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FLOOR ANALYSIS AND SPECIFICATION FOR PROTOTYPE MOBILITY AND RESTRAINT FOOTWEAR, CONTRACT NAS 9-9336

November 1969

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Engineer, Contract NAS 9-9336

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APPROVED

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FOREWORD

This document was prepared by the Martin Marietta Corporation under Contract NAS 9-9336, "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. This document defines the floor specifications to be used with the prototype footwear delivered under this contract.

CONTENTS

INTRODUCTION

Magnetic circuit design requires familiarity with both magnetic and mechanical characteristics of ferro magnetic materials. Often the mechanical properties of a magnetic material will have as great an influence as its magnetic properties. By varying the basic design parameters of a magnetic circuit (the permanent magnet, the air gap, and the armature), several solutions are available for a required result.

This report will state the lightest weight floor or armature configuration to be compatible with the mobility and restraint footwear known as the shufflers designed and developed under Contract NAS 9-9336. It will be handled in three parts, an introduction to the magnetic analysis, the analysis itself, and the final design specification.

I. MAGNETIC CHARACTERISTICS

Prior investigation has revealed the best permanent magnet material for our application is Indox V because of its high pull strength - small volume relationship. With this in mind, the magnetic circuit design will be centered in the area of the air gap and the armature to be used with the magnet. From the final report we find we need a 15 lb attractive force in the heel area of the shuffler. This will be the basis for the magnetic circuit design.

In general, magnetic circuits using permanent magnets have three elements as shown in Figure 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 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.

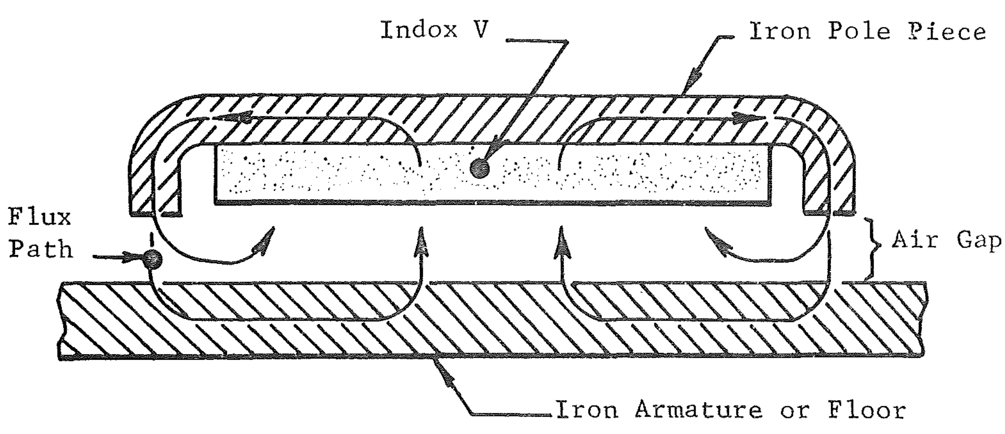


Figure 1 Basic Magnetic Circuit

One important factor in the design of a permanent magnet is that the magnet shall be capable of producing sufficient magnetomotive force to overcome the reluctance of the magnetic circuit and produce the desired flux throughout various elements of the circuit. The magnetic circuit in many cases must supply additional magnetomotive force over and above that indicated by the air gap itself. The total magnetomotive force is determined by adding together the magnetomotive force required for the pole piece, geometry of the air gap, the soft iron, and joint resistance.

The magnetomotive force required for joints is a direct function of the effective length of the gap times the flux density in the gap. In the case of Indox V, with the flux density normally designed to work in the area of 3000-3500 gauss, poor joints will require a certain portion of the magnetomotive force produced by the magnet. It should be noted, however, that even with very good joints, the equivalent gap length would be about 0.0015 inches.

The relation of the magnetomotive force required to pass a given flux density through a soft iron pole piece or armature can be developed as follows:

if $\phi = BA$

and $\phi = FP$

then $FP = BA$

but $P = \frac{\mu A}{L}$

and $\mu = \frac{B}{H}$

substituting, $\frac{FBA}{HL} = BA$

simplified, $F = HL$ or $F = \frac{BL}{\mu}$

Here the magnetomotive force (F) has units of gilberts, the magnetizing force (H) has units of oersteds, the length of the path (L) has units of centimeters, the flux density (B) has units of gauss, and the permeability (μ) has units of maxwells/gilberts.

