, to all programs. It should

Table 2.4: Effect of Simulated Cargo Mass on Linearized Timeline

LOCATION	MASS[a]	13[b]	12	11	10	9	8	6	4	3
1 COMMAND MODULE	0	28.8[c]	29.4	30.6	28.4	23.5	20.8	15.6	10.9	9.4
	3.4	34.1	33.7	35.1	34.0	29.2	24.8	18.6	13.1	11.0
	6.3	42.9	42.6	44.0	37.4	31.0	27.4	20.5	14.4	12.4
3 MULT. DOCK. ADAPT.	0	24.8	25.4	26.6	21.4	16.5	13.8	8.6	3.8	
	3.4	30.6	30.3	31.6	25.5	19.6	16.2	10.0	4.5	
	6.3	33.9	33.6	35.0	28.1	21.7	18.1	11.2	5.1	
4 STRUCT. TRANS. SEC.	0	24.0	24.6	25.8	20.6	15.7	9.4	7.8		
	3.4	29.6	29.3	30.6	24.5	18.6	11.0	9.0		
	6.3	32.8	32.5	33.9	27.0	20.6	12.3	10.1		
6 AIRLOCK MODULE	0	18.8	19.4	20.6	15.4	10.5	7.8			
	3.4	23.4	23.1	24.4	18.3	12.4	9.0			
	6.3	25.9	25.6	27.0	20.1	13.7	10.1			
8 FORWARD DOME	0	13.3	13.9	15.1	9.9	5.0				
	3.4	11.9	11.6	12.9	11.8	5.8				
	6.3	18.8	18.5	19.9	13.0	6.5				
9 FORWARD COMPART.	0	11.6	12.2	13.4	7.2					
	3.4	13.5	13.2	14.5	8.4					
	6.3	13.8	14.9	16.3	9.4					
10 EXP. COMPART.	0	5.0	4.2	5.0						
	3.4	5.8	4.8	5.8						
	6.3	6.5	5.4	6.5						
11 SLEEP COMPART.	0	9.2	3.8							
	3.4	10.6	4.5							
	6.3	11.9	5.1							
12 WARDROOM	0	4.2								
	3.4	4.8								
	6.3	5.4								

LEGEND

a - SLUGS
b - WASTE MGT. COMP.
c - SEC

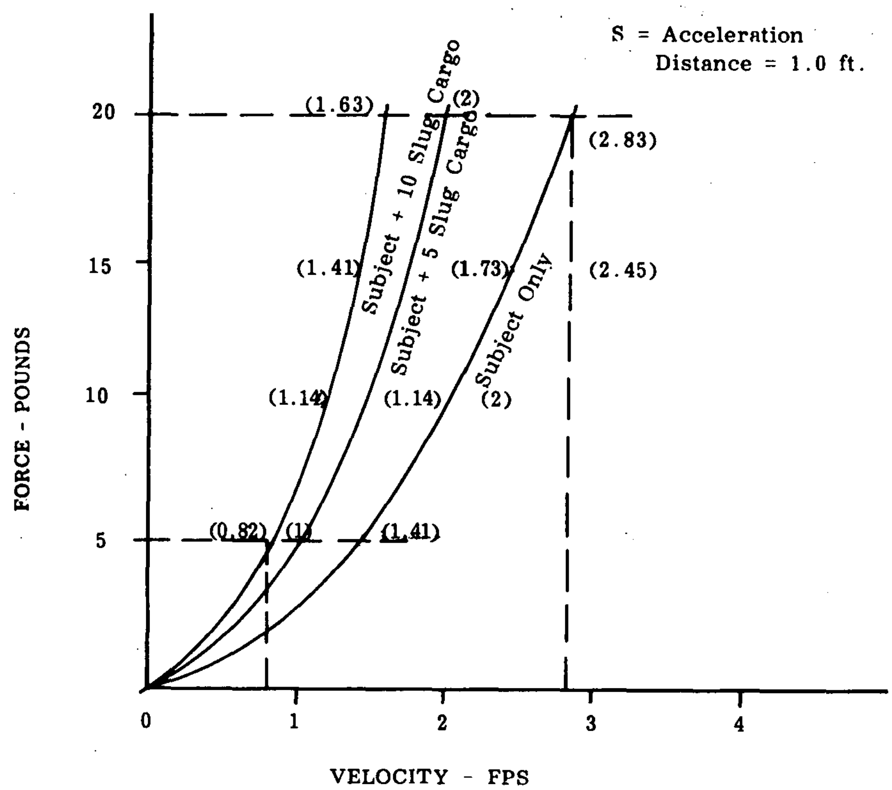


Figure 2.7: Expected Velocity Range for Manual Cargo Translation Tasks

be mentioned, however, that accurate measurements of translation times are also required for contingency planning, particularly that relative to the malfunction of equipment or to hazards such as meteoroid punctures. In these cases, the location of the equipment and its operational characteristics must be evaluated in light of the timeline performance in order to provide a margin of safety whenever a potentially hazardous situation exists.

For example, if a pressure leak were to develop in one of the modules while a crew member was present, his course of action must be considered on the basis of how quickly he can perform certain operations and how quickly he can transfer to new positions. A more precise knowledge of performance capabilities would allow better planning of responses to such a hazard. In short, this tells us that timeline estimates must be realistic rather than conservative. Therefore, there are three candidate sets of timelines for comparison--the original set, which was provided by the Skylab planning documents and which the authors of this study feel is extremely conservative; a second set, which was developed during the initial phase of Contract NAS9-12122 and was an analysis and extrapolation of force profiles measured during that experimental program; and the third timeline, which was developed during this study by an experimental program addressed to the specific task of translation to distances between 5 and 20 ft.

2.2.5 Significance of the Results

The timeline derived as a result of the present experiment program differs from the intermediate timeline in that the intermediate timeline considers translation velocities to be constant, independent of the distance traveled. This latter timeline, supported by the test program of this study, incorporates the principle that average velocity increases with an increase in distance over a limited set of distances. In applying this data to the cell-to-cell transfer times, each interface, such as the hatch and the dome connecting the airlock to the workshop, is assumed to constitute a full stop. A transfer time that includes 20 ft distance from one side of the interface and 10 ft distance from the other side is a sum of the two time periods, each of which includes acceleration, coasting, and deceleration to stop.

Some attention was paid to this problem during the experimental program, and a number of hatch sizes were tested in order to estimate the significance of the interfaces. The concensus was that, while it is not necessary to come to a full stop at such interfaces, the interfaces would probably be used for reorienting or adjusting attitude or directions.

Therefore, the Skylab timeline estimates given in Table 2.4 are a realistic representation of the minimum nominal times which will be experienced by the Skylab astronauts once they gain proficiency in learning to control themselves and additional masses. The term "minimum nominal" refers to the fact that these estimates reflect the probable comfortable lower boundry for translation times. If a continuous on-orbit record of translation times can be obtained on Skylab, there would be two important results:

1. The record would provide an estimate of human performance adaptation to weightlessness.
2. The asymptotic performance level would serve as a direct orbital comparison with the simulation results, thus permitting the simulation technique employed here to be extrapolated to other motion-performance cases.

2.3 MASS HANDLING AND TRANSFER

2.3.1 Simulation Requirements--Handling of Skylab Food Containers

The second area investigated during this contract was Mass Handling and Transfer. Two simulation techniques were used. The dynamics of mass transfer were assessed, as described in the previous section, using the hybrid water immersion simulator in conjunction with the NASA-LRC neutrally buoyant packages. The mass handling characteristics (the force levels required and the interaction of the cargo-man-restraints) were assessed by evaluation of representative task scenarios using conventional water immersion techniques.

Initially, there were two Skylab tasks identified which were to be simulated for the purpose of potential investigation during the M516 Crew Activities/Maintenance Study experiment. The first of these tasks, Food Container Transfer, considered the relocation of the six food containers (earth weight - 257 pounds) from the launch configuration around the center of the OWS to the wall-mounted orbital stowage locations (see Figure 2.8). The report for the previous contract, NAS9-12122, recommended that the scheduled relocation of the food containers be performed later in the mission in view of the potential difficulty of moving these containers, which are the largest masses handled by the astronauts in the weightlessness of orbital flight.

2.3.2 Simulation Description

During the course of the present study, a food container receptacle rack was constructed which permitted the placement of a simulated food container (a neutrally buoyant package approximately 6 slugs in mass) at three levels of height, corresponding approximately to the planned positions in Skylab. Subsequent to this investigation, it was learned that a redesign of the orbital stowage location area had been accomplished. The change (MAC/DAC DWG 1B77075, Chg D - Chg M), although significant, did not affect the results of the simulation since the data were derived parametric to the height of the stowage location above the datum plane.

A section of Skylab triangular grid flooring and the associated portable foot restraints were instrumented with a laterally oriented load cell to record the horizontal forces applied to the floor during container placement at the

