EVALUATION AND ANALYSIS OF FAST ACTING SOLENOID

B. K. VENKATARAMU, T. NAGARAJAN*, K. ANANTHA RAM, S. RAVISHANKAR and C. S. PRASAD

Spacecraft Propulsion System Group, Liquid Propulsion Systems Centre, Indian Space Research Organization, Bangalore 560 017, India.

* *Department of Mechanical Engineering, Indian Institute of Technology, Madras 600 036, India.*

ABSTRACT

A fast acting solenoid for an On/Off valve of a monopropellant reaction control system of spacecraft with a unique approach satisfying very stringent requirement of the On/Off valve notably the need of quick poppet travel times (< 10 ms) consuming less power (< 5 W) within a small envelope is attempted. These are to operate to the tune of 0.5 million On/Off cycles under deep space environments. Computer simulation techniques optimised the design and predicted the poppet travel characteristics. A prototype valve designed is assembled and tested to verify the performance.

INTRODUCTION

On/Off valves control the duration of flow of monopropellant into engines (thrusters) which generate small thrust of Newton levels and consequently the corrective forces required for attitude and orbit maintenance of spacecraft (table 1).

Design requirements (table 1) demand a spring-loaded poppet assembly of a few grams with a short stroke (say 0.5 mm), an integral solenoid bobbin coil housing and all welded construction. A sectional view of the On/Off valve is shown in figure 1. The spring-loaded poppet assembly closes the outlet port of the valve in the normally unenergised position and on energising, the magnetic force developed overcomes the spring and differential pressure forces and attracts the poppet assembly towards the stationary core. The non-magnetic spacer welded in the central portion of the bobbin minimizes flux leakages and quickens the poppet travel time. Poppet is made as light as possible by providing flat profiles and a longer spring groove to quicken its travel time.

Table 1 *Design requirements of the solenoid*

Actuator	: Solenoid
Operating pressure	: 24 bar
Operating voltage	: 28 V DC
Power	: 5.0 W (max)
Poppet actuation time	: 10 ms (max)
Pull-in/drop-out voltage	: 17 V (max), 2 V (min)
Cycle life	: 0.5 million
Operating medium	: Hydrazine (N_2H_4)

THEORETICAL ANALYSIS

Static and dynamic characteristics of the actuator is completely characterized by computer simulation. Empirical relations, analysis methods and equations from electromagnetic devices[1] are systematically adhered to, in constructing the mathematical model. The analysis considers all the magnetic flux leakages

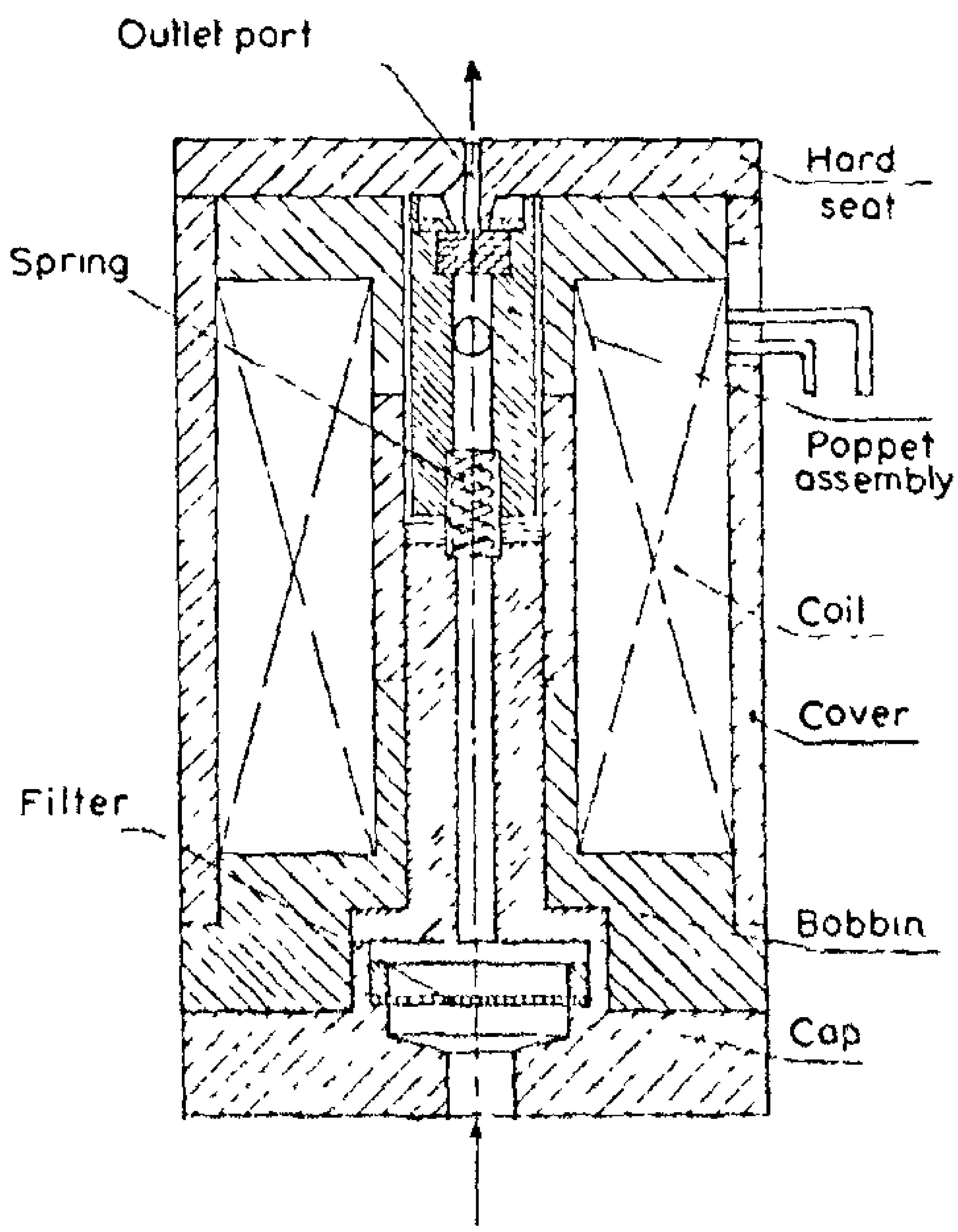

Figure 1. Sectional view of On/Off valve.

along with a useful air gap flux in the magnetic circuit. Magnetic properties have been determined from the nonlinear induction characteristics of stainless steel 430.

