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Final Report
Analysis/Design and Prototype Construction of a Selected Mobility and Restraint Device

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Prepared by

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FINAL REPORT

FINAL ANALYSIS/DESIGN AND PROTOTYPE CONSTRUCTION OF A SELECTED MOBILITY AND RESTRAINT DEVICE

November 1969

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FOREWORD

This report was prepared by the Martin Marietta Corporation under Contract NAS9-9336, "Final Analysis/Design and Prototype Construction of a Selected Mobility and Restraint Device," for the Manned Spacecraft Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Spacecraft Integration Office of the Manned Spacecraft Center with Mr. Maynard C. Dalton acting as the Technical Monitor.

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Mr. Herb Johnson, Indiana General;

Mr. Jim Place, Indiana General;

Mr. Dan Supkis, NASA-MSC.

CONTENTS

SUMMARY

Mobility and restraint equipment to date has been designed for relatively small volume spacecraft. In these vehicles, the crew is always within touch distance of installed equipment and work areas. In anticipation of larger and more spacious spacecraft, a NASA mobility and restraint concept was designed and prototype articles were fabricated. These articles are known as shufflers and use permanent magnets for a normal holding force. The concept utilizes a shuffling technique where both feet maintain constant contact with the surface. The shuffler's major application will be in transporting bulky equipment and assisting in equipment monitoring and adjustments.

A force analysis was performed for each proposed use of the shuffler to establish required magnetic attractive forces for stability. A magnetic analysis was then performed to establish the design parameters of the magnetic circuit necessary to achieve the required forces. Four engineering evaluation models were fabricated and each was evaluated in either a six-degree-of freedom simulator or a neutral buoyancy tank to simulate zero-gravity usage. Testing results finalized the actual shuffler configuration. Design drawings were prepared and two prototype shufflers were fabricated. In addition, a floor specification was established for use with the shuffler.

It was reasonably assured from preliminary testing that in zero gravity the shuffler can provide man with the capability of maintaining body position while doing useful tasks and transporting himself and objects of various sizes without using his hands for propelling forces. It is recommended that the shuffler be further evaluated on KC-135 parabolic flights. If these tests continue to confirm the usefulness of the shuffler as a mobility and restraint aid, we recommend that the shufflers be incorporated in an experiment package for further testing on an early AAP flight.

I. INTRODUCTION

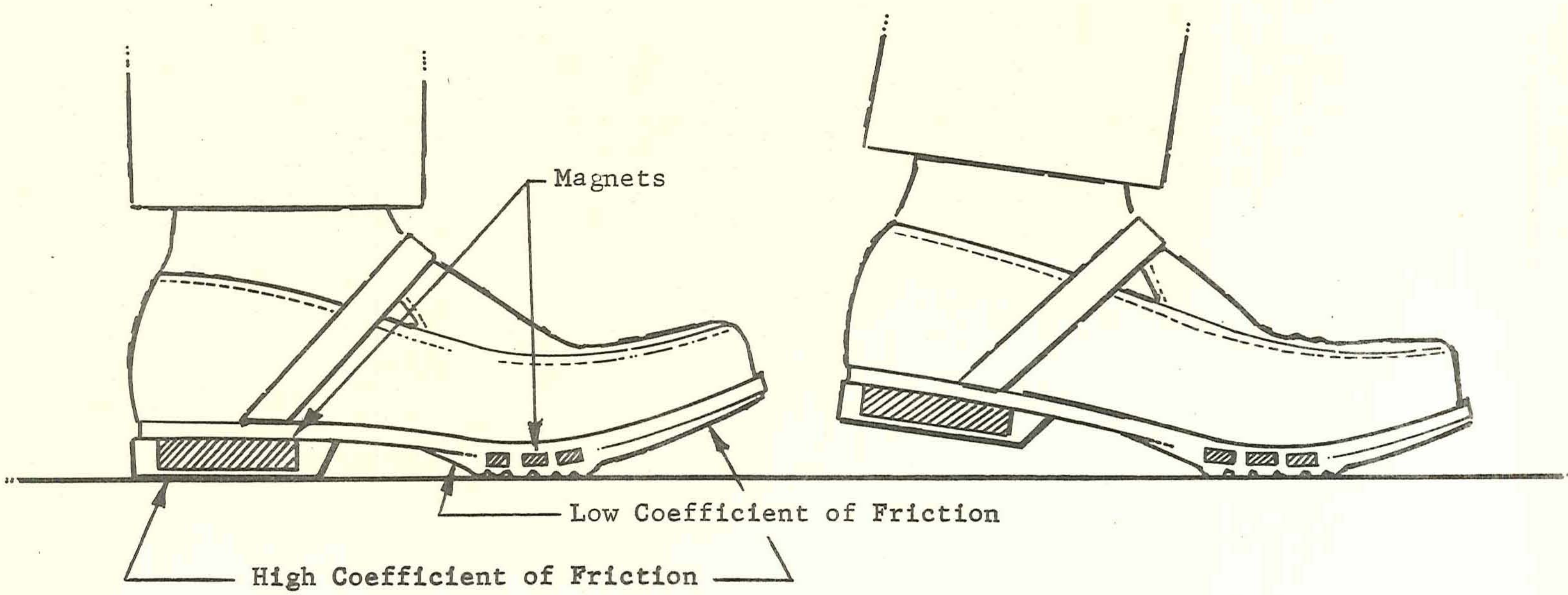
Since the duration of space flights will be lengthened in the near future, additional spacecraft volume will be required to accommodate the equipment needed to support such a mission. The larger volume spacecraft will require a mobility and restraint device to aid the crewman in performing his zero-gravity tasks and experiments. This mobility and restraint device must be designed to offer the crewman as much or as little restraint as deemed necessary. In addition to being simple and compact, the device should provide a simple interface with the user.

The mobility and restraint device developed, designed, fabricated, and tested at the Martin Marietta Corporation during this contract offers all the above advantages. The device is known as the "shuffler" and is a shoe that slips on as primary footwear. Permanent magnets are embedded in specific areas of the sole and are sized to meet attractive force requirements.

Magnetic attraction has been used previously as a mobility device, but its use has been more or less confined to an earth-oriented gait. The shuffling technique, as the name implies, deviates significantly from previous concepts. Here, both feet remain in continuous contact with the ferrous surface to assure continuous stability. A low coefficient of friction material is placed in the ball area of the foot and a high coefficient of friction material is placed in the heel and toe areas. The shuffling movement is facilitated by a permanent magnet in the ball area of the foot. The magnet has sufficient strength to maintain contact, but is not strong enough to impede the sliding motion required for this mode of transportation. See Fig. I-1.

The major use of the shufflers could be in transporting bulky or high inertia equipment. Some transport concepts are shown on Fig. I-2. In cases when only the individual is involved, a free-fly or swimming mode can be used. The shoes are so conceived as to facilitate easy separation from the floor for this mode.

The shufflers can greatly assist in equipment monitoring and making adjustments. Fig. I-3 indicates some of the possible capabilities. As shown in the erect position, the wearer can operate essentially in an earth-like condition. Once the shufflers are in place, they may function in a similar manner to floor-mounted restraints or "Dutch Shoes"; body twisting, bending and stretching are readily accommodated. If adjustments must be made outside of the man's reach while in a fixed position, simple short shuffling movements can easily reposition the body.



a) Pushing Foot   b) Moving Foot

Fig. I-1 "Shuffler Concept"

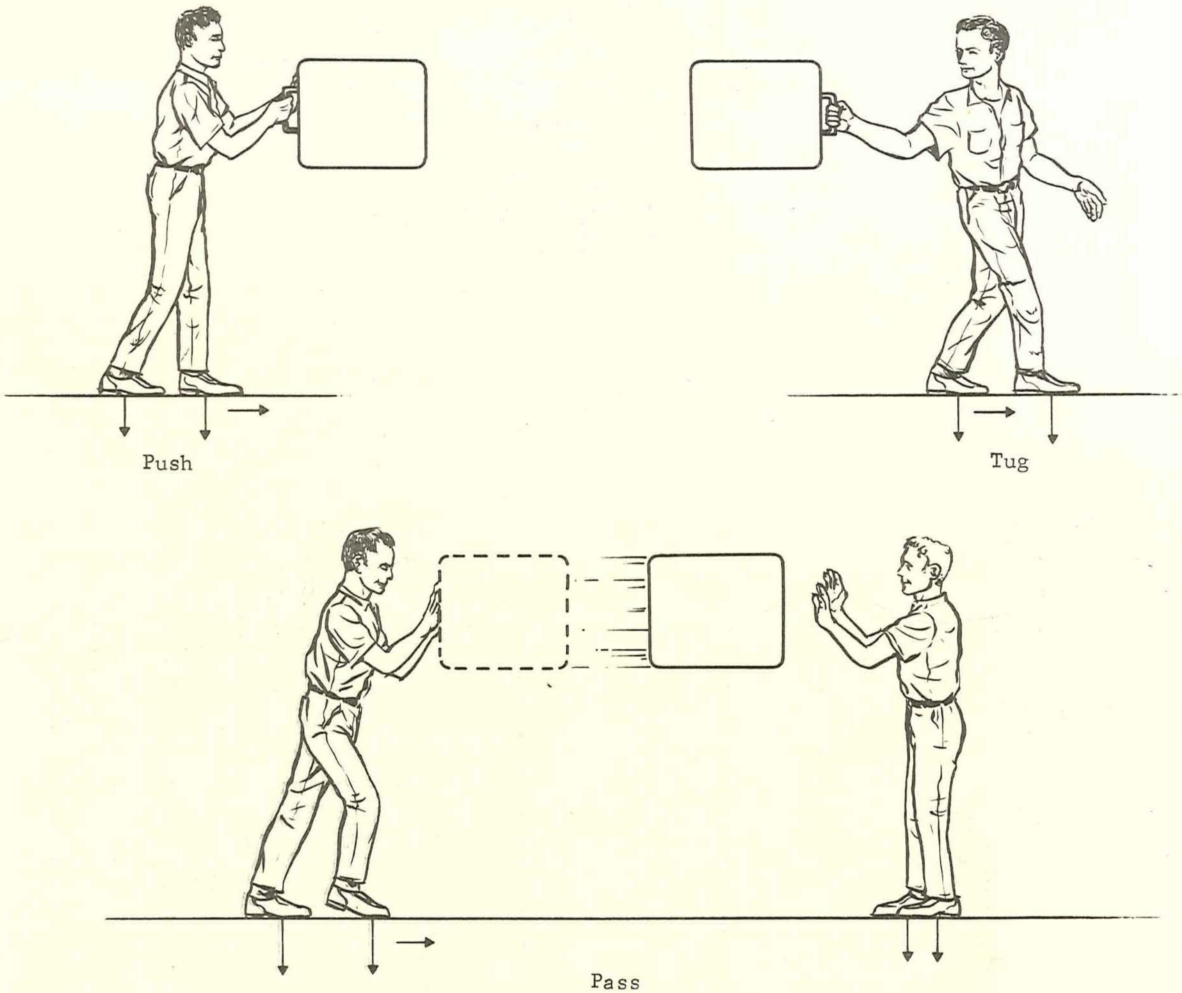


Fig. I-2 Transport Concepts

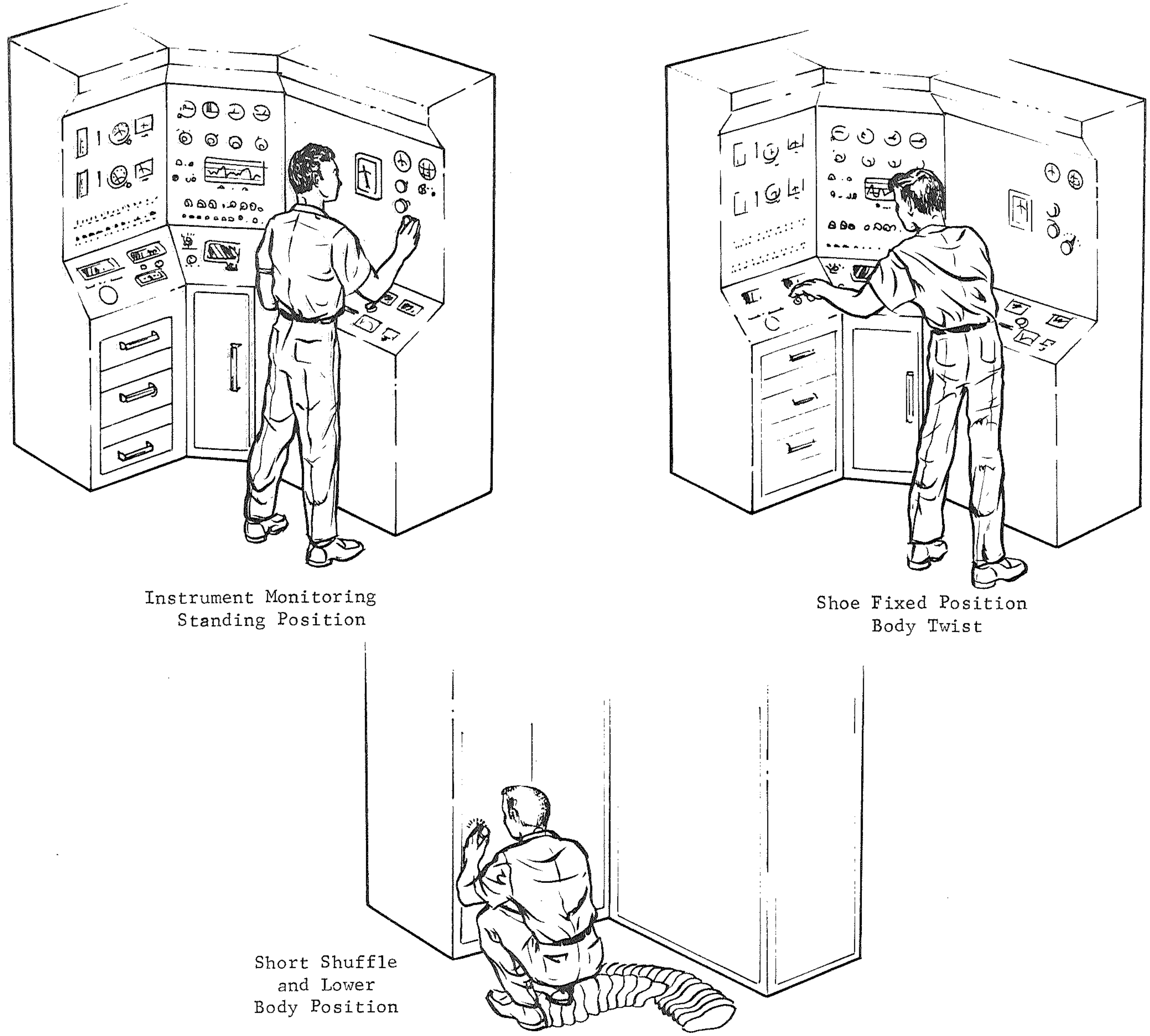


Fig. I-3 Shuffler Concepts for Adjustment and Monitoring

II. FORCE ANALYSIS

A. DYNAMIC

1. Shuffling

Magnetic attraction has been used before as a mobility device, but its use has been more or less confined to an "earth-oriented" gait. The shuffling technique, as the name implies, deviates significantly from previous concepts. It hinges on the fact that in zero gravity, if continuous contact with both feet is maintained, a continuous stability will result. The shuffling movement is facilitated by high and low coefficient of friction materials placed on the heel and ball areas of the foot respectively. The magnets in the pushing foot hold him to the ferrous surface, while the moving foot, by sliding the front magnet on the surface, prevents his overturning. With this shuffling movement, the astronaut's hands remain free to hold or push equipment. When sailing or free flight is desired, the astronaut may raise himself on his toes to free himself of the magnetic attraction. Then by using the high coefficient of friction material on the front of the shufflers, he may push himself into free flight.

In analysis of the shuffling movement, the path of the total center of gravity must be considered. This is the most essential part of the problem because velocity and acceleration of the body as a whole deal with the total center of gravity. For the purpose of analysis, it will be assumed that an astronaut could shuffle along at an average pace of 1 ft/sec. These assumptions are based on actual experimental motion studies in a one-gravity situation.

Figure II-1, based on studies by Arthur Steindler (Ref 1), shows how the velocity of the total center of gravity varies as a person shuffles at an average pace of 1 ft/sec. By assuming constant acceleration until the average shuffling pace is reached, the horizontal force required for a 95 percentile man (196 lb) can be found with the following formulas:

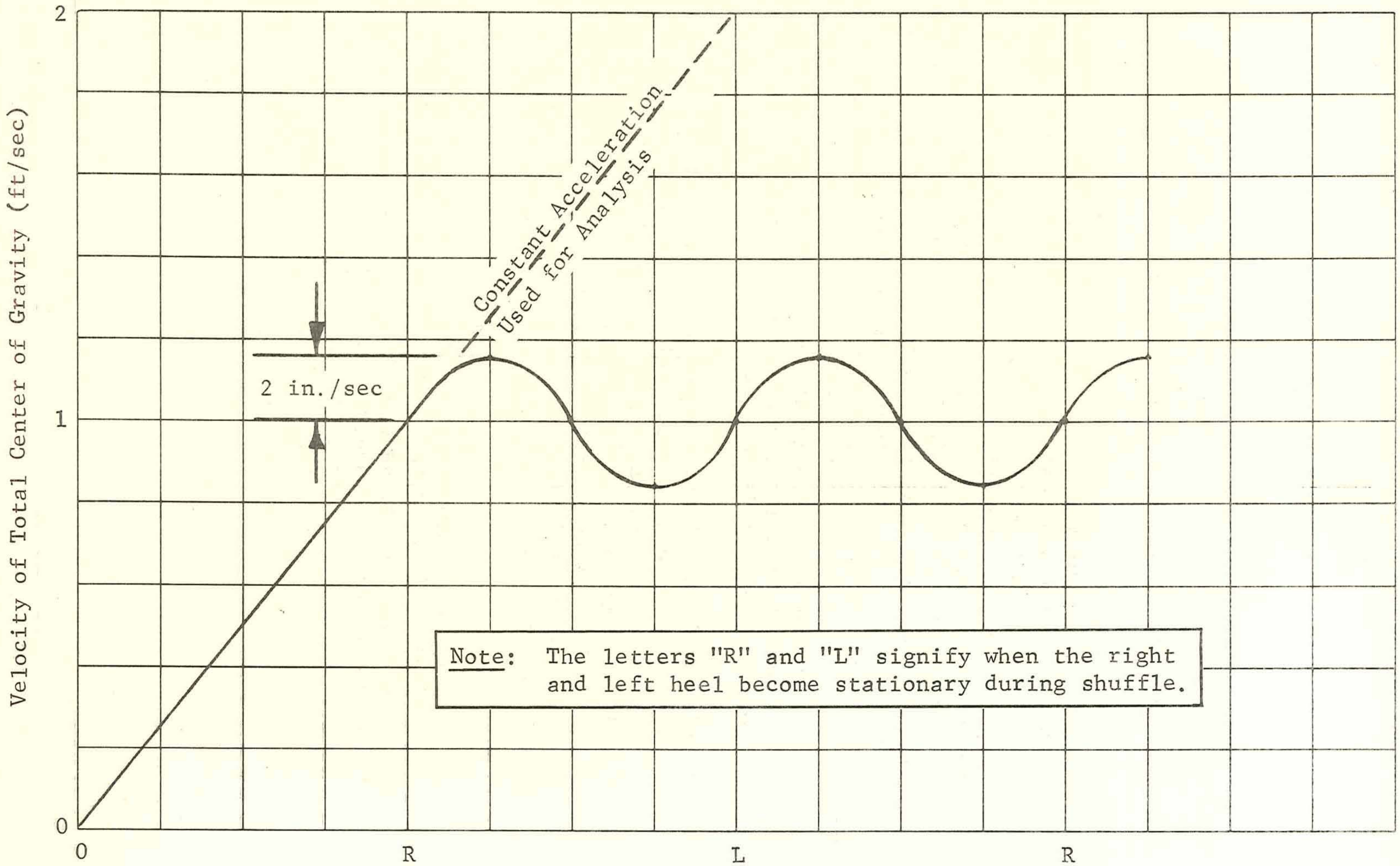


Fig. II-1 Typical Velocity Curve of Total Center of Gravity of a Body Shuffling at an Average Velocity of 1 ft/sec

$$V^2 = V_0^2 + 2ax$$

$$a = \frac{V^2}{2x}$$

$$F = ma$$

$$= \frac{mV^2}{2x} = \frac{W}{g_c} \frac{V^2}{2x}$$

$$= \frac{W}{32.2} \frac{(1.17)^2}{2(2.5)}$$

in general,

$$F = \frac{W}{117}$$

$$F = \frac{196}{117} = 1.67 \text{ lb}$$

As can be seen from the formula, the propelling force is directly proportional to the weight or mass of the astronaut. It might also be important to point out that the velocity of the shuffle will have considerable effect on the propelling force required. The velocity used, therefore, was for the maximum comfortable shuffling pace that was determined from motion studies in a one-gravity environment. The propelling force required to accelerate various men to a shuffling pace of 1 ft/sec is shown in Fig. II-2. For a 200-lb man this force would be 1.71 lb.

2. Passing a Package

Pushing may take place in any plane and apply to any type of object. Exactly where the propelling force is applied, and to a certain extent the direction in which it is applied, depend on the object and its possibilities for movement.

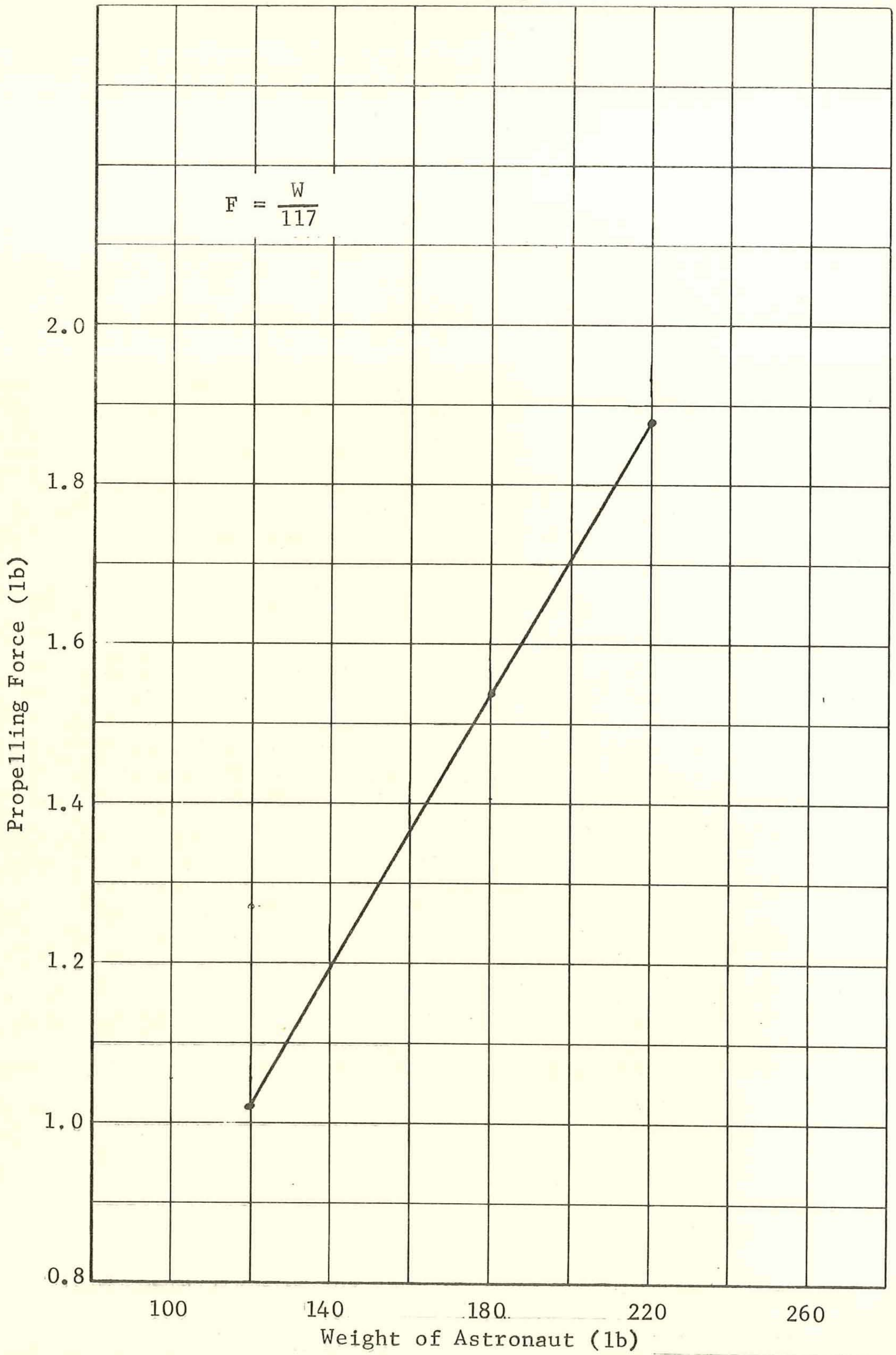


Fig. II-2 Propelling Force Required to Accelerate Various Men to a Shuffling Pace of 1 ft/sec

In zero-gravity conditions the largest forces on the shuffler will arise from passing and receiving large packages with a maximum mass of 150 lb. From past experience in low-gravity aircraft flights and on mobility transport systems utilizing mechanical transporters on "firemen's poles" in zero gravity, the optimum speed for passing large objects in zero gravity is approximately 1.5 ft/sec. The astronaut will accelerate the package from rest to 1.5 ft/sec with his arms (assume the rest of his body to be rigid). It will be a uniform acceleration that will take place in an arm's length (approximately 2 ft) and at shoulder height. Analysis will be shown for various percentile men with different stances.