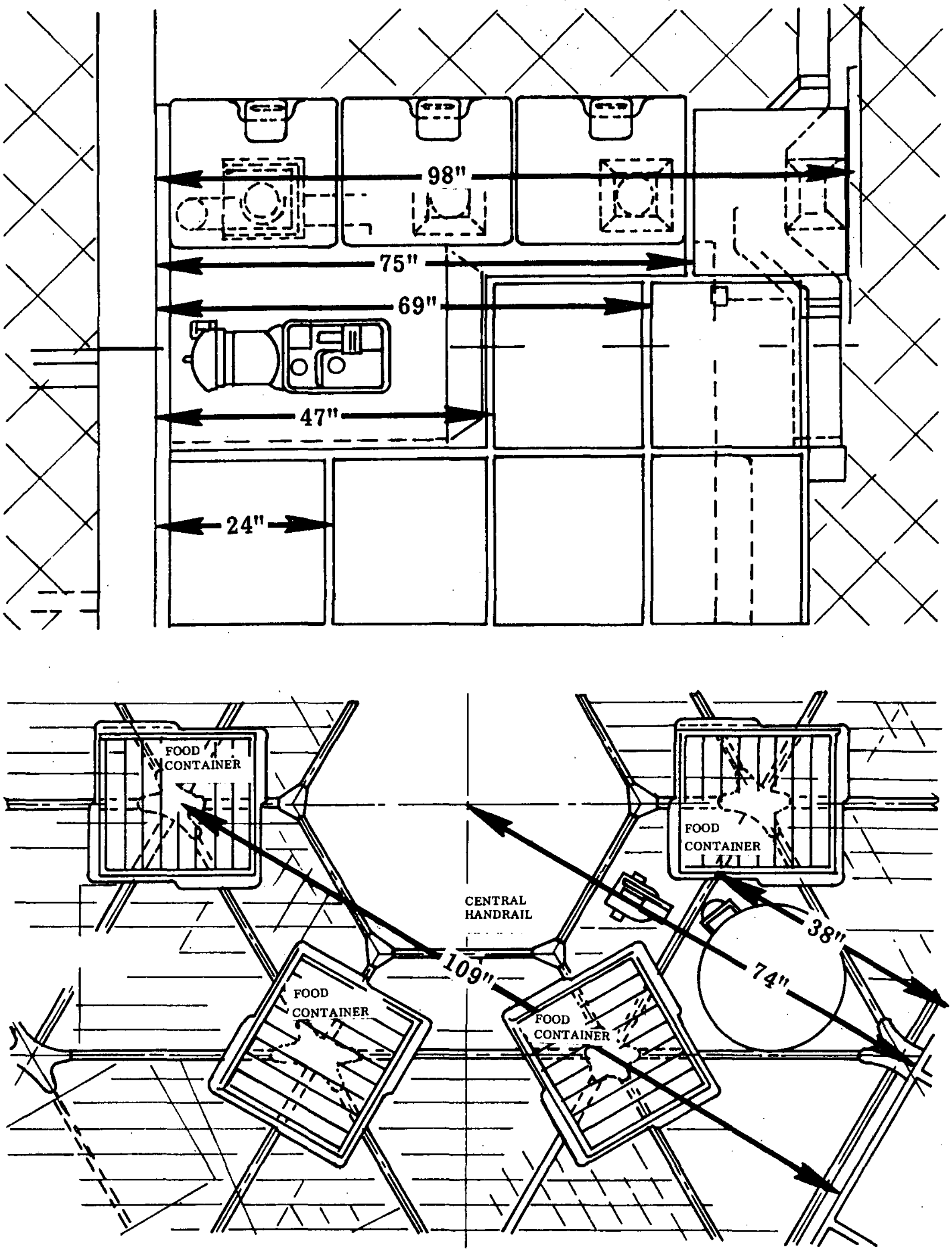


Figure 2.8: Food Container Launch and Orbit Stowage Locations

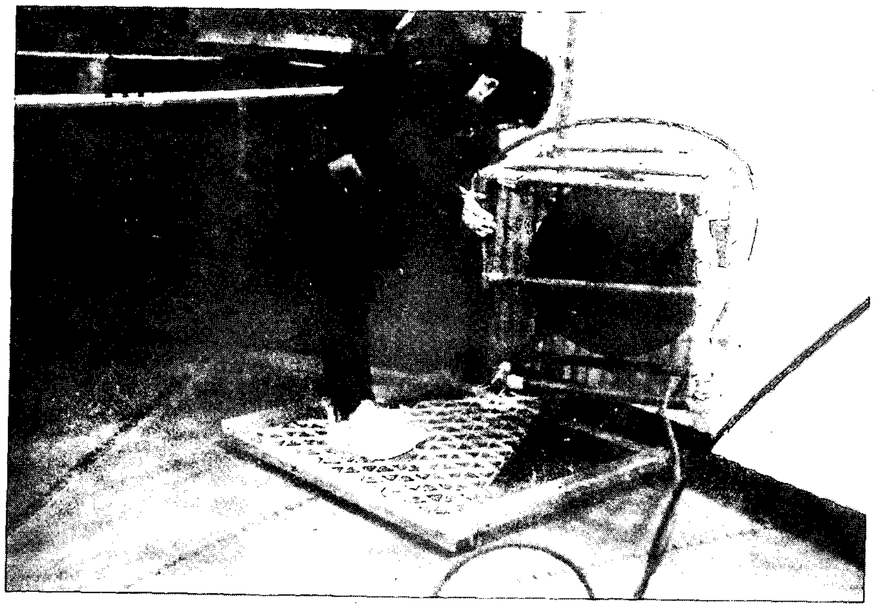
three average levels of container stowage heights selected--16 in., 40 in., and 64 in. above the datum plane.

Figure 2.9 shows the subject handling a simulated food container preparatory to placing it at the lower level. The horizontal force produced when the subject placed the container in the rack was recorded as a function of time, and it was used to ascertain the maximum force and the level and duration of the impulse that the test subject could apply. Force-time histories were recorded for subject performance with both feet confined in a fixed position by the portable foot restraints.

2.3.3 Test Results--Food Container Handling

It was generally observed that the subject's body configuration changed significantly in response to the horizontal thrust applied. A combination of ankle torque and body inertia was used to provide the impulses observed. This was due primarily to the task geometry, since frontal location with both feet approximately equidistant from the wall required that continuous thrust forces be a result of body torque provided by the ankle member.

Figure 2.10 is a representative force-time profile showing a single impulse at the midlevel of height. This data shows a peak force of 17.5 lbs, a total time of 2.2 sec, and a total impulse of 21.76 lb-sec. Additionally, the level of sustained force was measured wherein the subject was instructed to apply his maximum force for a sustained duration horizontal thrust without changing body position or using body inertia. The subject found it extremely



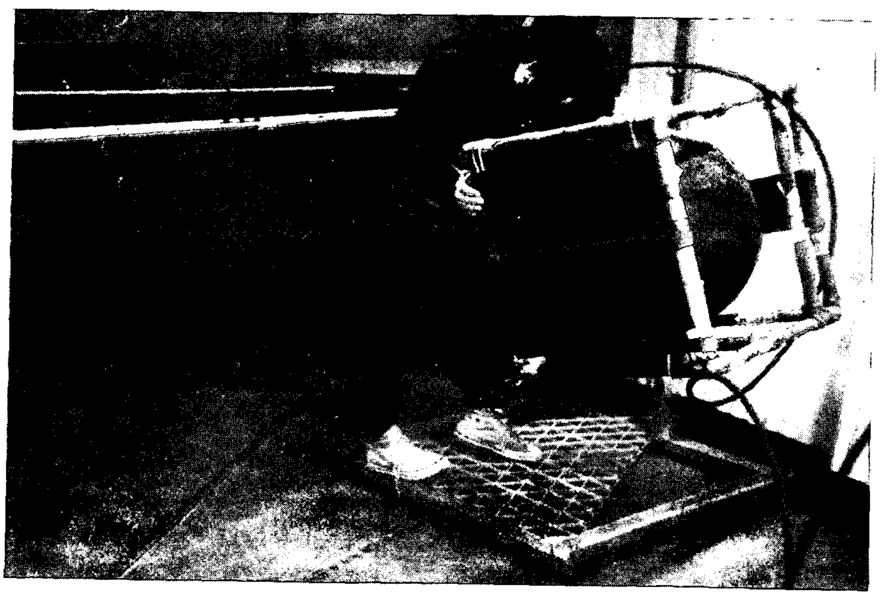


Figure 2.9: Subject Manipulating the Neutrally Buoyant Food Container Mockup

difficult to comply with these instructions. In certain instances, he found he could not supply a sustained force for longer than a few seconds.

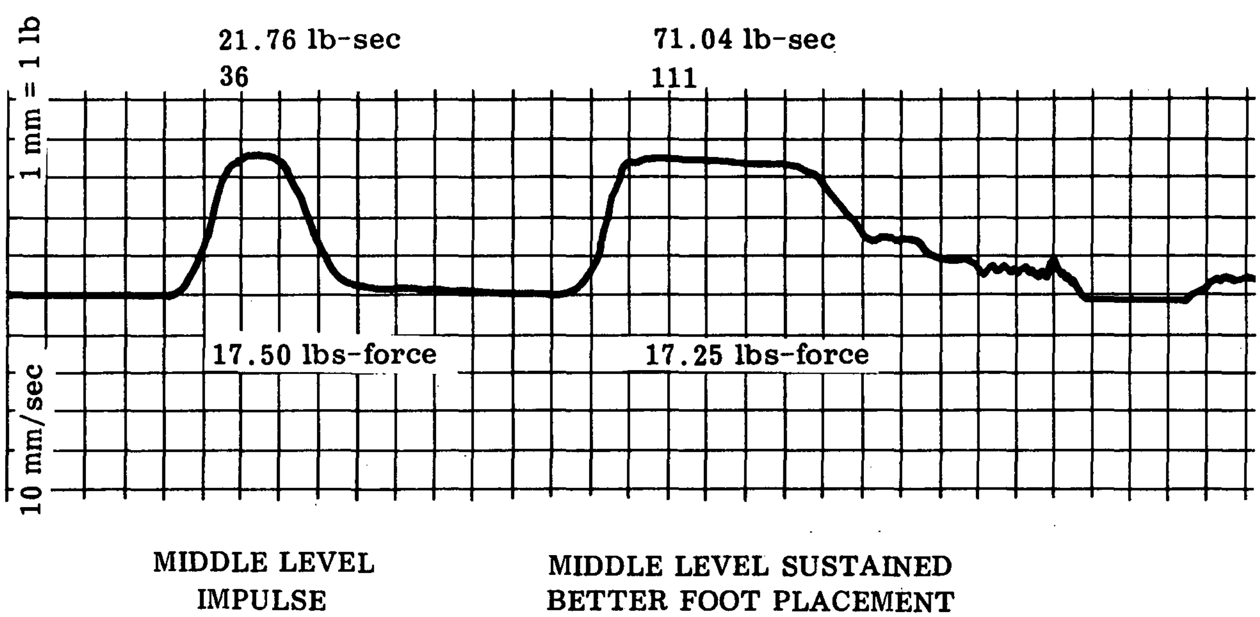


Figure 2.10: Representative Impulse During Food Container Placement--Midlevel Height

The resultant tests indicated that the largest impulse force and sustained force were accomplished with the package at midlevel. Reduced horizontal force values, for both impulsive and sustained forces, were attained at the lower placement level, and further reductions were seen during the attempt at high level placement. This information is in significant disagreement with the results of the computer model generated data reported in the results of NASA Contract NAS9-10973. Extrapolations of the data to the highest placement level of 88 inches indicate maximum forces below 10 lbs.

This contrasts sharply with the approximately 50 lbs maximum force level predicted by the model. Subsequent analytic treatment tends to support the lower force level.

Figure 2.11, Results of the Food Container Placement, is a compilation of the data showing the average forces and impulses at the three levels tested.

