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TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

DPST-72-544

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M E M O R A N D U M

TO: J. M. BOSWELL

FROM: J. W. REECE JWR/DMK

FLOW RESISTANCE OF REACTOR VENT PATHS

INTRODUCTION

Present analyses of reactor transients, which involve formation of steam in the reactor tank, neglect the effect of pressure feedback which results from resistance to flow through the reactor vent paths. The pressure feed-back increases the saturation temperature in the reactor which suppresses the formation of steam, the onset of flow instability in additional assemblies, and cavitation in the pumps and tank discharge piping. Therefore, pressure feed-back can affect a transient by delaying the negative reactivity caused by steam voids and the ultimate amount of melting before reactor shut-down.

A study was made to determine the combined resistance to flow of the various vent paths in the reactor system. This memorandum presents the results of the study. The effect of pressure feed-back on the course of a typical transient is illustrated in DPST-72-521.

SUMMARY

Friction resistance (head loss) as a function of combined flow through all of the vent paths is calculated by the following equation and illustrated in Figure 13.

$$\Delta P = 0.17 \left(\frac{Q_T}{1000}\right)^{1.98}$$

where

ΔP = pressure loss from tank to atmosphere (ft of fluid)

Q_T = total flow rate from tank, gpm

This correlation is valid for steady state conditions and slow transients where the effect of fluid inertia can be neglected. Similar correlations for the individual vent paths are presented in Figures 3, 4, 8, 11, and 12.

Hydraulic tests with a 1/4-scale model of the vacuum breaker indicate that its resistance to flow is about 2.0 times larger than previously used in calculations.[3] The measured flow resistance has been verified by recent calculations.[4,5]

This higher resistance to flow results in increased pressure beneath the shield in the unlikely event that emergency light water addition is required. The pressures under the shield for a light Mark 22 reactor charge for maximum emergency H_2O cooling (~12,000 gpm) are compared below with the calculated pressure which would result in failure of the roll anchors.[3]

- Roll anchors fail - 12.1 psig, P reactor; 23.7 psig, C-reactor
- Metallic seal on plenum skirt fails (roll anchors intact) ~27 psig
- Operating pressures at 12,000 gpm ECW flow 16.1 psig

Failure of the roll anchors would lead to failure of the metallic plenum skirt seal with upward movement of less than 1 inch which would then vent the reactor. Emergency coolant could still be added to the plenum to provide assembly cooling because the plenum nozzles, although deformed, would be intact. Alternatives are being evaluated by RED and Reactor Technology for reducing the resistance to flow through the vacuum breaker system to preclude lifting the top shield and plenum should emergency H_2O addition be initiated for any type of SRP reactor charge. A recommendation will be forthcoming.

DISCUSSION

D_2O or H_2O can flow out of the reactor due to operation of the emergency core cooling system or due to a reactor transient which pressurizes the tank due to steam formation. In either case the fluid exits from the tank in two places; (1) the vacuum breakers and (2) the forest standpipes over the septifoils, safety rods, and gas relief ports. The hydraulic resistance of the second path is much greater than the first so that most of the fluid exits through the vacuum breakers. The two flow paths are shown schematically in Figure 1.

The path involving the vacuum breakers has two main elements in series, the top shield and the vacuum breakers, while the flow through the septifoil, safety rod and gas port standpipes goes directly from the tank to the process room. The following sections provide details of the flow characteristics of each of these main elements.

A. THE TOP SHIELD

The top shield is a circular cylinder roughly 18 feet in diameter and about 40 inches in depth. It is perforated by numerous passages which allow flow of D_2O or H_2O in the presence of a pressure difference across the shield. A compilation of these flow paths include:

1. Standard four-inch Positions (Fuel, Target, and Septifoil)

2. One-inch Positions (Safety rods, tie bolts, and instrument rods)

3. Gas Ports and Motion Measuring Sleeves

4. Annulus between Shield and Tank Wall.

These flow paths are identified in part, in Figure 1. Calculations follow for each of these paths and the resulting flow vs. head curves are presented in Figures 3 and 4. These curves assume that there are 3 gas ports operating as designed and 3 gas ports with motion measuring equipment.