To accelerate a 150-lb package to 1.5 ft/sec requires the following force:

$$V^2 = V_o^2 + 2ax \quad (V_o = 0)$$

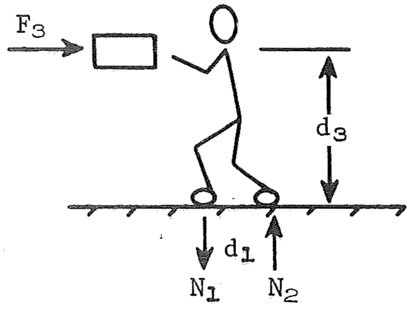
$$a = \frac{V^2}{2x} = \frac{(1.5)^2}{4} = \frac{2.25}{4}$$

and

$$F = ma$$

$$= \frac{150}{32.2} \cdot \frac{2.25}{4} = 2.62 \text{ lb}$$

Man accelerates a 150-lb package to 1.5 ft/sec within 2 ft at shoulder height. Assume stance (d_1) of 12 in.



Force acting on rigid man shown

$$M_3 = M_1$$

$$F_3 d_3 = N_1 d_1$$

$$N_1 = 2.62 \frac{d_3}{d_1}$$

let

$$d_1 = 12 \text{ in.}, 15 \text{ in.}, 18 \text{ in.}$$

Percentile Man	d_3 (in.)	Magnetic Shoe Attractive Force (lb)		
		d_1 = 12 in.	d_1 = 15 in.	d_1 = 18 in.
50	56.5	12.4	9.94	9.10
60	57.0	12.5	10.0	8.35
70	57.8	12.7	10.2	8.48
80	58.3	12.8	10.3	8.55
90	59.5	13.1	10.5	8.72
95	60.3	13.3	10.6	8.85
99	62.0	13.6	10.9	9.10

Figure II-3 illustrates the magnetic attractive force required for different percentile men to accelerate a 150-lb package to 1.5 ft/sec within a distance of 2.0 ft. This shows the maximum attractive force required per shuffler to be 13.6 lb for a 99 percentile man using a 12-in. stance.

A 95 percentile man accelerates packages to 1.5 ft/sec within a distance of 2 ft. The man has a stance of 15 in. and assumes rigid body position except for his arms, which accelerate packages. The packages are moved at 59.5-in. shoulder height. See Fig. II-4 for magnetic attraction required for the 95 percentile man to accelerate various packages to 1.5 ft/sec in 2.0 ft with a 15-in. stance.

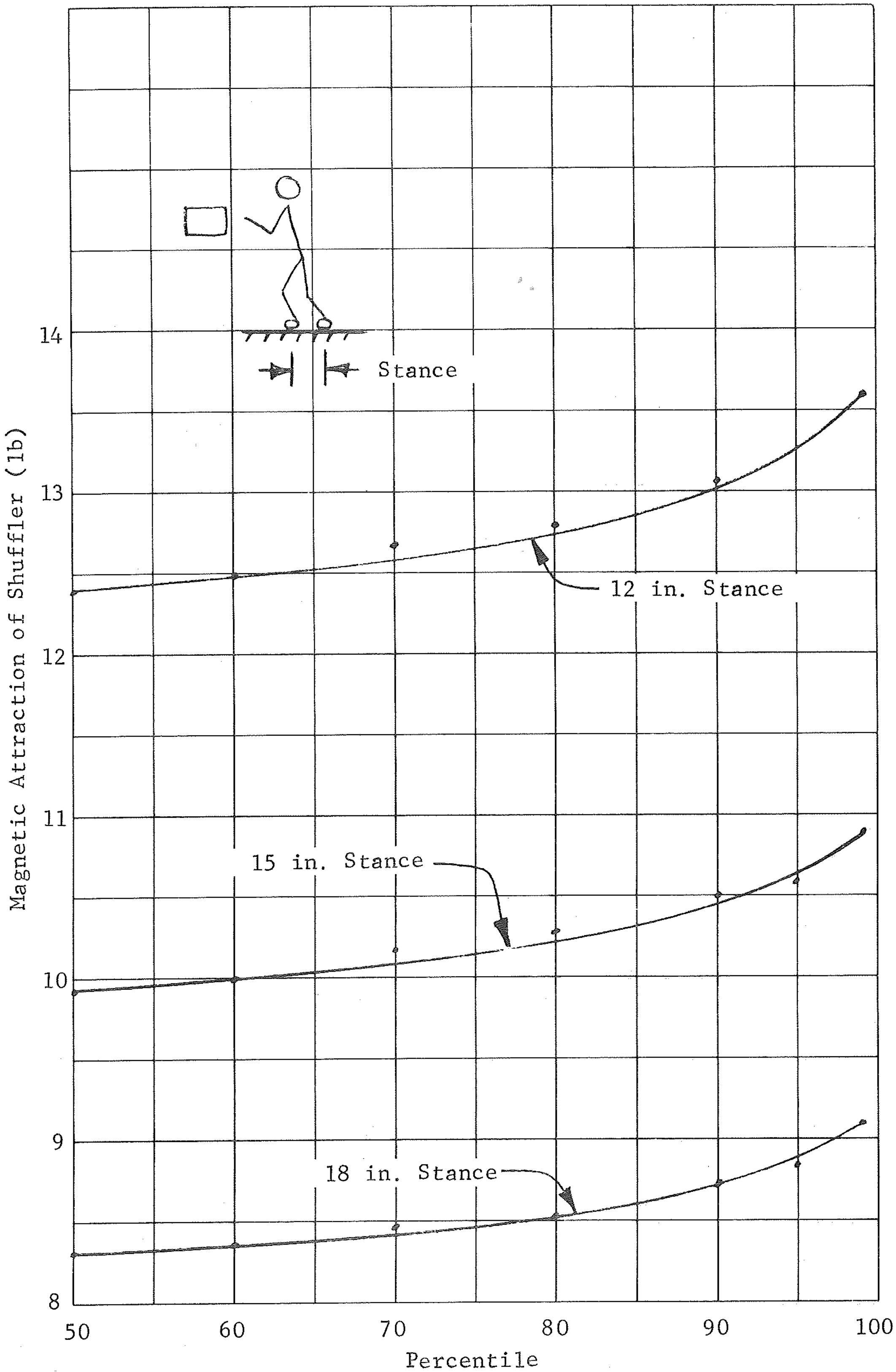


Fig. II-3 Magnetic Attractive Force Required for Different Percentile Men to Accelerate a 150-lb Package to 1.5 ft/sec in 2 ft

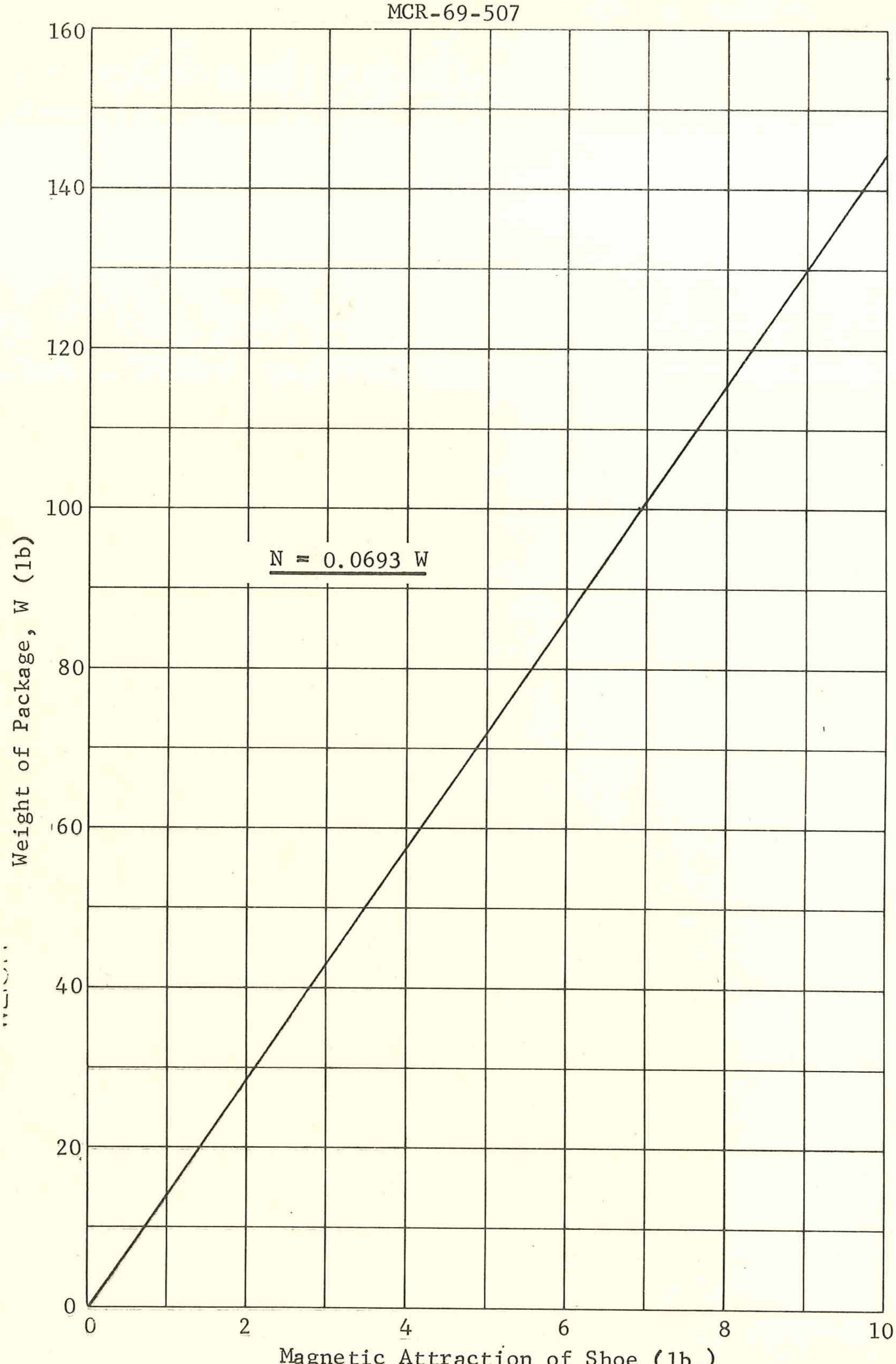


Fig. II-4 Magnetic Attraction Required for a 95 Percentile Man to Accelerate Various Packages to 1.5 ft/sec in 2 ft with a 15-in. Stance

$$V^2 = \not{V}_o^2 + 2ax$$

$$a = \frac{W^2}{2x} = \frac{2.25}{4}$$

$$F_3 = ma$$

where m is variable

$$ma\ (59.5) = N_1\ (15) \qquad N_1 \text{ is dependent on m}$$

$$m = \frac{W}{g}$$

$$\frac{W}{g}\ a\ (59.5) = N_1\ (15)$$

N_1	W
6.93	100
10.4	150

$$W\ \frac{(2.25)(59.5)}{4\ (32.2)(15)} = N_1 \text{ or } N_1 = 0.0693\ W$$

where

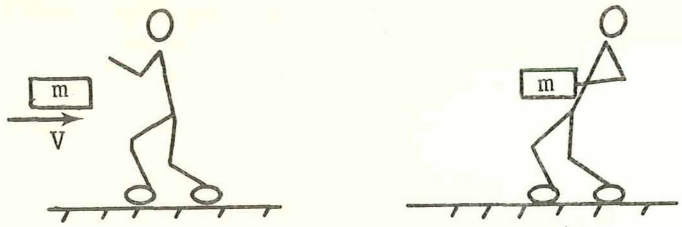
N_1 = magnetic attraction of shoes (lb)

W = weight of package (lb).

3. Receiving a Package

The reception of a package can, in many respects, be very similar to passing a package. In fact, the analysis used in receiving a package would be identical to that of passing a package if the package were caught at shoulder level with extended arms.

For the purpose of our analysis, consider another mode of reception, namely the manner in which a football player catches a football. The astronaut would receive the package near the midsection, offering little resistance with his arms. His body would remain rigid but would be moved in the direction of travel of the package. A steady moment would be transmitted from the shufflers. The moment would gradually stop the package and the astronaut's body movement.



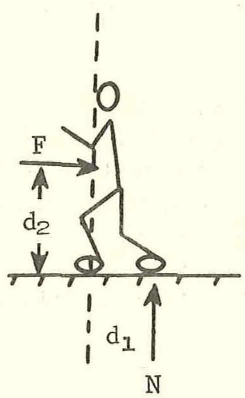
We will assume that 150-lb package moving at a velocity of 1.5 ft/sec strikes the astronaut at the midpoint between his shoulder joint (81.16% of his height) and his center of gravity (55.27% of his height), or at a level of 68.22% of his height. At this point, the impulse-momentum relation will be used as follows:

$$F \Delta t = mV$$

It is noted that the package has attained a momentum of

$$mV \frac{150\ (1.5)}{32.2} = 6.98\ lb_f\text{-sec}$$

Now, this is equal to the impulse ($F \Delta t$) but we have no relation between the two unknowns F and Δt. By sizing the magnetic attraction of the shoes, however, the constant force, F, can be determined. The sum of moments must equal zero, or, $Fd_2 = Nd_1$.



d_2 = 0.6822 (75 in.)

= 51.2 in. for 99 percentile man

From the previous section, we have sized magnetic shoes for various stances (d_1). To determine the largest force, F, possible, the values of magnetic attraction for the 99 percentile man from Fig. II-3 should be used. For instance, for a 12-in. stance (d_1 = 12 in.), the magnetic attraction N would be 13.6 lb and F would be as follows:

$$F = \frac{d_1}{d_2} N$$

$$= \frac{12}{51.2} (13.6)$$

$$F = 3.19 \text{ lb}$$

This small calculation points out a very interesting relation, in that the lower an astronaut receives a package the more apt he is to slide or skate backwards. This happens since the reactive horizontal friction force holding the astronaut stationary must become larger to compensate for the smaller moment arm at the point of reception. This in turn also points to the need of locating the magnets in the proper area of the shuffler, a topic that will be covered later.

To return to the movement of the body on reception of the package, the time required to bring the package to rest will be as follows:

$$F \Delta t = mV = 6.98 \text{ lb-sec}$$

but

$$F = 3.19 \text{ lb}$$

therefore

$$\Delta t = \frac{6.98}{3.19} = 2.13 \text{ sec}$$

The distance of body travel at point of reception is,

$$a = \frac{-F}{m} = \frac{-3.19}{150} \times 32.2 = -0.683 \frac{\text{ft}}{\text{sec}^2}$$

$$V^2 = V_o^2 + 2ax$$

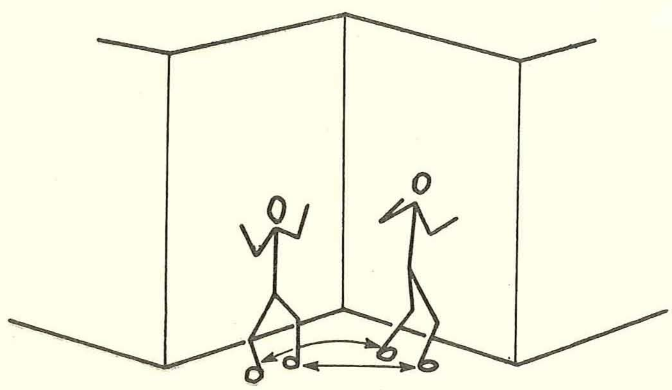
$$1.5^2 = 2(0.683)x$$

$$x = \frac{2.25}{2(0.683)} = 1.65 \text{ ft}$$

Therefore, the astronaut's body at the point of reception will move in the direction of travel of the package a distance of 1.65 ft. Of course this calculation does not account for the shock absorbing that the arms of the astronaut will have in slowing the package before it strikes his midsection, but deals with the worst possible situation where the arms are not used at all. See Fig. II-5 for reactive horizontal friction force required for various points of reception on a 99 percentile man receiving a 150-lb package moving at 1.5 ft/sec. Assuming the astronaut receives the package no lower than his center of gravity, the largest force developed would be approximately 3.97 lb.

4. Lower Body Reposition

This type of movement would involve a small shuffle of approximately 2 steps. It will enable the astronaut to move to different locations in front of the instrument panel as shown in the sketch or perform some activity at an adjacent work station. The motion described here is not the same as the shuffle described earlier. It includes the rotation of the body simultaneously with the shuffle.



For purposes of analysis, it is reasonable to assume that an astronaut could reposition himself (two steps with 90-deg body rotation) in approximately 2.0 sec. This is based on 1 revolution/8 sec.

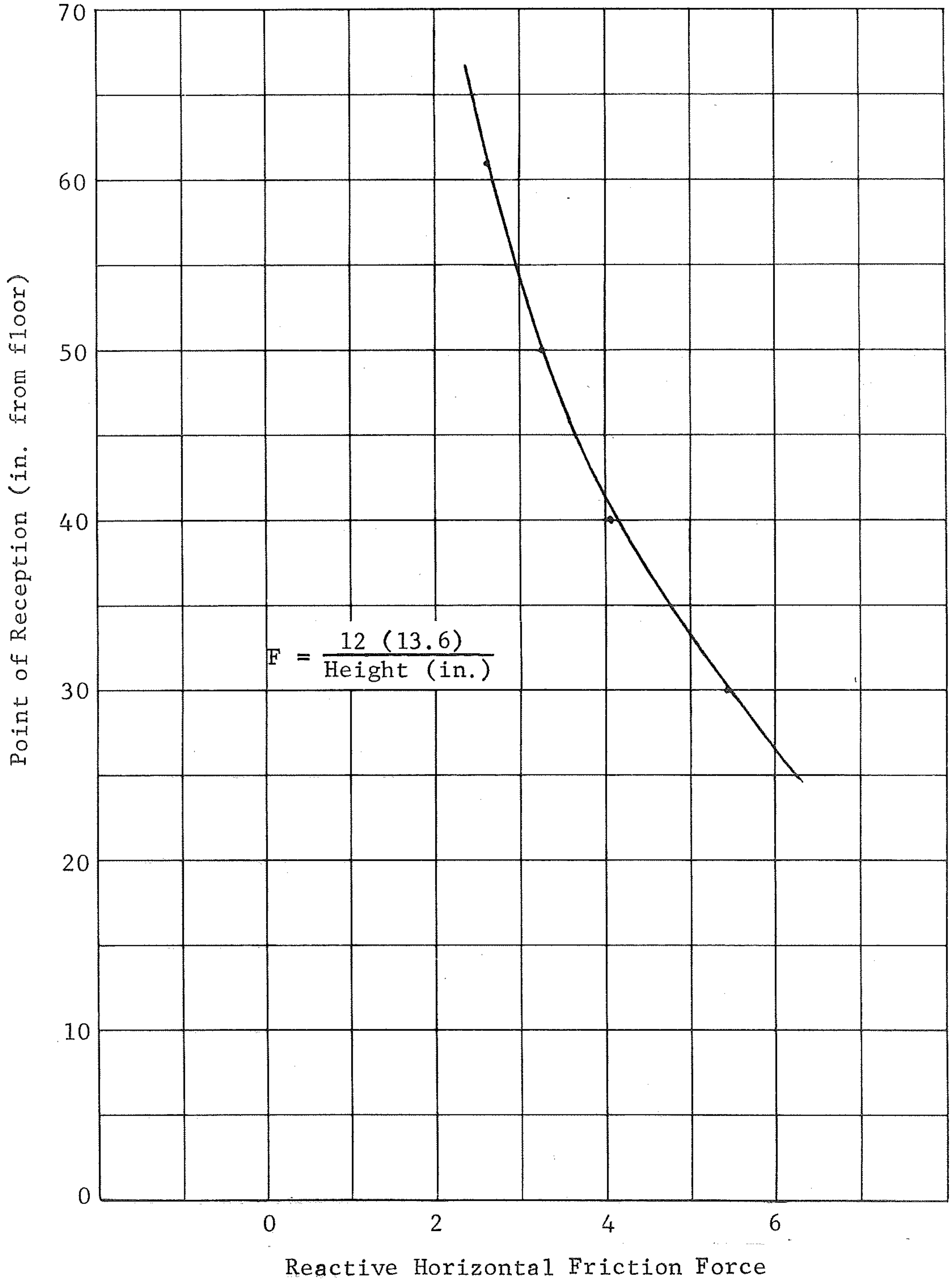
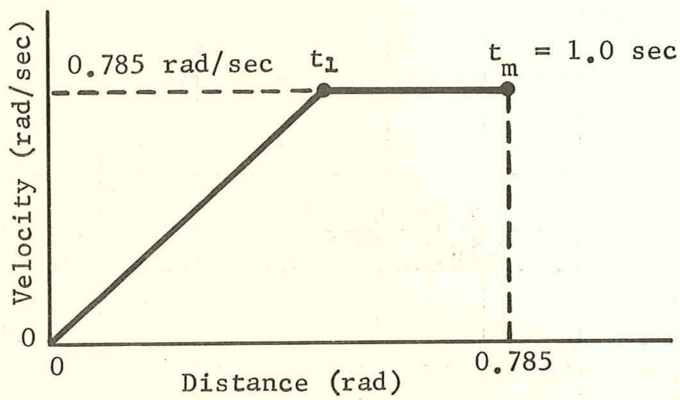


Fig. II-5 Reactive Horizontal Friction Force Required for Various Points of Reception on 99 Percentile Man Receiving a 150-lb Package Moving at 1.5 ft/sec

This motion can be broken into two different parts. The first is the movement of the astronaut's total center of gravity, and the second is the rotation of his body. The center-of-gravity movement will be assumed to be identical to the shuffling motion discussed earlier where the propelling force for a 95 percentile (196 lb) man was 1.67 lb. For rotation of the body, it will be assumed that an astronaut can rotate at the rate of 0.785 rad/sec (1 revolution/8 seconds). Furthermore, the astronaut will accelerate from rest, attain this radial velocity, and decelerate to a stop. For simplicity, we shall deal with the period of time dealing with radial acceleration and velocity to the midpoint of the motion. A graphic representation is shown in the following sketch.



