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COMPARISON OF TWO HSGT MAGNETIC SUSPENSION SYSTEMS (ATTRACTION)

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16. Abstract

Two alternate attraction magnetic suspension systems are compared on a magnetic performance basis as well as on their lift-to-weight (L/W) capabilities. On an equal current basis, the lower reluctance, flat track configuration has higher lift force and better L/W than the U shaped track configuration with its larger leakage flux. With equal magnetization (unequal currents) and low guidance forces ($F_G/F_L \leq 0.3$), the U shaped track has a higher L/W ratio, but both attraction systems suffer from low L/W when all elements of the suspension system are considered.

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1. INTRODUCTION

Magnetic attraction and repulsion[1,2] form the basis of two competing magnetic suspension schemes for high-speed ground transportation in the 500 km/hr range. However, in this paper we are only concerned with the attraction scheme, but with two alternate track configurations. The attraction approach (electromagnetic) uses conventional electromagnets in which the magnet currents are controlled by feedback to obtain stability and maintain a gap of about 1.5 cm between the vehicle magnet and the steel track. Whereas the repulsion system requires efficient generation of eddy currents to obtain good performance, eddy current generation in the attraction system decreases its performance with increasing speed. In addition, it may give rise to significant magnetic drag (for an unlaminated track) and magnet current control problems at high speed.[3] Nevertheless, vehicles built on such principles work, and two German firms, Messerschmitt·Bölkow·Blohm (MBB) and Krauss·Maffei (KM), each have manned vehicles that have run on short test tracks at speeds above 100 km/hr. The MBB system uses separate lift and guidance magnets while the KM system uses a combined lift and guidance magnet. It is these differences in the MBB and KM track configuration that we wish to examine. Resolution of the dilemma as to which attraction system is better is at present unresolved and may not be resolved on a purely magnetic basis, but will also depend upon system considerations, i.e., switching capability and guideway complexity, ability to operate reliably on practical guideways under varying environmental conditions, costs, and other as yet unknown criteria.

The MBB and KM magnetic suspension schemes are illustrated in Fig. 1. Figure 1a shows that in the MBB configuration separate magnets are used against two orthogonal surfaces to independently provide the requisite lift and guidance forces. Because a single magnet operates against a flat track, we will refer to this scheme as either the flat track or MBB configuration. In contrast, the KM scheme in Fig. 1b shows that pairs of magnets alternately displaced from the center line of an inverted U-shaped rail provide both horizontal and vertical forces. Changes in the required guidance force, such as that induced under a lateral wind load, is accomplished in the KM system by unbalancing the currents in the pairs of magnets keeping the average lift force for the pair constant. Of course, it is the amount of magnet offset from the center line of the U-shaped track that determines the maximum guidance force that can be obtained relative to the lift force. It is precisely this force dependence on magnet offset for the U-shaped track that we wish to examine and compare to an identical magnet operating against a flat track.

The experimental setup was described previously[3] and only the essential features will be given here for completeness. Small scale magnets were built having an arc shape (1.5 m diameter, length 20 cm) to allow accurate measurements of the forces against a 1.5 m diameter circular steel track of either the KM or MBB configuration. The circular nature of the track was required for velocity dependent results given in reference 3. The magnets were mounted on a nested set of platforms sliding on low friction linear bearings that permit three orthogonal force measurements to be taken: lift, guidance, and drag. The drag measurements (for $v\neq0$) are not reported here. Only the static measurements of lift and guidance were measured. The magnet-track cross section of both the KM and MBB configurations used in these experiments are shown in Fig. 2, along with the field plots predicted by the computer programs TRIM and FORGEY.[4] These two programs enable one to predict the fields, forces, and energy for arbitrarily placed iron and currents in a two dimensional array. B-H tables for several kinds of material can be included in these programs. TRIM generates a triangular mesh and performs a relaxation calculation of the magnetic field. FORGEY computes the forces on the steel and windings as well as the energy stored in the air and iron. Up to 5000 mesh points can be used in the region of interest and the output can be tabular and/or on magnetic tape. The latter possibility will allow the triangular mesh to be plotted as well as the flux lines and the outline of the iron. Figure 2 is an example of this output.

2. RESULTS

The TRIM and FORGEY programs were used to calculate the fields and forces on the cross section of the experimental magnet as a function of the magnet displacement from the center line of the track for the U-shaped track (or KM configuration) as well as for the magnet against the flat track (MBB configuration). These results are shown in Fig. 3 along with the experimental measurements.