Standard Positions

There are 673 bores through the top shield which are generally referred to as standard four-inch positions. They are further divided into:

600 Fuel Positions
61 Septifoil Positions
6 Sparjets
6 Gas Ports

In the present analysis the gas ports are treated separately because they differ hydraulically from the other positions. The pertinent dimensions of a typical standard position are shown in Figure 2. The flow path is up the annulus and out into the gas space via the two 1/2" x 1/2" slots in the side of each permanent plenum tube.[1] Pressure losses are calculated for the annulus according to

$$\Delta h_f = f \frac{L}{D} \frac{V^2}{2g} \qquad \text{(A1)}$$

where

f = friction factor

L = length of path (ft)

D = hydraulic diameter (ft)

V = fluid velocity (ft/sec)

g = acceleration due to gravity (ft/sec^2)

Δh_f = head loss (ft)

Minor losses are considered as

entrance to annulus = $\frac{1}{2} \frac{V_A^2}{2g}$

entrance to and expansion = $\frac{3}{2} \frac{V_H^2}{2g}$

from square 1/2" x 1/2" hole

where

V_A = velocity of fluid in annulus

V_H = velocity of fluid in the hole

per sleeve. The resulting flow vs. head loss curve in Figure 4 for the standard positions is based on H_2O at 20°C because the calculations were done in connection with an emergency cooling water system study. The results do not differ greatly, however, for D_2O at 90°C.

Note that this curve is not applicable at flows below about 4400 gpm because of transition from turbulent to laminar flow.

One-Inch Positions

There are 160 one-inch positions (1.3125 inch ID) through the top shield. During normal reactor operation there is a safety rod, instrument thimble, or rod plug in each position. The nominal diameter of a safety rod thimble is 1.2725 inches which provides a small annulus between the thimble and permanent sleeve in which water can flow through the shield. Equation (1) is used to calculate the head loss and one and one-half velocity heads are assumed for entrance and exit losses in the annulus. The flow vs. head loss curve is shown on Figure 3 for the 160 one-inch positions.

Gas Ports and Motion Measuring Sleeves

Gas port positions have septifoil semipermanent sleeves with six one-inch holes drilled through to the gas space while motion measurement positions may have either sleeves with holes or standard septifoil sleeves with no holes. For this analysis it was assumed that permanent sleeves in all six positions contained holes. The flow vs. head loss calculations are made on the basis of a one and one-half velocity head loss through the six one-inch holes. The curve is shown in Figure 3.

For operation without the six one-inch holes, the flow through the standard positions should be increased by a factor of 6/676, and no flow to the gas space should be assumed for the "gas ports".

Top Shield Annulus

There is a nominal one-half inch clearance between the top shield and the tank wall which admits upward flow of water (or downward flow if that be the case). The total head loss is calculated for this passage from Equation (A1) with an additional one and one-half velocity head loss for entrance and exit from the annulus. The result is shown on Figure 4.

Total Flow Across the Shield vs. Friction Loss

Figure 4 shows a curve labeled "Total Top Shield" which represents a compilation of all the various flow paths. For an assumed flow of 10,000 gpm across the top shield, the distribution among the various flow paths is given in the following example.

$Q_{1'' \text{ positions}}$	= Nil	= Nil	at $\Delta H_f = 3.2$ ft.
$Q_{\text{Gas Ports}}$	= 510 gpm	= 5.1%	
$Q_{\text{Top Shield Annulus}}$	= 3,950 gpm	= 39.5%	
$Q_{\text{Standard Positions}}$	= 5,540 gpm	= 55.4%	
	10,000 gpm	100.00%	

This example illustrates that most of the flow goes through the shield at the standard positions. Hydraulic head loss across the shield was 3.2 feet of water in the above example.

B. THE VACUUM BREAKERS

The vacuum breakers provide the least resistance to effluent exiting the reactor tank via the two parallel flow paths. The complex hydraulic resistances across the vacuum breaker system cannot be calculated with much certainty. However, because most of the resistance is due to form drag and expansion-contraction losses, the system resistance to flow can be modeled by adherence to the Euler Number, $(=\Delta H/V^2/2g)$. Accordingly, a 1/4-scale model was constructed to duplicate the hardware components from the plenum skirt through the vacuum breaker standpipe. Figure 5 shows the model ready for testing.* Figure 6 shows the plexiglass lifting hook in place in the hood exactly scaled to reactor proportions. The model flow rate was 1/16 that of a full scale vacuum breaker. The model was located atop the volume flow calibration tank at CMX. Tests were conducted at several different flow rates.

Figure 7 shows the system in operation from above. Note that the deflector keeps the effluent away from what would be the reactor side of the vacuum breaker.