A reasonable assumption of t_1 is $t_m/2$ or 0.5 sec. The angular distance for the period $0 \leq t \leq t_1$ can be found by the formula $\theta = \omega_0 t_1 + \frac{1}{2} \alpha t_1^2$ and the angular distance for the period $t_1 \leq t \leq t_m$ can be found by $\theta = \theta_0 + \omega t$. If these formulas were grouped together, the following expression is derived:

$$\theta = \tfrac{1}{2} \alpha t_1^2 + \left(t_m - t_1\right) \omega$$

By inserting all known and assumed values, this expression becomes:

$$0.785 = \tfrac{1}{2} \alpha (0.5)^2 + (1.0 - 0.5)\, 0.785$$

and solving for

$$\alpha = \frac{0.785}{0.25} = 3.14 \frac{\text{rad}}{\text{sec}^2}$$

By using the following formula, the torque required for this radial acceleration can be determined:

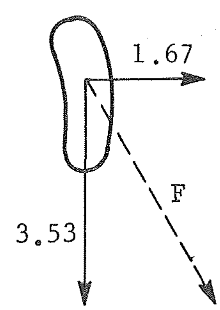
$$T = I\alpha$$

From page 252 of the <u>Bioastronautics Data Book</u> (Ref 2), the moment of inertia for a standing man $\left(I_z\right)$ was found to be 11.3 lb-in.-sec^2 with a standard deviation of 2.2 lb-in.-sec^2.

$$T = I\alpha$$

$$= \frac{13.5\ (3.14)}{12} = 3.53 \text{ foot-pounds}$$

Again assuming the astronaut has a 12-in. stance, the following force diagram can be drawn.



The resultant force on the shuffler is then

$$F = \sqrt{(1.67)^2 + (3.53)^2}$$

$$= \sqrt{(2.79 + 12.50)}$$

$$= \sqrt{15.29}$$

$$F = 3.91 \text{ lb}$$

5. Upper Body Reposition

This movement would essentially be an upper torso rotation accomplished by the moment supplied at the astronaut's feet. If his feet remained stationary, only a portion of the entire body would rotate and the upper body would rotate more than the lower body. With a graph drawn showing the amount of body rotation versus body height, a straight line curve could be approximated. Now, since only half of the body is moving on the average, we will assume only half the mass of the astronaut's body will be moving. Since the moment of inertia for an object is directly related to the mass of that object, the new moment of inertia can be found by simple proportions and would be exactly half of that for a standing man, or 5.65 lb-in.-sec^2 with a standard deviation of 1.10 lb-in.-sec^2. From previous discussion, we have found 3.14 rad/sec^2 to be a reasonable angular acceleration. With these data, the moment that must be exerted at the astronaut's feet to produce this acceleration can be found.

$$T = I\alpha$$

$$= \frac{6.75\ (3.14)}{12}$$

$$= 1.77\ \text{ft-lb}$$

As can be seen from this discussion, the torquing force required per foot with a 12-in. stance would be 1.77 lb.

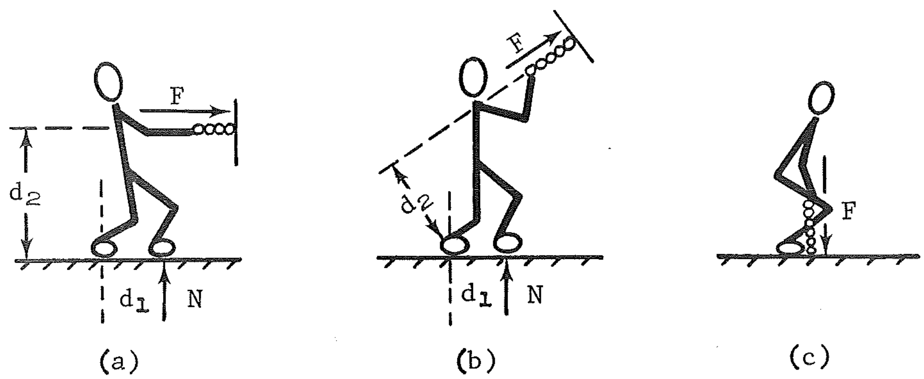
B. STATIC

1. Tugging

Tugging on some object will be very similar to passing or receiving a package. If the resistance is light, arm action alone is sufficient. Pulling in all planes requires flexing of the elbow, but shoulder action may vary considerably depending upon elevation or plane of pull.

In analysis the simple moment relation can again be used. This will show that the maximum pull an astronaut can exert will be equal to the attractive magnetic force* of his shufflers unless he pulls or tugs in a direction perpendicular to the surface his shufflers are attached and away from his feet. In this special case [see (c) in the following sketch] he would be able to exert a much greater force.

*This is, of course, assuming the coefficient of friction between the shufflers and the ferrous surface is less than 1.0.



$$\Sigma M = 0$$

$$Fd_2 = Nd_1$$

$$F = N \frac{d_1}{d_2}$$

By assuming different stances (d_1) with a constant attractive force in the shufflers, Fig. II-6 can be derived. It should be noted that the line of action of F does not have to be parallel to the surface to which the astronaut is attracted [see (b) in the preceeding sketch]. In fact this will probably seldom be the case, however, for illustration purposes and analysis this configuration will be entirely correct.

For analysis we shall use the 13.6-lb attractive force per shuffler (N = 13.6 lb), which is the maximum attractive force required from the dynamic force analysis.

$$F = N \frac{d_1}{d_2}$$

$$d_1 = 12 \text{ in.} \qquad F = \frac{(13.6)(12)}{d_1} = \frac{163}{d_1}$$

$$d_1 = 15 \text{ in.} \qquad F = \frac{(13.6)(15)}{d_1} = \frac{204}{d_1}$$

$$d_1 = 18 \text{ in.} \qquad F = \frac{(13.6)(18)}{d_1} = \frac{245}{d_1}$$

Figure II-6 illustrates the tugging force an astronaut can exert at various orientations with 13.6-lb shufflers and varied stances.

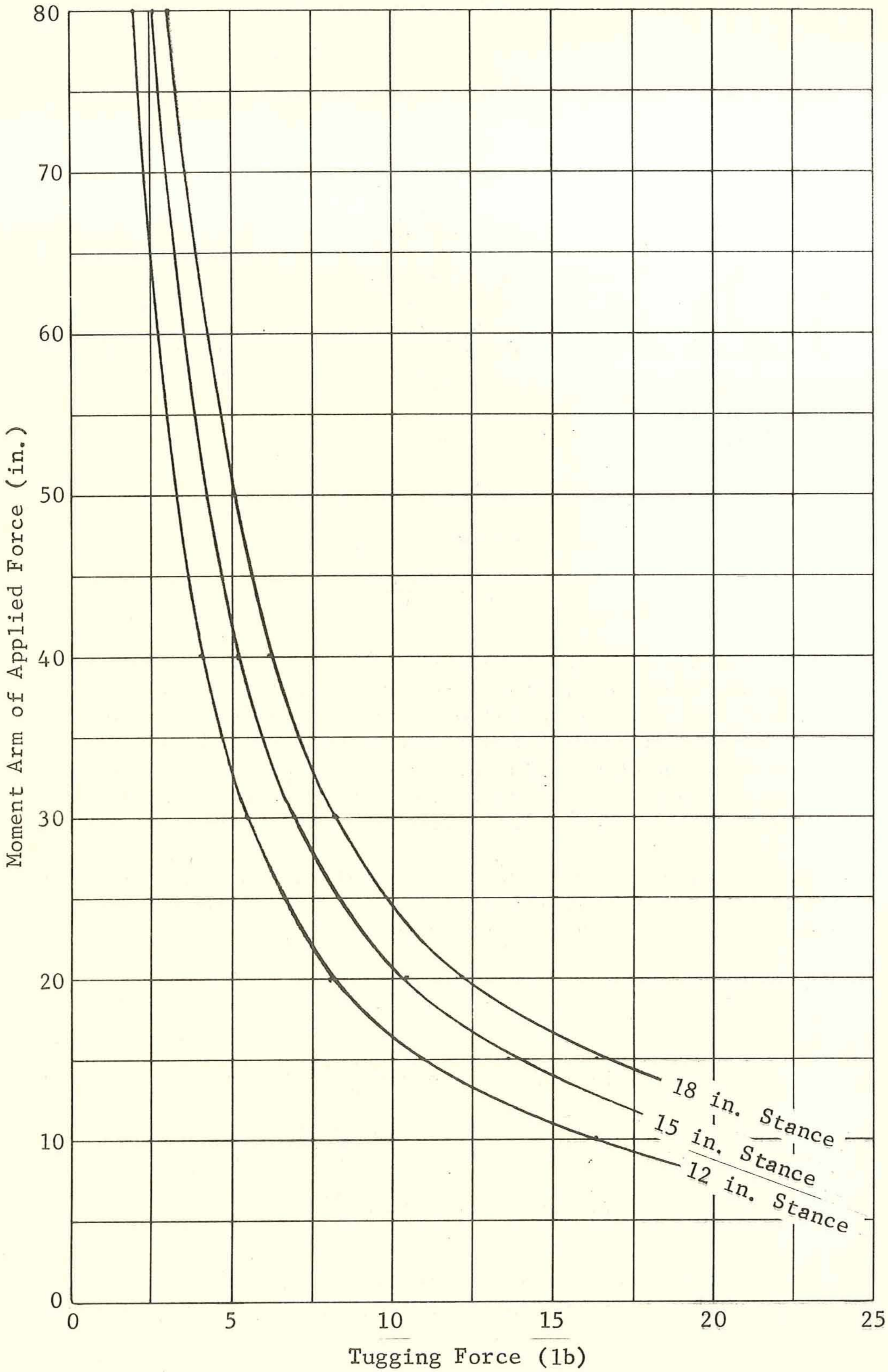
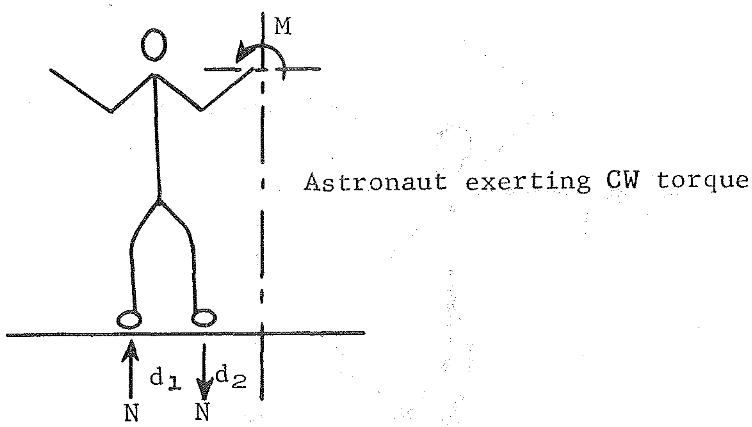


Fig. II-6 Tugging Force an Astronaut Can Exert at Various Orientations with 13.6-lb Shufflers and Varied Stances

2. Operation of Instrument Panel

The design of an instrument panel should allow for ease in operation of all controls. MIL-STD-803A-3 (USAF), 19 May 1967, (Ref 3) contains human engineering requirements that apply specifically to aerospace vehicles and aerospace vehicle equipment. Extracted from this reference are the following control resistance criteria to be used for this part of the analysis.

Control	Condition	Control Resistance	
		Minimum	Maximum
Rotary Selector	Torque	1 in.-lb	6 in.-lb
Thumbwheel	Torque	1 in-lb	3 in.-lb
Knob	Torque -		
	Fingertip up to 1-in. diameter	No performance limit, determined by vibration, etc	4.5 in.-oz
	Fingertip over 1-in. diameter		6 in.-oz
Pushbutton	Fingertip	10 oz	40 oz



For analysis, the astronaut will operate the rotary selector and pushbutton controls. This will enable us to see how these operating motions affect the astronaut and his shufflers.

The rotary selector has a maximum control resistance of 6-in.-lb or 0.5 ft-lb. We shall determine how large the magnetic attraction (N) of each shoe must be for an astronaut to exert a moment of this size.

$$\Sigma M = 0$$

or

$$M = N\ (d_1 + d_2)\ -N\ (d_2)$$

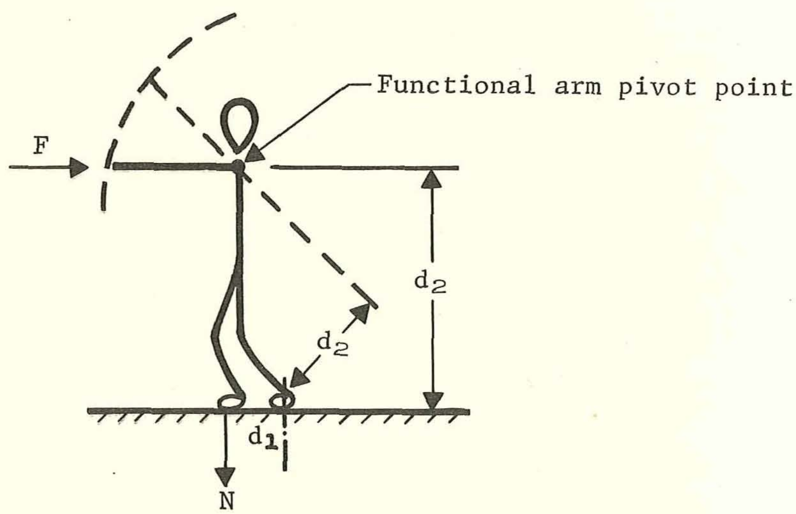
$$= Nd_1$$

in general $Nd_1 = 0.5$ ft-lb.

Now if we chose a stance (d_1) of 15 in., we would find the following attractive force necessary:

$$N = \frac{0.5}{d_1} = 0.5\ \frac{12}{15} = 0.4\ \text{lb}$$

The general magnetic attractive force required per shuffler for an astronaut to exert a moment of 6 in.-lb with varied stances is shown in Fig. II-7.



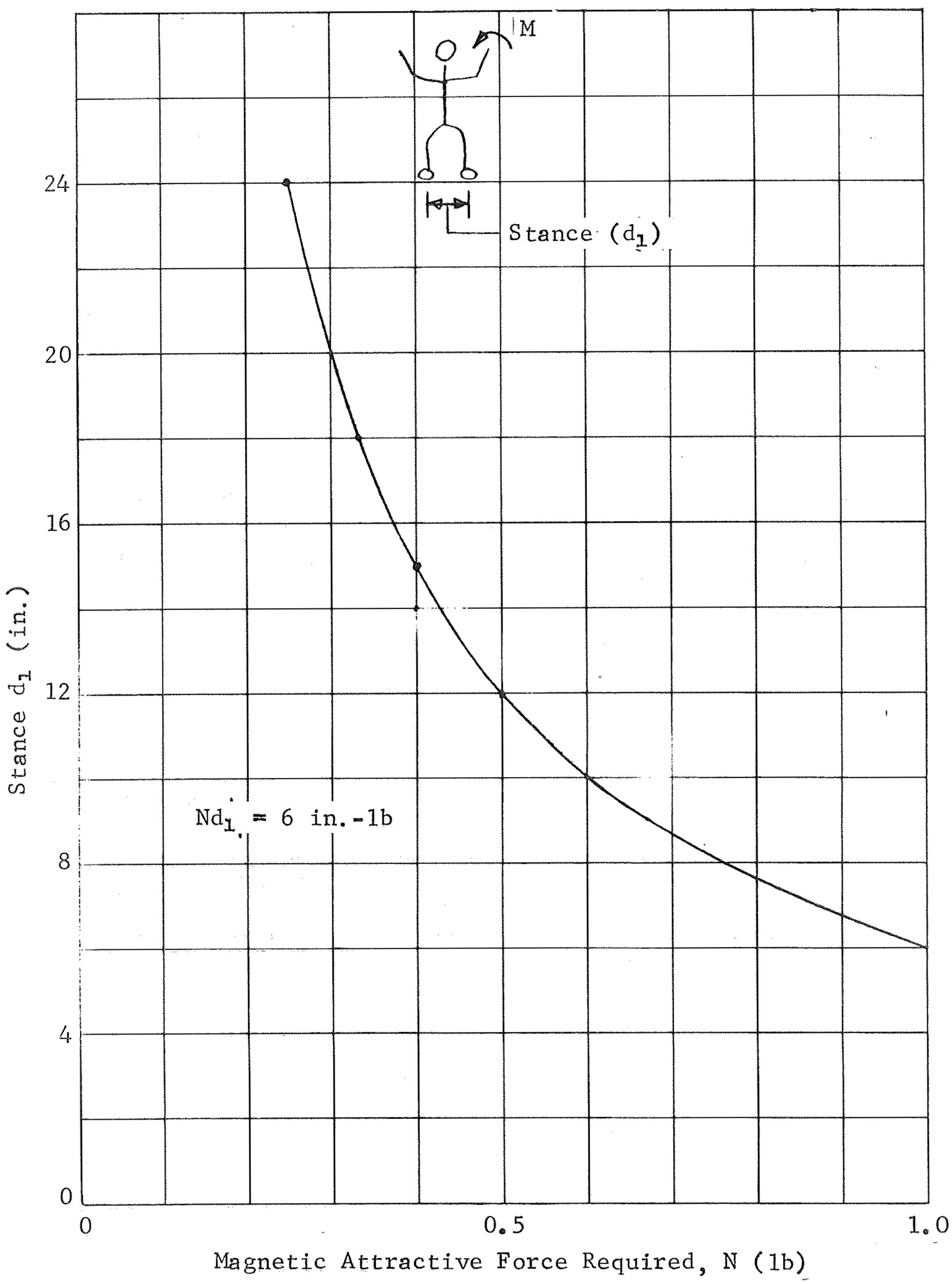


Fig. II-7 Magnetic Attractive Force Required in Shuffler for Astronaut to Exert Moment of 6 in.-lb on Control Panel with Varied Stances

The pushbutton control with fingertip operation is shown to have a maximum control resistance of 40 oz or 2.5 lb. From the diagram, it can plainly be seen that the largest moment arm (d_2) will occur when the astronaut pushes the button in a direction parallel to the surface to which he is attracted. This means the length of the moment arm d_2 will be approximately 81.16% of a man's height (this is the location of the shoulder joint). This would be d_2 = (0.8116)(75) = 60.8 in. for a 99 percentile man.

By summing moments, a simple relation between magnetic attractive force (N) and stance distance (d_1) can be shown.

$$Nd_1 = Fd_2$$

$$Nd_1 = 2.5(60.8) = 152 \text{ inch-pounds}$$

Figure II-8 shows the maximum attractive force necessary to operate the pushbutton control to be 12.7 lb with a 12-in. stance. This large attractive force is necessary because of the large moment arm associated with operation of this control.

C. SUMMARY

The following tabulation summarizes the maximum force and attraction for each task.

Task	Maximum Force, F (lb)	Maximum Attraction, N (lb)
Shuffling	1.71	6.0
Passing Package	2.62	13.6
Receiving Package	3.97	13.6
Body Reposition	3.91	5.4
Body Rotation	1.77	2.4
Operation of Instrument Panel	2.5	12.7

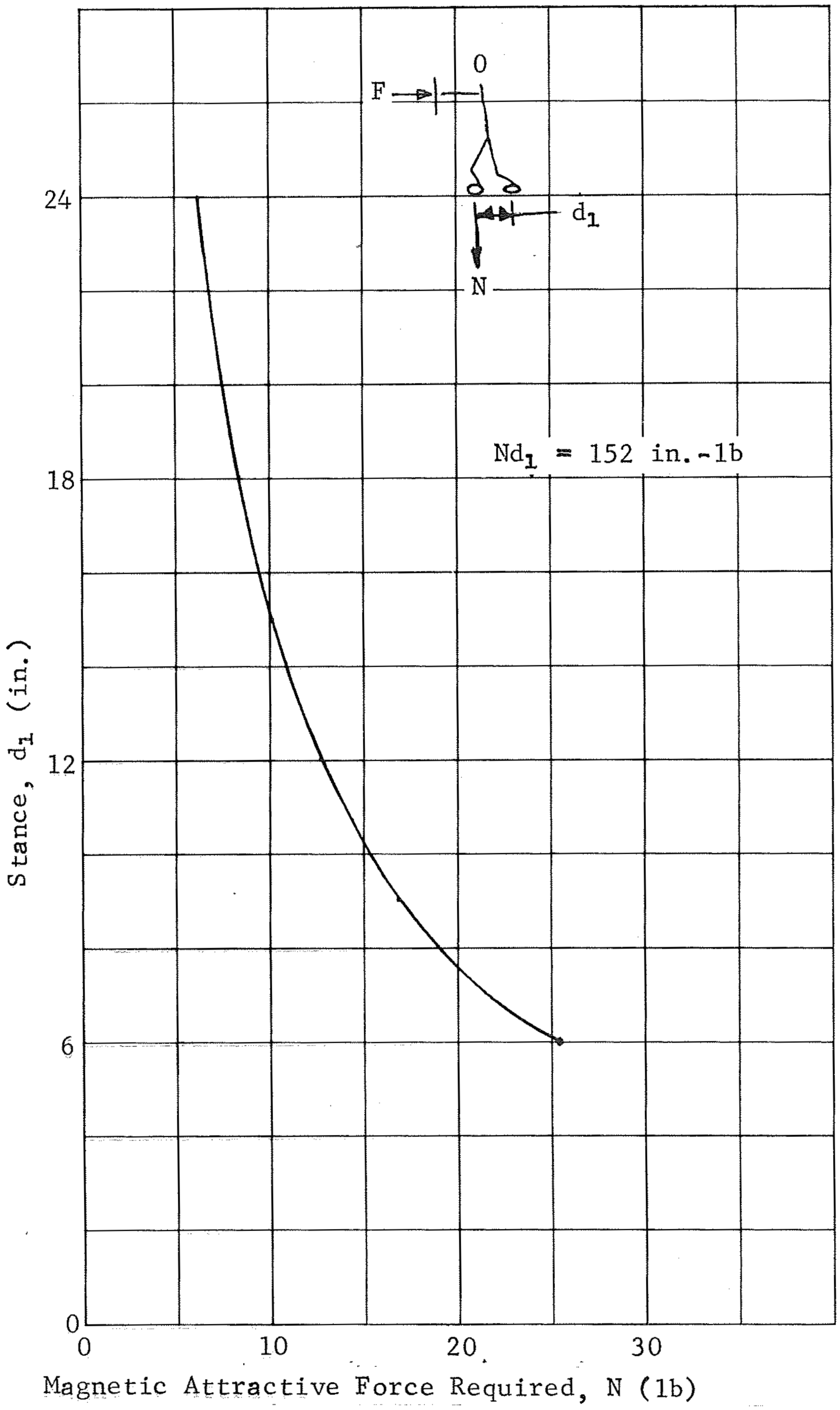


Fig. II-8 Magnetic Attractive Force Required in Shuffler for Astronaut Operating Pushbutton Control with Resistance of 2.5 lb with Varied Stances

III. PERMANENT MAGNET CHARACTERISTICS

To design a permanent magnet assembly that will meet all given specifications, one must be familiar with the fundamental characteristics of ferromagnetic materials. The magnetic circuit and its properties must be understood, along with the design calculations. Basically, the solution to a design problem for a permanent magnet gives the required length and cross-section area. This, however, is the ideal solution, resulting in a magnet of such size and shape that the minimum magnetic material is used. Practical considerations, such as cost of material, physical properties of the ferromagnetic material, size limitations, and others, can readily modify this ideal. More realistically, the design goal is to develop a magnet that will result in minimum cost consistent with the application.

In general, magnetic circuits using permanent magnets have three elements as shown in Fig. III-1: the permanent magnet, the useful air gap, and an iron armature that provides a path for the flux to follow. The armature of a magnetic circuit may be described as the ferrous material (in our case, the floor) to which the magnet attracts itself. The air gap is due to a separation of the magnet from the armature or any nonconductive material introduced between the armature and magnet. Increased air gap results in flux leakage which in turn lowers the attractive force between the magnet and armature.