The forces acting on the poppet assembly in the open and close positions are shown in figure 2. In the closed position the static force acting is given by

$$F = F_1 + F_2,$$

where F_1 is the initial spring force, and F_2 is the differential pressure force. In the open position, the pressure forces are balanced and the force acting is given by

$$F^1 = F_1 + F_3,$$

where F_3 is the spring compression force due to poppet stroke. Once the coil is energized, the current build-up in the coil with respect to time to overcome the static force and to initiate poppet motion is estimated.

A free body diagram of the dynamic system showing all the effective forces on the poppet is given in figure 3 and represented by the equation

$$M(\mathrm{d}^2x/\mathrm{d}t^2) + C(\mathrm{d}x/\mathrm{d}t) + Kx = F_s - F$$

where, $\mathrm{d}^2x/\mathrm{d}t^2$ is the acceleration of the poppet, $\mathrm{d}x/\mathrm{d}t$ the velocity of poppet, X the displacement of poppet, F_s the magnetic pull on poppet, F the static force on poppet, C the friction factor, K the spring constant, and M the mass of moving element. Once the poppet motion is initiated, the variation of attracting force, the poppet velocity, the coil current and the poppet displacement with time are characterized through the operating stroke by computer simulation (analysis according to the electromagnetic devices[1]). The frictional resistance and viscous drag during the motion are assumed to be zero in the analysis.

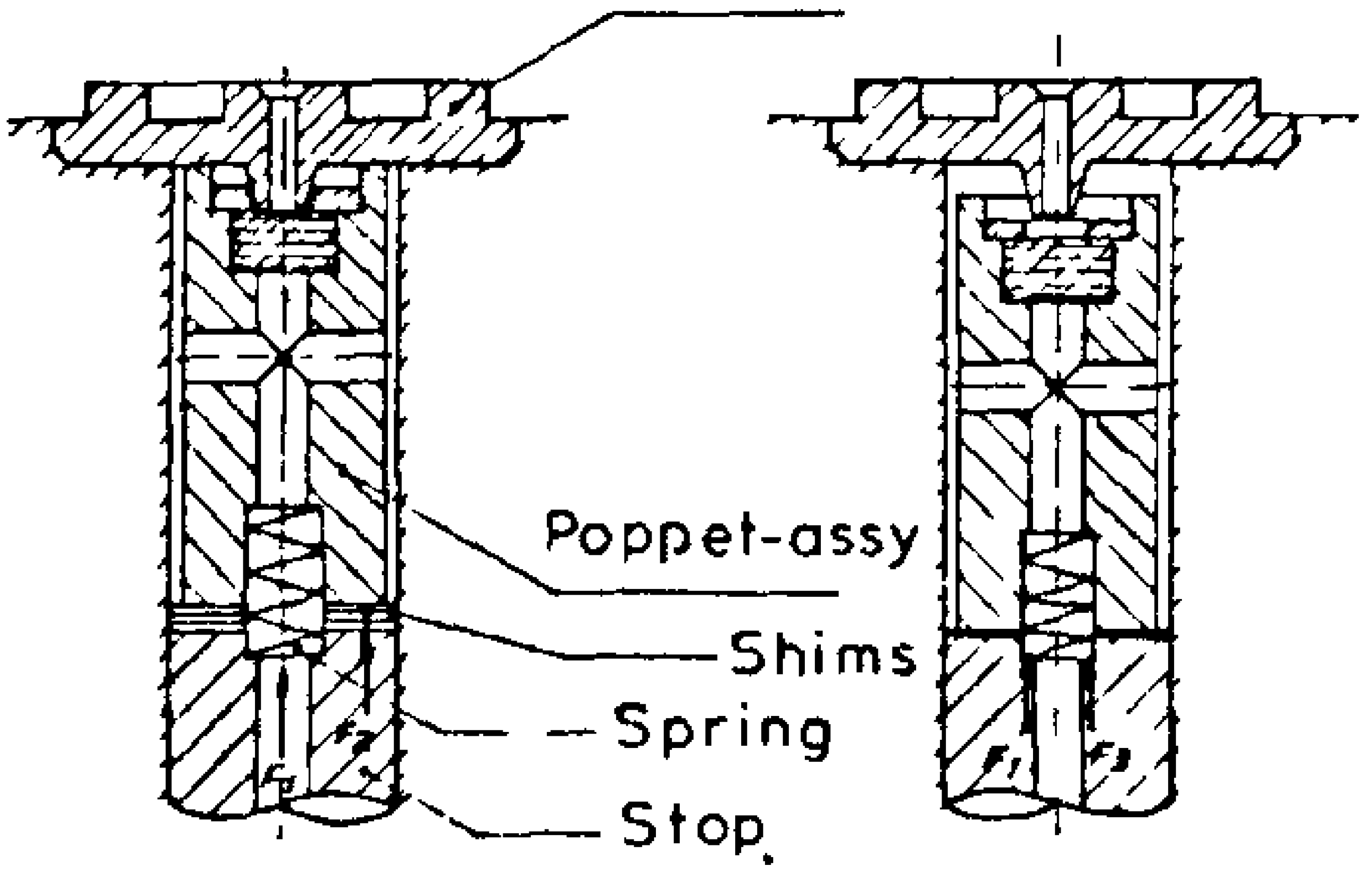

Figure 2. Forces acting on poppet assembly.

