ANALYTICAL AND EXPERIMENTAL STUDY OF LEAK RATES THROUGH A METAL-ELASTOMER INTERFACE IN AN ON/OFF VALVE

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ABSTRACT

A metal on an elastomeric seat (hard on soft seat) configuration is designed for a unique on/off valve for a monopropellant reaction control system for spacecraft applications. This special design satisfies very stringent requirement of extremely low leak rates of the order of less than 1×10^{-3} scc/sec of gaseous helium at mean operating pressure of the system over the operating life of 1 million operations under space environment (vibration and thermovac cycles mainly).

INTRODUCTION

A NORMALLY closed, direct acting, solenoid operated on/off valve with a metal-elastomer seating interface is designed to feed the monopropellant (hydrazine) into a catalytic thruster on electrical command in pulse mode or continuously for a reaction control system of spacecraft. The on/off valve presents very stringent design criteria notably the need of very low leak rates typically less than 1×10^{-3} scc/sec of gaseous helium. The sectional view of the on/off valve is shown in figure 1.

While the evaluation of leak rates through the seating interface analytically is a complex phenomenon due to a number of interdependent parameters, an attempt is made by the use of dimensional analysis to characterize the salient parameters.

Design criteria

Valve design criteria with respect to leak rate is given in table 1.

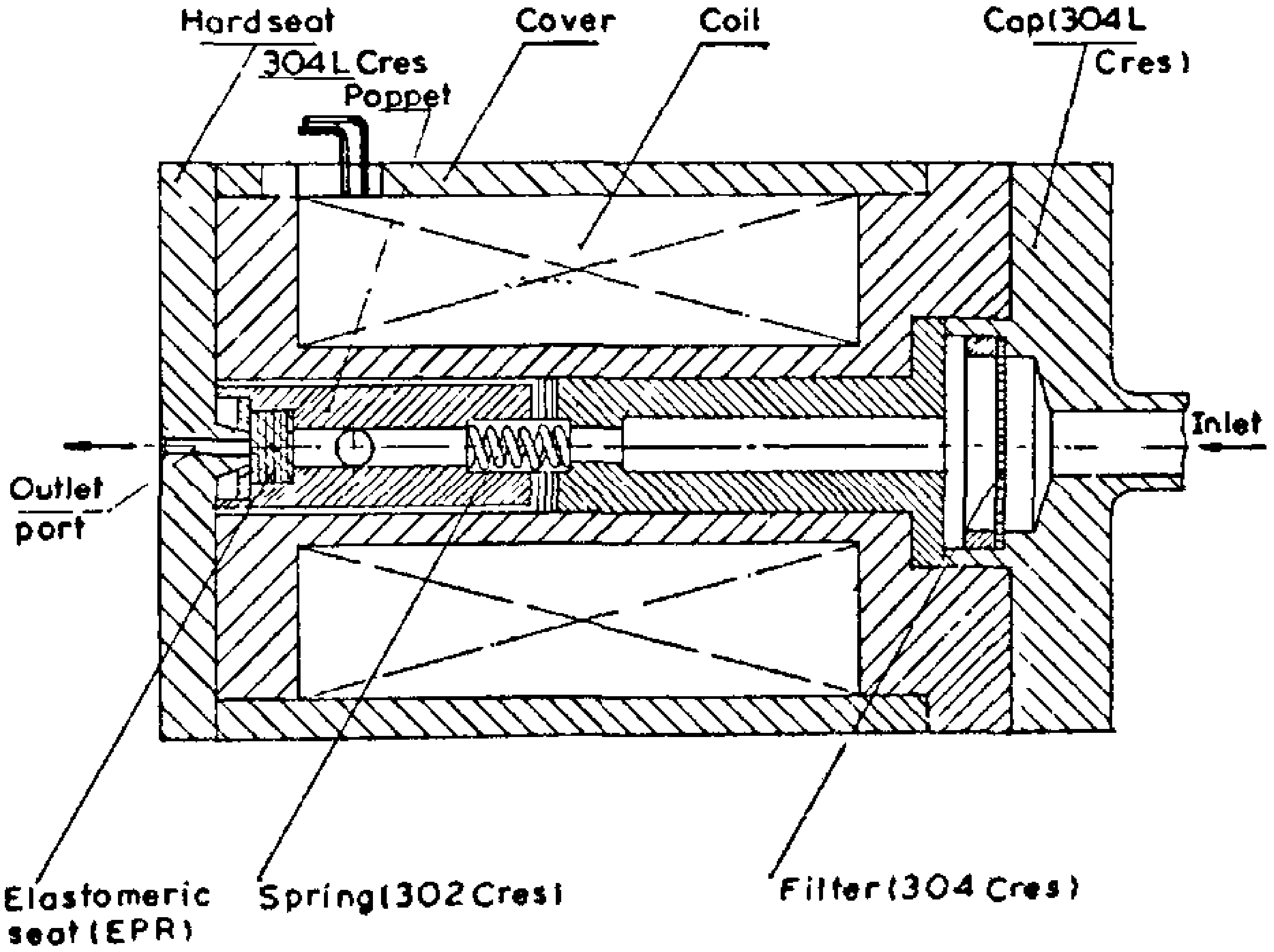

Figure 1. On/off valve assembly.

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*For correspondence.