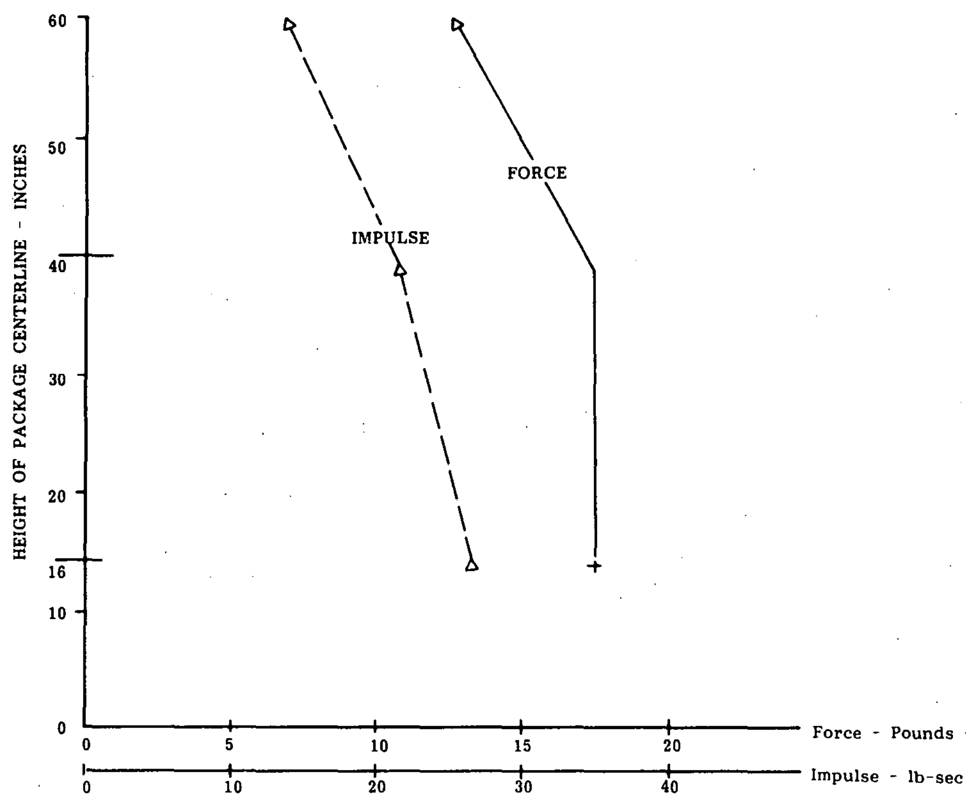


Figure 2.11: Results of the Food Container Placement Experiment

It is important to note that these test results are measurements of the horizontal force component. The orbital structure into which the food containers are placed includes a guide rail which mates with a small projection on the container. Since friction between the projection and the guide rail must be overcome by the astronaut, the data from the food container placement simulation can be considered as an upper performance limit for Skylab designers, if the only restraints to be used are the portable foot restraints.

Extrapolation of the data to higher placement levels indicates that only minimum forces and impulses could be provided by the astronaut at levels higher than those investigated. Since current Skylab designs require placement of food containers at levels higher than those tested, alignment constraints and attendant frictional resistance of the food container stowage racks must be carefully considered. Alternately, additional restraints or altered force application modes could be utilized if appropriate provisions are made.

2.3.4 Mass Handling Transfer Mode Comparison

The 6.4 slug neutrally buoyant cargo package was used to investigate the various modes of mass handling and transfer. The primary source of data for the conventional water immersion tests were 35 mm, 2 fps strip film.

The distance modes evaluated with conventional water immersion techniques were:

1. "normal" walking across the Skylab grid floor with the portable foot restraints
2. transfer across the Skylab floor using the grid as handholds
3. package manipulation using the magnetic shoes (Shuffler concept)

The data were compared with the results of the one stroke (perpendicular to the motion aid) transfer maneuver simulation using the hybrid water immersion technique.

Conventional water immersion simulation of the movement across the grid floor was accomplished for an approximately eight foot long gridded section supplied by MSC. A typical sequence of the handling and transfer of a neutrally buoyant package is shown in Figure 2.12. In Frames 1 - 12, the test subject may be seen using the Skylab grid floor as a series of handholds. He is transporting the 6 slug neutrally buoyant cargo in one hand. Frames 13 - 24 show the same subject using the portable foot restraints with triangular cleats in conjunction with the grid floor. There is an approximate 1/2 second time difference between successive frames.

In the previous study (NAS9-12122), it was observed that man exhibits a natural tendency to align his mass center close to a motion aid during cargo transfers, since this reduces the requirement to provide body torque in addition to the thrust forces required for cargo-subject acceleration. In this study (NAS9-12574), it was observed that the neutrally buoyant packages were moved in front of the subject during translation, but not so much that they compromised the subject's view of his course. This characteristic was exhibited for each translation technique. Using the rope motion aid, the test subjects consistently placed the package at a position just short of vision interference. In the sequence photos, Figure 2.12 (Frames 1 - 12), the mass is carried off to the side, but it is brought as close in to the body as possible during the translation.

Frames 13 - 24, on the other hand, show the subject maneuvering the package in his path of travel, but having some considerable difficulty in locating foothold positions using the portable foot restraints. It can be seen that he is

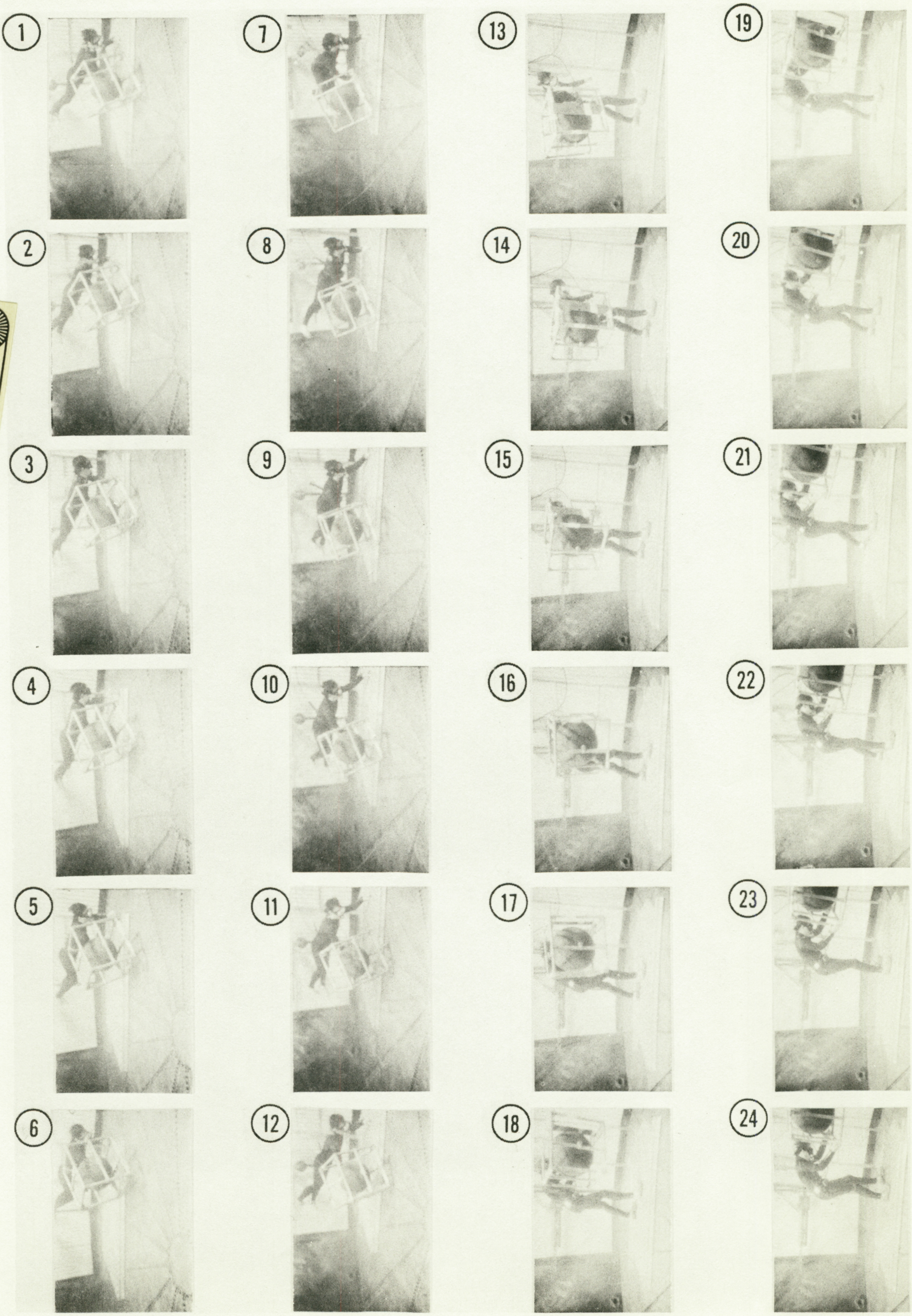


Figure 2.12: Comparison of Mass Transfer Using Conventional Water Immersion Technique

holding the package far enough ahead that he has a view of his next foot position. This is due to the difficulty experienced in engaging the portable foot restraints into the flooring in a simulated weightless state. The close fit of the cleats and implicit interference caused significant stability problems. When the package was moved to a hands-high position, the subject continually moved out from under the package due to its high inertia. Inertial forces also tended to hinder smooth motion due to the requirement to relax the body position in the rearward direction in order to release the rear foot.

Various studies considering the problem of mass transfer have identified the problem of package rotational inertia as a consideration in the transfer of packages. In the zero-gravity aircraft, perturbations of the aircraft provide misleading cues and indicate that rotational maneuverability becomes difficult even for movement of small packages. Water immersion simulation conducted at the Langley Research Center shows a significant increase in difficulty of rotational maneuverability with an increase of mass. However, the degree of difficulty is minor for the mass levels anticipated in the Skylab program.

2.3.5 Results of the Mode Comparison

In this study, the masses (shown in Table 2.3) were not found to be difficult to handle and, in fact, could be easily maneuvered without pushing through the mass center of the package. This was accomplished simply by grasping a handhold, providing an accelerating force, and, at the same time, providing a wrist torque which prevented the package from rotating. It was reported by one of the subjects that: "I can tell the difference in rotating or moving the packages if I handle one right after the other, but the requirements are so similar that I doubt I could tell you which package I was handling unless I was consciously prepared to answer that question."

Two important characteristics of mass handling are (1) the acceleration and deceleration of a mass being transferred and (2) the forces required to effect accelerations and decelerations. Figure 2.13 is a graph of the acceleration rates applicable to masses in terms of earth weight by the application of forces from zero to 10 lbs.