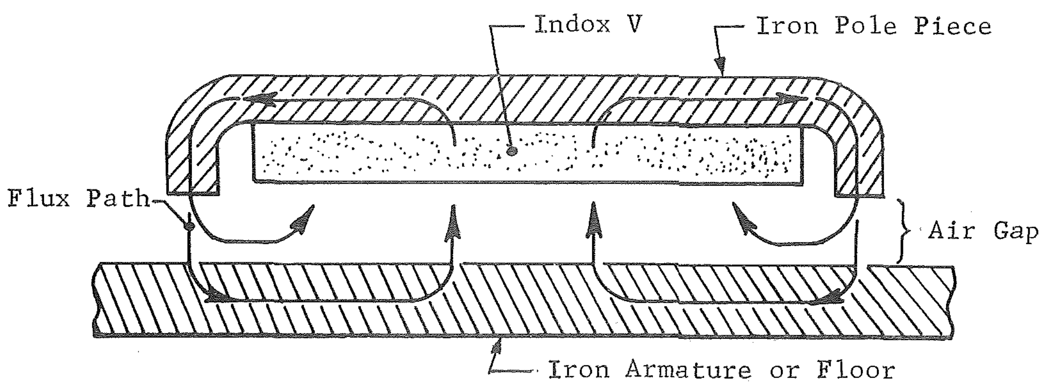


Fig. III-1 Basic Magnetic Circuit

In any such circuit, the magnetomotive force produced by the magnet determines the total flux (φ) in the external circuit since

$$\varphi = \frac{F}{R} \quad \text{or} \quad \varphi = FP$$

Reluctance (R) is the term for the opposition to flux within a magnetic circuit and is similar to the resistance in an electrical circuit. Permeance (P), the reciprocal of reluctance, is a measure of magnetic conductance which, if known, would enable an accurate prediction to be made concerning how much of the total flux of a magnet will reach the air gap.

Figure III-2 shows two holding designs that are used extensively. The slope of the pull characteristic curves or the ability to attract a steel member at a distance depends on the depth of field of penetration around the magnet. The bar has a deep field pattern because the poles are far apart and there is little flux leakage. As the poles are brought closer, the shape of the pull curve changes. The field energy is then concentrated in the region between the poles and drops off rapidly with the distance from the poles. Both designs involve the same weight of identical magnetic material, but by design configuration, the ratio of force to distance can be changed.

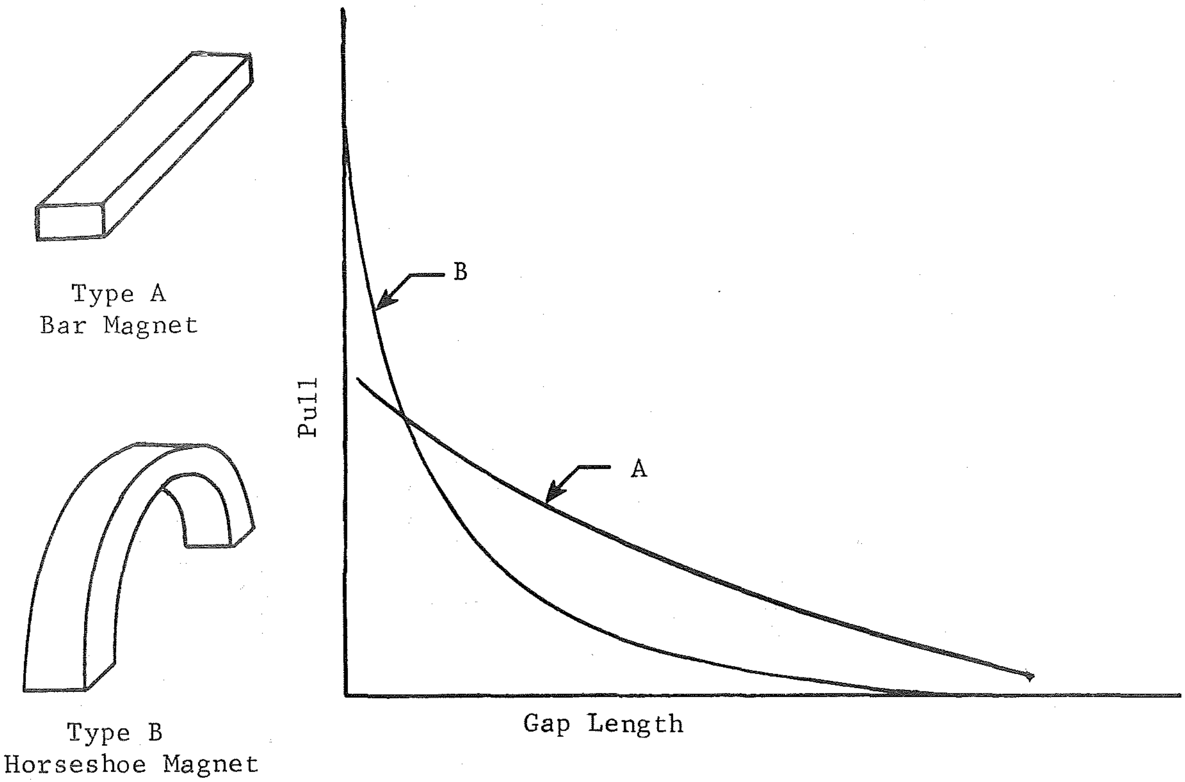


Fig. III-2. Comparison of Various Permanent Magnet Configurations for Mechanical Work Applications

Another interesting variable in dealing with the pull of a given magnet is the area of contact of the poles with the armature. By decreasing the area of contact, the pull characteristics of the magnet are greatly increased. This can be shown by the following formulas extracted from Permanent Magnet Handbook (Ref 4):

$$N = 0.577\ B^2\ A$$

$$\varphi = BA$$

With the total flux of a magnet remaining constant, it can plainly be seen that if the area of contact (A) were decreased, a proportional increase in the flux density (B) would result. Since the attractive pull of the magnet (F) is directly related to B^2, a larger pull will result. Indiana General Corporation of Valparaiso, Indiana, has done some testing with this concept, the results of which are shown in Fig. III-3.

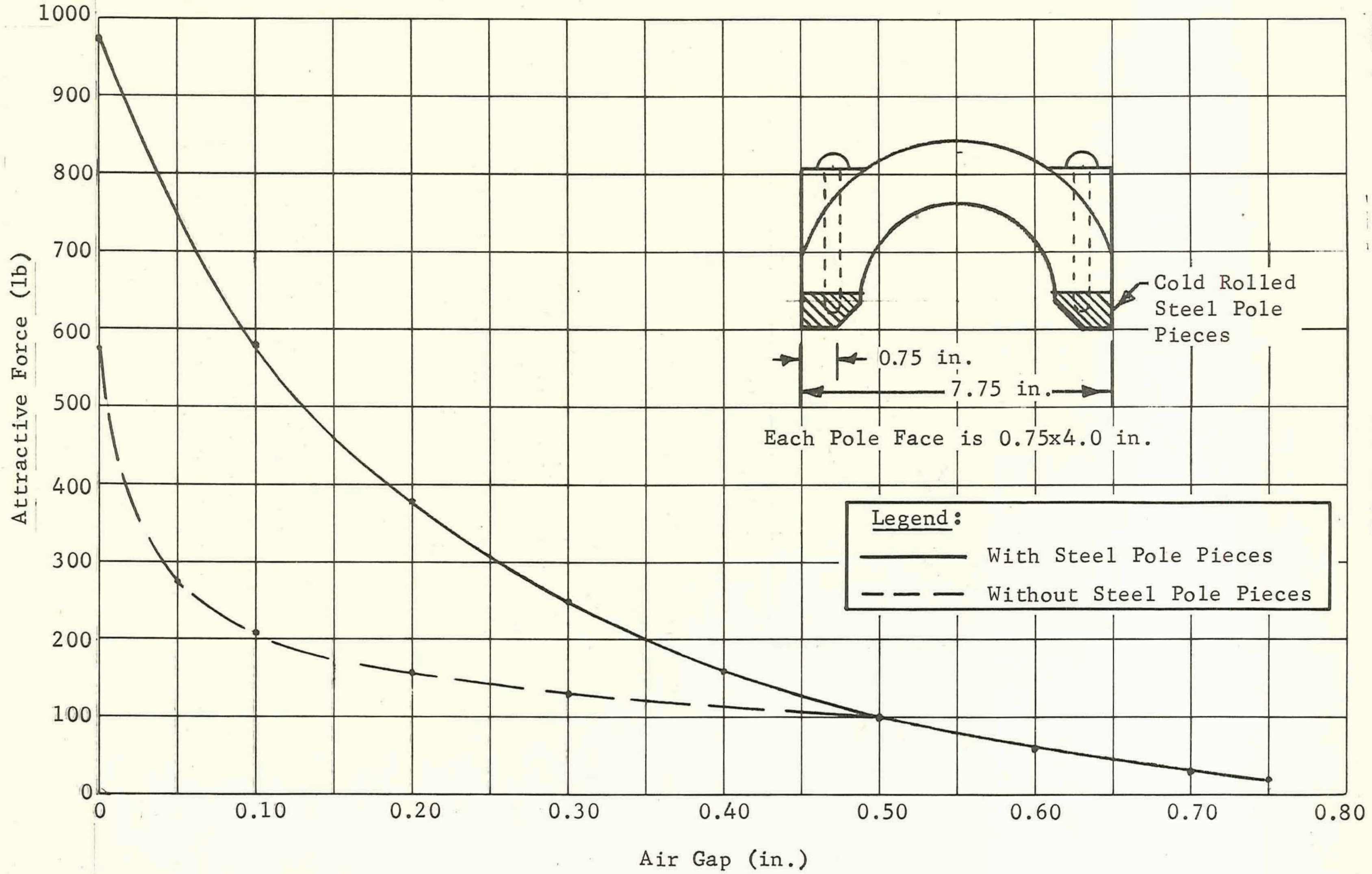
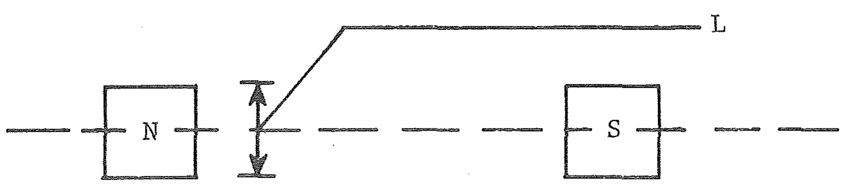


Fig. III-3 Pull Characteristic Curves for Varied Contact Area

To use the maximum pull of a permanent magnet, special attention must be paid to armature design. The function of the armature or soft magnetic material in conjunction with a permanent magnet assembly is to complete the magnetic circuit. Ordinarily, cold-rolled steel is generally used because of its low cost and general availability. Both cobalt iron (50-50) and Armco iron have slightly higher saturation levels, but are usually not used except where the ultimate in flux-carrying capacity is desired, because of their higher cost.

Regardless of the soft magnetic material used, it is highly desirable to operate the material at its point of maximum permeability (ratio of flux density to magnetizing force). This will ensure the maximum flux-carrying capacity with minimum expenditure of magnetizing potential.

A general rule to use in armature design states that at zero air gap, the cross-section area A_c of the armature should be equal or greater than the area of contact (A) of a single pole of the permanent magnet. The cross section of an armature can best be described as the length of the pole in a direction perpendicular to the flux path between the poles times the thickness of the armature.



If this cross-section area is maintained, the flux density will remain below the magnet industry's recommended 12,000 to 14,000 gauss maximum range. It is when the flux density is above this value that saturation occurs and the armature cannot carry the flux load. This is very similar to having a high resistance in an electrical circuit.

In practically all applications, the stability of a permanent magnet is of utmost importance. The strength of a permanent magnet after initial magnetization is affected by changes in basic magnetic properties with time and temperature, vibration and impact, stray magnetic fields, and contact with other magnetic materials.

There is a pronounced change in the degree of magnetization of all permanent materials immediately after magnetizing. The loss of magnetism is of the order of 1/3% to 2% depending on the material and most of this loss occurs in the first few moments after magnetizing. The effect of temperature on the degree of magnetization is an indirect relation. That is, the lower temperatures give a higher degree of magnetization. If plotted graphically, this relation would hold for temperatures that range from approximately -300°F to +600°F (-40°F to +860°F for ceramic materials). Beyond these extremes, the permanent magnet would lose its magnet characteristics. Strains set up by vibration and impact produce magnetic instability due to reorientation of the aligned magnetic domains. However, a stabilized condition is eventually reached where further impact or vibration has no effect. The magnitude of the effect of stray magnetic fields varies with the coercive force of the magnetic material. The higher the intrinsic coercive force, the greater the resistance to stray magnetic fields. It will be found, however, that properly processed magnets are inherently very stable with respect to time unless operating conditions are not constant and exceed the extremes expected.

In considering various types of permanent magnets, we must find one which has a small volume, high performance, light weight, and a high resistance to demagnetizing influences.

Comparisons between magnets built of different materials can be made on such diverse bases as demagnetization resistance, cost, or tensile strength. The first consideration is the material to be used, either for a simple magnet, or incorporated in mild steel backing plates or pole pieces.

Both Alnico and ceramic permanent-magnet materials function well in the majority of holding applications. Some differences in performance, physical characteristics, and cost make one or another more favorable in specific cases. For example, barium-ferrite ceramic maintains its magnetic strength despite such weakening influences as contact with other magnets or frequent pulling of the magnet from the steel armature. Alnico is more sensitive to demagnetizing influences, but has greater physical strength and is not so likely to chip as the brittle ceramic. Protective nonmagnetic plates may be used over ceramic magnets, however.

A ceramic magnet is usually cheaper except in small sizes, where quantity-produced sintered Alnico magnets are competitive. Cast Alnicos do not have the clean surface appearance and dimensional accuracy of pressed, sintered Alnicos, or the good appearance of barium-ferrites, but any magnet can be ground to accurate dimensions where necessary. Barium-ferrite has poor tolerances due to high shrinking during processing.

Both ceramic and cast-Alnico magnets can be made in large sizes. Two barium-ferrite ceramic types are available: nonoriented and oriented. The nonoriented type is pressed without specifically aligning the magnet grain or molecular structure. The latter is oriented in the direction of pressing. Both are efficient in short magnetic lengths, but if too short they warp during manufacture. All barium-ferrite magnets are pressed, hence, require expensive cooling.

Nonoriented barium-ferrite material costs less in some applications because plain or counterbored holes can be provided in the direction of pressing at no extra cost. Also, it can be magnetized before final assembly without loss of strength. The oriented material must be magnetized after assembly for best properties, cannot have counterbored holes, and must have at least 2-sq-in. area and 1/4-in. rounded corners, but the resulting pull is greater for the same weight of material.

Alnico V will meet most pull requirements with less weight than sintered Alnico V. The latter is useful where the need is for a small magnet (maximum 0.05 lb) with best physical properties and high performance. Sintered Alnico II is not oriented and can be magnetized without regard for direction of heat treatment. Cast Alnico can be made in multiple bars that can be broken apart to form separate bar magnets.

We have found through testing that certain types of Alnico magnets have lost their magnetism while the ceramic magnets have remained stable under external demagnetizing effects. Although these effects can be compensated for in system design, it is often easier to avoid a problem than to compensate for it. For this reason, a ceramic magnet was chosen for the shuffler design. Ceramic magnets also have the advantage of smaller size and less weight for a given attractive force. Ceramic magnets generally have less reach than Alnico magnets but this can be considered an advantage in our case because the shuffling movement can be accomplished more easily with this type of characteristic.

IV. MAGNETIC ANALYSIS

A. MAGNET DESIGN

We have chosen Indox V, an oriented barium-ferrite ceramic material, for use in the shufflers. The rectangular shape in a channel pole piece will work best for this particular application. A demagnetization curve is shown for this material in Fig. IV-1.

From the demagnetization curve for Indox V, we find the magnetic flux density (B) to be approximately 3700 gauss at room temperature with no demagnetizing force acting on the material. This is an ideal situation, however, and in actual application it will generally be true that the value will be near 3200 gauss. From this value and the zero gap pull (77.5 lb) of a particular ceramic assembly, we can determine the flux density of the pole piece. First, we must determine how much pull is due to the actual ceramic portion of the magnet:

$$N = 0.577\ B^2A$$

$$= (0.577)(3.2)^2(4)$$

$$N = 23.6\ \text{lb}$$

This indicates that the pole piece is responsible for (77.5 - 23.6) or 53.9-lb pull. Substituting this back into the formula, we can determine the flux density of the pole piece:

$$N = 0.577\ B^2A$$

$$53.9 = (0.577)(B^2)(0.550)$$

$$B^2 = \frac{53.9}{(0.577)(0.550)} = 170$$

$$B = 13.05\ \text{kgauss}$$

The flux density through the pole piece is then 13,050 gauss, within the recommended 12,000 to 14,000 gauss range.

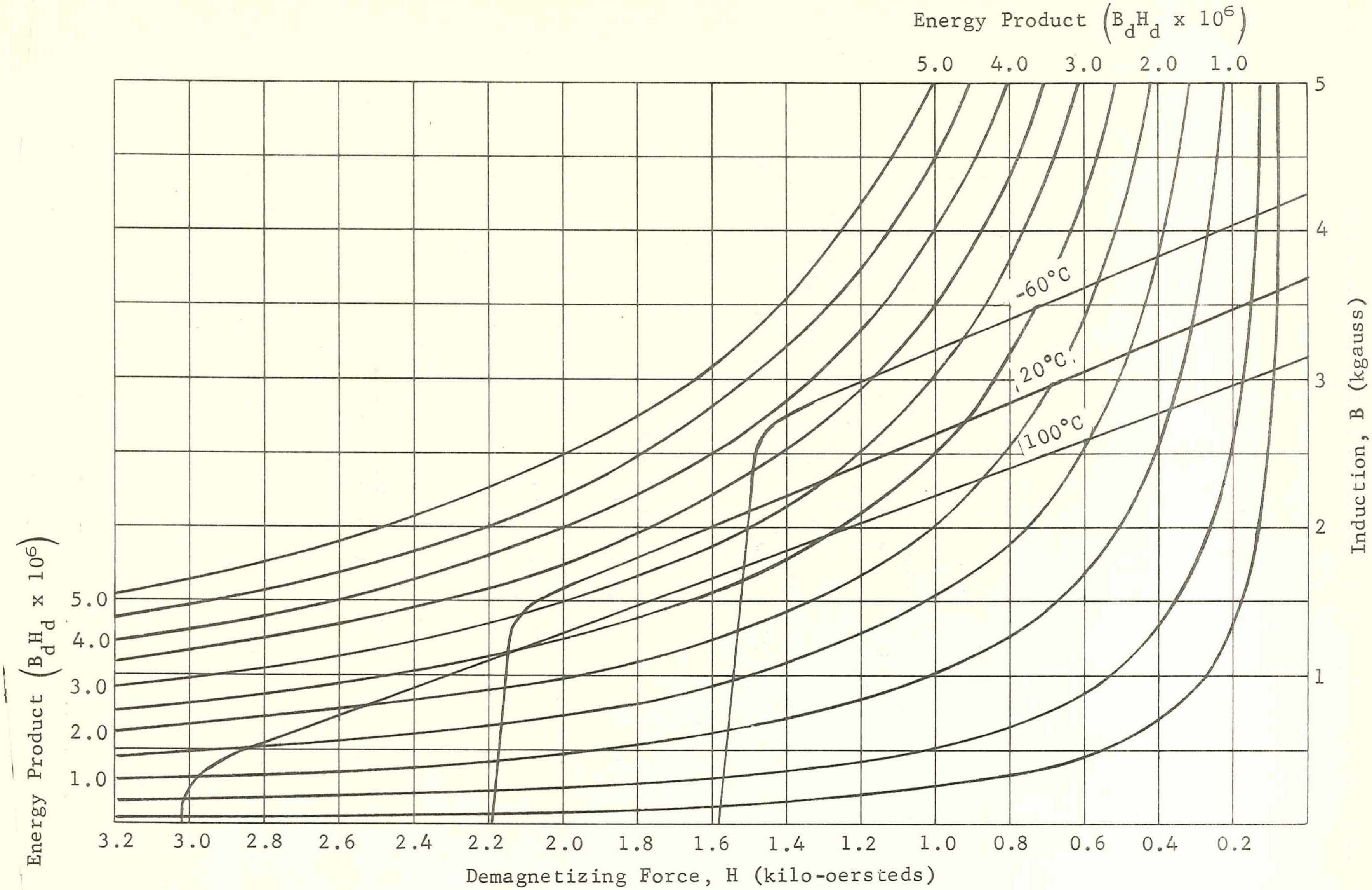


Fig. IV-1 Demagnetization and Energy Product Curve for Indox V

B. ARMATURE DESIGN

In the area of armature design, some tests at the Martin Marietta Corporation have given interesting results. In looking for floor materials, several ideas were derived, namely "magnetic rubber," impregnated fiberglass, sheet metal, and metal plate.

The "magnetic rubber" seemed to be a fairly simple solution at first. However, one vendor indicated that the magnetic particles inside the rubber are easily disoriented and lose their magnetism readily. This is not a desirable characteristic, so other approaches were considered.

A light fiberglass floor impregnated with iron filings was considered. Four small samples were quickly made with various percentages of iron in each. For the fifth sample, a small piece of 22-gage galvanized sheet metal was used. The compositions of the floor samples and the test procedure and results are discussed in the following paragraphs. The test setup is illustrated in Fig. IV-2.

Sample 1	Composition -	40 gm epoxy
		4 gm hardener
		10 gm iron (fine)
		4 layers of cloth (18.9 gm)
	Final Weight -	0.0845 lb (13.7% iron by weight)
Sample 2	Composition -	40 gm epoxy
		4 gm hardener
		30 gm iron (fine)
		4 layers cloth (13.6 gm)
	Final Weight -	0.1136 lb (34.3% iron by weight)
Sample 3	Composition -	50 gm epoxy
		5 gm hardener
		37.5 gm iron (fine)
		4 layers screen (25.7 gm)
	Final Weight -	0.1442 lb (53.4% iron by weight)

Sample 4 Composition - 50 gm epoxy
5 gm hardener
50 gm iron (coarse)
3 layers of cloth (6.4 gm)
Final Weight - 0.1806 lb (44.8% iron by weight)

Sample 5 22 gage galvanized sheet metal
Final Weight - 0.1388 lb

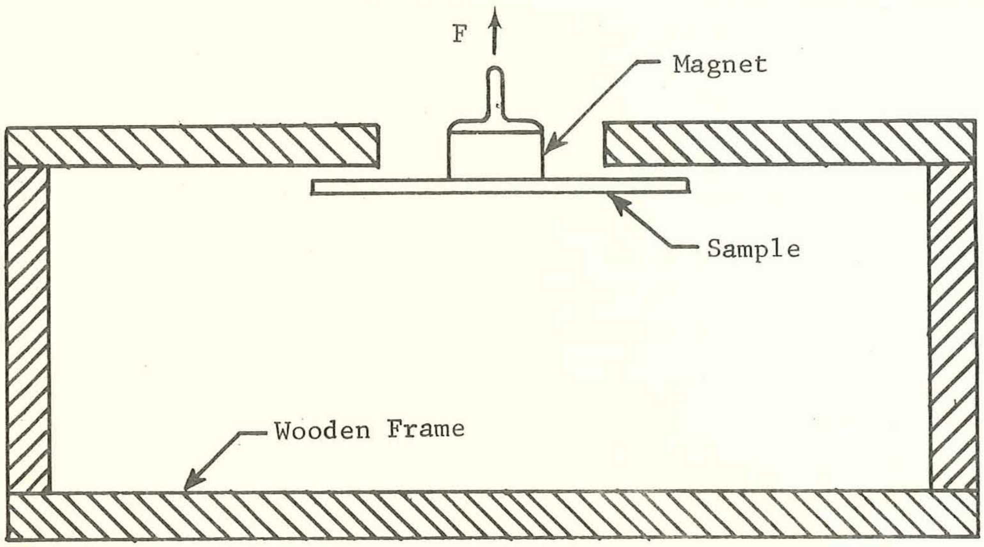


Fig. IV-2 Test Setup

A tensile test machine is used with the setup shown in Fig. IV-2 to get a relation of magnetic attraction of different samples with various air gaps. Maximum attraction occurs when the sample and magnet are in direct contact, and as they are pulled apart, this attraction decays. The results are shown graphically (Fig. IV-3) for the various samples.

The results of this test indicate that the optimum floor design would be one of 100% iron. There is a direct relation between the amount of iron in the floor material and the attractive force of the magnet. A floor of pure iron would also reduce the amount of reluctance within the magnetic circuit since there would be no gap between iron particles.