2.1 Experimental

As shown, both in the experimental and theoretical results, the guidance force (KM) at first increases linearly with displacement. The fall off in lift force is less rapid indicating that a small guidance force can be obtained at little or no reduction in the lift force in the KM design. Unfortunately, the maximum lift force for the U-shaped track still lies 20% below that for the flat track. At realistic guidance forces[5] ($F_G/F_L = 0.4$) where the guidance force is 0.22 kN/m, the lift force has fallen to 0.56 kN/m - a decrease of 41% from its original value or 50% of the flat track value.

A comparison between the two track configuration (for equal current) might be made for the most efficient U-shaped track condition, i.e., where $F_L + F_G$ = maximum. This occurs at $F_G/F_L = .22$ where $F_L + F_G = 0.96$ kN/m. However, to make the comparison to the flat track valid, we need the equivalent lengths of magnet to obtain the same lift and guidance forces. For a $F_G/F_L = 0.22$ this results in magnet length (flat track) = 0.85 magnet length (U-shaped track). That is, the equivalent magnet weight to obtain the same lift and guidance forces for the flat track is 85% of that for the U-shaped track. Note that this is for magnet weight alone and does not include the required control systems or weight differences that might result in the vehicle structure. Note also that this 85% value is an upper bound and is lower for the realistic case of $F_G/F_L = 0.4$ where magnet length (flat track) = 0.69 magnet length (U-shaped track) for equal magnet current. Because the equal current condition of the two magnets appears to penalize the U-shaped track configuration, force comparison of the two tracks under equal magnetization conditions will be considered in another section.

2.2 TRIM and FORGEY

While the TRIM and FORGEY results give the same dependence on B/A as the experimental results shown in Fig. 3, the magnitude of the predicted forces are lower than the experiment: ~ 12% for the flat track configuration and ~ 20% for the U-shaped track. This disagreement has not been resolved even though the experimental results have been checked and verified and found to be internally consistent with respect to the two track configurations. While this places the FORGEY results in question, other TRIM results such as magnetic field strength and structure are more accurately predicted, including the field peaking in the gap at the corners of the magnet.[3,6]

In Fig. 2 the larger reluctance of the U-shaped track as compared to the flat track is evident; note the relative amounts of leakage flux. While a larger leakage flux indicates decreased magnetic design "efficiency", such a penalty may not be so severe if magnet current could easily be increased up to saturation.

An attempt to assess and compare this performance feature between the two track configurations was done using TRIM and FORGEY on full scale magnets, a size comparable to what might be used on a passenger-carrying vehicle. The size of these magnets is shown in Fig. 4 along with the flux plots and the computed forces. Note that the central part of the magnet core is 4 cm thick compared to the 3 cm pole width. This was done to let the magnet saturate more uniformly. Also, the depth of the U in the track is shallow in order to intercept some of the leakage flux and convert it into useful lift.

Then the lift forces were obtained from FORGEY as a function of magnet current for the two track configurations, with the constraint that $F_G/F_L = \sim 0.3$ for the U-shaped track. This dependence is shown in Fig. 5 and clearly indicates the onset of saturation, $\sim 2 \times 10^4$ AT for the U-shaped track and $\sim 1.6 \times 10^4$ AT for the flat track. The difference in these two values for saturation can be interpreted as a measure of the reluctance of the magnetic circuit verifying the higher magnetic efficiency of the flat track configuration.

From Fig. 5, one can also obtain the normal operating point of the magnet and its lift-to-weight ratio with an assumption about the dynamic operating conditions. If a factor of two is allowed for the dynamic range of the magnet lift force (if less than this then the guideway is probably too smooth) then, for the magnets shown in Fig. 4, 20 kN/m is probably the maximum operating point for the flat track (2×10^4 AT) and 15 kN/m (2.3×10^4 AT) for the U-shaped track. This assumes similar levels of magnet saturation in each of the two configurations. Thus, the normal operating point is the 10 kN/m (flat track) and 7.5 kN/m (U-shaped track). If we include the requisite length of guidance magnets for the flat track configuration, we obtain the following magnet lift-to-weight (L/W) ratios.[7]

Table 1. Lift/weight comparison (equal magnetization, unequal current).

Track Geometry	Lift/Weight Ratio for $F_G/F_L = 0.3$	Lift/Weight Ratio for $F_G/F_L = 0.4$
Flat track	7.31	6.80
U-shaped track	7.13	5.85

Note, however, that these values were computed for different current densities in each of the systems. This is unrealistic in that practical magnet design dictates the maximum magnet current densities.[8] A better analysis can be done by incorporating the same current density for the U-shaped track as for the flat track by increasing the depth of the U-shaped track magnet. By this technique the winding area increases along with a small increase in the magnet weight.