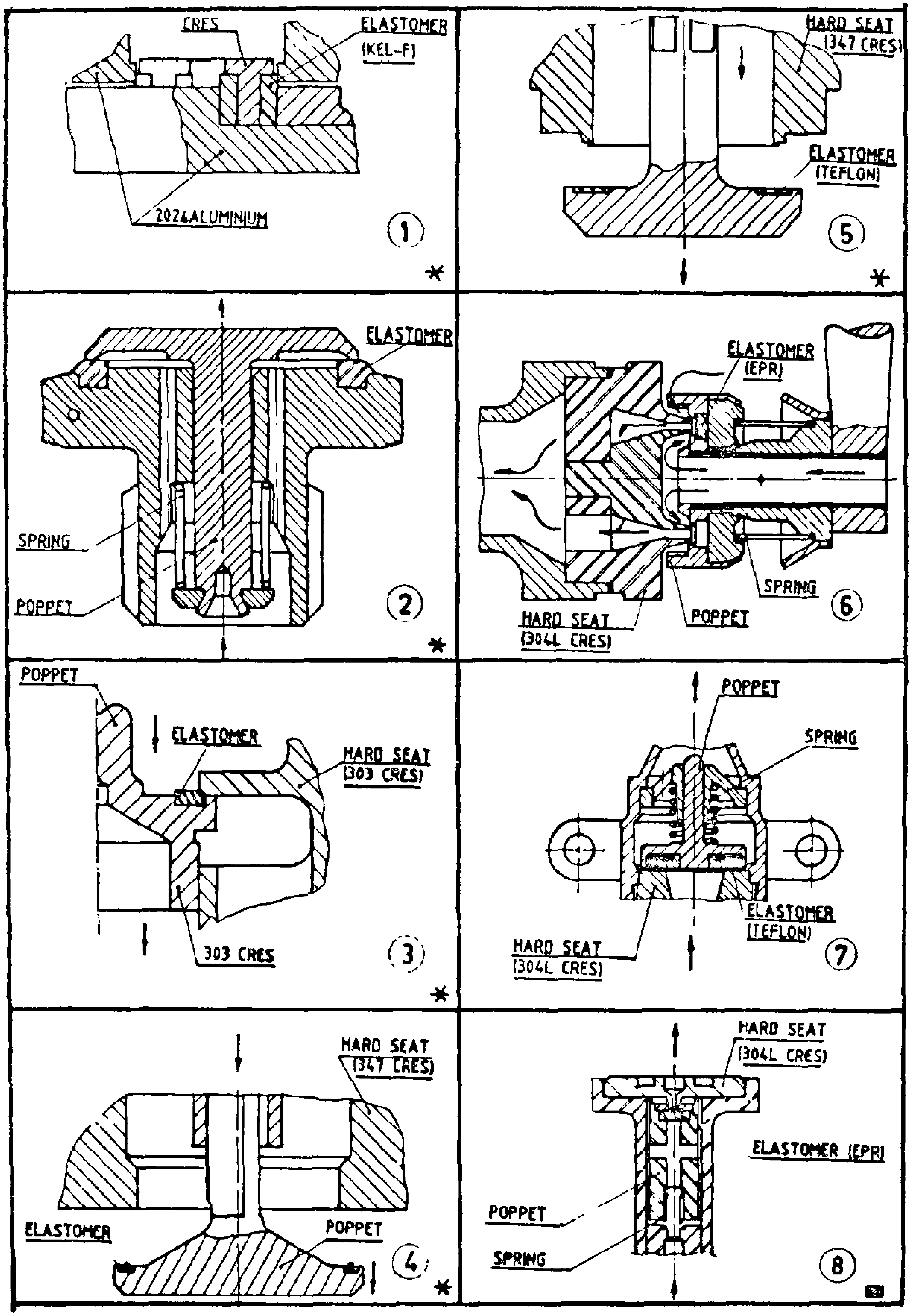

Figure 2. Flat poppet seats. (*Ref. 1; x Ref. 2)

Table 1 *Valve design criteria with respect to leak rate*

1. Operating medium	Hydrazine
2. Operating pressure	24 bar absolute
3. Valve seat interface	0.9 mm port diameter
4. Seat leakage	$<1 \times 10^{-3}$ scc/sec of GHe
5. Life	1 million operations
6. Seating materials	Compatible with hydrazine
7. Built-in filter	Valve shall be provided with a built-in filter of 25μ absolute rating

Flat seat configuration

A flat seat is designed for smaller seating diameter, shorter poppet stroke thus resulting in considerable weight saving of the valve.

Different flat seat designs and seat retention techniques are shown in figure 2[1,2]. Configurations shown in Sl. Nos. 1 to 5 require larger seating area and hence higher seating loads, thus, making the actuator (solenoid) size big and bulky. They are more suitable for high flow rate and ground applications. Configurations in Sl. Nos.6 and 8 require smaller seating area, smaller seat loads, smaller actuator size thus making these more suitable for low leak rate applications. Elastomeric seals are carefully restrained in the poppet with a retainer plate so that it will not rupture or blow out due to differential pressure.

Selected configuration

A hard on elastomer seating configuration selected for the on/off valve is shown in figure 3.

The sealing element is spring-loaded to control the loading on the elastomer so that the stresses remain within the elastic range. In the closed position of the valve, the spring-loaded elastomer acts against a raised controlled width land on the hard seat. Additional interface sealing forces are generated by differential pressure acting on the seal effective area.

Design

The seat inner diameter is established by the flow requirements of the valve. The seat-land-width thus decides the magnitude of the pressure imbalance forces and valve closed bearing loads.

Candidate materials considered for the elastomer for hydrazine application are Kel-F, teflon and ethylene propylene rubber (EPR). Teflon requires high squeezing stress of the order of 350 gmf/mm^2 for good leak tightness and also has a tendency to cold flow under pressure. Squeezing stress required for EPR is about 150 gmf/mm^2 and more commonly used for hydrazine applications in active mode reaction control system.