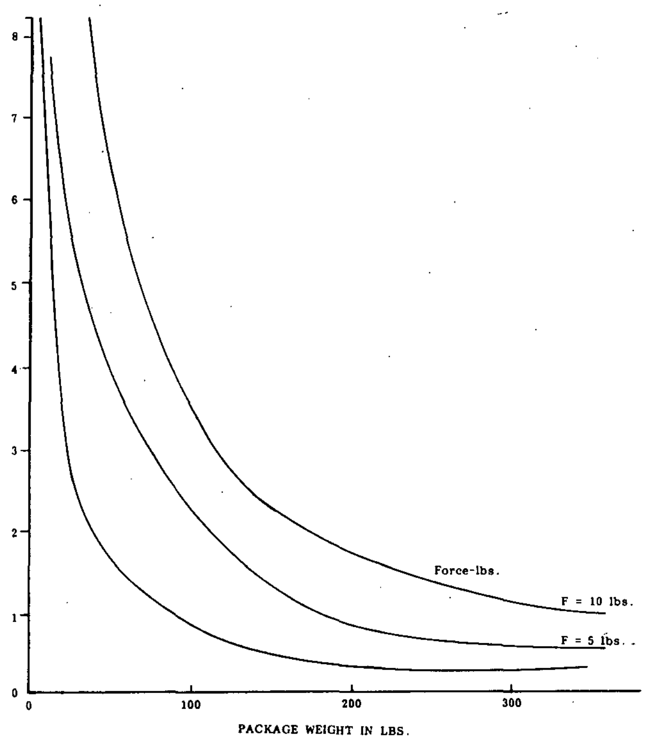


Figure 2.13: Acceleration of Skylab Class Mass Parametric to Acceleration Force

This graph encompasses the masses of the movable objects in Skylab. A 10 lb force is adequate to accelerate a 320 lb earth weight object. In Skylab, the majority of masses handled fall at the lower end of the scale. Therefore, it is important to consider what force levels will be experienced in the handling of these smaller masses. For example, a 32 lb earth weight object subjected to a 10 lb force would accelerate at a rate of 10 ft/sec^2. This acceleration rate is at the upper boundary of the normal accelerations experienced in manually handling objects. From the study experiments, it was shown that objects being handled in Skylab will rarely experience acceleration forces greater than 10 lbs. Normal deceleration forces, that is, those supplied by the astronaut and not considering impacts, tend to be somewhat higher. Simulation data indicate normal deceleration rates on the order of 1.2 times acceleration rates.

2.3.6 Skylab M509 Propellant Supply Subsystem--Transfer Evaluation

It is interesting to consider the dynamics of the situation in which an astronaut would attempt to apply forces against low mass objects in weightlessness. A Skylab task which serves as an example of this problem is the transfer of the propellant supply subsystem (PSS) for the M509 maneuvering equipment. The PSS is a spherical pressure tank, 14.5 inches in diameter, weighing approximately 57 lbs. Its protective shell is designed for a collision with a 90 degree corner (0.5 in. corner radius, 0.4 in. edge radius) with a maximum velocity of 2.5 ft/sec. The timeline data (Section 1.0 of this report) indicate that a 2.5 ft/sec translation rate for this task is realistic. Using the predictive formula developed in NAS9-12122 for acceleration as a function of cargo mass, a realistic acceleration rate for the subject PSS is 0.7 ft/sec . Forces normally expected during the transfer of the PSS in Skylab would be somewhat less than 2 lbs force for the acceleration phase and less than 4 lbs for the deceleration phase.

2.3.7 Observations on the Handling of Large Mass Packages

Figure 2.14 shows two sequences (25 - 36 and 37 - 48) taken at 2 fps of a test subject attempting to lift a 200 lb object in simulated weightlessness. His instructions were to lift the package as quickly as he could, i.e., use forces greater than he considered normal. As he attempted to apply vertical force to the object, reaction torque caused his body to pitch forward, so the package trajectory, instead of being maintained at the originally intended vector, shifted on the order of 45 degrees. It can also be seen that, as he continued to apply force, the velocity of the mass increased, and since he had no means of applying a decelerating force, he found himself travelling along with the mass at the velocity he had reached when his feet left the floor and in a direction other than that originally intended. Although it is not anticipated that the Skylab astronauts will have any serious problems associated with overpowering free masses, it is important to gain an understanding of force and acceleration levels for equipment design purposes and for task evaluation, so the role of man in orbital operations can be fully exploited without exceeding the limits of his natural capability. These limits will define the manual "thresholds" considered in the following sections.

2.3.8 General Skylab Mass Transfer--Test Results

The sequences described were subjected to visual analysis to determine the average translation velocities for the eight foot section of the Skylab

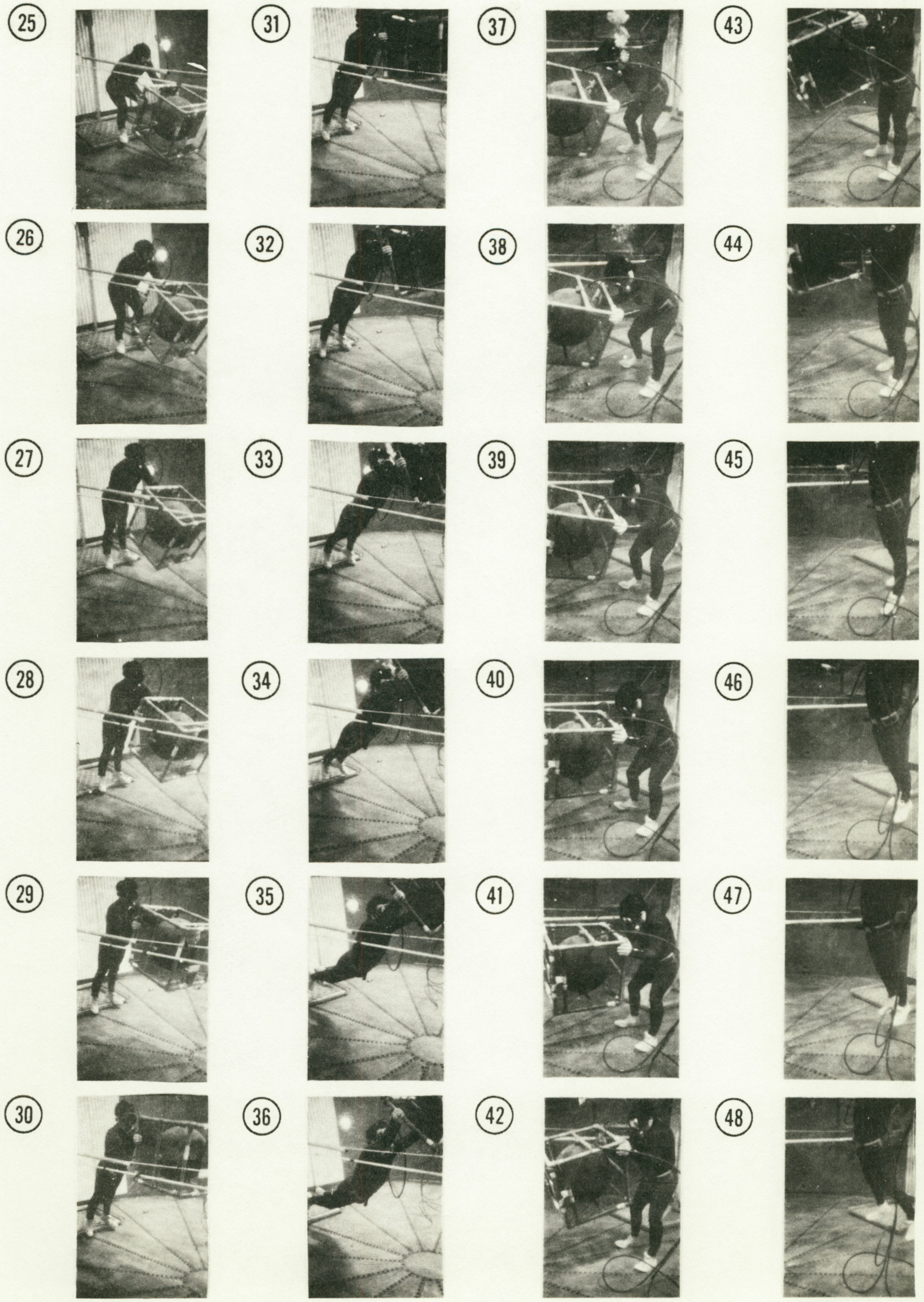


Figure 2.14: Application of High Level Acceleration Forces to Skylab Maximum Class Cargo

grid floor. The results of these two models were compared with the mass/ distance data derived in the previous section and are summarized in Figure 2.15.

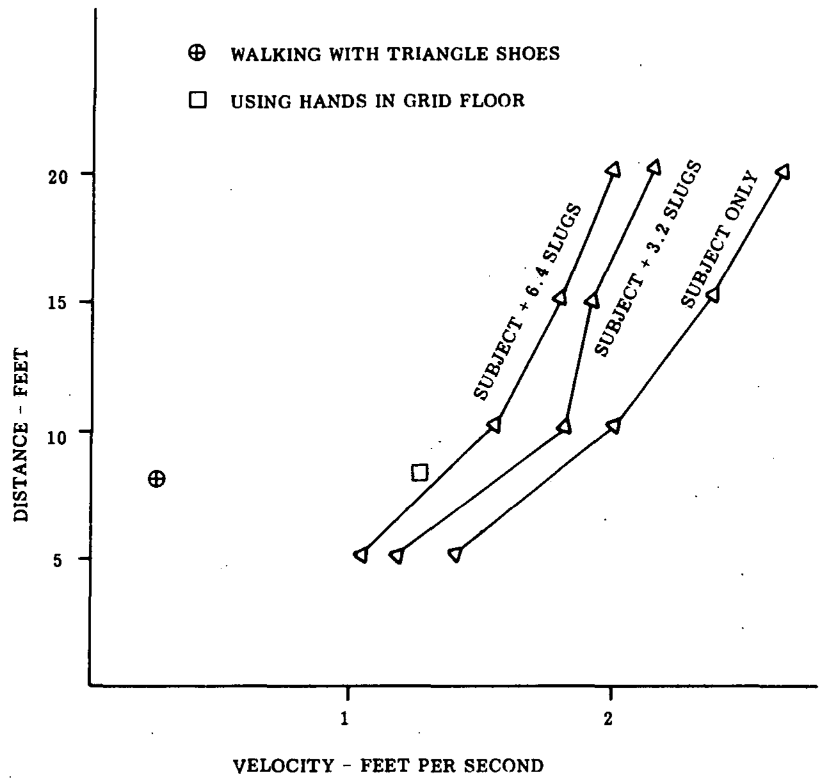


Figure 2.15: The Effect of Cargo Mass and Transfer Mode on Average Velocities

The handhold mode closely approximates the one stroke acceleration mode. The approximate 20% velocity depression is well within the range expected as a result of drag effects. These results contrast sharply with performance using the portable foot restraints. Even over these relatively short distances, the 0.25 ft/sec average velocity was significantly below the conservative original timeline estimate of 0.5 - 1.0 ft/sec. The results of the present experiment program have evolved a new portable foot restraint concept to use with the grid floor which permits ease of operation while optimizing the transverse force capacity. Recommendations as to the preferred concept and operation modes will be given in the conclusions and recommendations section at the end of this study report.