Comparison of the two systems (shown in Table 2) can then be done on an equal magnetization basis assuming the leakage flux of the U-shaped track magnet has not changed (untrue). Also, it should be noted that a larger magnet requires increased requirements of the magnet drivers due to the increased resistance and inductance of the larger magnet.

Table 2. Lift/weight comparison (equal current density but unequal currents).

Track Geometry	Lift/Weight Ratio for $F_G/F_L = 0.3$	(Corrected*)	$F_G/F_L = 0.4$	(Corrected*)
Flat track	7.31	(8.1)	6.80	(7.55)
U-shaped track	6.56	(8.2)	5.25	(6.56)

* The corrected values assume a 10% error in the forces predicted by TRIM and FORGEY for the flat track and a 20% error for the U-shaped track as noticed in the small scale experimental magnets. This assumes that the error remains the same for the large magnets.

Here we note that at the lower values of F_G/F_L the U-shaped track does have a lift-to-weight advantage over the flat track configuration, but only if the magnet current can be increased to bring the field levels in each of the magnets to the same value. Note also that the nominal lift force for the flat track is 10 kN/m while that for the U-shaped track is 7.5 kN/m ($F_G/F_L = 0.3$) or 6.15 kN/m ($F_G/F_L = 0.4$). Since a 50 kN revenue vehicle is expected to be ~ 30 m long a 10 kN/m lift force will require a double row of magnets 25 m long. If $F_L = 6.15$ kN/m for the U-shaped track, two 33 m rows of offset magnets will be required. The L/W values in Table 2 are for the magnet alone and do not include the power amplifiers, control circuitry, wiring harnesses, and magnet cooling - if required.

An estimate of the power amplifier requirements can be obtained from the size of the magnet windings and the energy stored in the field (from FORGEY) as given in Table 3.

Table 3. Stored energy comparison.

	Stored Energy (20,000 AT) U-Shaped Track	Flat Track
Air	485.3 J/m	560 J/m
Iron	12.4	24.7

Assuming a packing factor of 0.75 for the magnet winding and the requirement that the magnet follow the guideway to 10 Hz,[9] the magnet and magnet amplifier parameters listed in Table 4 were obtained for a 1 meter long magnet in the flat track configuration.

Table 4. Magnet/magnet amplifier parameters (F_L = 10 kN).

Nominal current (amperes)	30	50	70
Number of turns	443	266	190
Winding resistance (ohms)	1.48	0.53	0.27
Winding inductance (henries)	0.64	0.23	0.12
Dynamic voltage requirement (volts)	1235	740	540
Steady state power (watts)	132	132	132

The values in Table 4 are not meant to be definitive but to serve as an indication. Clearly, the inductive load of the magnet at 10 Hz is dominant and contributes to the difficulty of using this system at high speed. Note also that the results in Table 4 do not account for the increase in magnet current required at high speed.[3]

Finally, the large power amplifiers indicated by Table 4 plus the magnet cooling equipment as well as the magnet cabling and control circuitry will reduce the L/W values listed in Table 2 by roughly a factor of two.[10] Thus, a value of 3.3 to 4.1 for L/W (depending on F_G/F_L) is all that can be expected. If additional magnets are required for vehicle switching (or some other switching mechanism) a further reduction in L/W can be expected such that the overall suspension system (magnets, magnet drivers, cooling, switching mechanism, etc.) cannot be expected to have a ratio of lift-to-weight any larger than 3 to 3.5.

3. CONCLUSIONS

On the basis of these results some tentative conclusions can be drawn:

i) The ferromagnetic suspension system will require magnets running the full length of the vehicle (~ 30 m) to achieve the required lift force of ~ 10 kN/m. These long magnets will be composed of many shorter magnets of 1 to 1.5 m length for control purposes.

ii) At low F_G/F_L, the U-shaped track configuration may show a L/W advantage over the flat track configuration, but only if the magnet current can be easily increased to compensate for the higher leakage flux in the U-shaped track.

iii) The overall L/W ratio of the attraction magnetic suspension system including all associated components (magnets, magnet drivers, cooling, vehicle switching, etc.) will be ~ 3 to 3.5. For the repulsion magnetic suspension scheme this value is believed to be about 5 - primarily because of the high L/W potential of the superconducting magnets (≥ 25), low power supply requirements, and the ability of the wheels (required at low speed) to accomplish vehicle switching at low speed.[11]

4. REFERENCES

1. Pioneering work on this system was done by J. Powell and G. Danby, ASME Paper 66-WA/RR-5 (1966); Cryogenics 11, 192 (1971). For the latest contributions from government funded programs in Japan, Germany, Canada, and the United States, please see: Proceedings of the Fifth International Cryogenic Engineering Conference, Kyoto, Japan, May 7-10, 1974; Proc. IEEE 61 (1973); Trans. IEEE MAG-10, 397-470 (1974); and Applied Superconductivity Conference, Oakbrook, Illinois, U.S.A., Sept. 30 - Oct. 2, 1974; and the reports on the DOT funded programs PB223-237 (1973), PB210-506 (1972), PB210-505 (1972), PB236671 (1974), and PB238773 (1974).