The value of permeability ($\mu = B/H$) can vary greatly depending on the desired flux density. It can be readily realized from Table 1 and the formula $F = \frac{BL}{\mu}$, that it is desirable to work the soft steel or annealed iron at the lower flux densities since less magnetomotive force is required at that point.

FLUX DENSITY (gauss) B	PERMEABILITY (maxwells/gilberts) μ	
	PURE IRON, Annealed	COLD ROLLED STEEL
10,000	12,000	2,000
14,000	7,800	1,170
18,000	300	180
20,000	90	65

TABLE 1 PERMEABILITIES OF PURE ANNEALED IRON AND COLD ROLLED STEEL AT VARIOUS FLUX DENSITIES

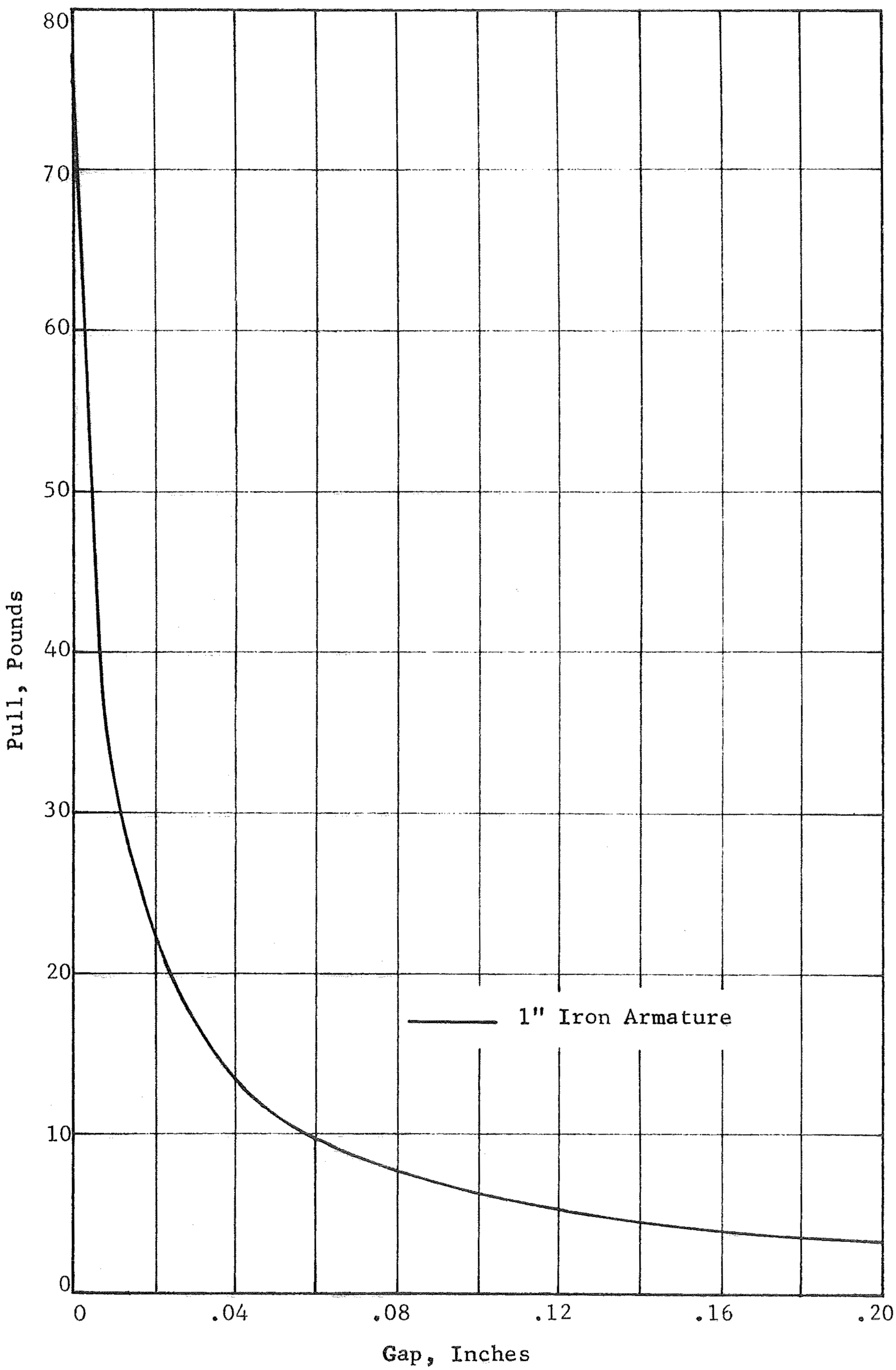
II. ANALYSIS

For maximum pull in zero-gap applications, the armature thickness should be at least the same relative thickness as the mild steel pole piece used with our magnets. For armature thicknesses 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.