One additional mass handling and transfer mode was evaluated--that using the NASA-MSC Shuffler concept. A representative sequence of mass handling using the Shufflers is shown in Figure 2.16. While consideration of the Shufflers in Skylab is precluded due to inappropriate transfer surfaces, the opportunity to compare modes was thought to be sufficient reason for including them in the present work. Four observations concerning the Shufflers are justified:

1. The Shuffler concept is significantly better adapted to cargo transfer than the present portable foot restraints (triangle shoes).

2. All subjects preferred to use the Shufflers in a normal walking manner rather than the abnormal shuffling mode.

3. The Shufflers are extremely useful in the positioning of objects and in providing low level transverse forces, less than 30 lbs.

4. The subjects were permitted infinite ease of foot placement and adjustment. Conversion of the magnetic shuffler to the electrostatic mode might offer distinct advantages.

2.4 GENERIC THRESHOLDS--STATIC FORCE APPLICATION

2.4.1 Background

The tasks previously described are, in general, related to a broad area generically described as thresholds. In weightlessness, all human

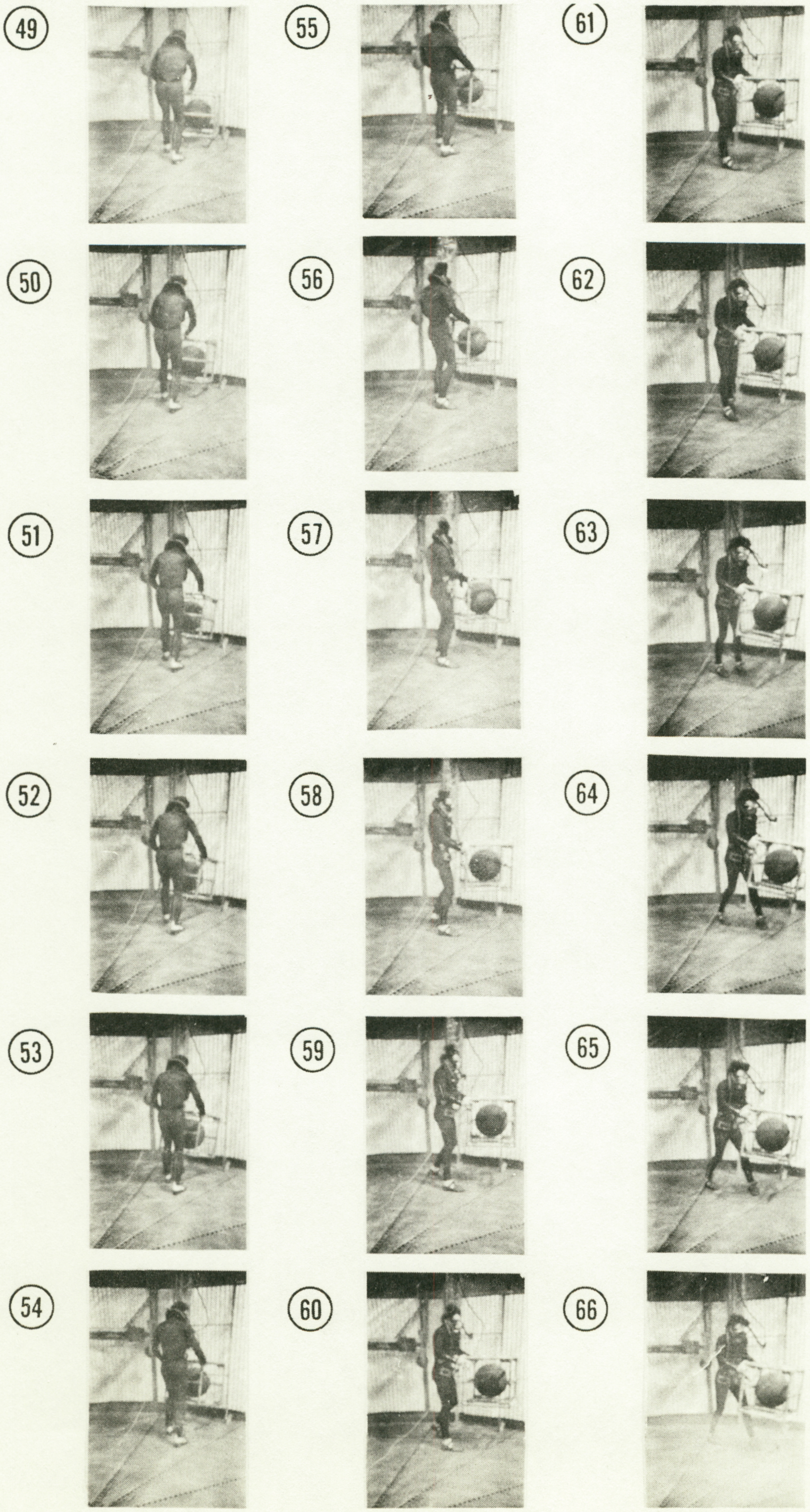


Figure 2.16: Sequence of Cargo Handling Using the NASA-MSC Shuffler Concept

manual task performance must be evaluated in terms of specific forces required over specified time intervals to determine the precise requirement for restraints. Tasks requiring only low force applications for short time periods may require no restraint at all, or at least no specialized restraint. Tasks requiring high force applications or low force for long periods generally require restraint.

High force applications have formerly been limited to the ability of the astronaut to provide peak and sustained forces, and these applications have been the subject of considerable study by NASA and various contractors. However, thresholds are not properly defined or measured in this fashion, particularly since they are strongly task dependent. Since it is impractical to include restraints at all the possible locations of low force task performance, it is important to develop a rationale for minimum restraint requirements or, conversely, maximum capability without restraint.

2.4.2 Crewman Motion Analysis

Consider as the limiting case of astronaut unrestrained motion a constant force exerted over the duration of one arm stroke. Specifically, the astronaut is considered to be producing a linear force through his mass center, and the only restriction to motion is his inertia.

The force profile is described as follows:

$$F(x) = \begin{cases} F_o, & 0 < x \le x_o \\ 0, & x > x_o \end{cases}$$

This implies that the subject will experience a maximum velocity $\dot{x}_{max}$ equal to some constant x_o to be determined after his position reaches a point $x = x_o$, where x_o is the total length of the accelerating stroke. Note $x_o \le x_{max} \approx 2$ ft.

For $0 < x \leq x_o$, double integration with respect to time using the initial conditions

$$x(0) = \dot{x}(0) = 0$$

yield

$$x(t) = \frac{F_o}{2m} = t^2$$

and correspondingly

$$\dot{x}(t) = F_o t/m$$

where

x = the linear distance
$\dot{x}$ = the velocity
m = the subject and cargo mass.

At $x = x_o$, therefore,

$$t_e = (2mx_o/F_o)^{1/2}$$

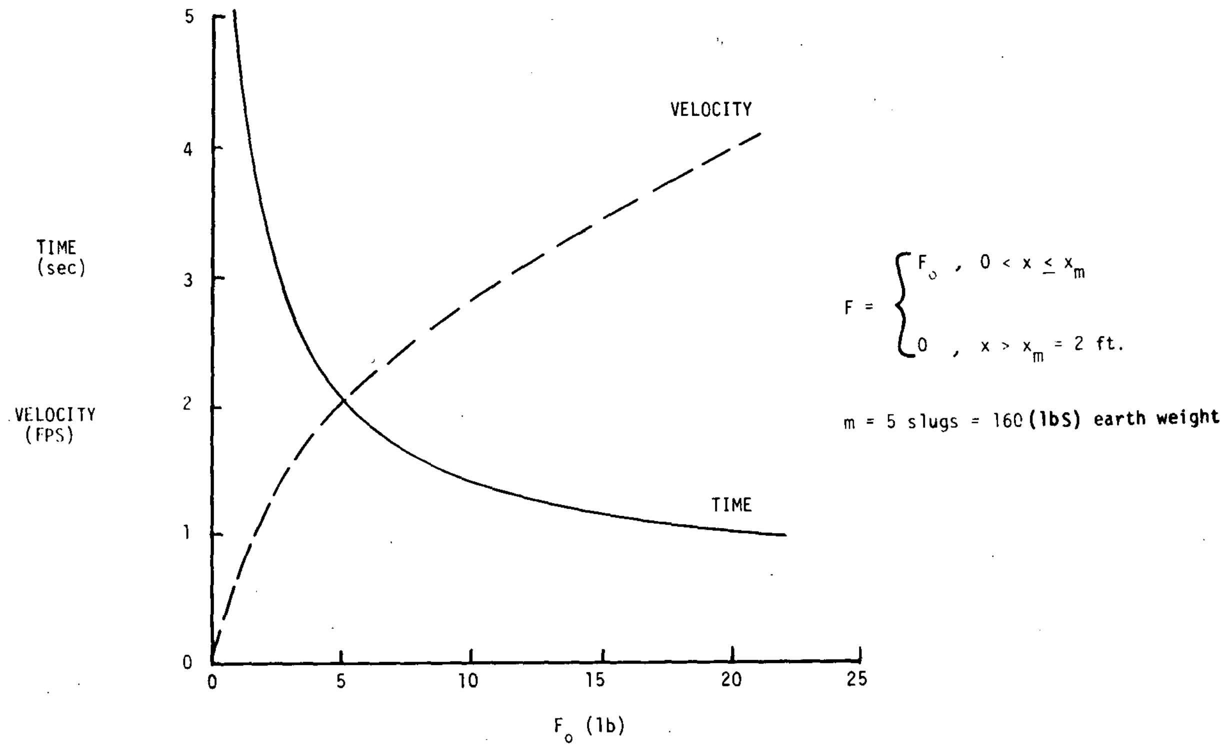
and

$$\dot{x}(t_e) = \left(\frac{2F_o x_o}{m}\right)^{1/2} = \dot{x}_{max}.$$

The complete description of the subject's motion is given by

$$x(t) = \begin{cases} \dfrac{F_o t^2}{2m}, & 0 < t \leq \left(\dfrac{2mx_o}{F_o}\right)^{1/2} \\ \left(\dfrac{2F_o x_o}{m}\right)^{1/2} t - x_o, & t > \left(\dfrac{2mx_o}{F_o}\right)^{1/2} \end{cases}$$