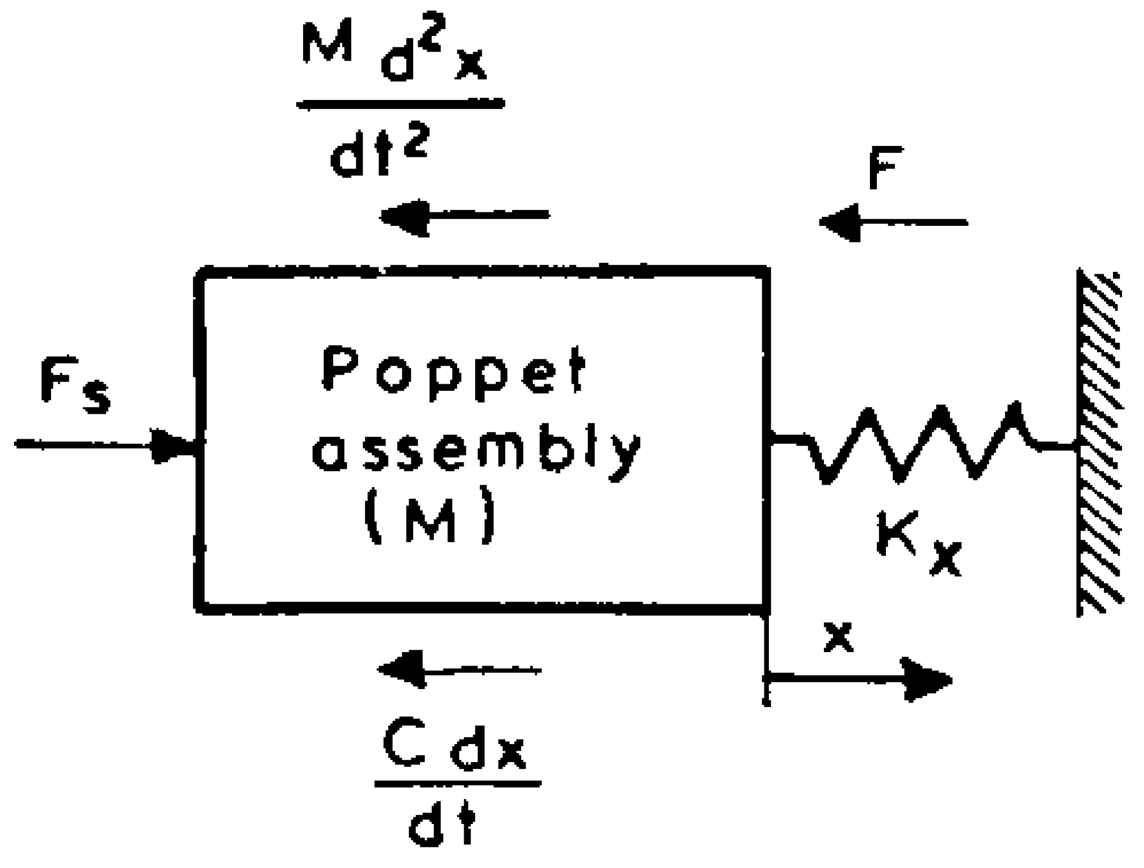

Figure 3. Free body diagram of dynamic system.

PARAMETERS OPTIMIZATION[3] (ANALYTICAL)

Optimization studies are carried out on some of the following parameters influencing the poppet travel time: Non-magnetic spacer; Initial spring force on poppet assembly; Poppet travel (stroke); Weight of poppet assembly; Coil design; Operating pressure and Materials of construction.

Non-magnetic spacer

The effect of the length of non-magnetic spacer in the magnetic circuit on the poppet travel time has been studied for spacer lengths from 10 mm to

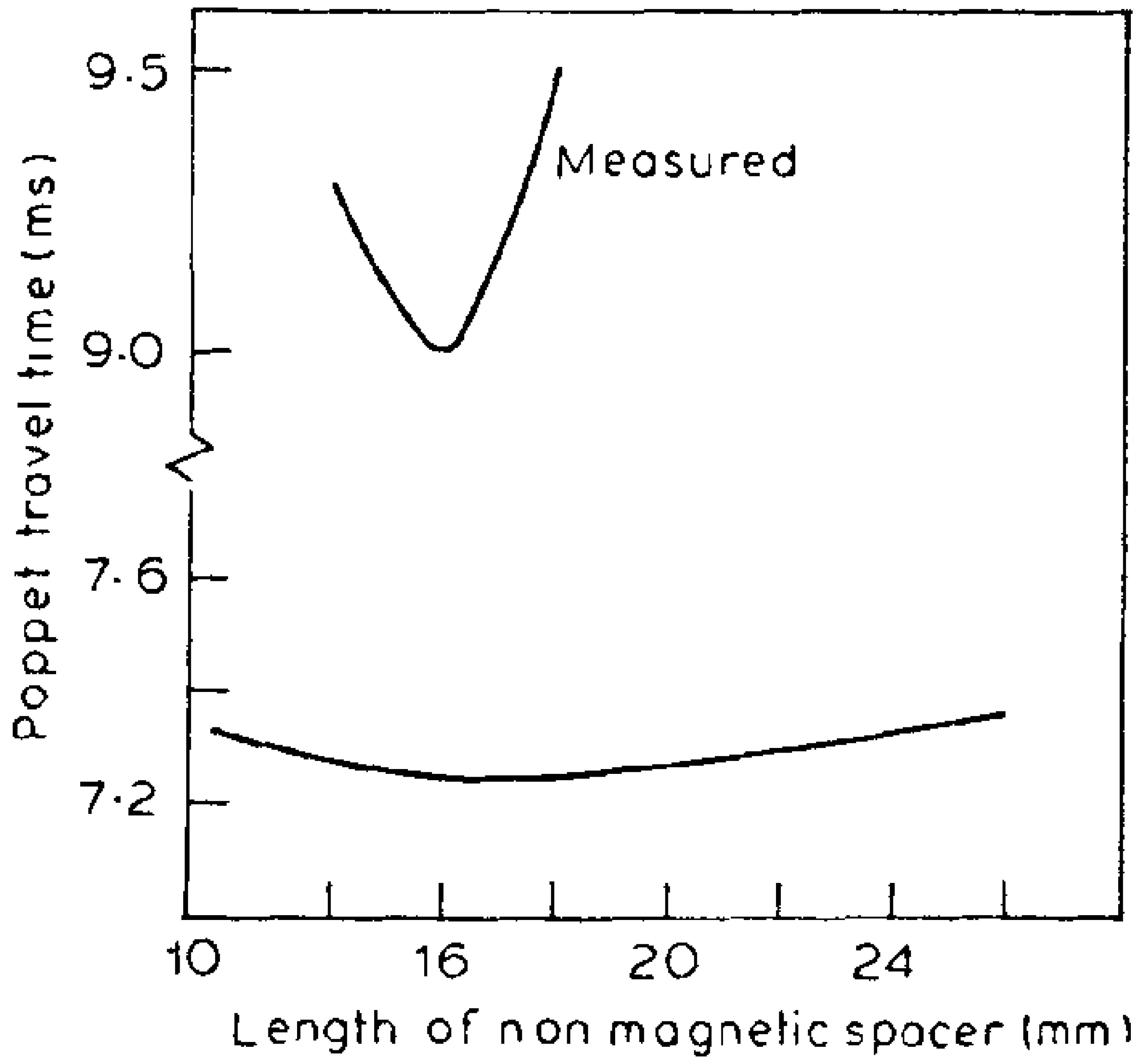

Figure 4. Length of spacer vs poppet travel time.

26 mm in steps of 2 mm increments and is plotted in figure 4. There is an optimum length of spacer that gives the quickest poppet travel time. The travel time decreases from 7.3 ms for a 10 mm spacer to 7.2 ms for a 16 mm spacer and again increases to 7.38 ms for a 26 mm spacer. Study of the saturation curves for different non-magnetic spacers (figure 5) indicates that the useful work done in a 16 mm spacer is maximum and hence contributes to the quickest poppet travel time.