2. Primarily because of proprietary reasons, technical publications on the attraction magnetic suspension system have been few. G. Bohn, P. Romstedt, W. Rothmayr, and P. Schwärzler, Proc. 4th ICEC, Eindhoven, p. 202 (1972); E. Gottzein and B. Lange, 5th IFAC Symposium on Automatic Control in Space, Genova, Italy, June, 1973; P. M. Navé, Proc. Int. Conf. HSGT, p. 255, January, 1975 or Journal of HSGT, 9; G. H. Bohn and J. Langerholc, ibid. A-18.

3. R. H. Borcherts and L. C. Davis, MAG-10, 425 (1974); J. R. Reitz, R. H. Borcherts, L. C. Davis, C. C. Wan, and A. U. Mohdulla, Parameter Optimization Studies of Magnetic Suspensions for High Speed Ground Transportation, April 1974, NTIS Assession No. PB238773.

4. Supplied by R. Lari, Argonne National Laboratory.

5. A precise value for the guidance force depends upon curves, wind loading, and guideway tolerances - yet to be experimentally determined. A useful guide (consensus value) is $F_G/F_L \sim .3$ to .5.

6. Recent experiments at MIT by D. Wormley gives similar errors when FORGEY results are compared to experiments.

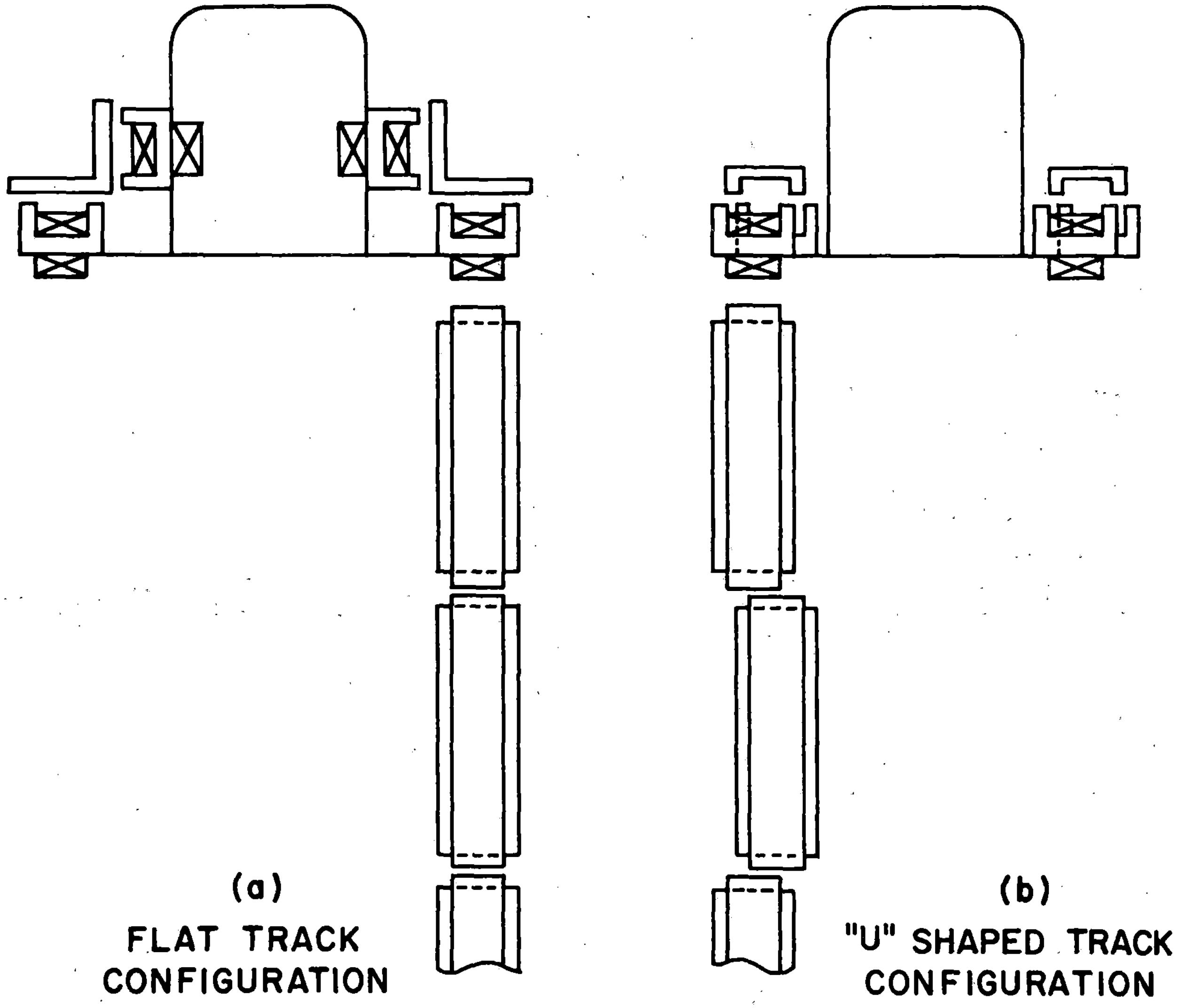
7. Similar L/W ratios have been obtained by D. L. Atherton and A. R. Eastham, Trans. IEEE, MAG-10, 410 (1974).