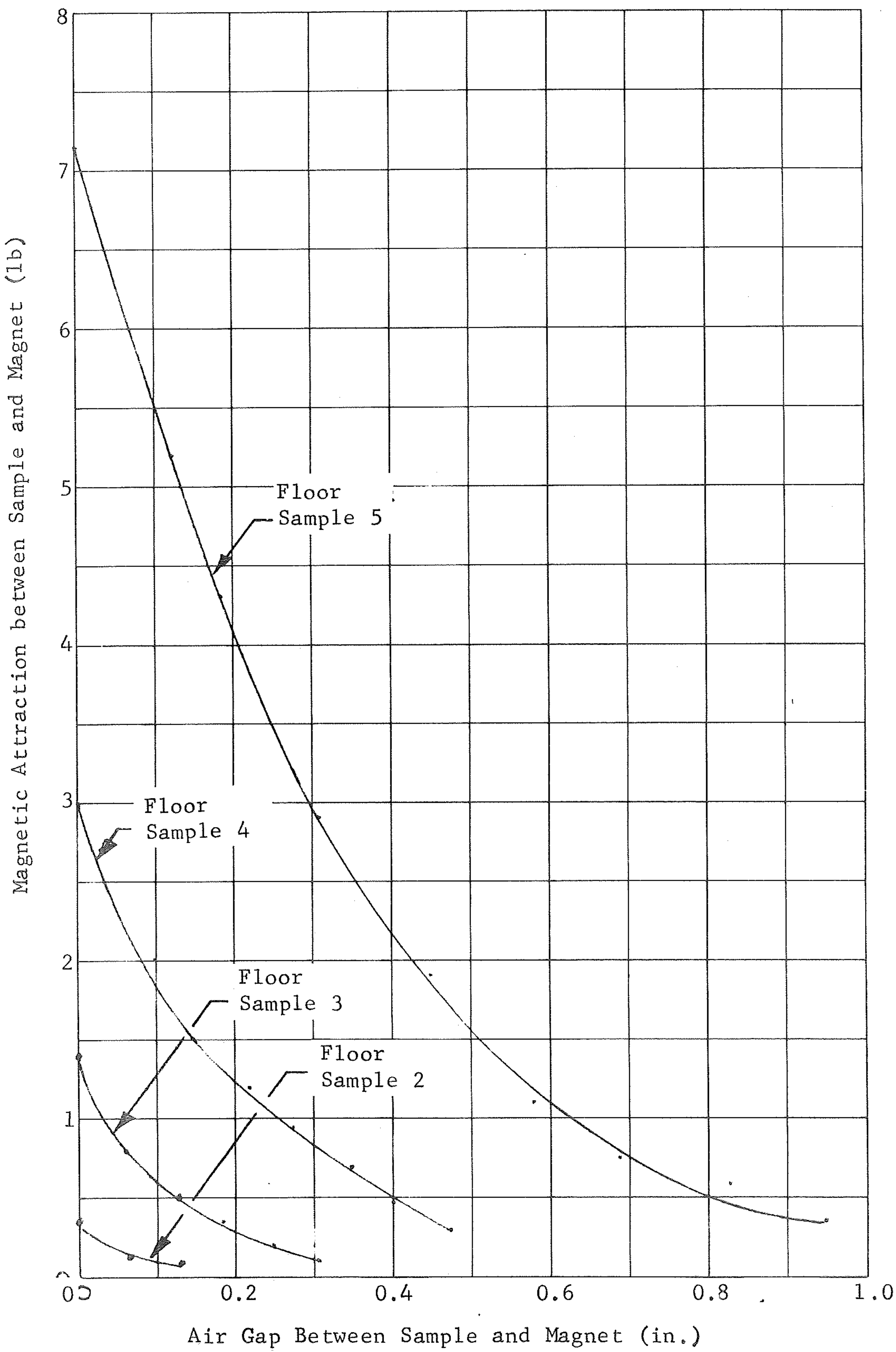


Fig. IV-3 Magnetic Attraction for Various Air Gaps and Samples with 10.3-lb Magnet

From an earlier analysis, the largest attractive force to maintain stability was required when the 99 percentile man accelerated a package from shoulder level. This force was 13.6 lb per shuffler. It should be stressed that this force is necessary for the astronaut to remain stable. Based on neutral buoyancy tests at Denver and tests at the zero-gravity simulator in Huntsville, a safety factor in the range of 1.5 to 2.0 should be introduced. This would require the attractive force per shuffler to be from 20.4 to 27.2 lb. To meet this design standard, there will be approximately 15 lb attraction in the heel and 8 lb in the ball area of the shuffler.

An important design consideration in the shuffler assemblies will be the simulated air gap between the magnet assembly and the ferrous floor surface. This simulated air gap is due to the materials making up the sole configuration that cover the magnet assemblies.

For maximum pull at zero gap applications, the armature thickness should be at least the same relative thickness as the mild steel pole piece used with the magnets. For armature thickness less than this, the armature material will become saturated and flux leakage paths will develop. When this happens, the attractive force of the magnet will decrease considerably. The same type of phenomena will happen when the air gap is introduced between the magnet and the armature as shown in Fig. IV-4 and IV-5, but because of the leakage paths that develop, the armature will handle a smaller flux load and, therefore, can be made proportionally thinner.

Three armature materials were investigated: vanadium permendur, pure annealed iron (similar to cobalt iron), and hot rolled, low carbon sheet metal. To determine the thickness of the armature, the characteristics of the permanent magnet assembly were investigated. Figure IV-4 shows the attractive force of the magnet to be 77.5 lb at zero gap and 16.2 lb at a 1/32-in. gap. From the formula $N = 0.577\ B^2A$, the pull (N) is proportional to the flux density squared (B^2). For a drop in pull from 77.5 to 16.2 lb, the flux would decrease by a factor of

$$\left[\frac{16.2}{77.5}\right]^{\frac{1}{2}} = 0.457$$

This means for the particular assembly from Bunting Magnetics (Part Number BM4974) the thickness of the armature (if made from the same material as the pole piece) could be 0.457 as thick as the pole piece (0.1046 in.) to maintain the 16.2-lb attractive force. If the armature material were changed from low carbon sheet metal to a material with higher permeance characteristics, this factor could become smaller yet.

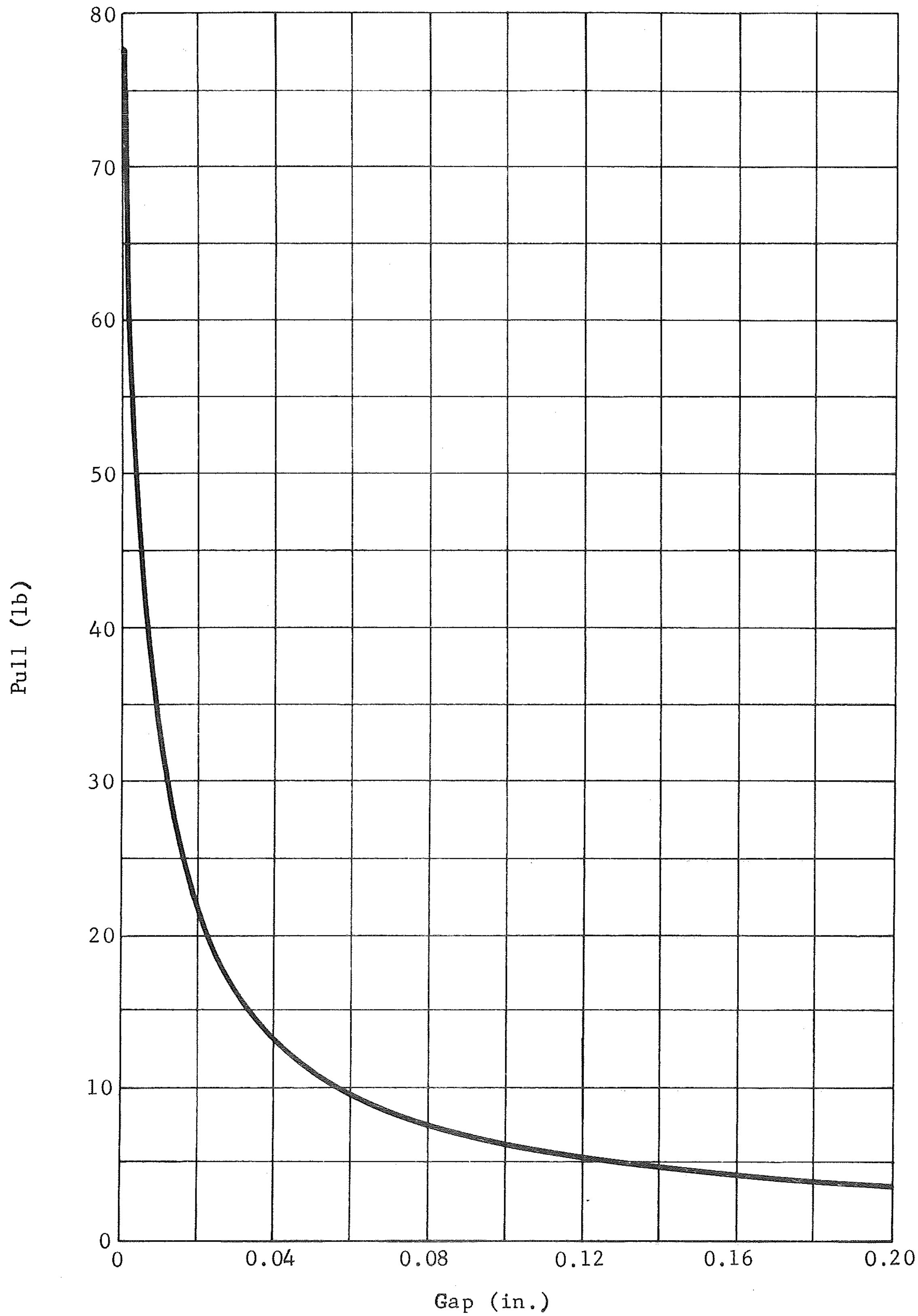


Fig. IV-4 BM-4974 Pull Characteristic Curve, 1-in. Iron Armature

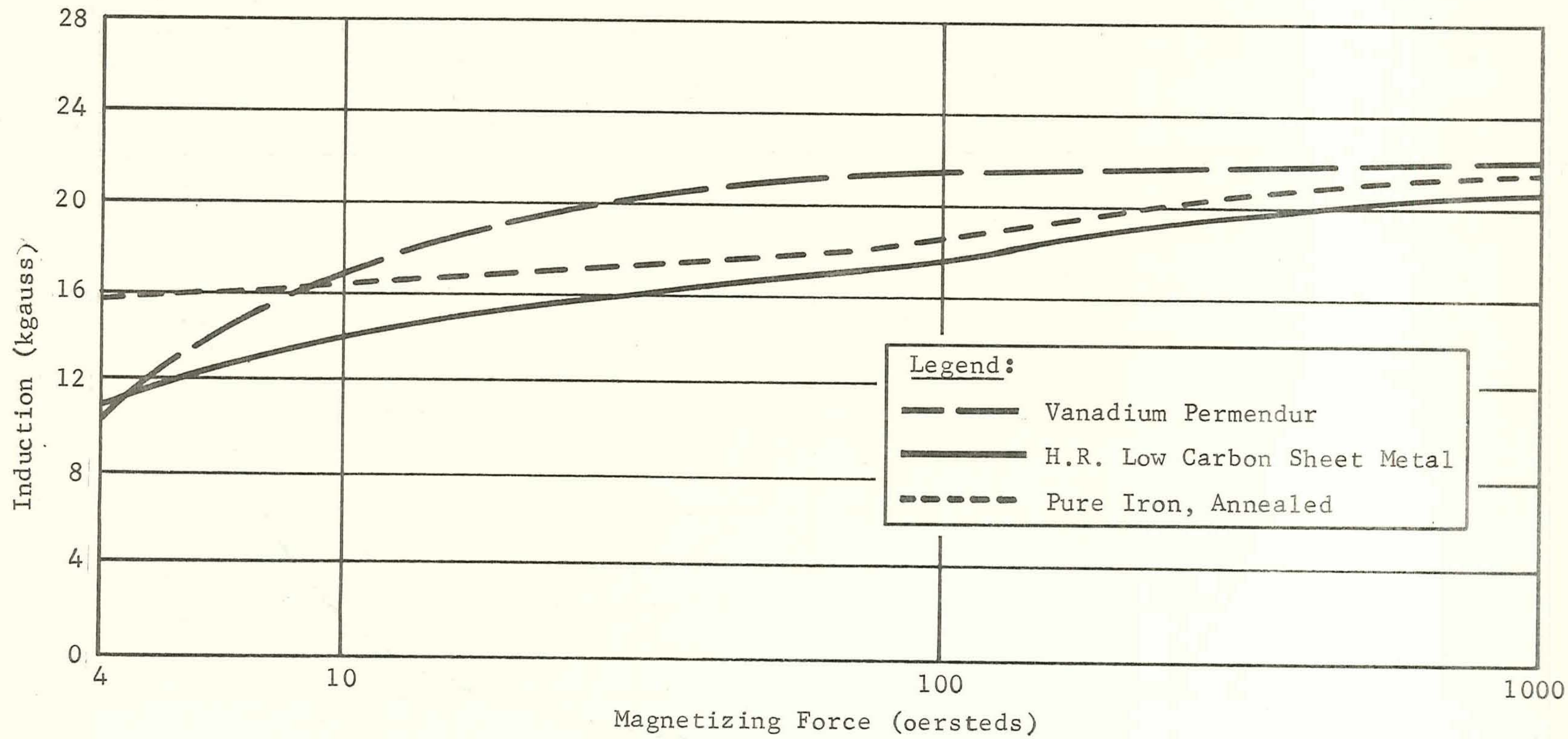


Fig. IV-7 Magnetization Curves of Various Magnetic Materials

Armature design in the magnet industry is usually based on a magnetizing force between 2.5 and 10 oersteds. Figure IV-5 shows that for a magnetizing force of 10 oersteds acting on the armature materials, the resulting induction is:

1) Vanadium permendur - 16.7 kgauss;

2) Pure iron, annealed - 16.5 kgauss;

3) H.R., low carbon sheet metal - 14.0 kgauss.

If pure annealed iron is used instead of low carbon sheet metal, the factor would be

$$\frac{14.0}{16.5} \; (0.457) \; = \; 0.388$$

The thickness of the armature would then be

$$t = (0.388)(\text{thickness of pole piece})$$

$$= (0.388)(0.1046)$$

$$t = 0.0406 \text{ in.}$$

The results of this series of calculations is shown on Fig. IV-6. It shows the armature thickness required to obtain certain attractive force levels for the particular magnet assembly used in our shufflers. The design point for our shufflers is shown on the curve.

This analysis is based on the assumption that the flux path through the armature is a straight line between the pole piece. This is not entirely true, however, since the lines of force actually tend to bow outward. The precise flux path can only be estimated, but it is clear that the cross-section area of the flux path will become larger as the flux lines deviate from this straight line path. It was found through testing that the floor thickness could be reduced by a little over 25% in the case of the iron armature.

Pull characteristic (Fig. IV-7) curves were developed on a tensile test machine for low carbon sheet metal with thicknesses of 0.020 and 0.030 in. The 0.030-in. armature met design standards of 15 lb with a 1/64-in. air gap.

We have found vanadium permendur to be very susceptible to impact as far as retaining its high permeability characteristics, therefore, our recommendation is that the floor design incorporate a smooth pure iron material with a thickness of at least 0.030 in.

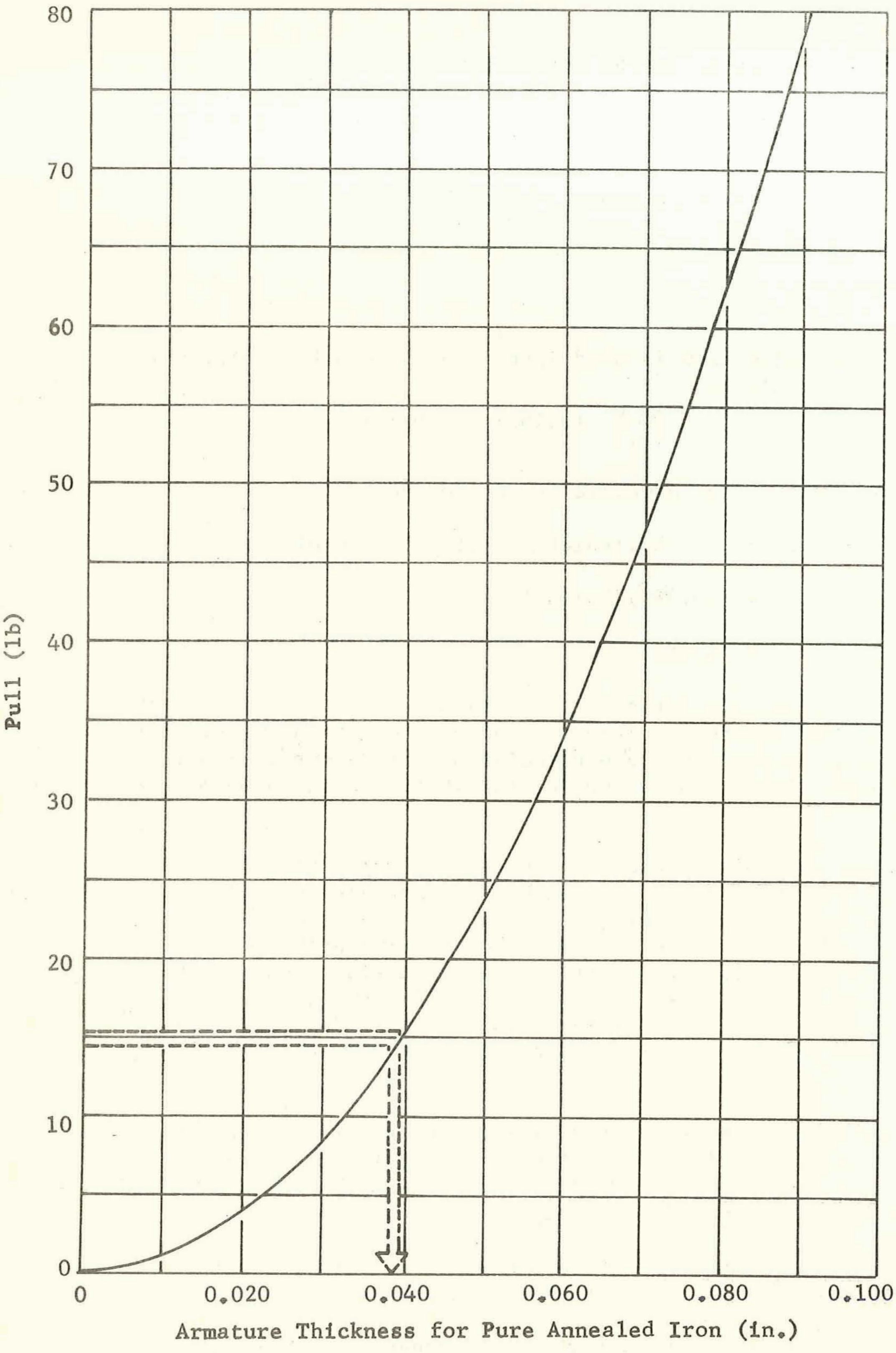


Fig. IV-6 Armature Design Curve for BM-4974 Magnet Assembly

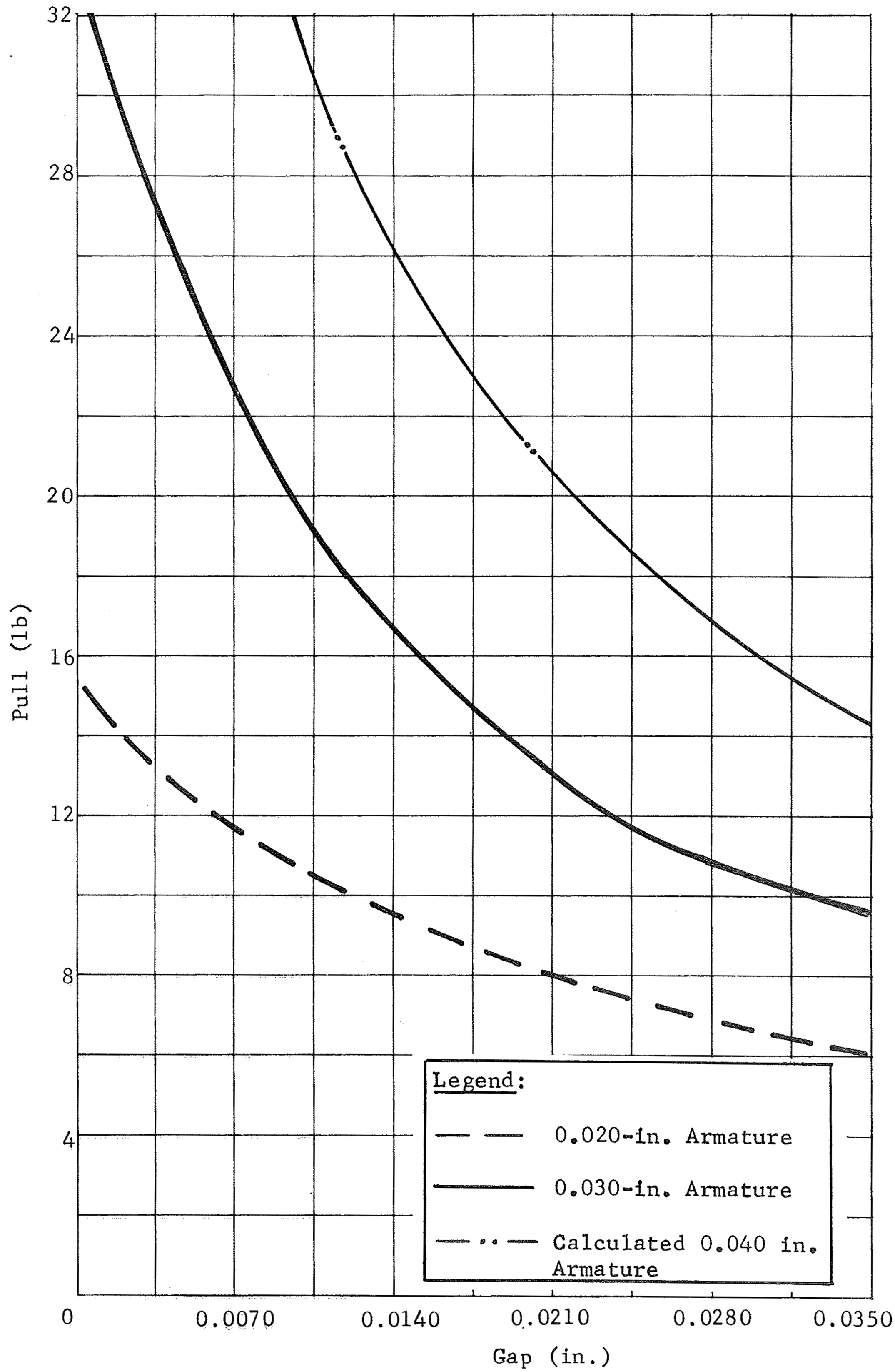


Fig. IV-5 BM-4974 Pull Characteristic Curve Comparing Calculated and Empirical Results

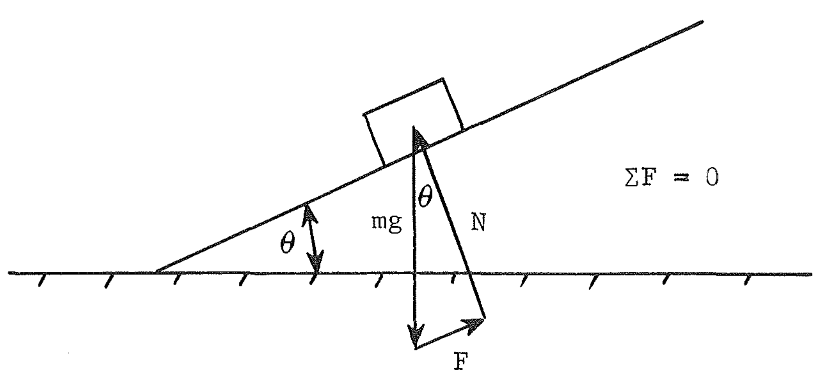
V. DESIGN CONFIGURATION

The frictional requirements of the shuffler are discussed in this chapter. By using the relation for friction that $F = \mu N$, the minimum coefficient of friction can be found. It has been determined that the largest horizontal force developed happens when the astronaut receives a package. Assuming the astronaut receives the package no lower than his center of gravity, the largest force developed would be approximately 3.97 lb (see Fig. II-5).