Poppet travel: (Stroke)

Actuating stroke of the poppet has a significant effect on the poppet travel time (PTT) which analysed for five different air gaps from 0.6 mm to 0.8 mm (including compliance for shim thickness of 0.24 mm) is shown in figure 6. It may be observed that PTT increases from 6.28 ms for a 0.6 mm air gap to 8.61 ms for a 0.8 mm air gap. A minimum stroke of 0.51 mm is chosen to meet the flow requirement of On/Off valve.

Weight of poppet assembly

The poppet assembly consists of a plunger which houses a retainer plate and an elastomer. Five poppets have been considered with weights varying from 2 g to 3 g.

The effect of the weight of poppet assembly on the travel time is plotted in figure 7. The PTT increases

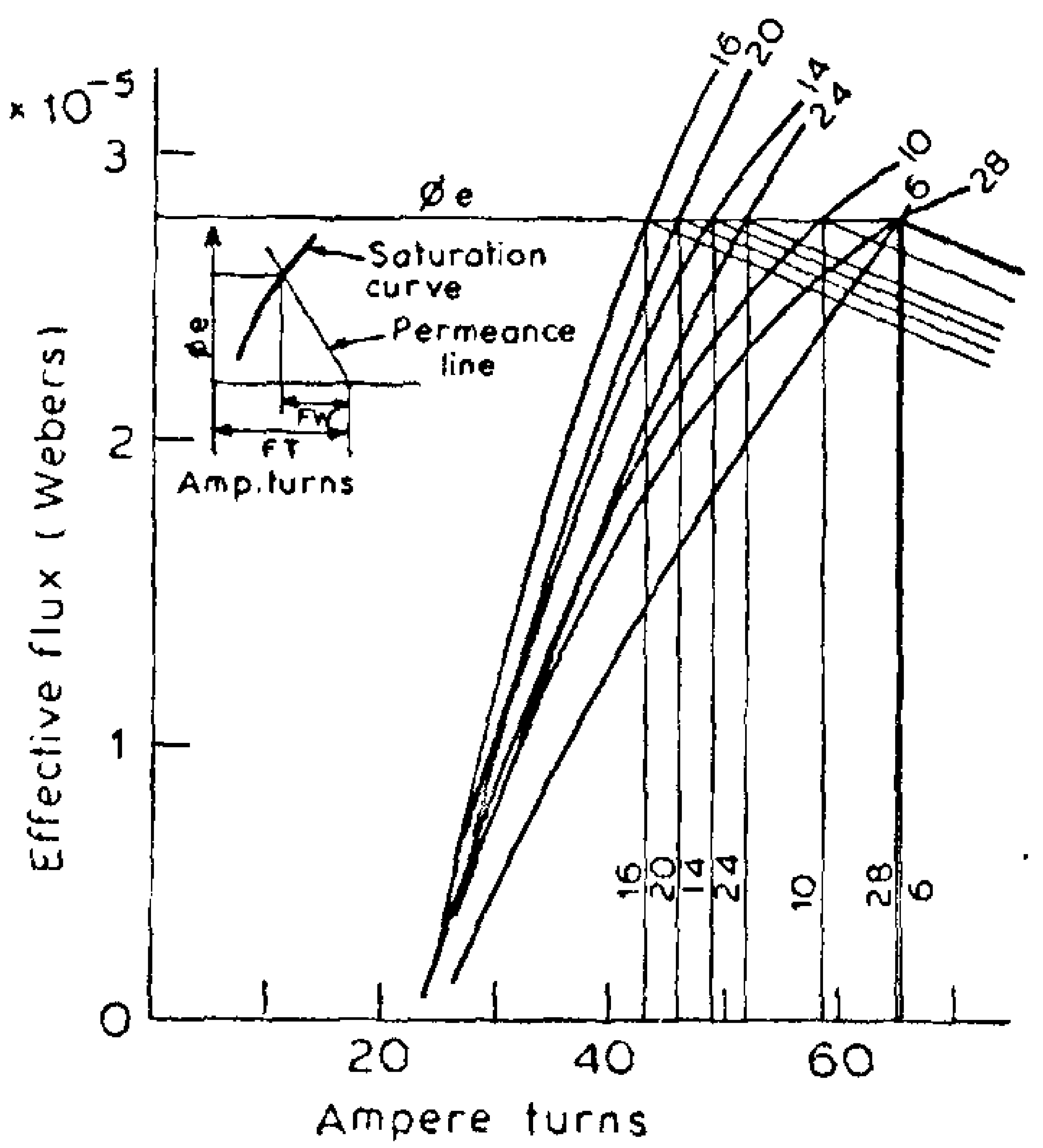

Figure 5. Magnetic circuit saturation curves.