8. Magnet current density is limited by internal heating. For aluminum windings, current densities above $1.6\ A/mm^2$ are expected to be force cooled.

9. E. Gottzein, B. Lange, and F. Ossenberg - Franzes, HSGT Journal 9, 435 (1975). As indicated in this paper, the magnet break frequency depends upon vehicle speed, magnet gap, guideway roughness, and mass ratio. A value of 10 Hz appears to be an acceptable, if not low, value.

10. P. Navé - personal communication.

11. DOT Report No. FRA-OR & D-75-21, Feb. 1975, "Conceptual Design and Analysis of the Tracked Magnetically Levitated Vehicle Technology Program (TMLV) - Repulsion Scheme," Vol. I, Technical Studies; Vol. II, Appendices A-F; Vol. III, 5 DOF Computer Program Report.



(a) FLAT TRACK CONFIGURATION

(b) "U" SHAPED TRACK CONFIGURATION

Fig. 1 Magnet Configuration, Flat Track and U-Shaped Track

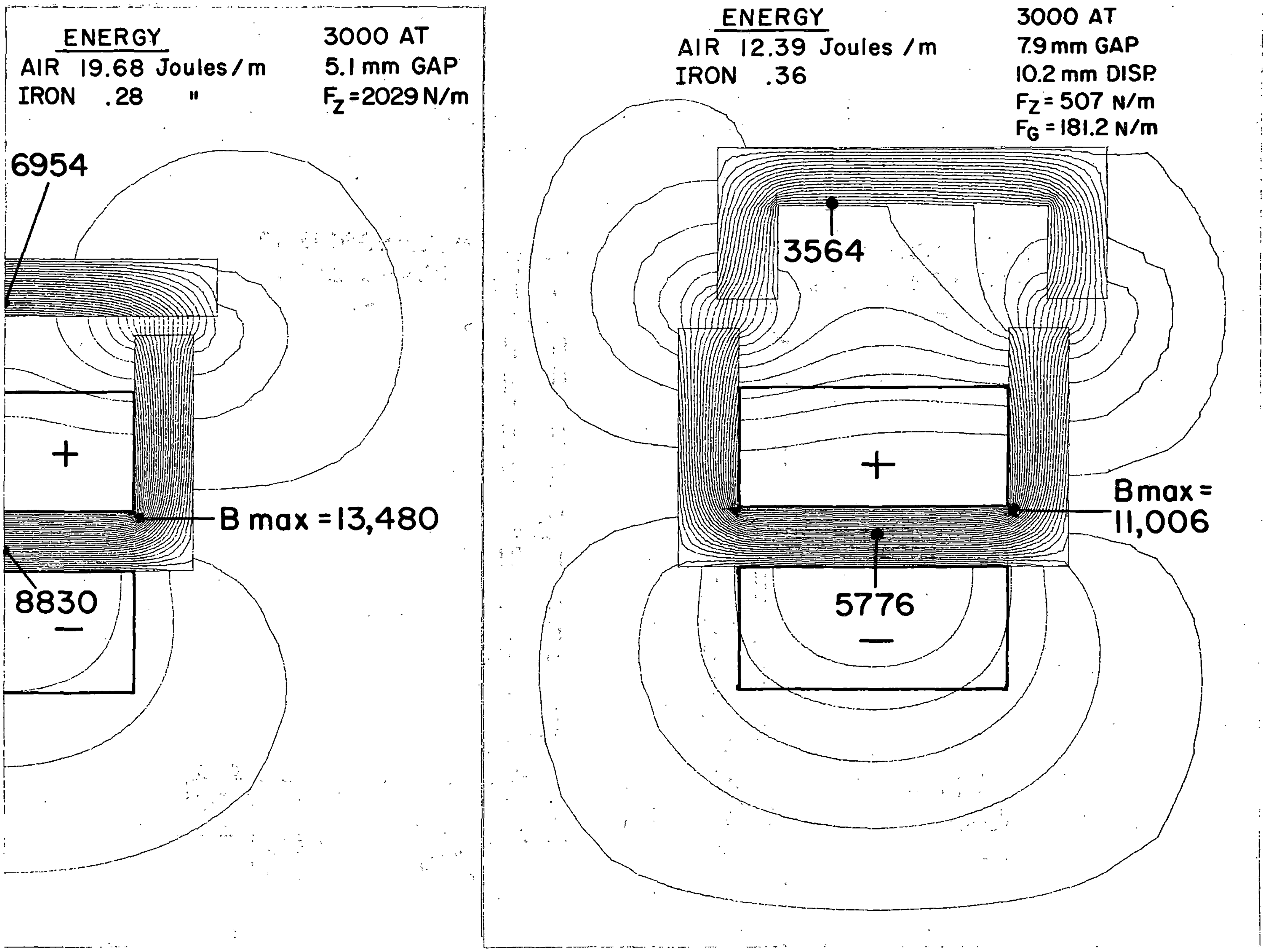


Fig. 2 Flux Plots, TRIM and FORGEY Results, Experimental Magnets

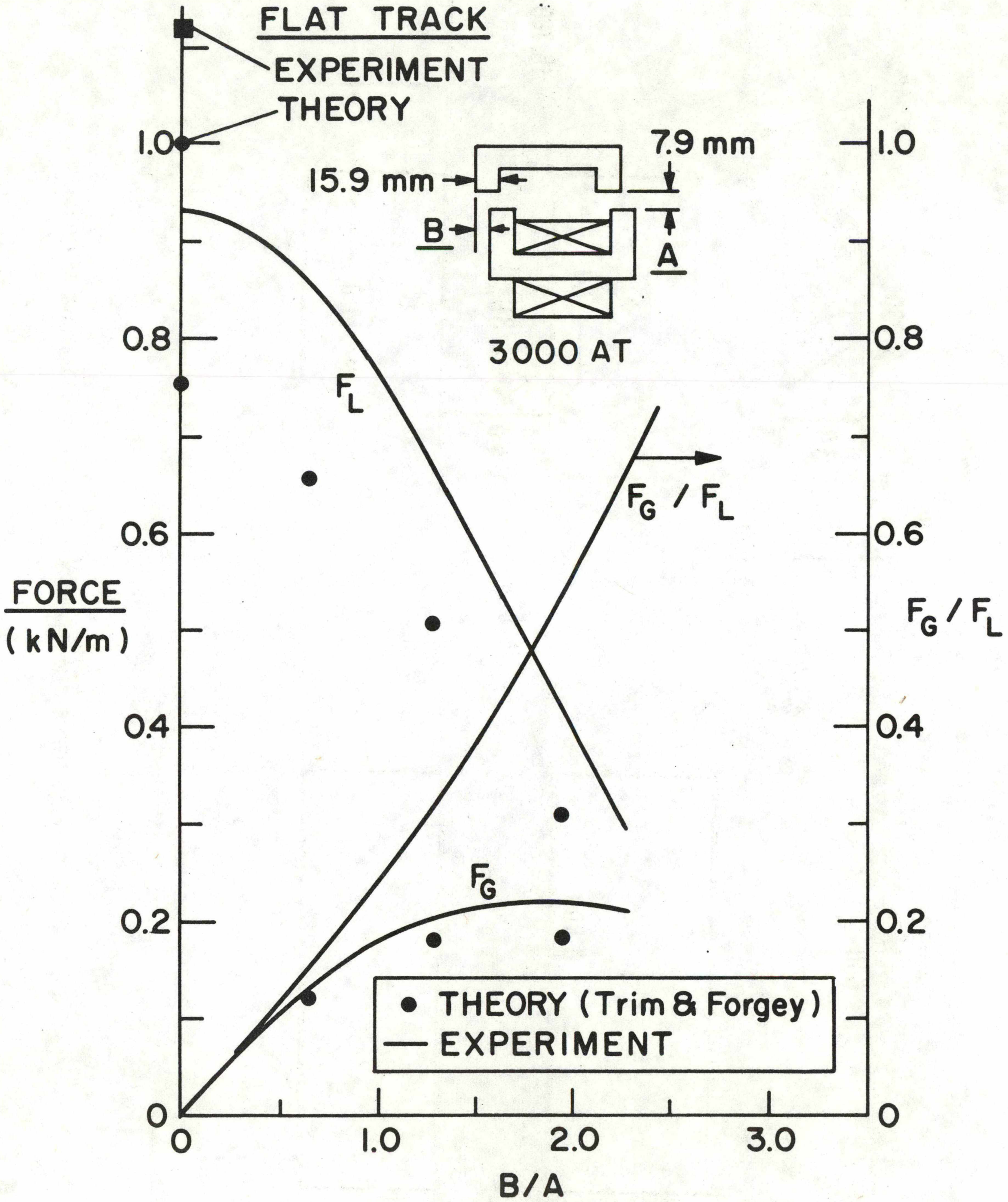


Fig. 3 Dependence of Lift and Guidance Force on Magnet Displacement, Theory and Experiment