Figures 2.17 and 2.18 show typical results of the application of this constant force case. The mass of the subject is 5 slugs, or 160 lbs earth weight, and



(te) - TIME TO PASSAGE OUTSIDE RESTRAINT ENVELOPE

Figure 2.17: Restraint - No Restraint Threshold (2 ft Envelope)

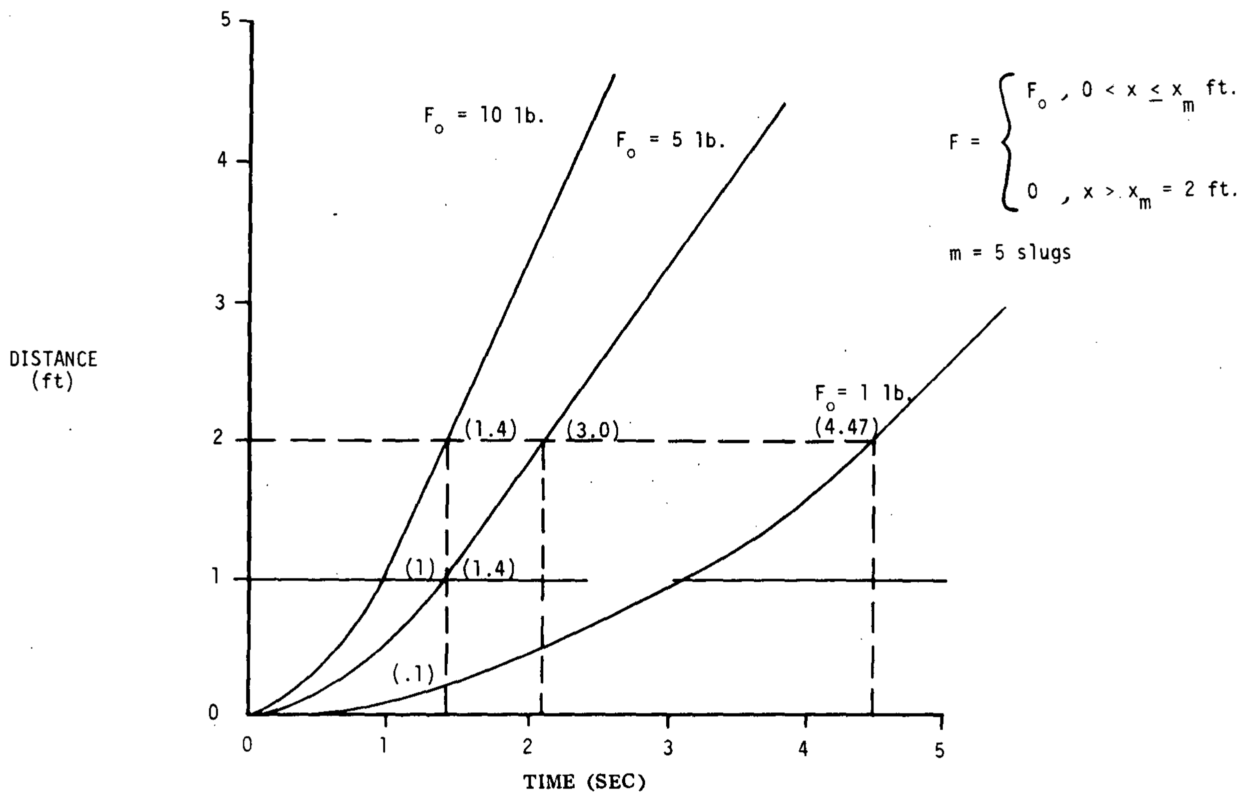


Figure 2.18: Restraint - No Restraint Threshold

it is considered that the force can be applied directly through the mass center of the subject and that the force can be applied for a distance of 2 ft. This would be the case if the astronaut were to push himself away from a position by applying a force with his arm through his mass center. When the mass center had been moved a distance of 2 ft, the arm applying the force would no longer be in contact with the structure. The figure shows the time of that action as a result of force level and the velocity of the mass center at that point in time.

It is important to note that the 5 lb force level can be maintained for 2 sec, or a total impulse of 10 lb/sec, while the twenty lb force level can only be maintained for 1 sec but produces 20 lb/sec, or twice the total impulse of the 5 lb force level. Actual force profiles from the previous study indicate peak force levels in excess of two times the average force level.

The effect of limited strokes, i.e., strokes less than maximum, can be considered by letting $x_o = kx_{max}$ for $0 < k \leq 1$. Since $x_{max} \doteq 2$ ft, substitution for $x(t)$ yields:

$$t_e = \left[\frac{(1+k)^2}{k}\right]^{1/2} \left(\frac{m}{F_o}\right)^{1/2}$$

where (t_e) is the time of passage outside the restraint envelope.

The Skylab mission will produce data (film, videotape, etc.) from which the subject's velocity can be measured. From this, the total impulse can be derived, but the force profile and the peak forces must be estimated on the basis of simulation. The data from Experiment T013, Crew Disturbance, as it is currently planned, will return some force profiles which can be used in the comparison analysis of threshold forces. The simulation experiments for the Skylab timelines in this study show that a human subject modifies his level of force application, depending upon the distance he intends to travel. Nevertheless, if the force profiles from the single distance traveled in the T013 experiment reflect the same characteristics as the force profiles recorded during hybrid simulation, it will lend weight to the use of the simulation force profiles as an analytical tool in the evaluation of Skylab task performance.

2.4.3 Trash Disposal Airlock Actuation Evaluation

An evaluation was made of the use of the Trash Disposal Airlock as a potential task to be included in Experiment M516 evaluations. This airlock, shown in Figure 2.19, is located in the center of the lower floor of the orbital workshop. It provides an interface between the orbital workshop and a large waste holding tank. The airlock is scheduled to be used five times each day and is operated manually by means of pneumatic valves with lever handles. The force requirements to operate the handles were not specifically identified within the information available to this study. Another study (NAS9-109730) measured and reported a maximum of 8 lbs force to operate a model of the trashlock.

A simulation test article was fabricated to determine the manual operation mode preferred for lever operation, and measurements were made of the maximum manual force levels applied. In a one gravity walkthrough of the operation, the astronaut assumed a squatting position near the airlock controls. In simulated weightlessness, the test subject could have assumed the same position, but he preferred to operate the controls in a quasi-isometric fashion.

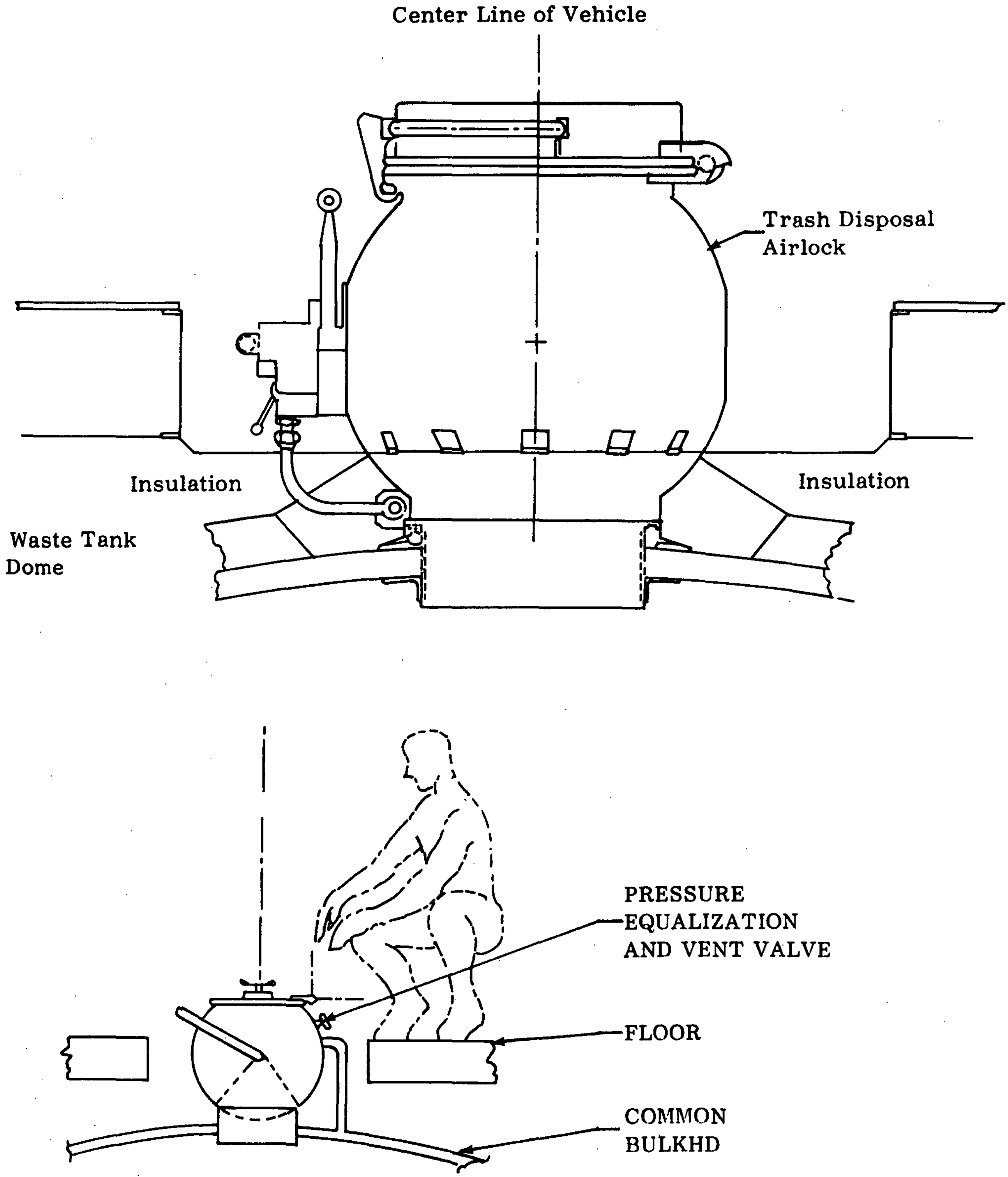


Figure 2.19: Trash Disposal Airlock Configuration

Figure 2.20 shows the results of simulated performance in which the isometric (counterbalanced) hand locations were varied from 8 to 24 inches. This was contrasted with simulations utilizing the Skylab portable foot restraints. The lowest force levels reported were approximately 30 lbs, or about four times the requirement for lever operation. Maximum forces greater than 60 lbs were recorded when the subject had a nearby position to react against. Using the foot restraints, horizontal pulling forces were found to be greater than horizontal pushing forces, but again both were comfortably over the 8 lb requirement.