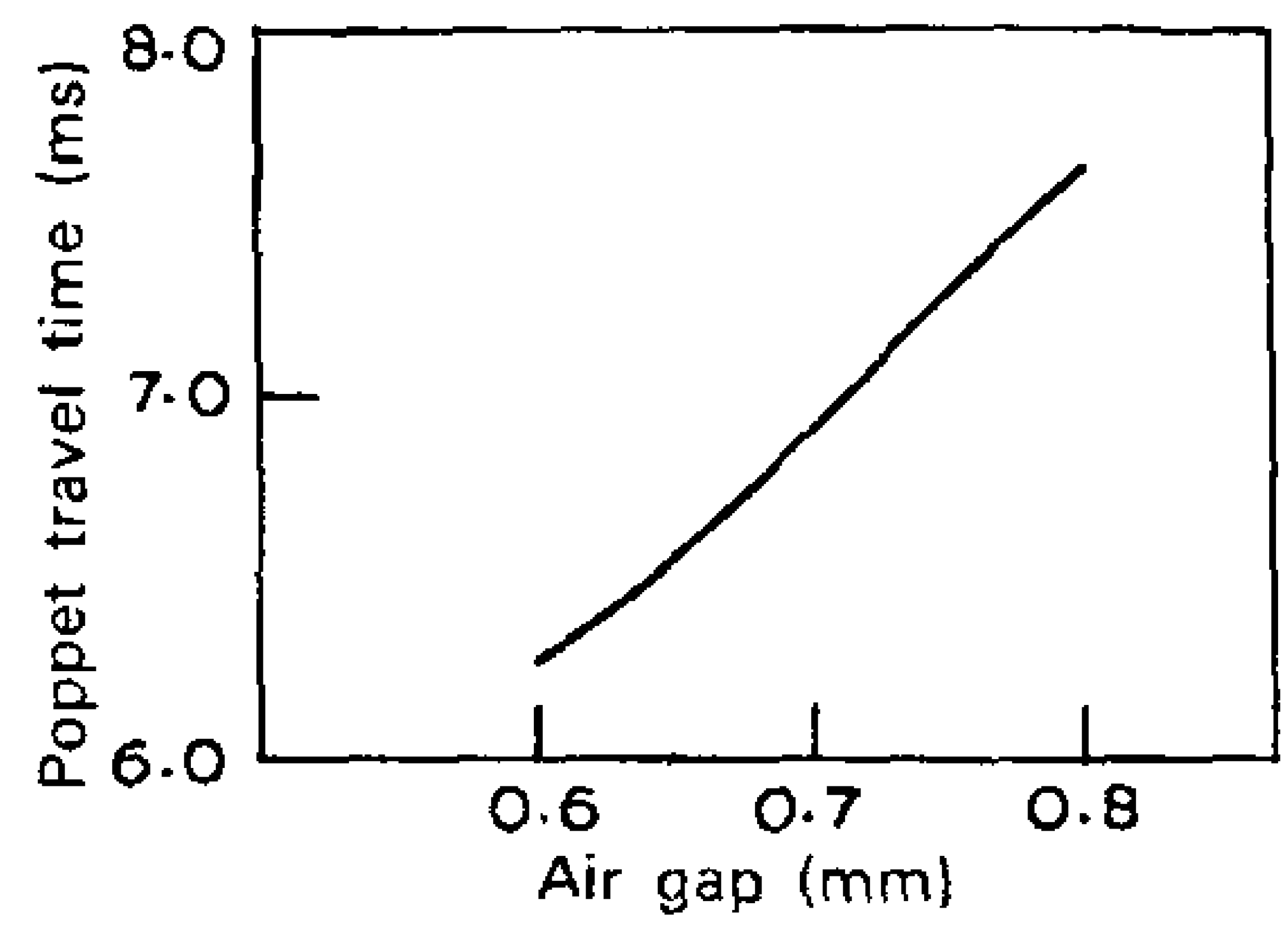

Figure 6. Air gap vs poppet travel time.

from 7.18 ms for a 2 g poppet to 7.42 ms for a 3 g poppet. With increase in the weight of poppet assembly, the acceleration and hence velocity of the poppet comes down and hence higher travel time. The poppet weight is kept at 2.5 g to accommodate the elastomer and retainer plate.

Coil design

The plot of ampere turn vs the poppet travel time computed for different power is shown in figure 8. With increase in the ampere turns, PTT decreases from 8.9 ms for 600 ampere turns to 6.5 ms for 900 ampere turns. The ampere turn is tentatively fixed at 750 based on the coil envelope constraint, power available which is 5 W (max) and the PTT desired i.e. < 10 ms.

Materials of construction

Welding of stainless steel 430 with stainless steel 304 L does not pose any problem. These materials

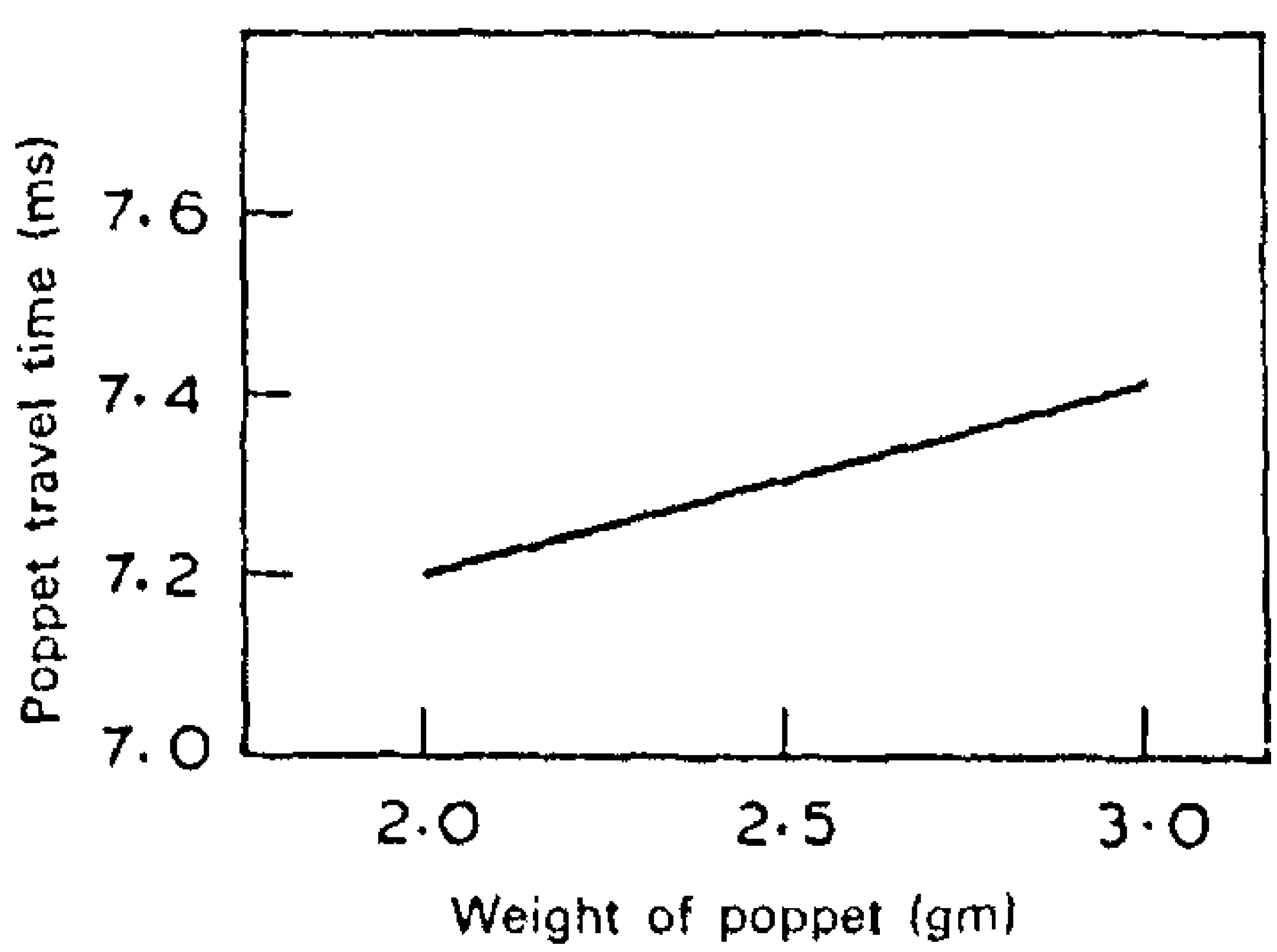

Figure 7. Weight of poppet vs poppet travel time.