For the analysis, we shall investigate three armature materials: vanadium permendur, pure annealed iron (similar to cobalt iron), and hot rolled, low carbon sheet metal. To determine the thickness required for the armature, we must first investigate the characteristics of the permanent magnet assembly used in the circuit.

Bunting Magnetics of Chicago has commercially available a ceramic assembly that will meet our design standards. The results of a pull test (Figure 2) with this magnet shows the attractive force to be 77.5 pounds at zero gap and 16.2 pounds at a 1/32-inch gap. From the formula $N = 0.577\ B^2A$, extracted from Permanent Magnet Handbook (Ref. 1), we see that the pull (N) is proportional to the flux density squared (B^2) at the point of interface. For a drop in pull from 77.5 pounds to 16.2 pounds, the flux density would decrease by a factor of

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



<u>**BM-4974 PULL CHARACTERISTIC CURVE**</u>

Figure 2

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 inches) to maintain the 16.2 pound attractive force. If the armature material was changed from low carbon sheet metal to a material with higher permeance characteristics, this factor would become smaller yet. With a magnetizing force of 10 oersteds (the magnet industry uses 2.5-10 oersteds as a design standard) acting on the armature, we find from Figure 3 an induction of:

1. Vanadium Permendur -- 16.7 kgauss
2. Pure Iron, Annealed -- 16.5 kgauss
3. H.R., Low Carbon Sheet Metal -- 14.0 kgauss

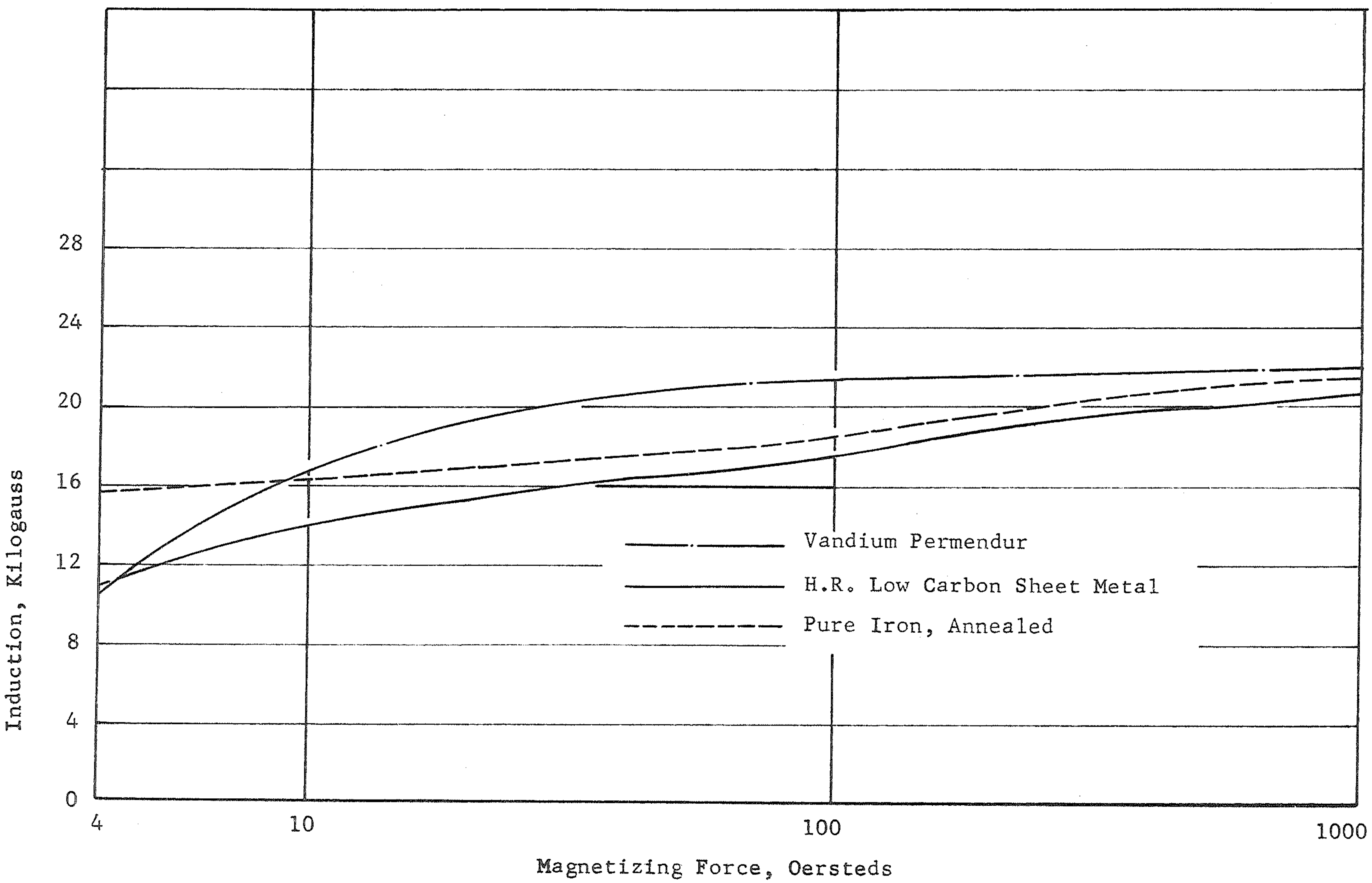
If we used pure annealed iron instead of low carbon sheet metal, the factor would be