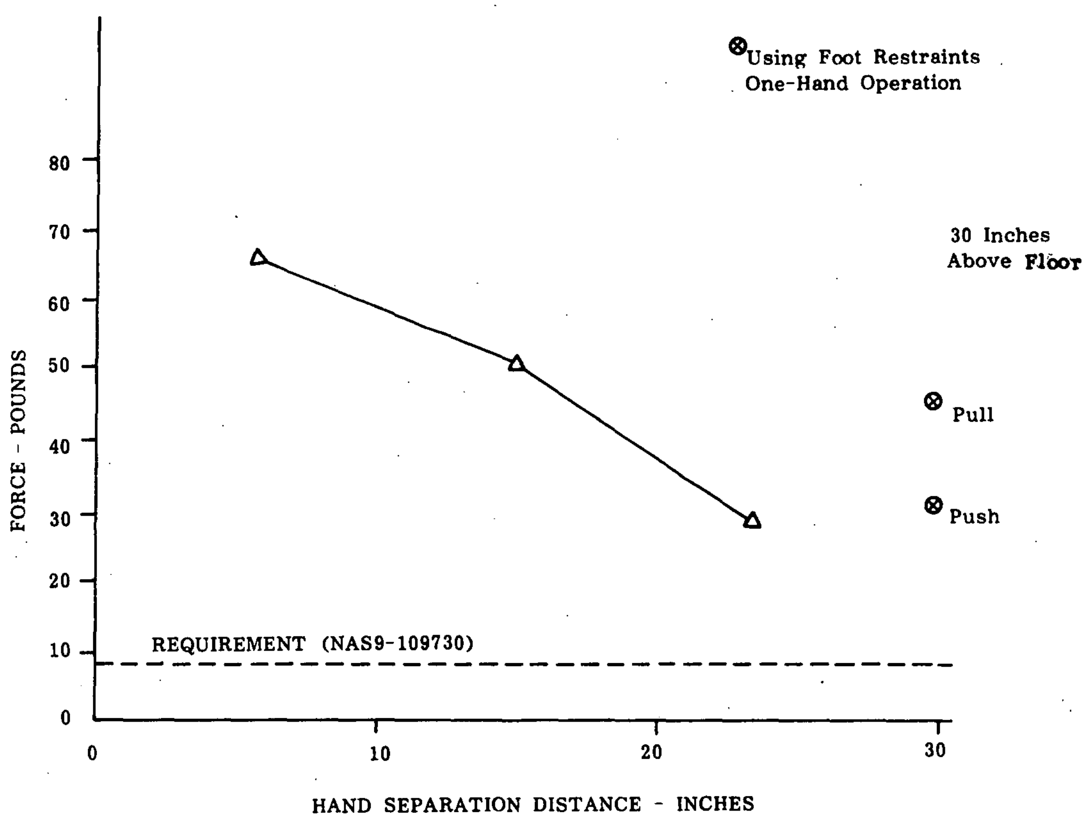


Figure 2.20: Results of the Simulation of Trashlock Operation

In general, it was determined that if the 8 lb force requirement is realistic, the operation of the airlock is well within the astronaut's capability to perform. The preferential position for operation, however, will be drastically different from one gravity operation, although it is not anticipated that this difference in position during operation will have any effect on the operational timeline.

2.4.4 SAL Rod Extension

A second task evaluated was that of extending the boom used in conjunction with the scientific airlock for purposes of positioning equipment outside the spacecraft. The boom is approximately one inch in diameter and is extended in sections through a sealing mechanism on the airlock for distances up to 16 ft outside the spacecraft. A review of data available from Experiment T025, Coronagraph Contamination Measurements, indicates a maximum push-pull force of 24 lbs for boom extension. However, it was reported that in some one-gravity tests the push-pull requirements were found to range from 40 to 70 lbs. Although this higher force level may be associated only with the test model or other factors which may be corrected, it was determined that a test series addressing this particular problem should be conducted.

A simulation article was fabricated in which test subjects utilizing the Skylab portable foot restraints (triangle shoes) were required to provide a thrusting force against a section of simulated boom. Since the astronauts differ in height, it was decided to vary the pushing position's height above the floor and to correlate this during the simulation with varying lengths of simulated booms in order to identify physical relationships to gain a better understanding of the force level as a function of position.

Figure 2.21 (shown on the following page) shows a series of 35 mm pictures, taken during the simulation, identifying the technique used. Three position attitudes were investigated. The subjects' preferred attitude is shown in Figure 2.22.

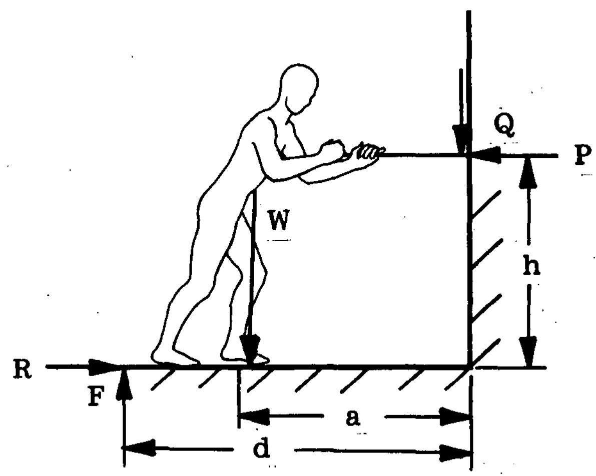


Figure 2.22: Subject-Preferred Attitude for SAL Rod Extension

This figure shows the left hand forward on the boom and the right hand grasping a flange on the boom end. The left foot is forward providing body control, and the right foot is to the rear, providing the reaction to the generated thrust. In this position, the test subjects were able to generate an average of 60 lbs force at a level 40 inches above the floor and a slightly lower force at the upper and lower positions. In the test set (2), the foot position was maintained, but both hands were placed on the end flange of the boom. The force levels in this case were considerably lower than the test set (1). A third test (3) was performed with the feet side by side and both hands on the boom

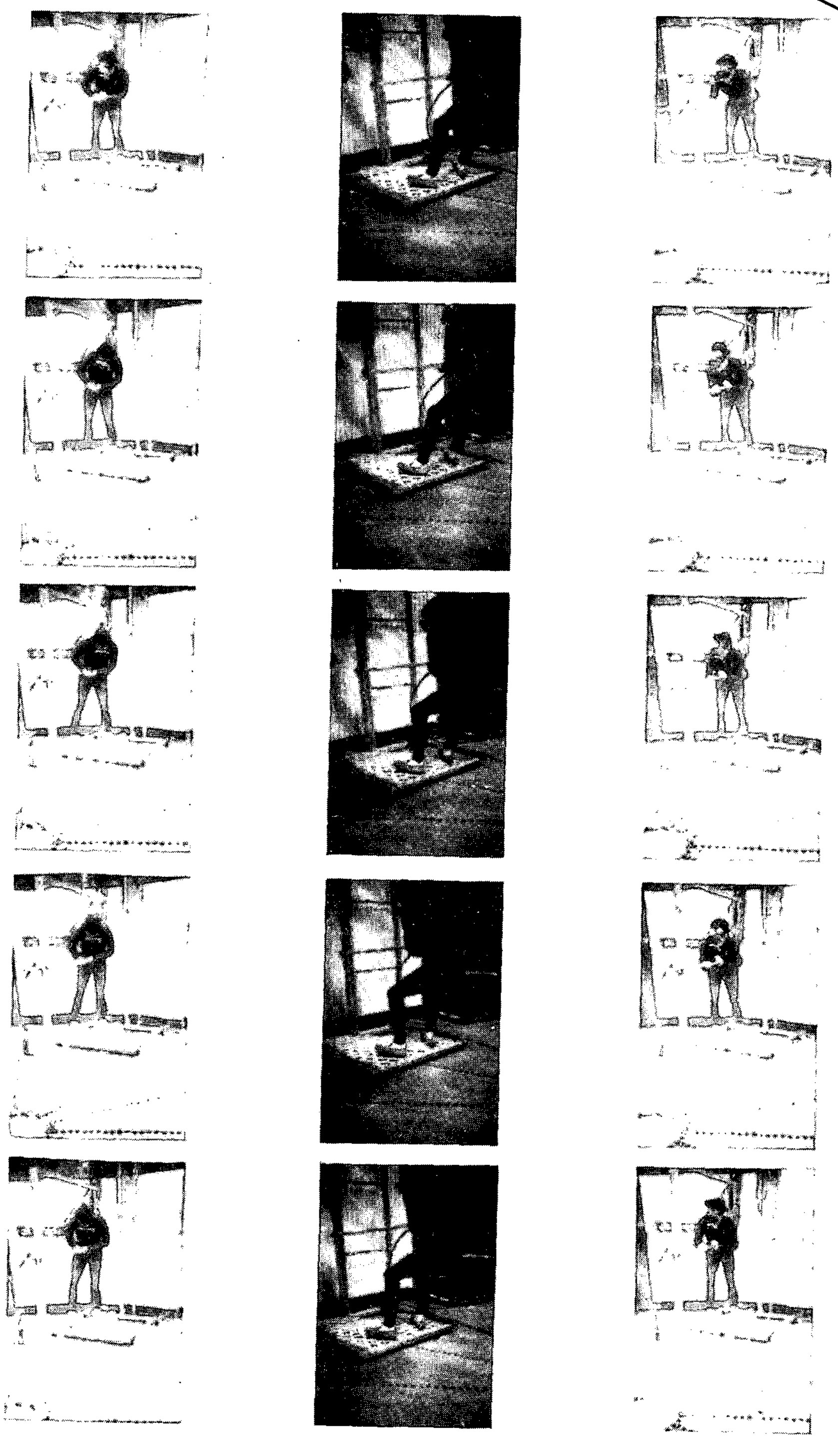


Figure 2.21: SAL Rod Extension

end flange. In this case, the minimum force levels were recorded. Two additional comparative tests were performed with the left hand placed on the airlock flange and the right hand on the boom end flange, allowing a quasi-isometric force application. At the 40 inch level, this technique, coupled with the use of the portable foot restraints as in test set (1), resulted in a force application of approximately 75 lbs. A similar test without the use of foot restraints produced a force level of approximately 60 lbs. The results of the tests are summarized in Figure 2.23.