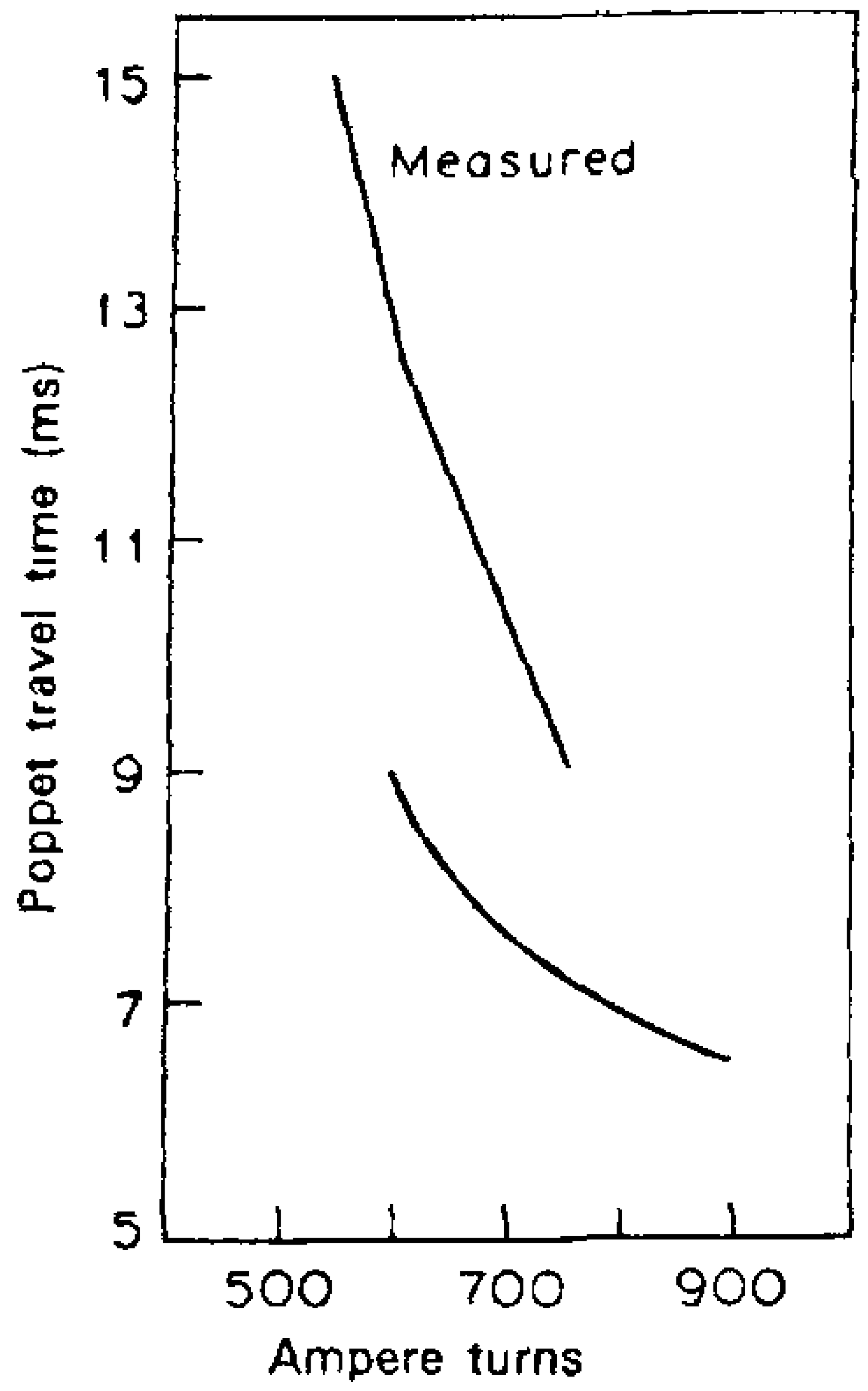

Figure 8. Ampere turns vs poppet travel time.

also do not undergo any reaction with the operating medium i.e. hydrazine.

PARAMETERS STUDY[3] (EXPERIMENTAL)

Experimental studies are carried out on the hardwares by varying the length of the non-magnetic spacer and the ampere turns. Due to the limitation on the number of hardwares available, the poppet stroke is fixed at 0.51 mm and the poppet weight at 2.25 g for the study.

The PTT measured for three different non-magnetic spacers i.e. 14, 16 and 18 mm (for 750 ampere turns) are shown in figure 4. It is clear from experimental results that a 16 mm spacer gives the quickest PTT as predicted i.e. 9 ms compared to 14 mm and 18 mm spacers which give 9.3 and 9.5 ms respectively.

The PTT variation measured for different ampere turns (power) (figure 8) shows a decrease from 15 ms for 535.7 ampere turns to 9 ms for 750 ampere turns indicating the trends of analytical results.

DESIGN EVOLVED

Based on the parametric studies (experimental and analytical) conducted, the design evolved for the solenoid is indicated in table 2.

Table 2 *Design parameters of solenoid*

Type	: Direct acting solenoid
Operating pressure	: 24 bar absolute
Poppet assembly weight	: 2.25 g
Poppet spring load	: 0.195 kgf (coil de-energised) 0.320 kgf (coil energised)
Supply voltage	: 28 V DC
Power	: 5 0 W (max)
Non-magnetic spacer length	: 16 mm
Poppet lift	: 0.51 mm
No. of coil turns	: 4200
Coil resistance	: 156.8 Ohms
Coil wire size	: 37 SWG

ANALYTICAL RESULTS

The current build-up in the coil, the attracting force, the poppet velocity and the poppet stroke as a function of time from the instant coil is energised till the completion of the stroke is predictable by computer analysis. This analysis is carried out and shown in figure 9 for an actuator whose design parameters are tabulated in table 2.

When the coil is energised, the current in the coil gradually increases to 115.31 mA in 5.95 ms where the plunger motion is initiated. As the poppet moves and gains velocity, the current dips down to 50.56 mA at the end of stroke due to back e.m.f. The time consumed for the mechanical movement of poppet as read from figure 9 is 1.3 ms and the total PTT from the instant coil is energised till the completion of stroke is 7.25 ms.