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

The thickness of the armature would then be

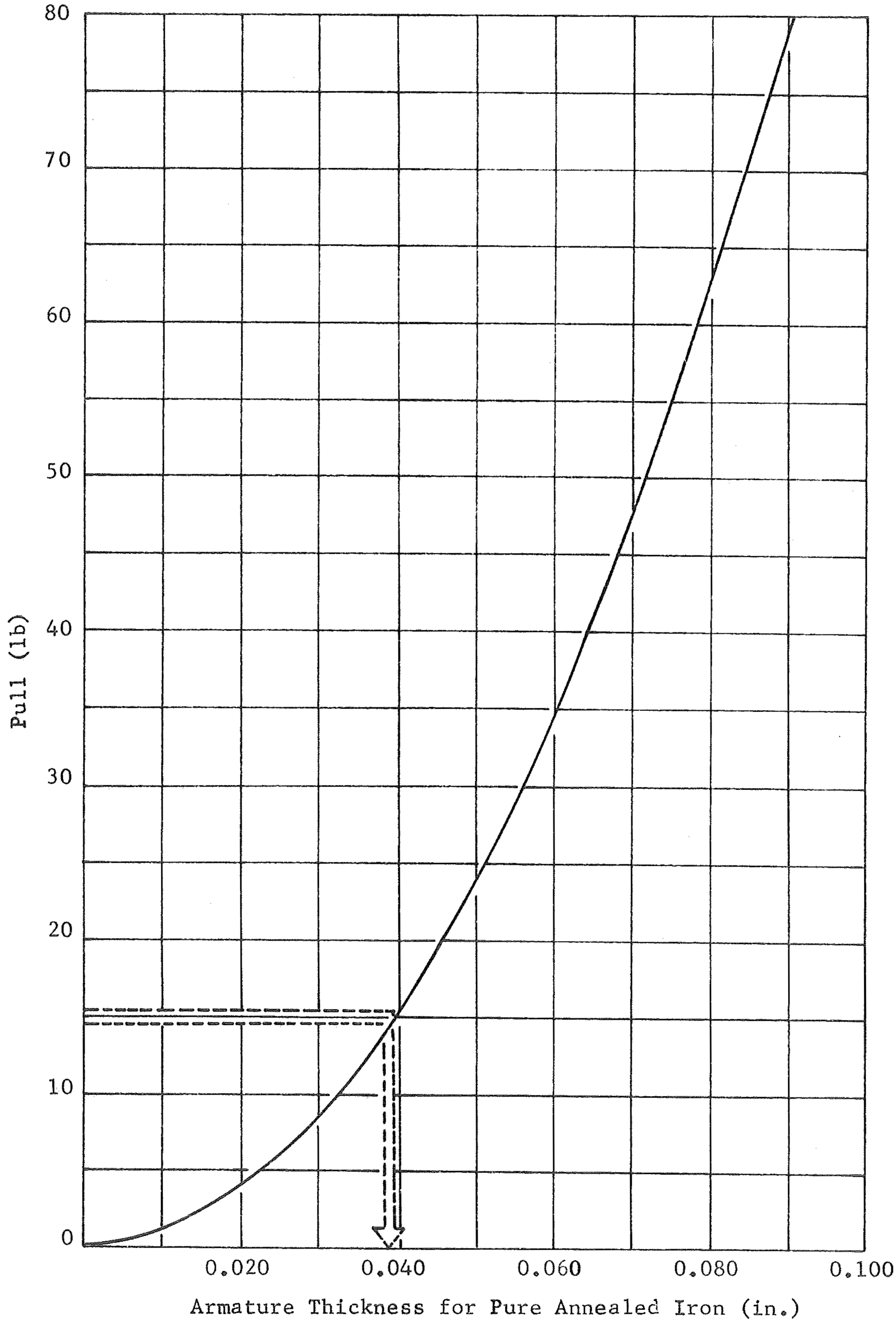
$$t = (0.388)\ (\text{thickness of pole})$$
$$= (0.388)\ (0.1046)$$
$$t = 0.0406 \text{ inches}$$