2.4.5 SAL Rod Extension Simulation Results

The data from tests (1), (2), and (3) were recorded by means of an instrumented section of Skylab flooring which was configured in a fashion providing only the horizontal force component of the thrust. The two isometric tests were measured by an arrangement which allowed the boom to protrude through a vertical upright via a loose bearing and to react against a spring scale.

The force diagram shown in Figure 2.24 illustrates the considerations observed during the performance of this task. It is interesting to note that the attitude assumed by the subject in simulated weightlessness is approximately the same as that which is assumed in one gravity. This results from the placement of the scientific airlock relative to the Skylab flooring and other structures. In one gravity, a force component is provided by gravity attracting the mass of the subject, which the subject can shift forward of his center of gravity to obtain a horizontal force by leaning against the boom. In weightlessness, however, all of the horizontal force application must be provided by the subject's muscles. In the preferential position identified in

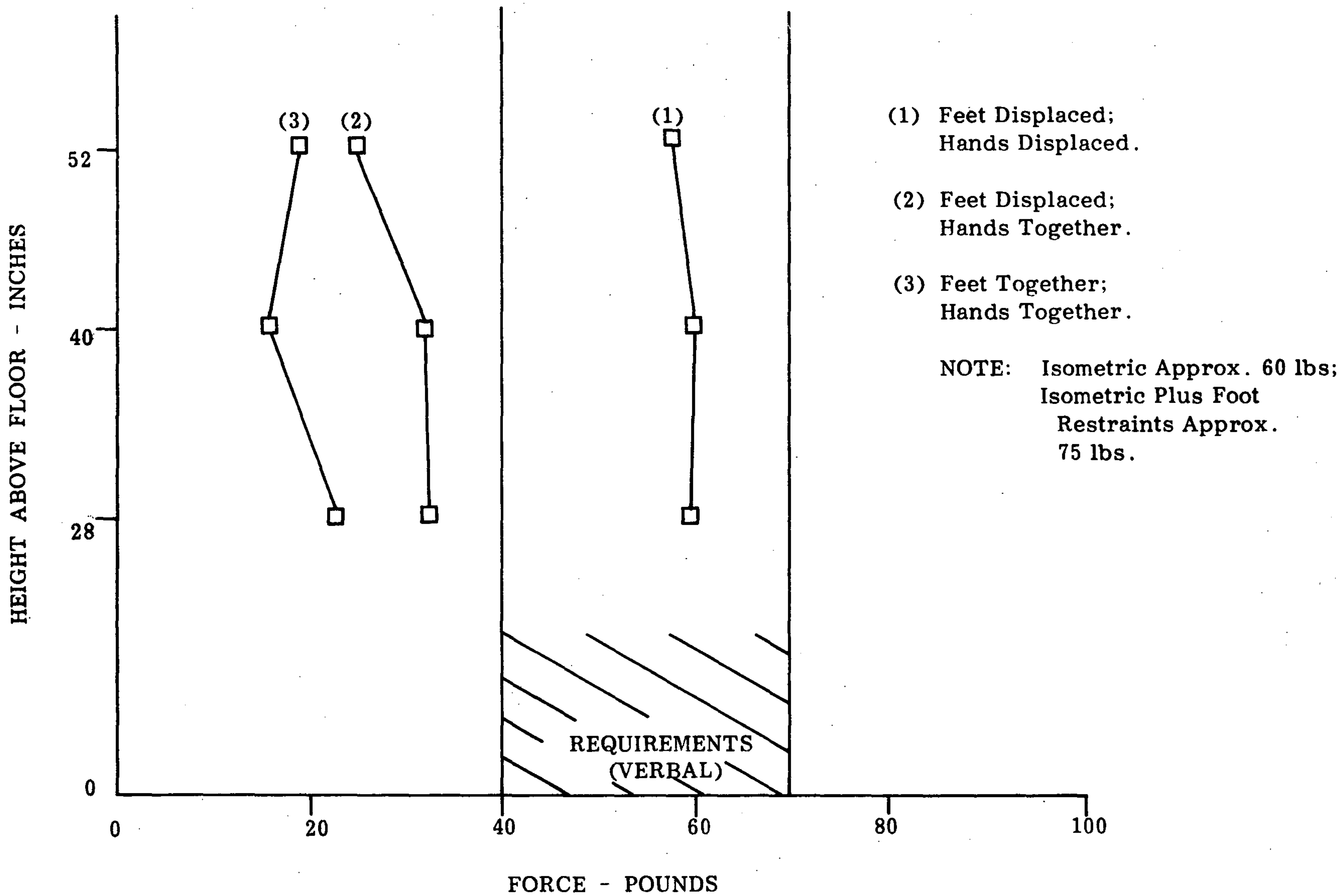
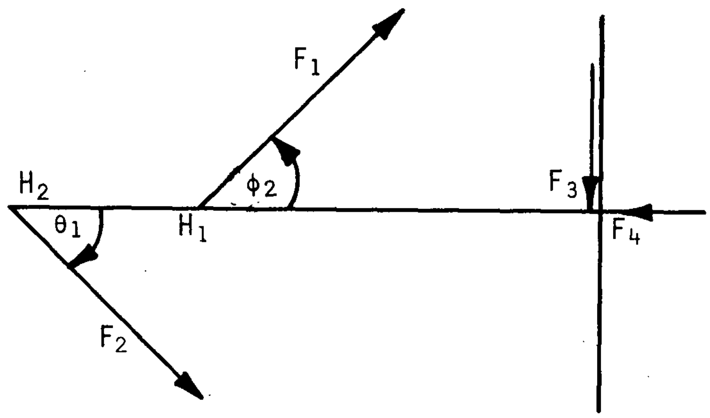


Figure 2.23: Results of the Scientific Airlock Rod Extension Simulation



$$F_2 \cos\theta + F_1 \cos\phi - F_4 = 0$$

$$-F_1 \sin\phi + F_2 \sin\theta + F_3 = 0$$

$$F_1 \sin\phi \, a - F_2 \sin\theta \, d = 0$$

$$F_1 = F_2 \frac{\sin\theta}{\sin\phi} \cdot d/a$$

$$F_3 = F_2 \, (d/a - 1) \sin\theta$$

$$F_4 = F_2 \cos\theta + F_1 \cos\phi$$

$$= F_2 \cos\theta + F_2 \sin\theta \, d/a \cdot \frac{\cos\phi}{\sin\phi}$$

$$= F_2 \, (\cos\theta + d/a \sin\theta \tan\phi)$$

Figure 2.24: Force Diagram for Preferred SAL Rod Extension Mode

Figure 2.23, test mode (1), it was found that each of the subjects was using the left hand forward providing a force F which was horizontal and up, and using the right hand at the flange end of the boom, providing force F which was horizontal and down, thereby providing a couple. When this couple was shortened in test mode (2), the force level was significantly reduced. It was determined that in providing the higher force levels in test mode (1), the subject also produced a significant vertical force on the boom at the point of entry into the seal mechanism. This factor assumes importance if the seal mechanism is designed so side loads or bending loads increase the thrust requirement for extension. Potentially, this could result in a Skylab experiment failure or, at least, an extreme inconvenience to the astronaut attempting to extend the boom.

It is recommended that the boom extension mechanism be subjected to tests to determine the side load and bending moment characteristics as they affect the force requirement for boom extension and that a water immersion test program, with a high fidelity mockup instrumented for horizontal and vertical loads as well as bending moments, be conducted in order to ensure that the task performance requires only nominal forces to be supplied by astronauts.

SECTION 3.0
CONCLUSIONS

The following conclusions and recommendations address the particular questions engendering this study.

1. Present Skylab station-to-station translation timelines are in error.

   Average velocity of the Skylab crewmen will be significantly higher than the Skylab timelines indicate, resulting in shorter translation times. The more realistic timelines presented in this report were determined by experimentation and analysis. It was proven that both the total mass transported and the distance of translation have a significant effect on the velocity of translation.

   Planning for contingencies, such as meteoroid impact and slow decompression, must be done on the basis of realistic translation rates. Overly conservative planning may induce the risk of unnecessary abort.

   It is recommended that the timelines presented in this report as minimum-nominal be used as the basis of Skylab translation times without a reduction for safety margin.

2. There are potential problems in Skylab mass handling tasks which may lead to equipment damage.

   Human subjects can provide the necessary forces to control and transport masses and volumes equal to or greater than the Skylab equipment complement. However, in order to accomplish transfer of large masses, a handhold should be provided which will allow the astronaut to use one hand for acceleration and control of the object. The other hand and both legs should be free to interface the vehicle.

A review of the Skylab documents disclosed that sensitive equipment has been designed to withstand impact based on a conservative maximum anticipated velocity. The first part of this study determined that these translation velocities are unrealistic. Sensitive equipment may, therefore, be subjected to impact above design tolerance.

It is recommended that a portable handhold, such as the electrostatic handhold developed by the Langley Research Center, be provided for the handling of large masses. It is also recommended that sensitive equipment subject to change in location during the mission be reviewed for impact design criteria.

3. Evaluation of Skylab tasks, such as the extension of a boom through the scientific airlock, indicates that the man-machine relationship in weightlessness has not been considered in the design of some Skylab equipment.

It is recommended that water immersion simulation be conducted for all Skylab tasks requiring more than minimal (on the order of 10 lbs) force application.

In addition, the following conclusions and recommendations are based on our overall knowledge of task performance in weightlessness.

4. Threshold force levels (those levels at which an astronaut is required to change his mode of operation) should be the subject of continued

investigation in order to understand and make best use of the capabilities of man in future space missions.

5. Skylab portable foot restraints should be redesigned to allow flexing at the ball of the foot, and the triangular section of the boot should be replaced with a small disc sized to capture a corner of the Skylab floor triangle.

6. The Apollo camera should be modified to include lower frame rates and longer exposure times. This modification, coupled with faster film, would eliminate the need for additional lighting during filming of task performance. As it is currently planned, however, lighting will be a constant source of annoyance.