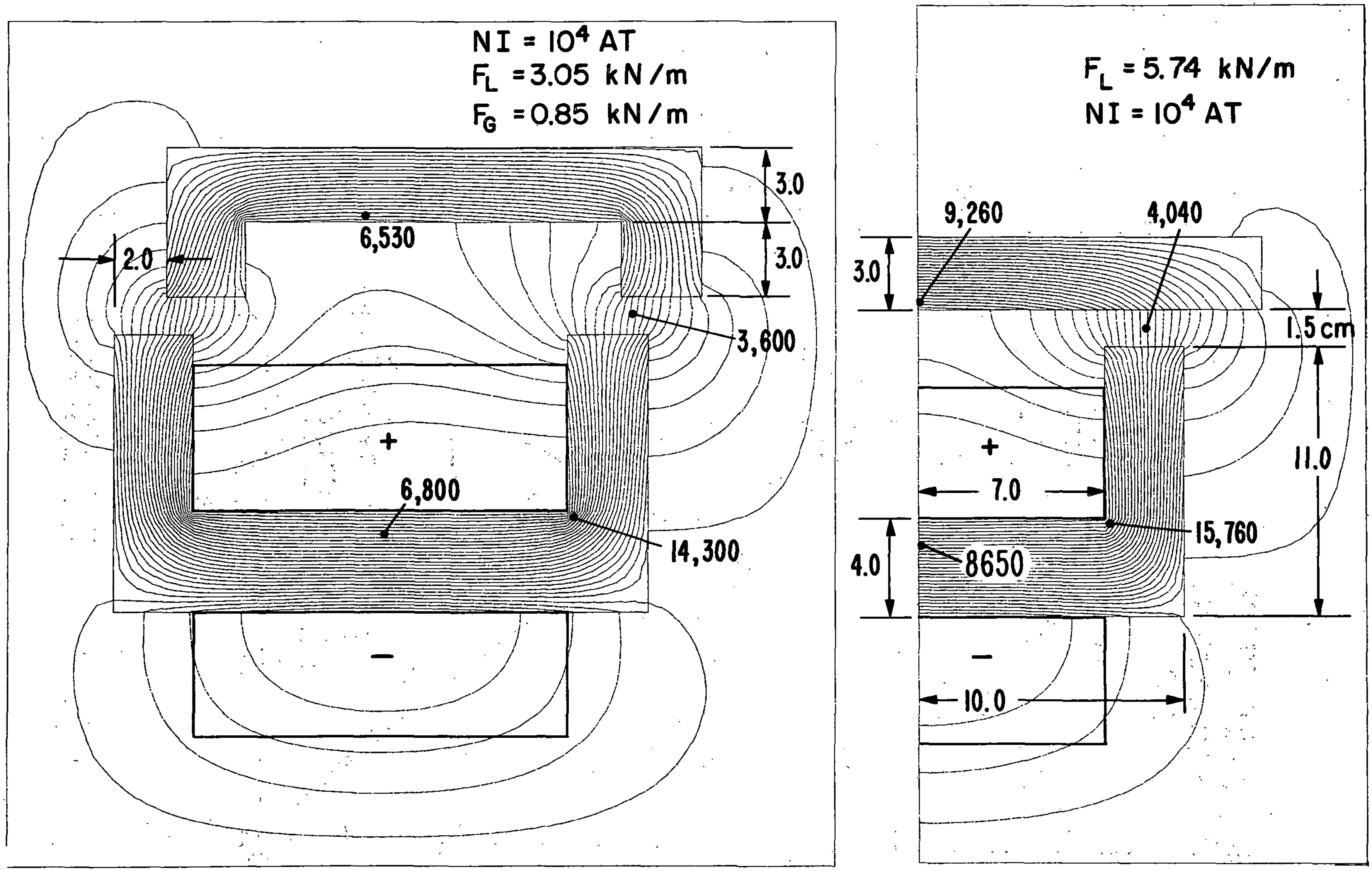


Fig. 4 Flux Plots, TRIM and FORGEY Results, Full Size Magnets

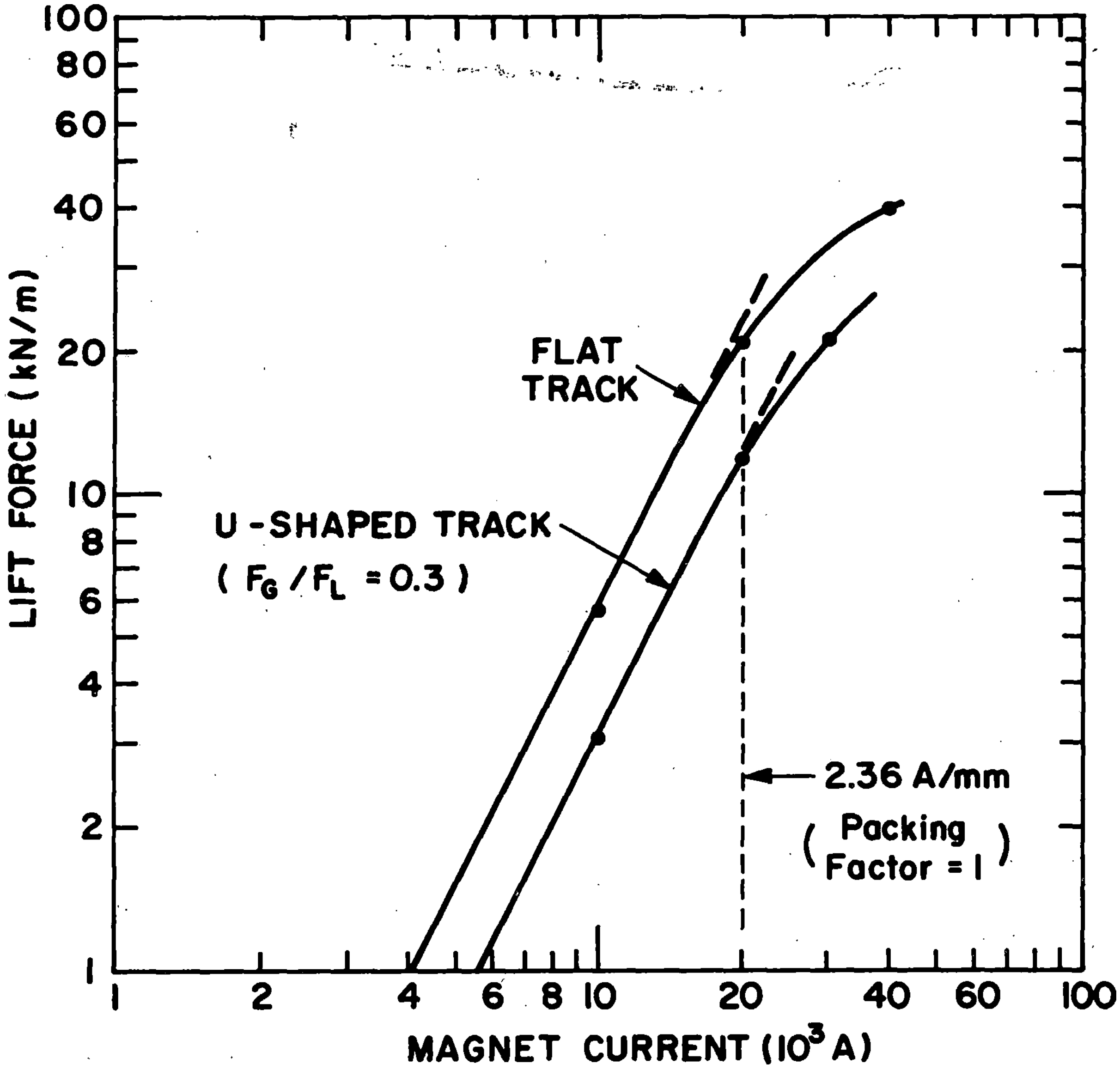


Fig. 5 Lift Force Dependence on Magnet Current Showing Saturation. FORGEY Results. Track Gap 1.5 cm.

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