The results of a series of these calculations is shown on Figure 4. It shows the armature thickness required to obtain certain attractive force levels for the particular magnet assembly used



MAGNETIZATION CURVES OF VARIOUS MAGNETIC MATERIALS

Figure 3



ARMATURE DESIGN CURVE FOR BM-4974 MAGNET ASSEMBLY

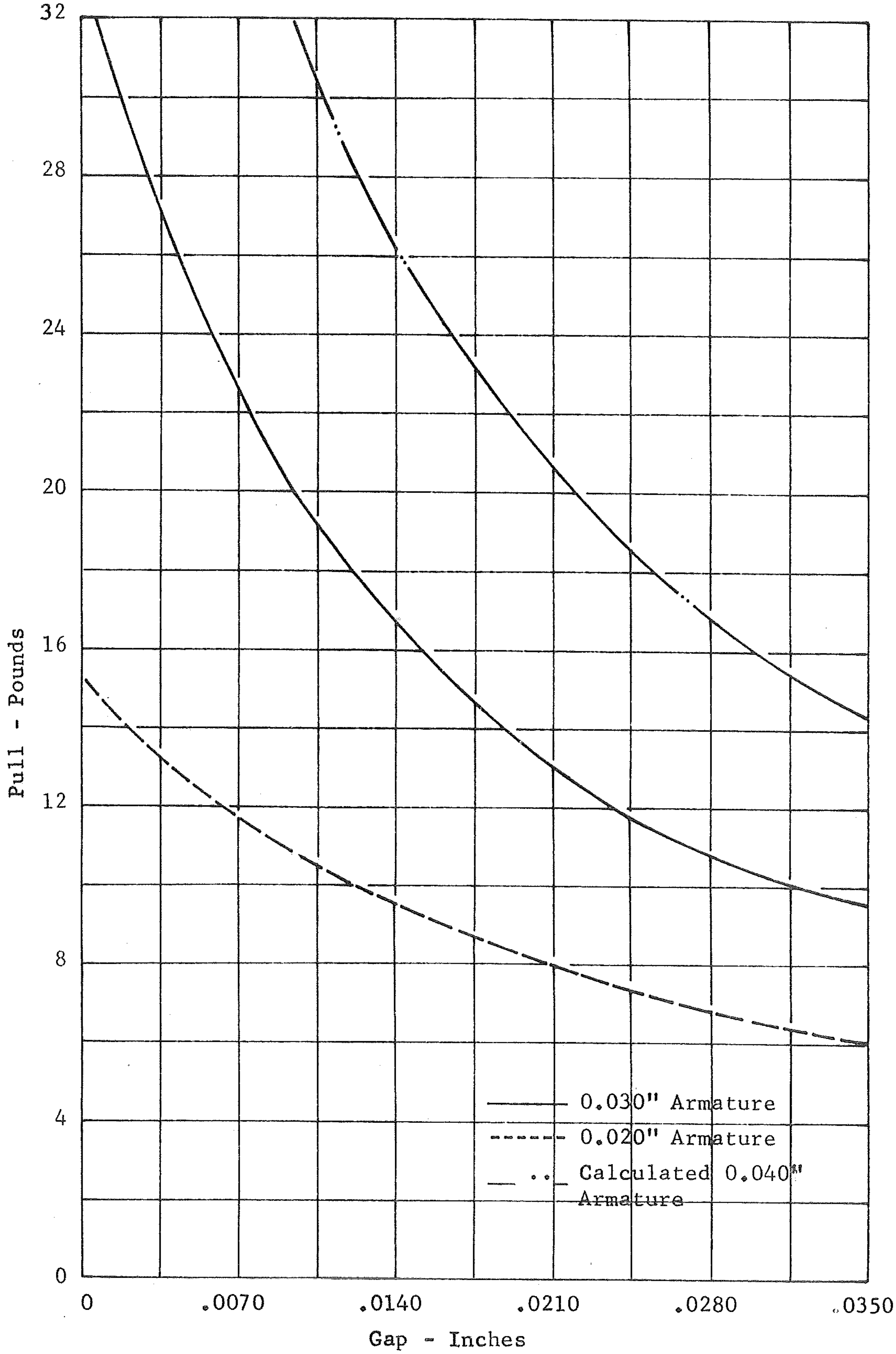
Figure 4

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 path from the pole piece. This is not entirely true, however, since the lines of force tend to bow outward. The exact 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. The testing results of Figure 5 show that the armature thickness can be reduced by a little over 25 percent due to this characteristic. These curves were developed on a tensile test machine for low carbon sheet metal with thicknesses of 0.020 and 0.030 inches. The 0.030-inch armature met design standards of 15 pounds attraction with a 1/64-inch gap.

Introducing any air gap between the magnet and armature will greatly reduce the attractive force of a magnet. This is especially true for a ceramic assembly, as shown in Figures 1 and 5.

The precise mathematical calculation of the permeance of flux paths through air, except in a few special cases, is a practical impossibility. This is because the flux does not usually confine itself to any particular path which has a simple mathematical law. For this reason, computations are carried out by making simplified assumptions for probable flux paths.



BM-4974 PULL CHARACTERISTIC CURVE COMPARING CALCULATED AND EMPIRICAL RESULTS

Figure 5

The first step in the application of this method is to break the magnetic field into flux paths which are of simple shape and still probable. The word "probable" as used here means that the assumed path is sufficiently similar to the true path in that the permeance determined from the mean length and area will be somewhat close to the true value. The "somewhat close" of the last sentence is purposely vague. Some of the assumed paths will have higher estimated permeances than those of the true paths and others will have lower permeances, but as the entire path is broken into several assumed paths, chances are that the error in estimating will tend to balance out. The following formula is used to determine permeance with this method:

$$P = \frac{\mu A}{L}$$

Here A is the cross-section area of the flux leakage path in square centimeters, L is the average length of the leakage path in centimeters, and μ is the permeability. For a vacuum, in the CGS metric system, μ is equal to 1.0, and it is essentially the same for air. A more detailed description of the more complex paths is given by H. C. Roters in Chapter 5 of his book entitled "Electromagnetic Devices".

The armature thickness could only be reduced below 0.030 inches by altering the physical characteristics of the ceramic assembly. Maintaining the same area of contact, we could decrease the pole thickness and increase its width. This would distribute the flux load over a larger portion of the floor and allow us to decrease the floor thickness. This, however, would leave us with a magnet design that would not fit into the shuffler without modification of its shoe-like appearance. At present we have the largest magnet commercially available that will both fit in the shuffler and meet design standards.

III. CONCLUSIONS

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, annealed, pure iron material with a thickness of 0.030 inches. This particular floor material used in conjunction with the ceramic magnetic assemblies embedded in the shufflers will give the lightest weight floor configuration that will still meet the design requirements set forth in the final report of Contract NAS 9-9336.

The floor material can be procurred from Steel Sales in Chicago under the trade name "magnetic iron". The typical analysis for this material is shown:

Carbon	0.015%
Manganese	0.028%
Phosphorus	0.005%
Sulphur	0.025%
Silicon	0.003%

APPLICABLE FORMULAS

1. $\phi = BA$
2. $\phi = FP$
3. $P = \frac{\mu A}{L}$
4. $\mu = \frac{B}{H}$
5. $N = 0.577\ B^2A$ (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, square centimeters

B = flux density, gauss or maxwells per square centimeter

F = magnetomotive force, gilberts

H = magnetizing force, oersteds

L = length of flux paths, centimeters

N = pull of magnetic on ferrous surface, pounds

P = permeance, maxwells/gilberts

ϕ = flux or lines of force, maxwells

μ = permeability, gauss/oersteds

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