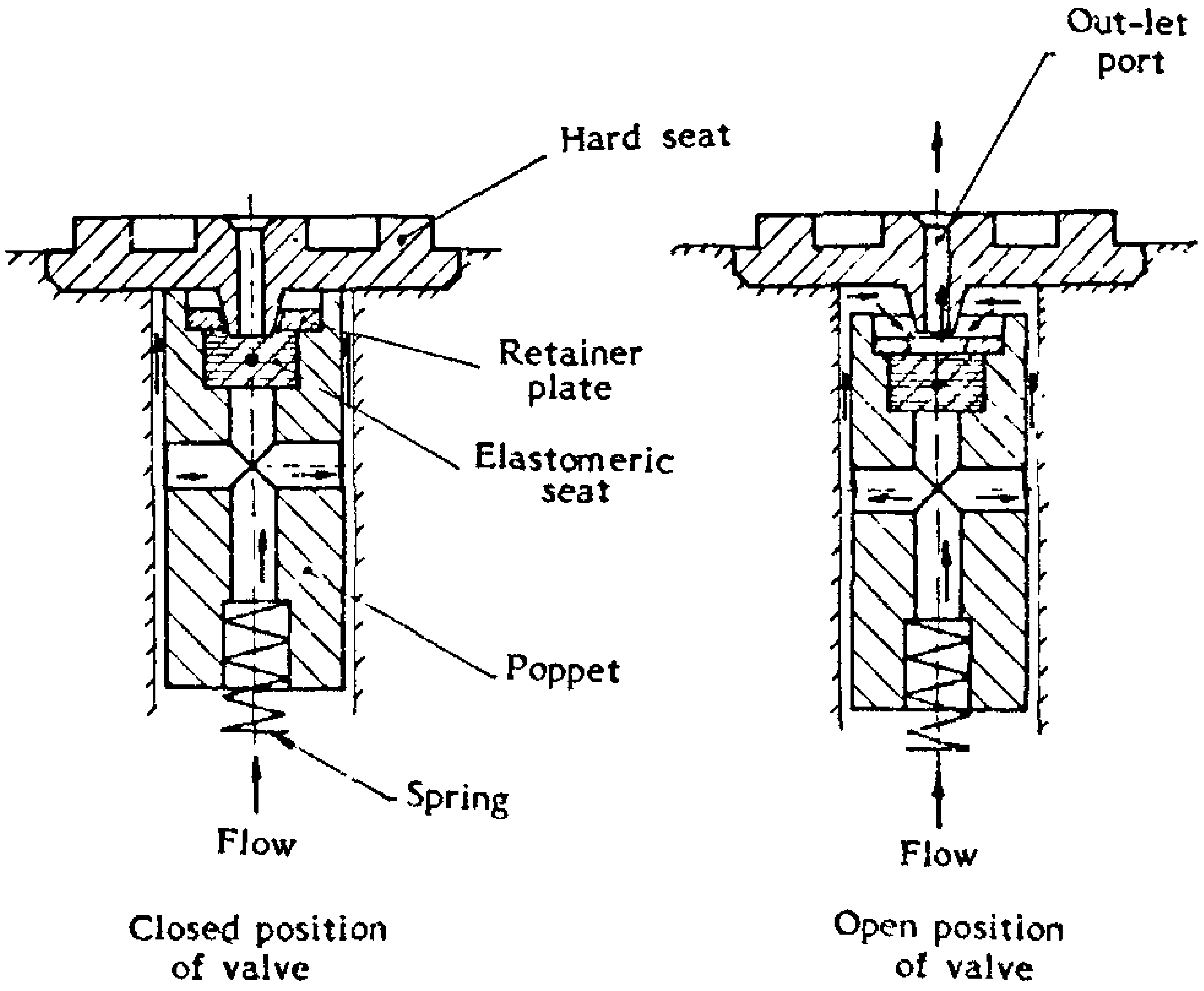

Figure 3. Hard on elastomer seating configuration.

Dimensional analysis[3]

Major parameters influencing the leak rate through the hard on elastomer configuration are: 1. Mean seat diameter (D); 2. Seat land width (L); 3. Pressure drop (ΔP); 4. Seat squeezing stress (S); 5. Surface roughness on hard seat (h_1); 6. Surface roughness on elastomer (h_2); 7. Viscosity of the medium (μ).

Using Buckingham π theorem, the above parameters are grouped and simplified into non-dimensional terms as

$$Q\mu/(L^3\Delta P) = K\ [h_1 h_2\ D/L^3]^x[\Delta P/S]^y,$$

where K, x and y are constants and are to be determined experimentally.

Evaluation of constants

In order to evaluate constants, three full scale models are simulated by varying parameters h_1, h_2, L, D and S. Design summary of the three models is given in table 2.