The shuffler will essentially have two areas of contact. These two areas combined with the magnetic attraction must impart a total frictional force greater than the 3.97-lb impact force to maintain the location of the astronaut's feet. This means for a shuffler with 13.6-lb magnetic attraction, the average coefficient of friction must be

$$\mu = \frac{F}{N} = \frac{3.97}{13.6} = 0.292$$

The two materials to be used on the sole of the shuffler are Viton and white Teflon. Since no suitable data were available on the coefficient of friction of these materials with an iron surface, a small test setup was made. A sample of Viton was cemented to one end of a solid metal cylinder and a sample of white Teflon on the other. To experimentally find the coefficients of friction between the samples and various surfaces, the surfaces were tilted until the cylinder moved. A simple force analysis will show that the tangent of the angle of tilt will be the coefficient of friction:



$$\text{tangent } \theta = \frac{F}{N}$$

but

$$\mu = \frac{F}{N}$$

therefore, μ = tangent θ, where θ = angle of tilt.

The angle of tilt and coefficient of friction for various materials are tabulated in Tables V-1 thru V-4.

Table V-1 Viton on Galvanized Sheet Metal

Static		Kinetic	
Angle of Tilt (deg)	Coefficient of Friction	Angle of Tilt (deg)	Coefficient of Friction
34	0.675	34	0.675
35	0.700	33	0.649
34½	0.687	33	0.649
	0.687 Average		0.658 Average

Table V-2 Viton on Iron

Static		Kinetic	
Angle of Tilt (deg)	Coefficient of Friction	Angle of Tilt (deg)	Coefficient of Friction
35½	0.713	37	0.753
37	0.753	37	0.753
36	0.726	37	0.753
	0.731 Average		0.753 Average

Table V-3 White Teflon on Galvanized Sheet Metal

Static		Kinetic	
Angle of Tilt (deg)	Coefficient of Friction	Angle of Tilt (deg)	Coefficient of Friction
5	0.087	4	0.069
5	0.087	$4\frac{1}{2}$	0.079
5	0.087	$4\frac{1}{2}$	0.079
	0.087 Average		0.076 Average

Table V-4 White Teflon on Iron

Static		Kinetic	
Angle of Tilt (deg)	Coefficient of Friction	Angle of Tilt (deg)	Coefficient of Friction
$14\frac{1}{2}$	0.259	$11\frac{1}{2}$	0.203
$14\frac{1}{2}$	0.259	10	0.176
13	0.231	$10\frac{1}{2}$	0.185
	0.250 Average		0.188 Average

It becomes apparent from the results of this test that the area of the shuffler covered by Teflon will have little effect in contributing to a reactive horizontal friction force. The majority will, therefore, have to come from the heel area of the shuffler or the surface covered with Viton. If each shuffler had a 13.6-lb force, the heel must have at least the following attractive force:

$$F = \mu_b N_b + \mu_h N_h$$

where $N_b + N_h = 13.6$ lb

$$3.97 = (0.250)\left(13.6 - N_h\right) + (0.731)\ N_h$$

$$0.57 = (0.481)\ N_h$$

$$N_h = 1.19 \text{ lb}$$

If all the friction force were to initiate from the heel, the required magnetic attraction must be

$$F = \mu_h N_h$$

$$N_h = \frac{3.97}{0.731} = 5.43 \text{ lb}$$

The shoe-like appearance of the shufflers introduces the space allotment problem of what physical size magnet can be placed in the sole. The optimum design of commercially available magnets meeting the small volume and large pull characteristic comes from Bunting Magnetics in Chicago. With the use of two of their magnet designs, the attraction in the ball and heel areas of the foot will be approximately 8 and 15 lb, respectively. This adds a considerable safety factor to the heel area, maintains ample attraction to keep the ball area of the foot in contact with the ferrous surface at all times, and keeps the total attractive force per shuffler in the 20.4- to 27.2-lb range derived during armature design.

The contract design concept states that the "design shall allow variation of magnets to increase or decrease nominal holding strength." Our choice of magnets is more than ample for the 99 percentile man performing all tasks described in the analysis. It also eliminates the need for changing magnets for each task performed. Therefore, we conclude that the shuffler concept should incorporate a magnetic attraction of sufficient strength to handle all the various applications intended for it in a zero-gravity environment.

VI. TESTING RESULTS OF VARIOUS SHUFFLER ENGINEERING EVALUATION CONCEPTS

Engineering evaluation models of varying configurations were fabricated to verify the analysis and to confirm that the shuffler was a workable concept. The testing of these models aquainted the design engineers with configuration design requirements which had to be incorporated in the final design.

A. WATER TEST 1

Location	Magnetic Strength (lb) Right	Magnetic Strength (lb) Left	Magnet Type	Surface Material
Heel	5.99	6.00	Indox V	Viton
Ball	1.12	1.06	Alnico V	Armalon
Toe	N/A	N/A	N/A	Viton
Sole	N/A	N/A	N/A	Flexible Crepe Rubber

The first shuffler concept was fabricated from a nylon-mesh summer loafer (see Fig. VI-1). In the test tank, Viton was an effective high coefficient of friction surface and Armalon proved to be a good low coefficient of friction surface. An 18-gage galvanized sheet metal surface was used as the ferrous shuffling surface on the botton of the tank.

Due to the Armalon and Viton surfaces covering the magnets, the magnetic attraction was greatly reduced. Both subjects has a good "feel" for the magnetic attraction, however.

Shuffling at first seemed a little awkward, however, when each subject learned to pull with his leading foot, the shuffling movement worked fairly well. One subject tried to stop abruptly near the end of the metal sheet. He had the sensation of stopping his feet, but having his body continue in forward motion. Both subjects expressed a need for a larger attractive force in the ball of the foot area.

Fig. VI-1 First Shuffler Engineering Evaluation Model

Shuffling up a vertical wall was attempted a short time later, but both subjects had difficulty in orienting themselves in the horizontal position. Their bodies floated upward and broke the heel contact. One subject was finally able to orient himself, but had difficulty in movement. The Viton had been removed from the heel area, leaving a low coefficient surface, thus making movement difficult because of sliding. Both subjects agreed that the vertical ascent would be an ideal test.

B. WATER TEST 2

Location	Magnet Strength (lb)		Magnet Type	Surface Material
	Right	Left		
Heel	5.59	6.00	Indox V	Viton
Ball	4.30	4.73	Alnico V	Armalon
Toe	N/A	N/A	N/A	Viton
Sole	N/A	N/A	N/A	Flexible Crepe Rubber

This test was conducted very similarly to test 1 using the same shuffler, except, stronger magnets (horseshoe type) were placed in the ball area. Viton (1/64 in.) was used for the high coefficient of friction surfaces of the heel and toe and Armalon (0.008 in.) was used as the low coefficient of friction surface in the ball of the foot area of the shuffler. The Armalon surface was quickly worn through by the sharp magnets during the shuffling process, indicating a more durable or thicker material should be used.

The stability of the subjects during the shuffle was much improved with the addition of the stronger magnets. An attempt was made to push suspended weights, but this was considered a poor test because of the highly viscous water surrounding the subject. A static test would give a much better indication under these circumstances.

Shuffling up and down a vertical wall was accomplished this time using scuba gear. The subject donned the shoes, made himself neutrally buoyant, and shuffled up the vertical ferrous surface with little difficulty. The shuffling pace was slower than expected, however. This again was attributed to the highly viscous water surrounding. A better test would be a zero-gravity simulation or a zero-gravity aircraft simulation maneuver.

C. SIX-DEGREE-OF-FREEDOM SIMULATOR TESTING OF FIRST SHUFFLER CONCEPT

On August 1, 1969, the NASA-MSFC P&VE Laboratory was used to verify the shuffler concept. Test equipment included the following items:

1) Two 4x8 ft, 1/8-in. thick plates of structural steel;
2) Torque wrench (0 to 1 ft-lb range);
3) Stop watch;
4) Tape measure;
5) Fish scale;
6) Rolling cart (225 lb);
7) Movie coverage.

The test evaluation model incorporated Viton heel and toe pieces and an Armalon piece in the ball area of the foot (see Fig. VI-1). The holding strengths of the magnets in the shuffler assemblies are shown. They are somewhat smaller due to the thicker surface materials used.

Location	Magnet Strength (lb)		Magnet Type	Surface Material
	Right	Left		
Heel	4.77	4.54	Indox V	Viton
Ball	1.14	2.63	Alnico V	Armalon
Toe	N/A	N/A	N/A	Viton
Sole	N/A	N/A	N/A	Flexible Crepe Rubber

The following tests were performed:

1) Shuffling on ferrous surface;
2) Pulling;
3) Rotating body;
4) Pushing into free float;
5) Torquing;
6) Receiving object;
7) Pushing object.

1. Shuffling

Shuffling times are given in the following tabulation.

Try	Distance (ft)	Time (sec)	Velocity (fps)
Comfortable Shuffle			
1	8.0	12.0	0.66
2	8.5	13.5	0.63
3	8.75	15.0	0.58
4	9.0	20.0	0.45
5	8.2	12.7	0.64
6	8.25	11.3	0.73
Maximum Shuffle			
1	9.0	12.5	0.72
2	9.0	14.5	0.60
3	9.5	8.4	1.13

Each subject, after 10 to 15 minutes of familiarization was able to shuffle across the floor without difficulty (see Fig. VI-2). The mass and inherent bias of the simulator created difficulties in excess of those of neutral buoyancy according to the subject experienced with the shufflers. Each test subject soon devised his own mode of shuffling, all of which only differed slightly.

The speeds at which the floor could be crossed varied with the individual, the amount of initial familiarization with both the shuffler and the simulator, and the amount of familiarization time permitted the subject. All subjects felt that stronger magnets were required and would result in much easier and faster shuffling.

2. Pulling

A spring scale (similar to a fish scale) was fastened to the wall beside the test setup. Each subject grasped the hook of the scale and pulled. In each case, pulling was not difficult. The rear foot of the subjects consistently pulled loose first. The subject was able to replace his foot without difficulty.

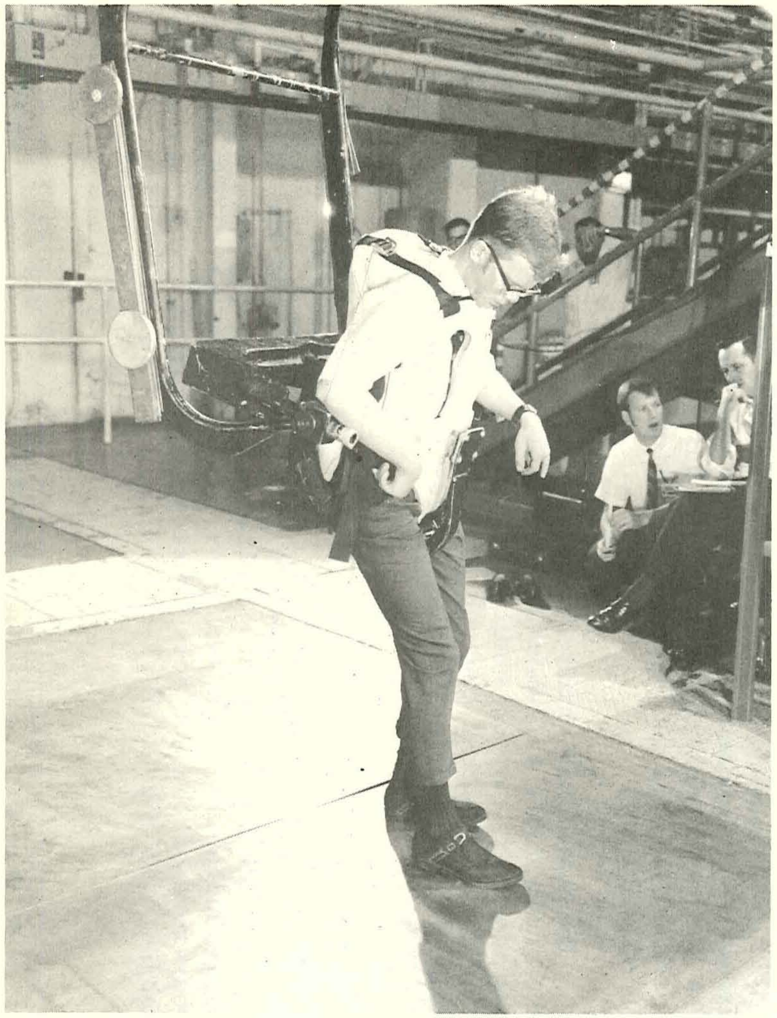


Fig. VI-2 Subject Shuffling over Ferrous Surface

Fig. VI-3 Subject Rotating Body

3. Rotating Body

The test subjects were directed to rotate their feet, bodies, and simulator 90 deg. The action is simple and natural, and the only problem is the moment of inertia created by the simulator. Each subject felt that the rotational motion would be easy without the additional mass (see Fig. VI-3).

4. Pushing into Free Float

Each test subject was directed to take two shuffling steps and push off. Stopping at a location would depend on a subject's ability to rotate and "come down" on his feet. This should provide little difficulty in a zero-gravity field (see Fig. VI-4).

5. Torquing

Because testing time was limited, only one subject completed the torque testing. One man held the bolt with a wrench while the test subject attempted to rotate the bolt with the torque wrench. When the test subject had both feet planted on the ferrous surface, the only limitations in torquing movements appeared to be the subject's strength. With a 15-in. stance, a moment of 150 in.-lb was applied.

6. Receiving a Package

Each test subject caught the cart as it was pushed into him. The cart had a total mass of 225 lb and was mounted on wheels for easy movement. Under increased cart velocity, one foot slid a small distance before the cart was stopped (see Fig. VI-5).

7. Pushing Object

Each test subject was directed to push the 225-lb cart used in the previous experiment. Once the inertia of the cart was overcome, the cart was moved easily (see Fig. VI-6).

8. Conclusions

The tests generally confirmed the shuffler concept and mathematical analysis. Before testing the attractive force of magnets in the evaluation model was believed to be too small. The testing verified this to be true.

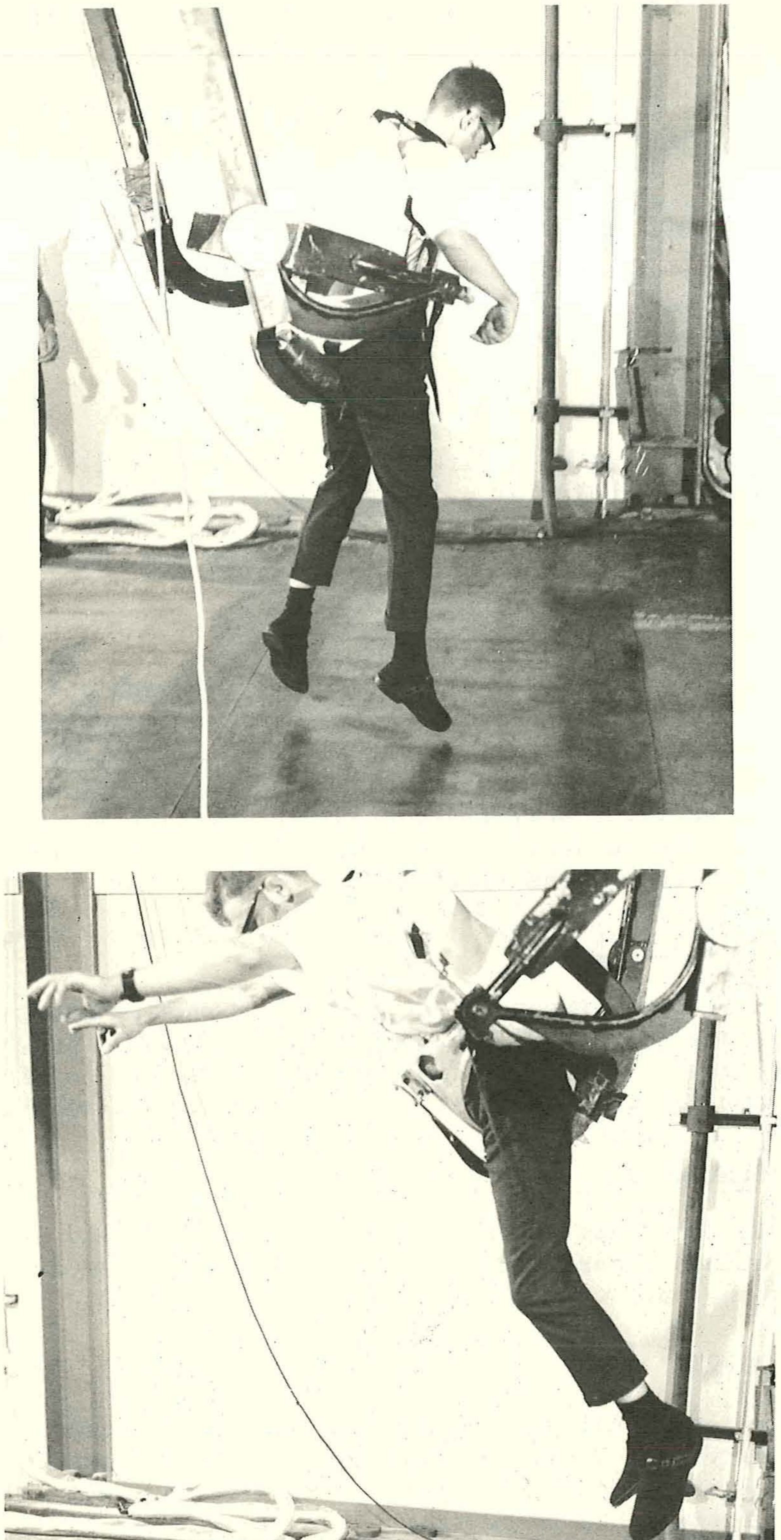


Fig. VI-4 Two Views of Subject Pushing Off into Free Float

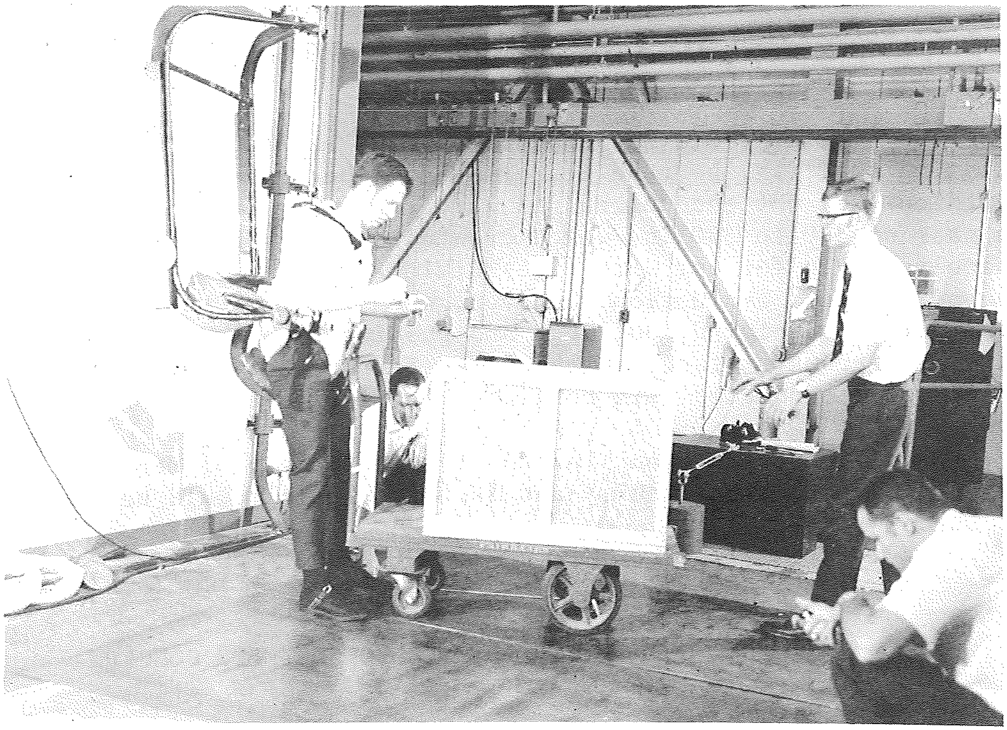


Fig. VI-5 Subject Receiving Package

Fig. VI-6 Subject Pushing Object

The simulator did not appear to be an exceptionally good testing facility, because its mass and inherent bias present difficulties not encountered in zero gravity. The simulator had a mass of 300 to 350 lb, which created a total mass of approximately 500 lb for use with the shufflers (Fig. VI-5). It did permit concept evaluation, however, when the test subjects tried shuffling, receiving, pulling, and pushing with and without use of the ferrous surface. Without the ferrous surface, these tests were conducted with considerable difficulty.

Complete cooperation from the testing people of MSFC was obtained without difficulty and further testing could be conducted.

D. NEUTRAL BUOYANCY TEST OF SECOND SHUFFLER CONCEPT

On August 7, 1969, an evaluation test was performed in the Littleton YMCA swimming pool to verify magnet design and demonstrate the feasibility of shuffling on a ferrous surface. This test was accomplished by professional divers with scuba gear and the following test equipment:

1) 4x8-ft sheet of 18-gage galvanized sheet metal;
2) Torque wrench and shaft with "T" handle;
3) Movie camera and film;
4) Fish scale;
5) 5- and 10-lb weights;
6) Tape measure;
7) Stop watch;
8) Rope, broom handle.

The shuffler configuration was similar to the former models. The difference was that a sandal model with a greater pull strength was used as shown in Fig. VI-7. The holding strengths of the permanent magnets in the shuffler assemblies are shown in the following tabulation.

Location	Magnet Strength (lb)		Magnet Type	Surface Material
	Right	Left		
Heel	10.9	11.0	Indox V	Viton
Ball	3.5	4.4	Indox V	Armalon
Toe	N/A	N/A	N/A	Viton
Sole	N/A	N/A	N/A	Stiff Foamed Sole

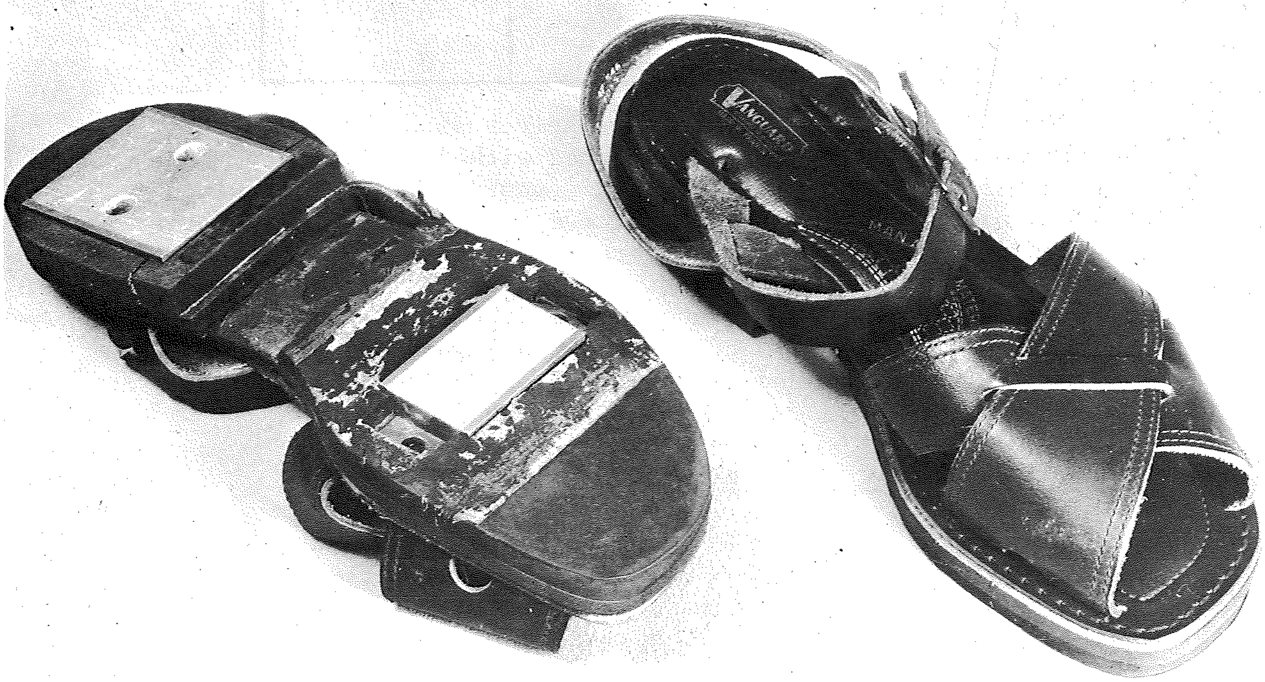


Fig. VI-7 Second Shuffler Engineering Evaluation Model

The following tests were accomplished:

1) Shuffling along a ferrous surface, both vertically and horizontally;
2) Demonstrating pushing off in a free float;
3) Pushing on a fixed object;
4) Pulling on a fixed object;
5) Shuffling to reposition body;
6) Donning and doffing shufflers;
7) Exerting torque on fixed object.