The attracting force gradually increases and attains a value of 0.944 kgf at the end of stroke. The velocity initially increases from zero to 815.0 mm/s at the end of the stroke.

PROTOTYPE TEST PERFORMANCE

A prototype hardware according to design evolved (table 2) is assembled and tested for performance verification. The following tests are conducted on the prototype.

Poppet travel time

PTT is measured at 28 V DC using a driver circuit and a storage oscilloscope at 24 bar inlet pressure using simulated fluid viz. distilled water. A current time trace obtained on an oscilloscope during On/Off actuation is photographed and is shown in figure 10. The actuator takes 7.5 ms to initiate the

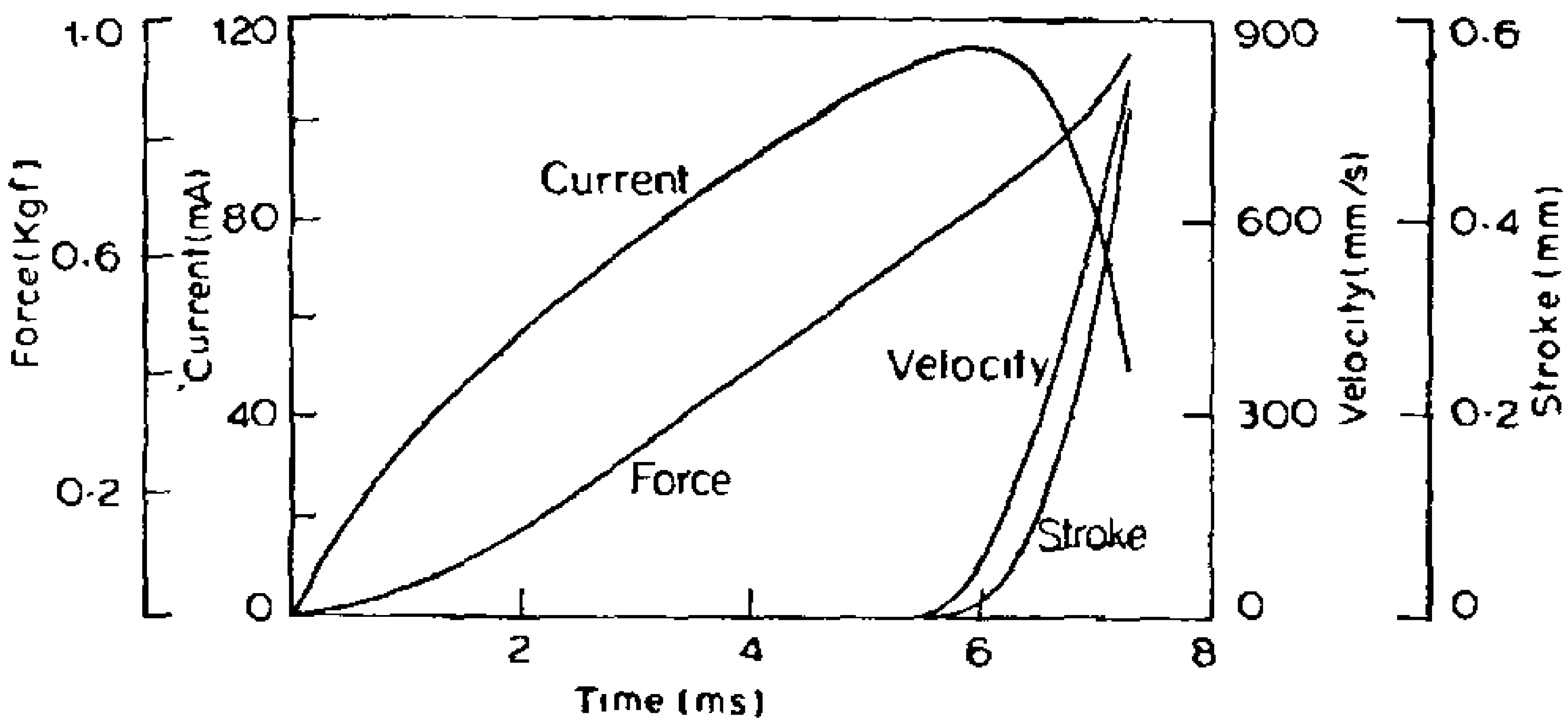

Figure 9. Current, velocity, stroke, force vs time.

poppet movement and 1.5 ms for mechanical movement of poppet and a total actuation time of 9 ms. The return time of poppet measured is 8 ms.

Pull-in/drop-out voltage

The minimum voltage required for poppet to complete the stroke and drop-out voltage is monitored at 24 bar pressure of distilled water. The pull-in voltage measured is 16 V DC and drop-out voltage is 3 V DC.

Endurance

Endurance test is conducted on the hardware in distilled water medium. The valve is operated On/Off in pulse mode at 28 V DC for 0.5 million operations. Post-test condition of the hardware is excellent without any degradation in performance. PTT varies from 9 ms to 9.5 ms and the return time is 8 ms measured after every one lakh On/Off cycles and at the end of endurance test.