Leak rate thus is given by

$$Q = 0.66[h_1 h_2 D/L]^{3/2}(\Delta P^2/S\mu).$$

Performance studies

Performance studies on the seating interface are carried out by monitoring the leak rate through the seating using a mass spectrometer leak detector. Leak rate is monitored for each of the models at four different valve inlet pressures (i.e. 10, 15, 20 and 24 bar). The experimental results are shown in figure 4.

Performance analysis

It may be observed from figure 4 that in each of the models, the leak rate increased with pressure. The increase however is marginal. Further the leak rate increased from 7.9×10^{-6} scc/sec in model 1 to 4.36×10^{-5} scc/sec in model 2 and subsequently to 1.1×10^{-4} scc/sec in model 3, at 24 bar pressure. This is explained below: Leak rate is a function of s, D, u, h_1, h_2, and L. It may be seen from table 2 that there is an increase in D and L from models 1 to 3. The corresponding squeezing stress on the elastomer has reduced from 56.12 kgf/cm^2 in model 1 to 52 kgf/cm^2 in model 2 and further to 49.7 kgf/cm^2 in model 3, thus resulting in increased leak rate.

Table 2 *Design summary of the models*

	h_1 cm ($\times 10^{-4}$)	h_2 cm ($\times 10^{-4}$)	L cm	D cm	Initial S Kgf/cm^2
Model-1	0·2	0·6	0·1188	0·0298	19·15
Model-2	0·6	0·6	0·1225	0·0325	16·24
Model-3	0·6	1	0·1245	0·0345	14·81