1. Shuffling Along Ferrous Surface

Shuffling times are given in the following tabulation.

Try	Distance (ft)	Time (sec)	Velocity (fps)
1	7	19	0.38
2	7	27	0.26
3	7	23	0.30

After the divers acquainted themselves with the shufflers, the mode of shuffling was accomplished without difficulty. The test subject had a tendency to lean forward as if walking into a strong wind, possibly because of the tank on his back and the water surrounding. Velocities were slower than expected, but can be attributed to the viscous water surroundings. The vertical shuffle was impressive, however, as the films show, the subject was not neutrally buoyant over all parts of his body. His legs seemed heavy and his body seemed too buoyant. See Fig. VI-8 for various views of the test subject.

2. Pushing Off into Free Float

The subject shuffled along the bottom of the tank, stopped, and pushed off into a free float with little difficulty. Once the magnet contact was broken, the subject "floated" in a weightless manner as shown in the film coverage.

Fig. VI-8 Subject Shuffling over Ferrous Surface

Fig. VI-8 (concl)

3. Pushing

The subject pushed on a broom handle that was connected by twine to a fish scale, trying to maintain a rigid body position. The subject found it difficult to maintain this position but was able to exert an impulse force before instability occurred.

4. Pulling

The subject found it much easier to maintain the rigid body position in this test, therefore, satisfactory results were achieved. With a stance of 18 in., the subject was able to pull steadily 2-1/2 to 3 lb at shoulder height and 4 to 4-1/2 lb at waist level (Fig. VI-9). This exceeded expectations shown on Fig. II-5 of the motion analysis.

5. Repositioning of Body

In this test, the subject took two steps and rotated 90 deg simultaneously. This was performed in approximately 2 sec, confirming the analysis assumption. This type of motion appears to be performed much more easily than expected.

6. Donning and Doffing Shufflers

The subject removed and put on shufflers both on and off the ferrous surface. He had the opinion that it was much easier to perform this operation on the ferrous surface. The film seems to confirm this opinion (Fig. VI-10).

7. Exerting Torque

The test subject was capable of producing 50 in.-lb of torque both on and off the ferrous surface (Fig. VI-11). However, when off the ferrous surface, the subject could not maintain the 50 in.-lb torque without instability. This torque range is in excess of the range indicated in the motion analysis.

Difficulty was encountered in much of the testing because of the stiffness in the sole of the shuffler. In the early part of the testing, the sole in the center part of the foot was partially carved away. This helped considerably, but there was still need for flexibility in the ball area of the shuffler. This flexibility is required to allow the magnets to have a direct contact with the ferrous surface. With the stiff sole, the magnet could not align itself; this is shown clearly in the films.

Fig. VI-9 Subject Performing Static Pull Test

Fig. VI-10 Subject Donning and Doffing Shufflers

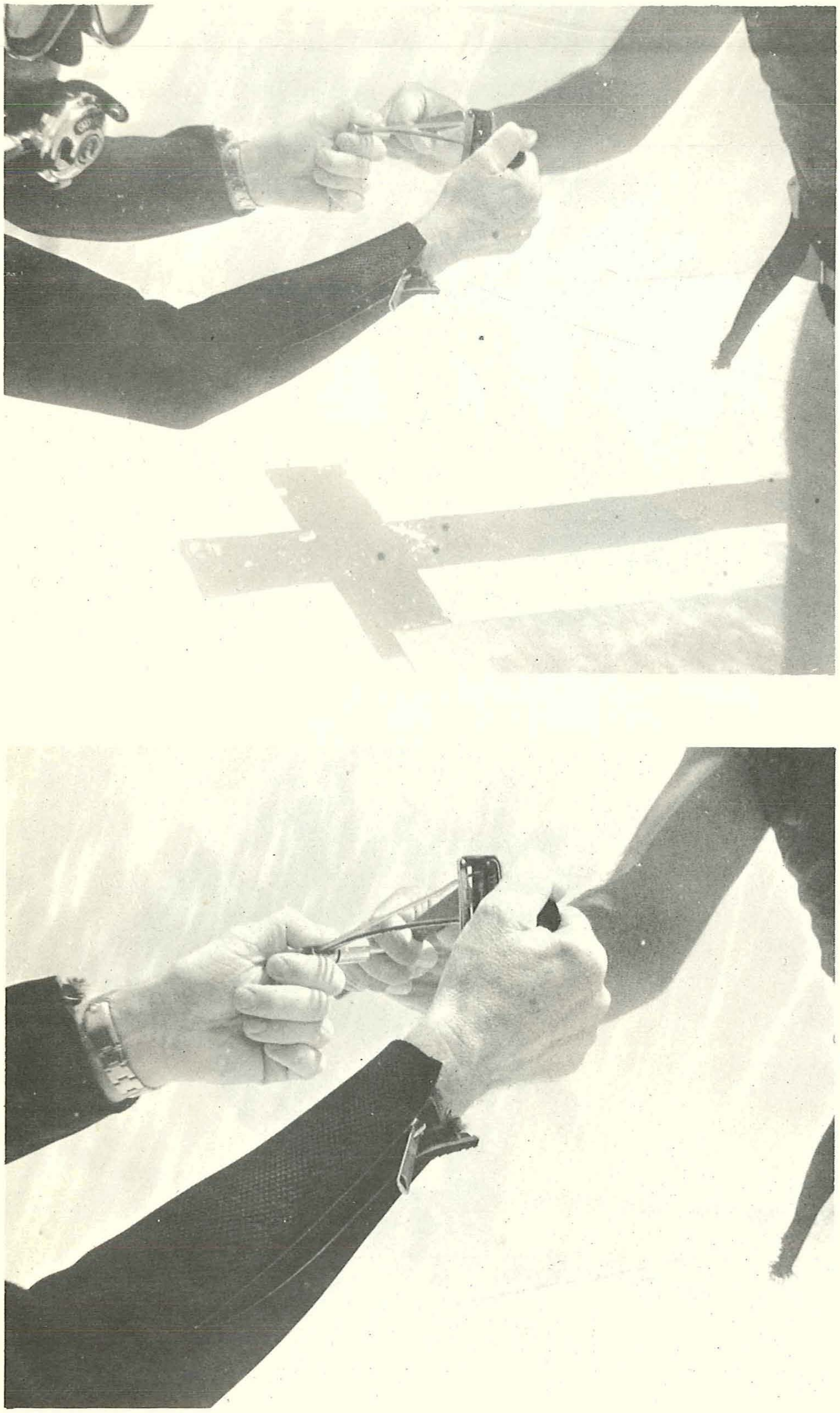


Fig. VI-11 Subject Performing Torque Test

E. NEUTRAL BUOYANCY TEST OF THIRD SHUFFLER CONCEPT

Following the neutral buoyancy test performed on August 7, 1969, another pair of shoes were fabricated with a single piece of Flourel as the sole piece. The magnets used in the previous test were fastened to the sole and covered with Armalon and Viton, depending on the location (Fig. VI-12).

Fig. VI-12 Third Shuffler Engineering Evaluation Model

Location	Magnet Strength (lb) Right	Left	Magnet Type	Surface Material
Heel	10.9	11.0	Indox V	Viton
Ball	8.0	8.0	Indox V	Armalon
Toe	N/A	N/A	N/A	Flourel
Sole	N/A	N/A	N/A	Flexible Flourel

The shuffling mode was attempted both horizontally and vertically with success. The flexible sole seemed highly desirable since direct magnet contact was readily achieved. When the Armalon was removed from the magnets in the ball area, shuffling was difficult and an "earth-oriented" gate seemed more natural. This increased the holding strength of the magnets, however, and the test subjects thought this to be the most stable pair of shufflers. After the Armalon was removed, the magnets in the ball and heel area of the shuffler had approximately the same holding strength. This did not hinder pushing off into a free float, however. This testing seemed to indicate that an attractive force in the area of 20 lb and the flexible sole would be highly desirable in the final design configuration of the shuffler.

VII. FINAL SHUFFLER CONFIGURATION AND FABRICATION

A fourth prototype shuffler (Fig. VII-1) was fabricated out of noncompatible materials in accordance with the marked drawings from the midterm presentation. This prototype was sent to the Contract Technical Monitor for review and returned. The criticism of this prototype led to the final design, which includes the closed-toe configuration and "floating" front magnet.

The closed-toe configuration permits better operation of the shuffling mode and offers a more streamlined appearance of the shuffler itself. The front magnet of each shuffler will "float", or remain flexible pertaining to orientation, and will be removable to allow replacement of the 10 mill Teflon covering when necessary. The rear magnet is large enough to align itself, so it will be rigidly attached and covered with a high coefficient of friction material called Viton, which is 1/64 in. thick.

The "D" ring buckle configuration permits finite adjustment of the restraint straps, has excellent holding strength, has no sharp edges to pinch or snag, and is easy to fasten and unfasten. Velcro tie downs were considered, but were rejected because of their tendency to break down and release small particles. Snaps and conventional buckles were considered, but were rejected because of their lack of adjustability, presence of sharp corners, and the greater degree of difficulty in operation.

The tops of the shuffler will be made from PBI, polybenzimazole, a compatible cloth material similar to nylon. The tops will be sewn together with Nomex thread and bonded to the Fluorel insole configuration with 3M adhesive 2216 flexible epoxy. The magnets will also be attached to the insole. The PBI restraint straps will be provided for use as a tie down device to keep the loose end of the strap secure after it passes through the stainless steel "D" ring assembly. The insole assembly will then be bonded to the sole which is built up in the ball and heel areas to accommodate the magnets. The bonding of the sole and insole will give a flexible sole assembly.

The construction technique described above will provide a shuffler configuration that will be compatible for spacecraft environment. It is designed as primary footwear with a 9D nominal foot size. See Table VII-1, Fig. VII-2, and Fig. VII-3 for the final design configuration.

Table VII-1 Summary of Shuffler Configuration

Location	Magnet Strength (lb)	Magnet Type	Surface Material
Heel	15.0	Indox V	1/64 in. Viton
Ball	8.0	Indox V	0.010 in. Teflon
Toe	N/A	N/A	Flexible Flourel
Sole	N/A	N/A	Flexible Flourel
Tops	N/A	N/A	Polybenzimidazole

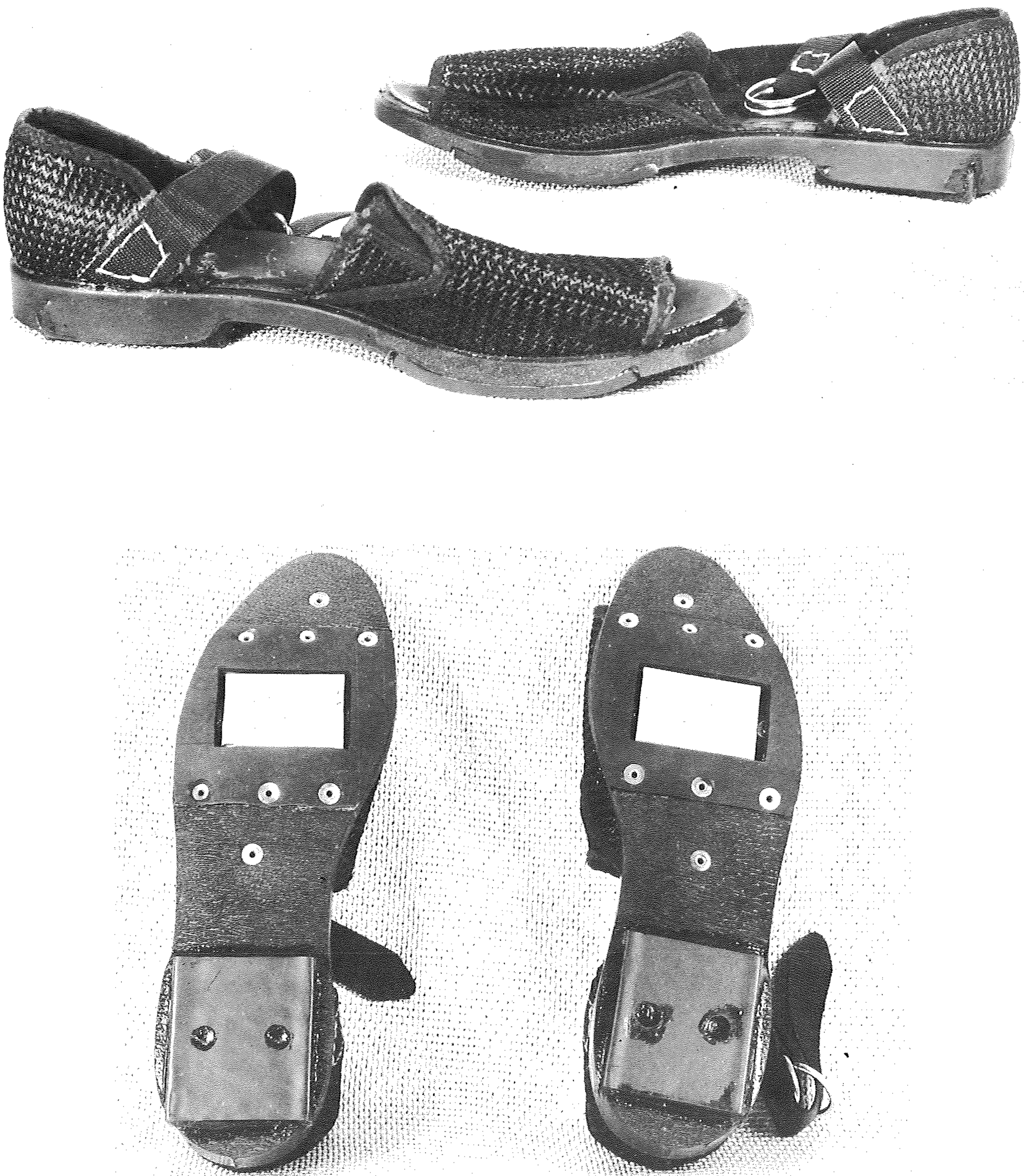
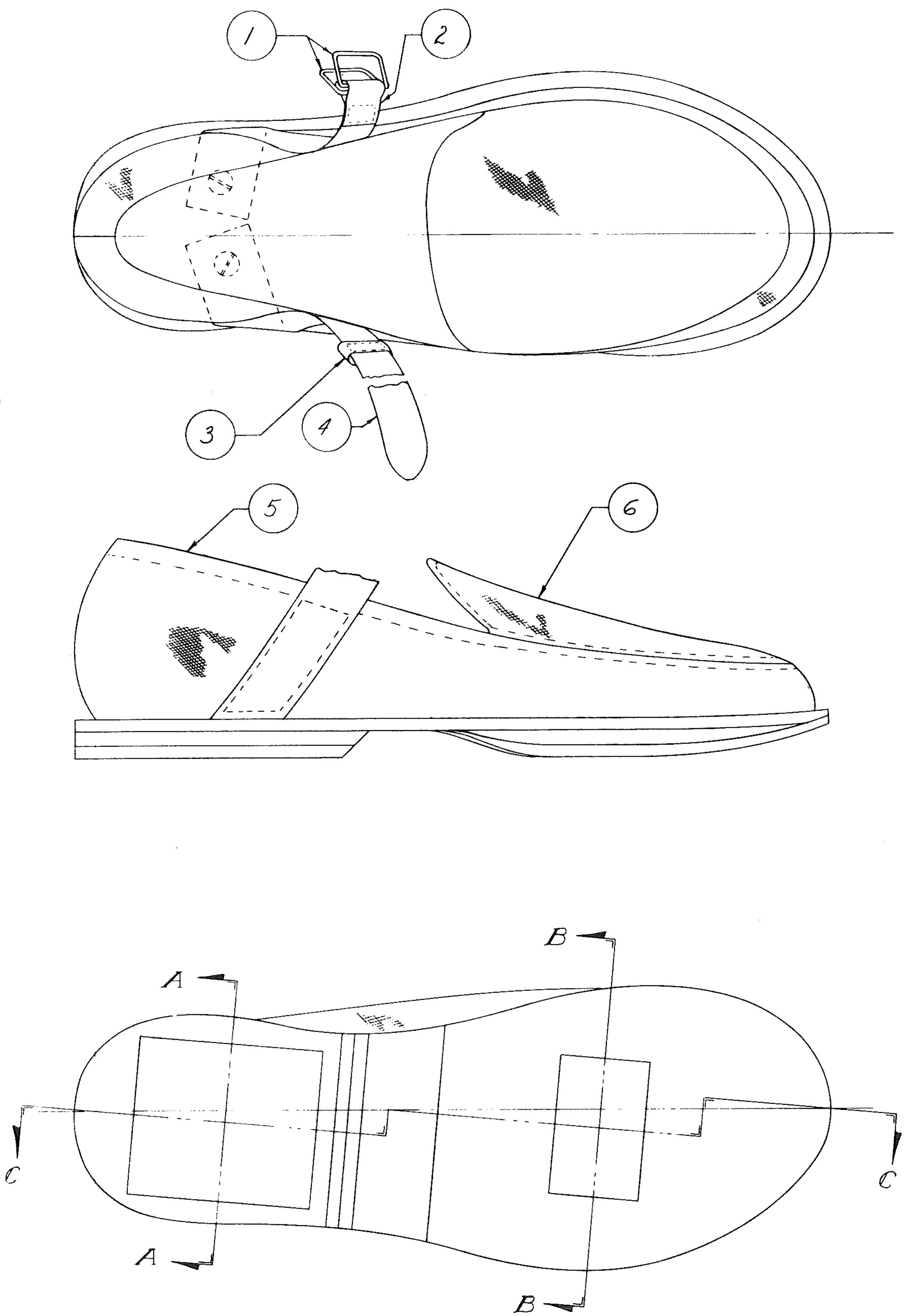
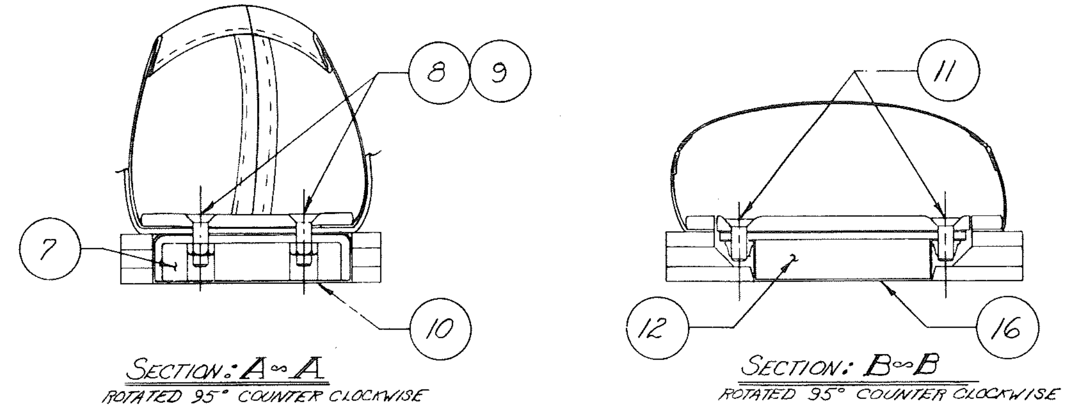
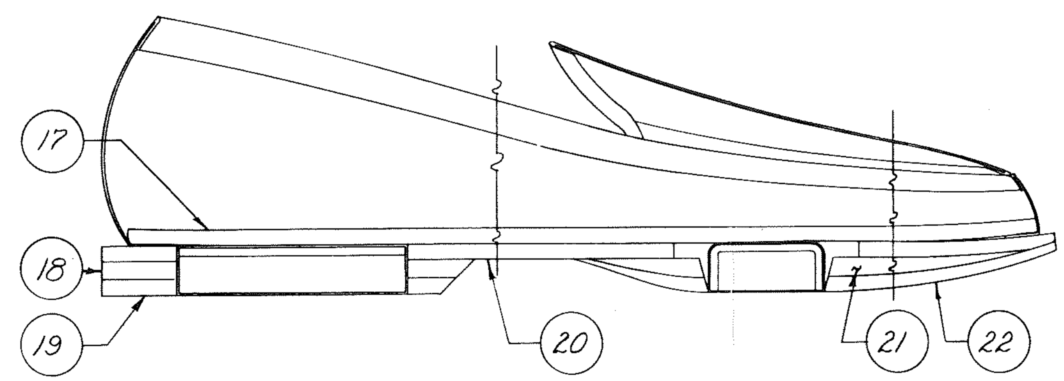


Fig. VII-1 Fourth Shuffler Engineering Evaluation Model







SECTION: C∾C

ROTATED 5° COUNTER CLOCKWISE

NOTES:

1) LEFT SHOE SHOWN - RIGHT SHOE OPPOSITE SHOWN

[1] 2) POINTS A, B, C, D, E, & F ARE MATCH POINTS BETWEEN ITEMS 5, 6, & 17 RESPECTIVELY

[2] 3) ITEMS 23 & 24 ARE NOT CALLED OUT ON FACE OF DRAWING. ITEM 24 IS USED ON ITEMS 2, 3, 4, 5, & 6 ONLY. ITEM 23 IS USED ON ITEMS 2, 3, 4, 5, 6, 7, 10, 17, 18, 19, 20, 21, & 22.

4) ASSEMBLY PROCEDURE

a) SEW ITEMS 5 & 6 TOGETHER & ROLL & SEW FREE EDGES WITH NOMEX THREAD (ITEM 24).
b) ATTACH ITEMS 1 TO ITEM 2 & SEW IN PLACE WITH ITEM 24.
c) SEW ITEM 4 TO ITEM 3 WITH NOMEX THREAD (ITEM 24).
d) USE EPOXY (ITEM 23) ON FREE ENDS OF ITEMS 2, 3, & 4 TO PREVENT UNRAVELING.
e) BOND ASSEMBLED TOP (ITEMS 5 & 6) TO INSOLE (ITEM 17) WITH EPOXY (ITEM 23).
f) ATTACH ITEMS 1, 2, 3, 4, 7, 8, 9, 10, 11, 12 & 16 TO INSOLE (ITEM 17).
g) BOND ITEMS 18 & 21 TO SOLE (ITEM 20) WITH EPOXY (ITEM 23) & GRIND TO CONFIGURATION SHOWN.
h) BOND ITEMS 19 & 22 TO ASSEMBLED ITEMS 18, 20, & 21 WITH EPOXY (ITEM 23) & GRIND TO CONFIGURATION SHOWN.
i) BOND ASSEMBLED ITEMS 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 16 & 17 TO ASSEMBLED ITEMS 18, 19, 20, 21, & 22 WITH EPOXY (ITEM 23).
j) SEW STRAPS (ITEMS 2 & 4) TO SIDES OF SHOE (ITEM 5) AS SHOWN WITH NOMEX THREAD (ITEM 24)
k) SMOOTH ALL ROUGH EDGES & MAKE SURE MAGNETS EASILY ATTAIN COMPLETE CONTACT WITH A FLAT FERROUS SURFACE.