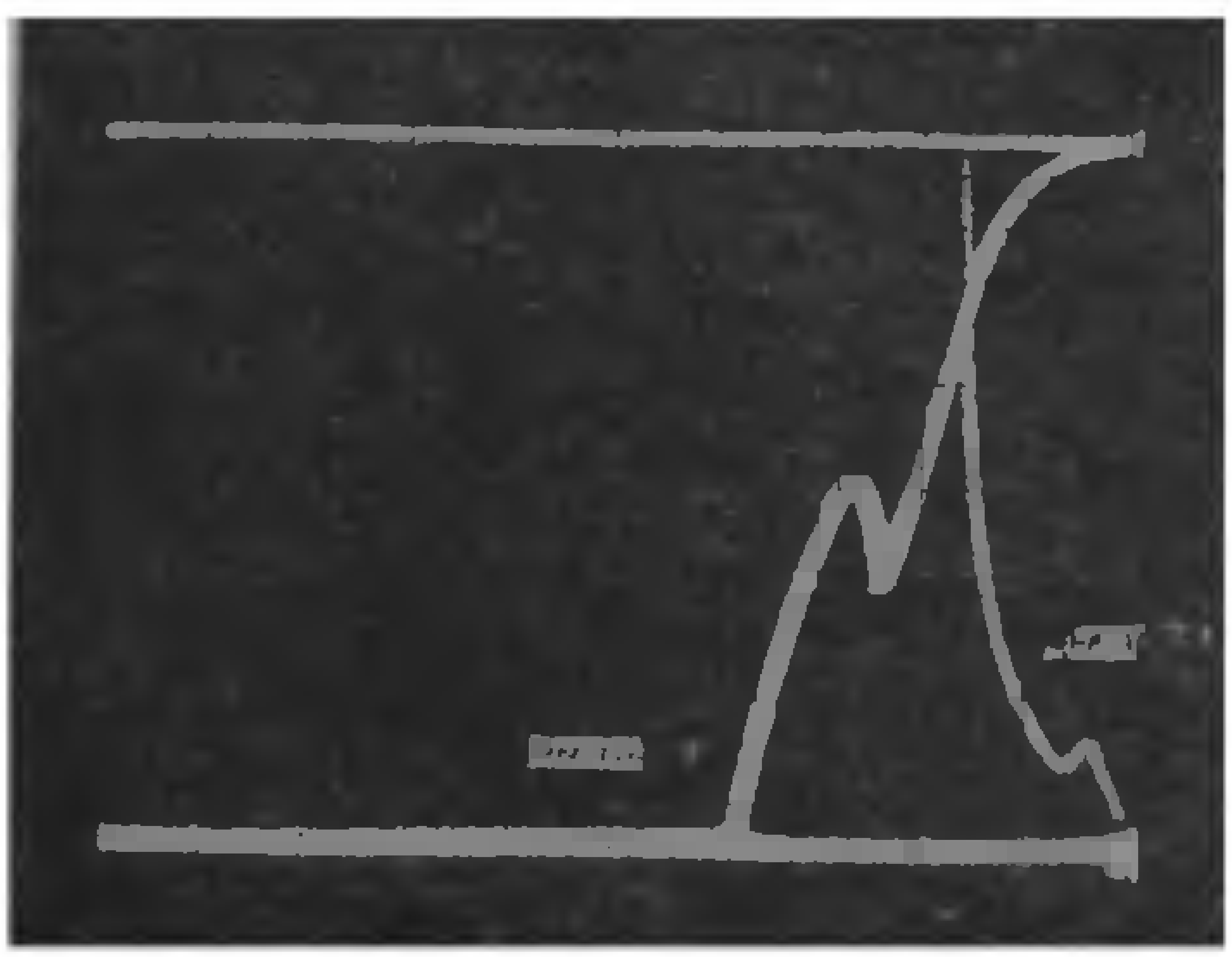

Figure 10. Solenoid current signature.

A comparison of experimental and analytical results showed the following: The measured PTT of 9 ms compared to 7.25 ms analytically predicted for a 16 mm spacer (figure 4); Higher PTT measured than the analytical prediction for variable ampere turn (figure 8) and the PTT of 9 ms in the actual prototype hardware, against 7.25 ms predicted.

It is observed that the measured values are higher than those predicted which could be due to the following reasons: Friction and viscous drag are assumed to be zero in the analytical prediction: The weight of poppet assembly is only a measured value. The air gap for poppet stroke is only a computed value and cannot be measured in the assembly and indicates that a marginally higher value could cause such a behaviour combined with viscous drag effects. The pressure force and the spring force used in the analysis are only computed and cannot be measured in assembly.

CONCLUSION

The solenoid magnetic circuit has been analysed together with the parameters like the non-magnetic spacer length, the poppet stroke, the poppet weight and the coil optimised by computer simulation. This design approach and the computer simulation techniques satisfied the stringent requirements of quick actuation times (9 ms), good cycle life (0.5 million) and less power consumption (5 W) within a limited envelope.

The test results and the analysis are useful in predicting the trends that can be expected of the solenoid actuators with different configuration and varying parameters.

23 July 1987; Revised 27 February 1988

1. Herbert C. R., *Electromagnetic devices*, John Wiley, New York, 1963.
2. Glen, W. H. and Terry, M. W., *Aerospace fluid component designers hand book*, Vol. I, Rev. D, February, 1970.
3. Reinicke, R. H. and Sims, J. C., *Design and performance of a unique 10^7 cycle life pulse valve*, AIAA/SAE/ASME/15th Joint Propulsion Conference, June, 1979.

NEWS

SQUABBLE STALLS SEX-SURVEY DATA RELEASE

..."A one-of-kind national survey on human sexuality has been held captive for the past eight years because the investigators fought over whose name should appear first on the manuscript. The spat is particularly galling to researchers who believe that the data would be valuable for predicting the spread of the AIDS epidemic. The long-lost survey has become critical because so little is known about sexual behavior in the US. The field is so bereft of good data, for example, that when the Ctrs. for Disease Control was recently asked by the White House to estimate how many Americans are infected with the AIDS virus, it based its answer on surveys done during the late 1930s and early 1940s by Alfred Kinsey, who relied on respondents who were white, middle-class, college-educated, and from the Midwest. [In 1980, Albert D. Klassen, Eugene Levitt, and Colin Williams, all formerly of the Kinsey Inst. for Research in Sex, Gender, and Reproduction at Indiana U. (Bloomington)], squabbled over whose name should appear first on the title page of their 500-page manuscript.... What makes the lost Kinsey data set so special is the fact that it is the only one of its kind in which a large number of Americans from across the country were selected at random and quizzed about sexual behavior, including homosexuality.... In the fall of 1970, the Natl. Opinion Research Ctr. at U. Chicago, [Illinois], on contract with Klassen and the Kinsey Inst., asked 3018 men and women what they thought about various sexual practices, many of which were labeled at that time 'deviant'.... After the data were collected, nothing happened very fast. Klassen describes himself as 'meticulous'.... In 1975, Paul Gebhard, [then director of the Kinsey Inst.], brought in Williams, a young sociologist at the Kinsey Inst., to help Klassen [and Levitt] produce a manuscript.... Williams spent the next five years of his life doing just that." [William Booth in *Science* 239(4844): 1084-5, 4 Mar 88 (American Assn. for the Advancement of Science), Reproduced with permission from Press Digest, *Current Contents*®, No. 21, May 23, 1988, p. 14, (Published by the Institute for Scientific Information®, Philadelphia, USA.)]

THE SUGAR-SHAPED DEFENCES OF PLANTS

Analysis of plant material brought around the world to the Royal Botanic Gardens at Kew, London, has led to the discovery, isolation and investigation of a whole range of naturally occurring compounds, so-called sugar mimics. Subsequent work has shown them to be useful research tools and possible agents against cancer and AIDS. Within a decade they have provided a great deal of information about some of the most challenging areas of molecular biology. (*Spectrum*, No. 211/1, 1988, p. 2–3; Published by: British Information Services, British High Commission, New Delhi 110 002).