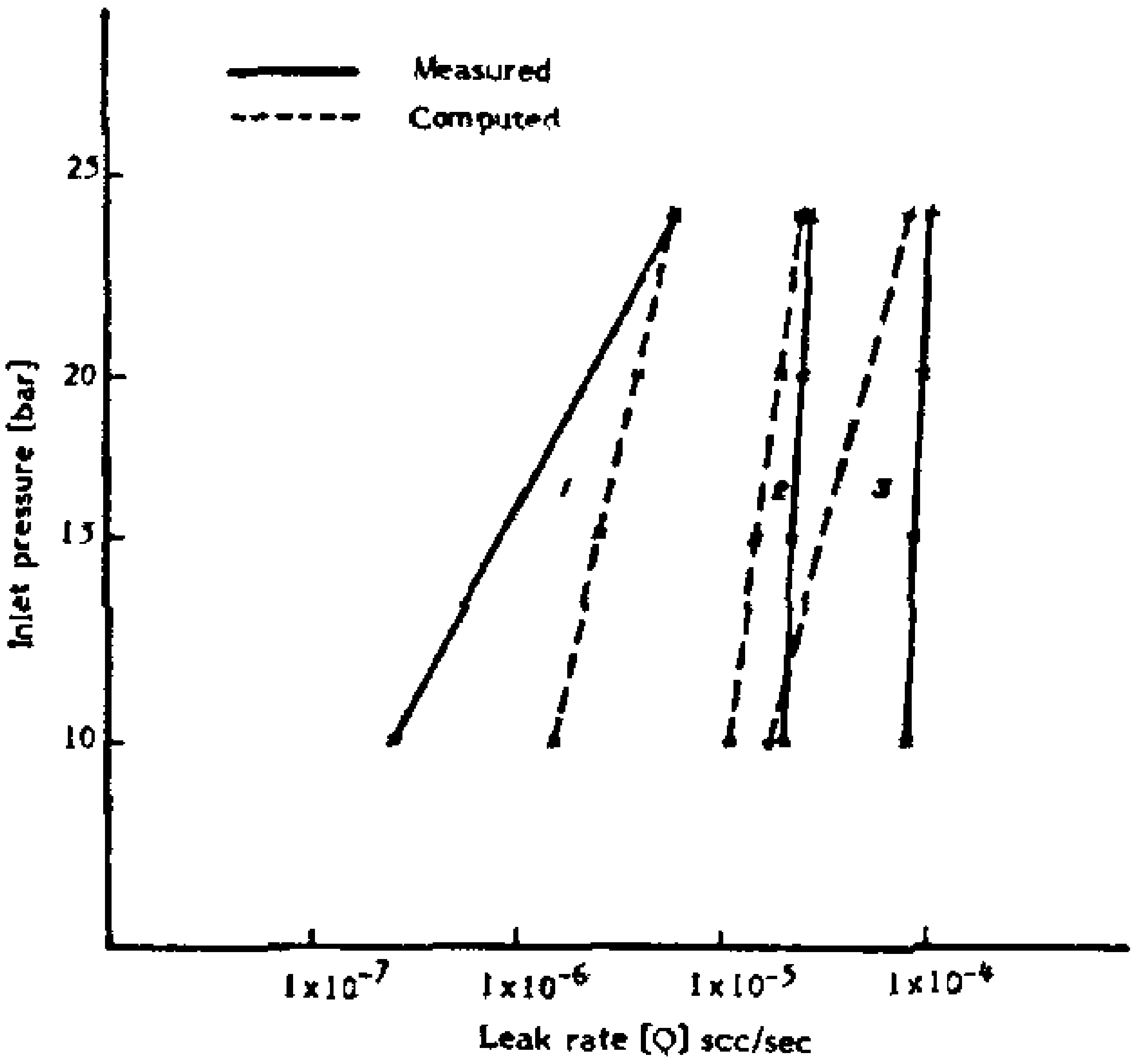

Figure 4. Inlet pressure vs leak rate.

Also, tight sealing requires yielding of one material into the surface waveness of the other to block direct leakage paths, thus, making these paths long and tortuous[4]. However from table 2 it is noticed that the surface roughness of the hard seat and the elastomer have increased from model 1 to model 3, thus again resulting in an increased leak rate.

Analytical vs experimental performance

Analytical and experimental results for the three models are shown in figure 4. From the results the general observation is that the measured leak rates are slightly higher than the computed values. However the deviation is very marginal and could be due to the following reasons: (a) Surface roughness measurement on the hard seat and elastomer is quite complex. Any minute variation would lead to errors in computed leak rates; (b) Spring force and pressure forces on the seating are only computed values and cannot be measured in assembly; (c) Computed leak rate does not take into account the misalignment between hard seat and the elastomer.

Nomogram

Equation for leak rate (Q) is represented on a nomogram (figure 5) with $h_1 h_2$ varying from 1×10^{-10} to 1×10^{-7} cm^2, $\Delta P^2/S$ from 0.1 to