ITEM	QTY	SIZE	DESCRIPTION	MAT'L
[2] 24	100 YDS	—	THREAD	NOMEX
[2] 23	3	TUBE KITS	3M FLEXIBLE EPOXY	2216 B/A CLEAR AMBER
22	2	3/16"x6 1/2x4 3/4	SOLE BUILD-UP	FLUOREL 1059
21	2	1/4"x6 1/2"x4 3/4"	SOLE BUILD-UP (FOAM)	FLUORELL 1066
20	2	3/16"x12"x4 3/4"	SOLE	FLUOREL 1059
19	2	3/16"x4 3/4"x3 1/2"	HEEL BUILD-UP	FLUOREL 1059
18	2	1/4"x4 3/4"x3 1/2"	HEEL BUILD-UP (FOAM)	FLUOREL 1066
17	2	3/16"x11 1/2"x4 1/4"	INSOLE	FLUOREL 1059
16	2	.010"x5"x3 3/4"	MAGNET COVERING	TFE TEFLON
15	8	MS20426AD3-5	RIVIT, SOLID, CSK	2117-T4 AL-AL
14	4	NAS1068C3	NUT, SELFLOCKING, PLATE	CRES
13	2	BM4982	MAGNET-BUNTING MAGNETICS CO.	INDOX V
12	2	—	SUB ASSY MADE FROM ITEMS 13, 14, 15	—
11	4	AN510-10R6	10-32x3/8"LG FLAT HEAD SCREW	CRES
10	2	1/16"x4 1/4"x6"	MAGNET COVERING - DUPONT VITON	#249-196-1
9	4	AN315C3R	10-32 HEX NUT	CRES
8	4	AN510-10R8	10-32x1/2"LG FLAT HEAD SCREW	CRES
7	2	BM4974	MAGNET - BUNTING MAGNETICS CO.	INDOX V
6	2	7"x8"	CLOTH - SHOE TOP	PBI CLOTH
5	2	9"x27"	CLOTH - SHOE SIDES	PBI CLOTH
4	2	1"Wx15"LG	STRAP	PBI WEBBING 101
3	2	1"Wx3 3/4"LG	STRAP	PBI WEBBING 101
2	2	1"Wx6 1/2"LG	STRAP	PBI WEBBING 101
1	4	1"	"D" RINGS	CRES

MATERIAL REQ'D FOR ONE PAIR OF SHOES

Fig. VII-2 Mobility and Restraint Footwear - Design Configuration

A
FOLDOUT FRAME

B
FOLDOUT FRAME

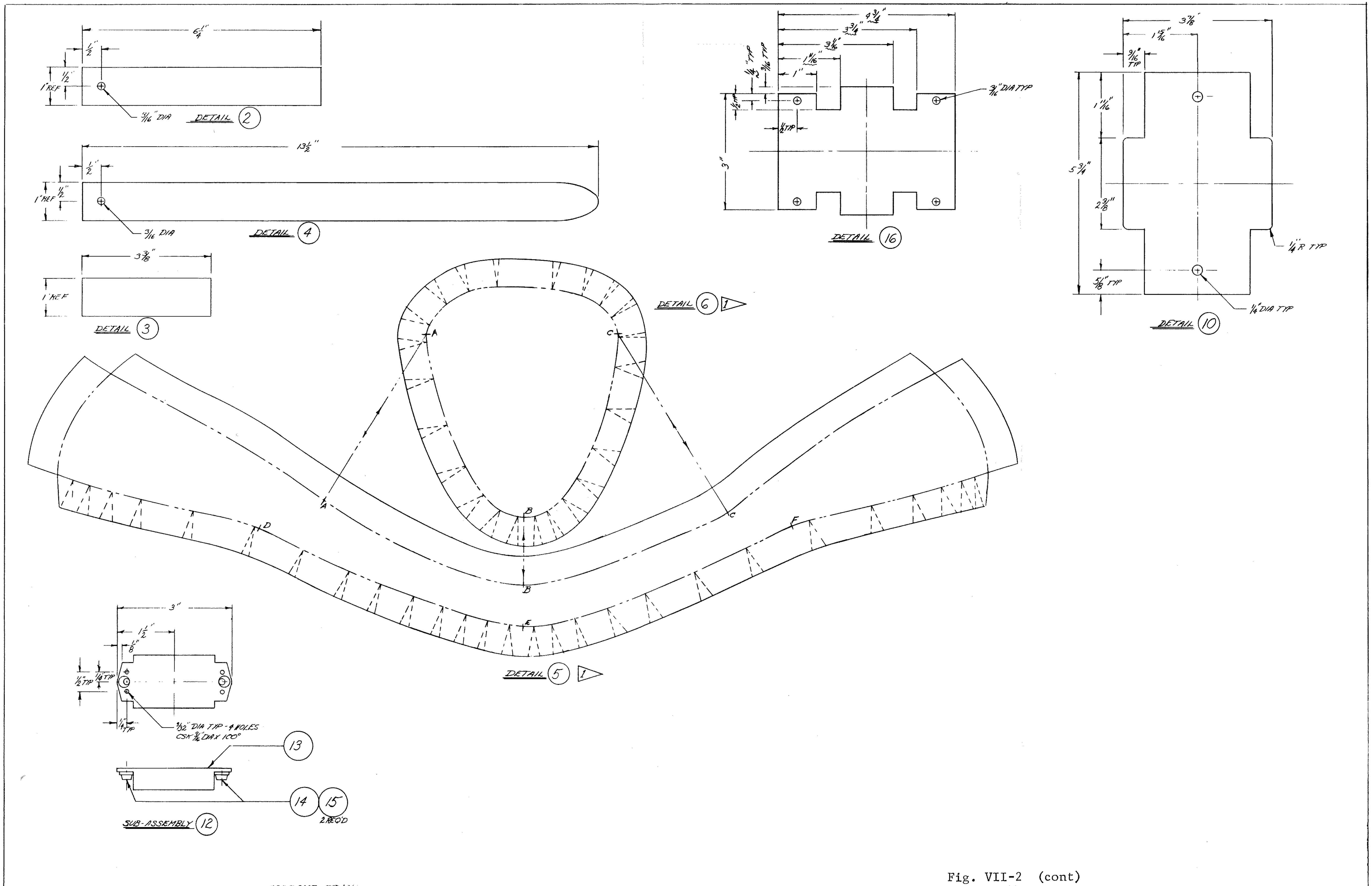
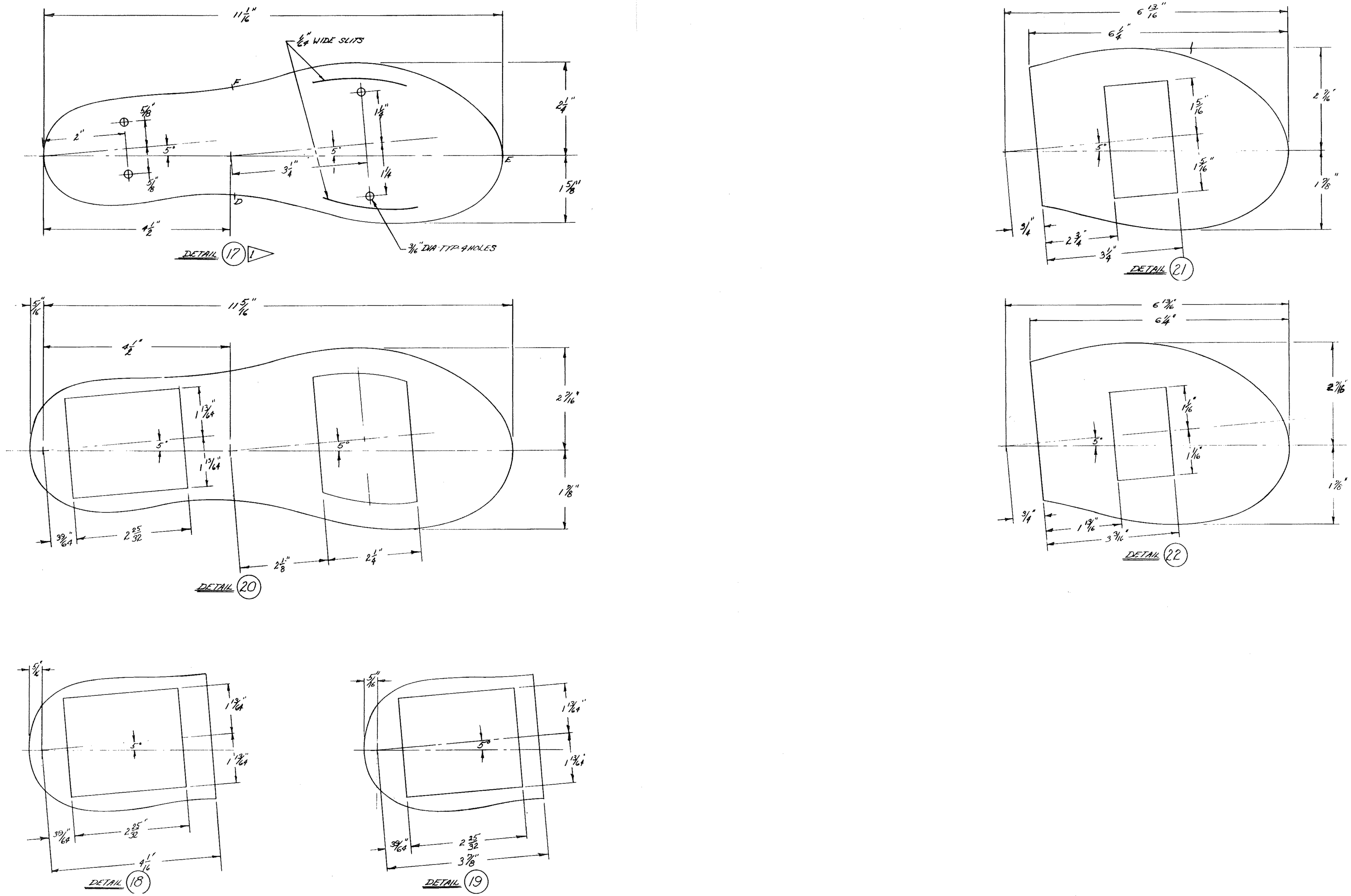


Fig. VII-2 (cont)

FOLDOUT FRAME A

FOLDOUT FRAME B



FOLDOUT FRAME

A.

Fig. VII-2 (concl) FOLDOUT FRA

B.

Fig. VII-3 Final Shuffler Configuration

VIII. CONCLUSIONS

The need exists for man to have a mobility and restraint devide for use in zero-gravity environment to maintain body position while performing useful tasks and transporting objects to different locations. Mobility and restraint footwear, known as shufflers, has been designed to fulfill this need by using permanent magnet assemblies in conjunction with a 30-mil ferrous floor. This concept provides a 23-lb distributed normal holding force per shuffler, 8 lb in the ball area of the foot and 15 lb in the heel area.

As the name implies, the concept uses a shuffling technique, or sliding one foot forward on a low coefficient of friction surface, maintaining constant contact with the floor. The propelling force will originate from the high coefficient of friction surface in the heel area of the foot. The low coefficient of friction and high coefficient of friction materials are Teflon and Viton, respectively. The use of these materials in conjunction with the distributed attractive force not only provides the user with stability in shuffling and performing tasks but allows easy separation from the floor when free float is desired.

A detailed force analysis of different percentile men performing various tasks revealed that the largest normal holding force required for stability was 13.6 lb. Several evaluation prototypes were constructed and tested in simulated zero gravity. The results confirmed the analytic work and showed the shuffler to be a workable concept. The tests also acquainted the design engineers with configuration design requirements that were incorporated in final design. They are as follows:

1) The shuffler sole must be flexible to permit correct orientation of the magnet assemblies;
2) The magnet assembly in the ball area of the foot must float to allow constant contact while shuffling;
3) A closed toe cap is necessary to permit lifting of the toe area of the foot while shuffling;
4) A restraint strap is necessary to lift the heel magnet from the ferrous surface;
5) Provisions must be provided for removal and replacement of the Teflon surface in the ball area of the shuffler due to wear;
6) D-ring fasteners are preferred over buckles, snaps, or velcro for use on the restraint straps.

There is a wear problem associated with the teflon covering of the front magnet assembly. This introduces the maintenance problem of replacing the worn teflon surfaces. We investigated other methods of applying a low coefficient of friction surface to the magnet assembly but because of the limitation on time and cost, the teflon covering was retained.

Magnetic attraction has been used previously as a mobility device, but its use has been more or less confined to an earth-oriented gait. Previous concepts often used magnets as the actual contact surface and stiff soles for the support of these magnets. Test subjects experienced a skating effect when they attempted to propel themselves forward. The shufflers have been designed to eliminate this problem by introducing various coefficient of friction surfaces throughout the sole area. The flexible sole has been introduced to keep the magnet aligned with the ferrous surface at all times.

The two prototype articles fabricated as part of this contract have been finalized as follows:

1) Size - The footwear is nominally designed for a 9D foot;

2) Material - The materials used in the shufflers are compatible with spacecraft environment and the waters of a neutral buoyancy test tank;

3) Don - The shufflers will slip on as primary footwear;

4) Magnets - Permanent magnets with constant holding strengths will be used in the shufflers;

5) Temperature - Temperature limitations of the magnets are $-20^{\circ}F$ to $180^{\circ}F$.

The contractual requirements of providing the final design for the prototype mobility and restraint footwear has been fulfilled. Several engineering evaluation models were fabricated and tested by design engineers to achieve a realistic and workable footwear. Test films are available from Maynard C. Dalton, Technical Monitor at MSC, Houston, or Arthur A. Rosener, Program Manager at Martin Marietta Corporation, Denver. Further zero-gravity testing on KC-135 parabolic aircraft flights or an early Apollo Applications flight can be carried out with reasonable assurance of success without modification of the shufflers.

IX. RECOMMENDATIONS

A. SHUFFLERS

The wear problem associated with the teflon covering on the front magnet assembly indicates that further work in this area should be accomplished. We have investigated armalon covering, teflon spray, and potting the permanent magnet assembly in teflon. The armalon covering was quickly worn through during testing and was rejected because teflon has better wear characteristics. Teflon spray was rejected because we could not obtain as durable a coating as desired. Potting the magnet assembly in teflon introduced another problem. Because of the curing process involved with such an operation, the magnet assembly would have to be remagnetized. We feel that with development, the most promising solution would be the teflon spray.

It should be noted that the shufflers fabricated during this contract have been designed as primary footwear. In actual flight usage, the shufflers should be designed as secondary footwear. If this were the case, a simple donning and doffing operation could take place, eliminating the need of exchanging two pair of primary footwear.

B. USE OF SHUFFLERS

The results of this contractual study indicate that further shuffler testing would be useful in a zero-gravity condition. This testing should be performed first on parabolic flights of the KC-135 aircraft. If the concept continues to look promising, a shuffler package should be incorporated as an experiment on an early Apollo Applications Program flight. The shufflers could be used in conjunction with existing scheduled experiments.

The analysis has indicated that a 0.030-in. pure iron floor will be required for use with the shufflers in their area of operation. For the zero-gravity parabolic aircraft flights, an 18x156x0.030-in. iron sheet could be secured to the ceiling of the aircraft cabin. This iron sheet would weigh approximately 23.2 lb and should have structural support. If incorporated on an early Apollo Applications flight, it would be very impractical to completely cover the existing grid-type floor design of the Orbital Workshop with a large piece of sheet metal. Therefore it would be desirable to use smaller pieces that can be easily stored or fastened in particular operational areas. This decreases the weight factor considerably and still allows experimental use of the shufflers.

The area of the floor is directly associated with the type of work activity to be handled while using the shufflers. For example, with the work task board used in experiment M508 the astronaut must work the experiments on the panel with his feet positioned in a pair of immovable "Dutch" shoes. If these shoes were replaced with the magnetic shufflers and a ferrous surface, a direct comparison could be made between the two foot restraints.

The work task board is mounted on the wall of the Orbital Workshop approximately 40 inches from the grid floor and is 30 in. wide and 10 in. deep. Assuming a clearance on either side of the panel of 3 inches, a floor piece 36 in. long can be used in front of the panel. A larger dimension in this direction might lead to difficulties as far as spacing is concerned. With this sheet metal plate located in front of the panel, a width of 2 ft would be sufficient. Various combinations of this 2x3-ft area could be used to provide a ferrous surface that could be used with several other experiments such as the Human Vestibular Function Rotating Chair Assembly (M131) and the Metabolic Activities Bicycle Ergometer (M171). These two experiments involve two people, a subject and an observer. The observer in each case would be ideally suited to use the shufflers to move about and record what he saw during the experiments.

We recommend that six separate pieces of the above dimension floor be incorporated into an experiment package for use in the workshop. This would enable an astronaut to have two 3x4-ft work areas connected by a 6-ft walkway. Also, by aligning the floor pieces in a straight line, an astronaut could exercise the shuffling mode over a distance of 18 ft.

The floor will consist of structural members sandwiched between two grid networks. The grid network will be 4 in. thick and will have a uniform grid pattern throughout the floor area. This uniform pattern will allow the metal sheets to be used in nearly any orientation desired.

Since the flat sheets must remain fairly flexible as far as location is concerned, they need not be attached permanently.

The attachment to the grid-type floor could be accomplished in several ways. Some possibilities are magnets, spring clips, or clamps. They must leave the metal sheet relatively free from discontinuities on its surface so the astronaut could move about without stumbling.

Consideration must be given to MS33586, Definition of Dissimilar Metals, since the ferrous sheet metal and the grid floor design are made of different materials. As indicated by this military standard, the contact surfaces of dissimilar metals should be separated by a protective material to prevent galvanic corrosion. Corrosion of the ferrous surface itself must also be considered. These factors may lead to a thin protective coating of the iron sheet metal that would meet spacecraft compatibility requirements. This film will have to be considered in the magnetic circuit design.

When the metal floor pieces are stacked and banded together, they will require little storage space. A container containing three pairs of magnetic shoes and the floor attachment devices could be fastened to the stack of metal plates, making a single packaged unit as shown in Fig. IX-1.

The following is a weight breakdown of a proposed experiment package:

Materials	Weight (lb)
6 2x3x0.030-in. iron sheets	51.20
24 fastener assemblies	6.00
1 metal box	10.50
2 fastening straps	0.75
3 pairs of magnetic shoes	13.50
Total	81.95

The shufflers have been designed with and fabricated from materials compatible with spacecraft environment. No further development of the shufflers will be necessary to incorporate this as an experiment on an early Apollo Applications Program flight.

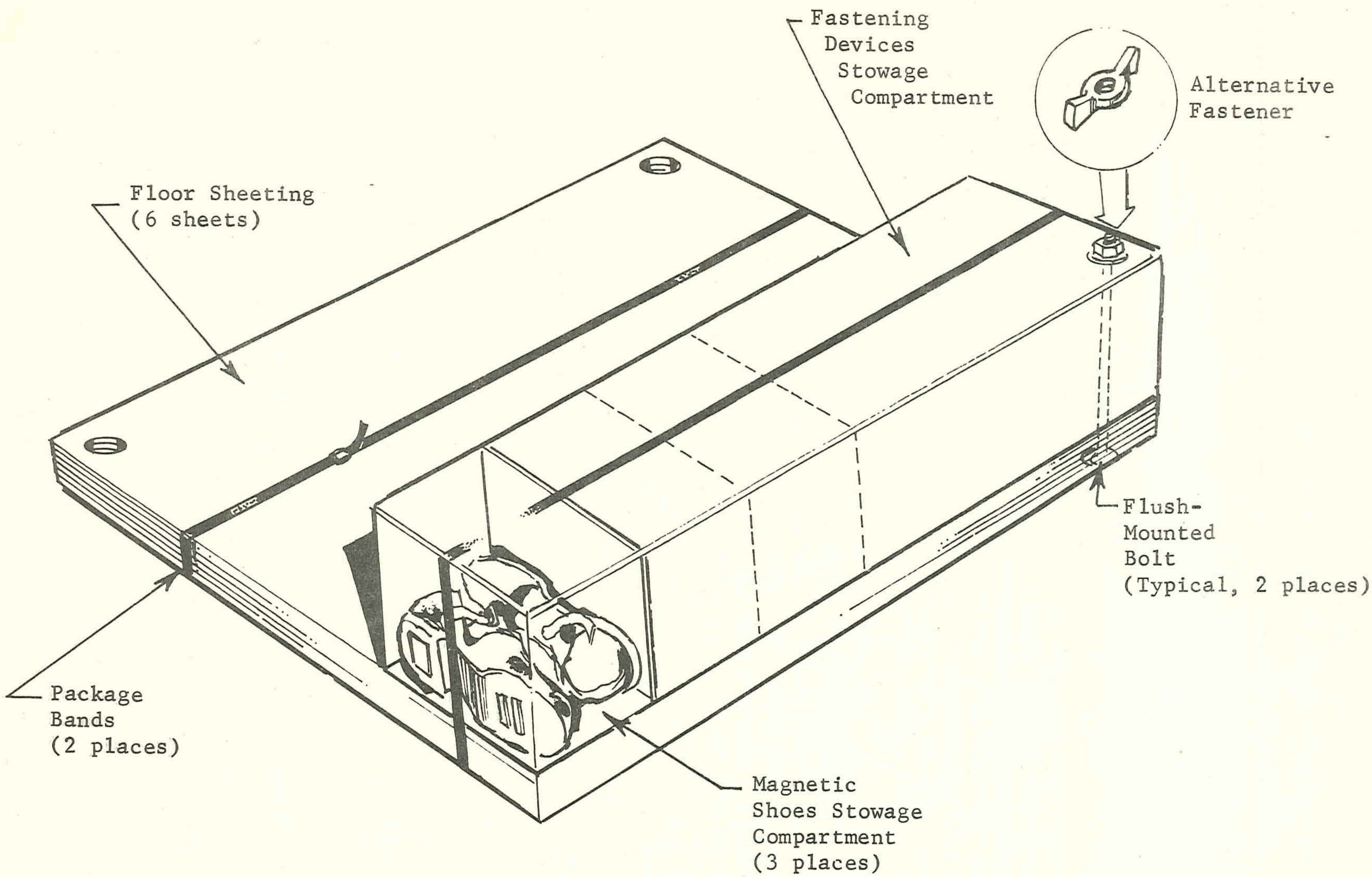


Fig. IX-1 Mobility and Restraint Footwear Experiment Package

X. APPLICABLE FORMULAS

A. FORCE ANALYSIS

1. $V^2 = V_o^2 + 2ax$
2. $F = ma$
3. $F\Delta t = mV$
4. $\theta = \omega_o t + \frac{1}{2}\alpha t^2$
5. $\theta = \theta_o + \omega t$
6. $T = I\alpha$
7. $F = \mu N$
8. $W = mg$

Symbols

a	acceleration (ft/sec^2)
d	distance (in.)
F	force (lb)
g	acceleration of gravity, 32.2 ft/sec^2
I	moment of inertia (lb-in.-sec^2)
m	mass (lb)
N	normal force or attractive force of magnet (lb)
t	time (sec)
T	torque (ft-lb)
V	velocity (ft/sec)
V_o	initial velocity (ft/sec)
W	weight (lb)
x	distance (ft)
α	radial acceleration (rad/sec^2)
θ	radial distance (rad)

θ_o initial radial distance (rad)

ω radial velocity (rad/sec)

ω_o initial radial velocity (rad/sec)

μ coefficient of friction

B. MAGNETIC ANALYSIS

1. $\varphi = BA$
2. $\varphi = FP$
3. $P = \frac{\mu A}{L}$
4. $\mu = \frac{B}{H}$
5. $N = 0.577\ B^2\ A$ (where the constant 0.577 is a conversion factor, A has units of square inches, and B has units of kilogauss)

Symbols

A cross-section area of flux path perpendicular to lines of flux (cm^2)

B flux density (gauss or maxwells per square centimeter)

F magnetomotive force (gilberts)

H magnetizing force (oersteds)

L length of flux paths (cm)

N pull of magnetic on ferrous surface (lb)

P permeance (maxwells/gilberts)

t thickness (in.)

φ flux or lines of force (maxwells)

μ permeability (gauss/oersteds)

XI. REFERENCES AND BIBLIOGRAPHY

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