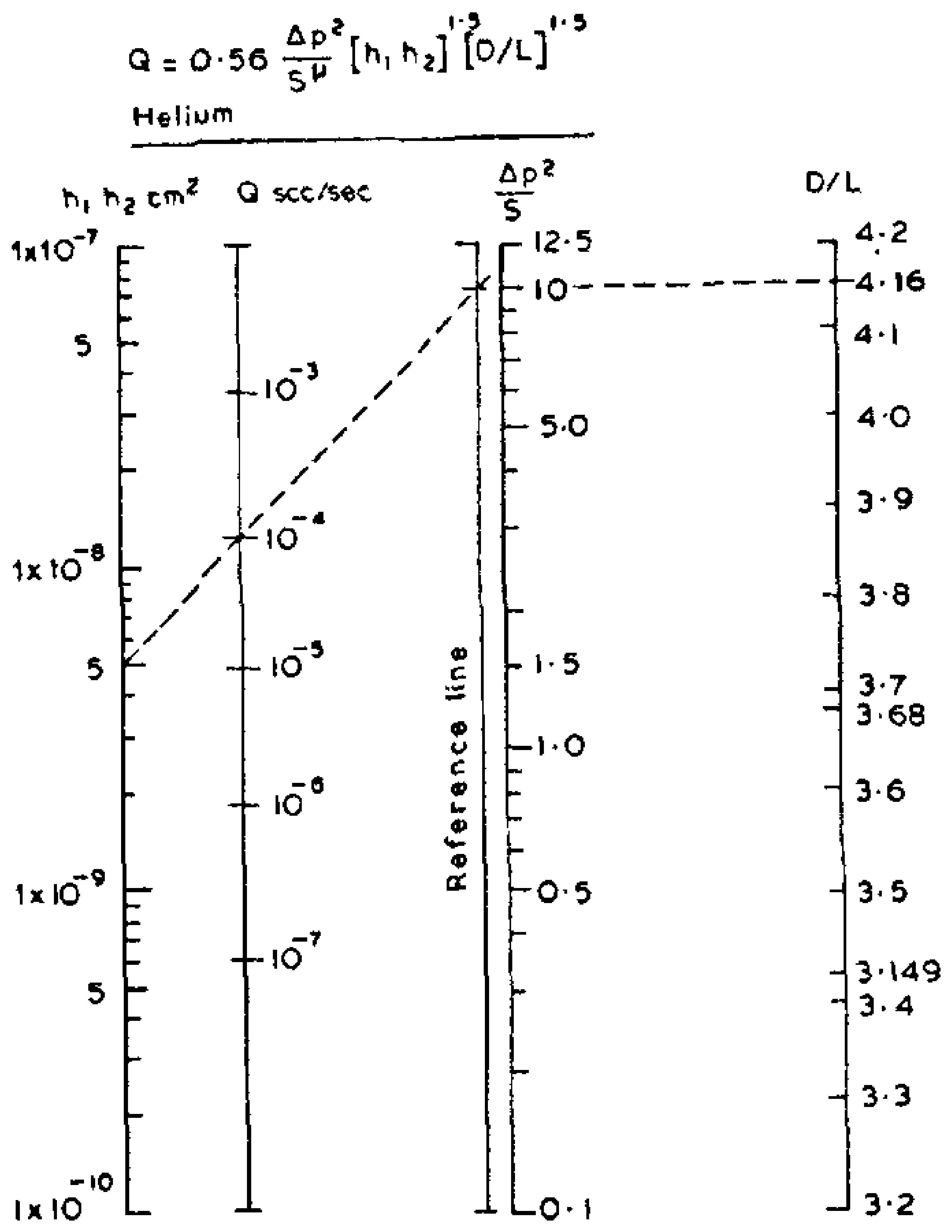

Figure 5. Nomogram for valve leak rate.

12.5 kgf/cm^2 and D/L from 3.2 to 4.2 with the following construction details.

Height of (D/L) scale 200 mm
Height of $(\Delta P^2/S)$ scale 200 mm
Height of $(h_1 h_2)$ scale 200 mm
Distance (Ref line and D/L) 75 mm
Distance (Ref line and $h_1 h_2$) 75 mm
Distance (D/L and $\Delta P^2/S$) 69.59 mm.
Distance ($h_1 h_2$ and Q) 25.2 mm.

CONCLUSION

A mathematical equation for the leak rate has been evolved and the constants determined by experimental studies on models. Measured leak rates are found to almost agree with the computed leak rates. Equation for Q is represented on a nomogram. This nomogram provides the guideline for the design of seating parameters of the valve.

Scope for further work

Equation for Q has been verified for a single configuration by varying parameters. The same may be verified for different configurations and for different materials.

17 February 1987

1. Rocket engine valve poppet and seat design data–May 1964: Technical documentary report No. RPL–TDR–64–68, p. 451.
2. *A manual of wright valves (space valves)* Wright Components Inc., USA, Oct. 1974.
3. Glen, W., Howell and Weathers, T. M., *Aerospace fluid component designers handbook*, Volume 1, Feb. 1970.
4. Hutchinson, J. W., *ISA hand book of control valves*, Instrument Society of America, Pittsburgh, 1971.

ANNOUNCEMENT

NATIONAL SYMPOSIUM ON ANALYTICAL SPECTROSCOPY INCLUDING HYFENATED TECHNIQUES

The above Symposium is organised by the Indian Society of Analytical Scientists, Analytical Chemistry Division, Bhabha Atomic Research Centre, Bombay and Regional Research Laboratory, Hyderabad, during January 18–20, 1988 at Regional Research Laboratory, Hyderabad.

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