Figure 8 shows the head loss vs. flow scaled to reactor dimensions. Figure 9 shows the head loss in number of velocity heads vs. the flow.** The latter curve is almost flat over the range at which the system is likely to operate in the emergency core cooling water mode. This provides a good confidence measure for scaling up the results for reactor operation. Thus the friction loss through the vacuum breaker system can be given by

$$\Delta H_f = 8.00 \frac{v^2}{2g} \qquad \text{(B1)}$$

where v is the velocity of the water in the 12-inch vertical standpipe in (ft/sec) and ΔH_f is in feet of fluid flowing. This value of friction loss is about 2.0 times that used in previous ECCW calculations.[2] While this does not mean a great decrease in design ECCW flow, it does mean that the pressure beneath the top shield and the plenum is considerably greater than previously calculated.

* The model used to obtain the data in this memorandum did not include a 2 inch segmented orifice dam located in the 14" line from the plenum hood to the vacuum breaker pot. This would not affect the results significantly.

** Based on velocity in the vertical standpipe.

C. FOREST STAND PIPES

The hydraulic resistance of three parallel flow paths must be considered for this exit path.

Septifoil Muff and Guide Tubes

Figure 10 shows typical components in a septifoil position. The fluid encounters resistance due to entrance and exit losses and pipe friction for flow into and out of the muff inserts and the guide tubes. The flow is so low that the flow is laminar. The pipe friction is given by equation (A1) with the friction factor

$$f = 64/N_{REY}$$

where N_{REY} is the Reynolds number. The results are:

MUFF	Entrance and Exit		$9 \frac{V_{in}^2}{2g}$
	Friction	4 long inserts	$.265 \; V_{in}$
		2 short inserts	$.0294 \; V_{in}$
			$.140 \; V_{in}^2 + .294 \; V_{in}$
Guide Tubes	Entrance and Exit		$1.5 \frac{V_{GT}^2}{2g}$
	Friction		$6.75 \; V_{GT}$
			$.0233 \; V_{GT}^2 + 6.75 \; V_{GT}$

The total loss from below the top shield out to the process room +14 foot level is

$$\Delta h_f = .140 \; V_{in}^2 + .294 \; V_{in} + .0233 \; V_{GT}^2 + 6.75 \; V_{GT} \qquad \text{(C1)}$$

where

V_{in} = velocity in insert annulus (ft/sec)

V_{GT} = velocity in guide tube annulus (ft/sec)

Δh_f = friction loss (ft)

Equation (C1) was used to calculate the head loss vs. flow characteristics for all 61 septifoil positions presented in Figure 11.

Safety Rod Standpipes

Of the 160 one-inch positions only 61 have safety rods and standpipes. The combined entrance and exit losses along with friction losses are

$$\Delta h_f = 8.578 \frac{V_{GT}^2}{2g} \tag{C2}$$

where V_{GT} is the fluid velocity (ft/sec) in the annulus between the safety rod and its forest guide tube. The coefficient is due to losses in the thimble, transition to the guide tube, and in the guide tube itself. Hydraulic characteristics of the safety rod positions are given in Figure 12.

Gas Relief Tubes

The third path of direct exit from beneath the top shield is through the three gas relief tubes (Gas ports). These positions have septifoil sleeves and a forest standpipe of 2.65" ID. The flow through these ports is quite high and is limited by the small diameter of the forest standpipe.

The combined pressure loss equation is

$$\Delta H_f = 2.723 \frac{V_{SP}^2}{2g} \tag{C3}$$

when V_{SP} is the fluid velocity (ft/sec) in the gas relief tube forest stand-pipe. Flow resistance as a function of flow through the gas port relief tubes is presented in Figure 11.

D. TOTAL FLOW

The objective of the present study is to provide a correlation which will allow prediction of the pressure beneath the top shield as a function of total flow through the reactor vent paths.

From Figures 11 and 12 the flow rate through the forest stand-pipes can be calculated from

$$Q_{FR} = Q_{SP} + Q_{SR} + Q_{GT} \tag{D1}$$

where the terms on the right hand side are the flows through the septifoils, safety rods, and the gas relief tubes, respectively. The combined resistance vs. flow for these vent paths is shown in Figure 12 as the "forest flow characteristics".

Adding the friction loss through the shield to that through the vacuum breakers gives

$$\Delta H_{fT} = \Delta H_{TS} + \Delta H_{VB} \qquad (D2)$$

Flow resistances from figures 4 and 8 can be combined to give the total flow resistance as a function of flow for the vacuum breakers as shown in Figure 13. This is the second of the two parallel exit paths from beneath the top shield.

Finally, by adding the flow through the vacuum breakers from Figure 13 to the flow through the forest stand-pipes from Figure 12 the total reactor overflow vs. friction loss can be obtained. The results are shown in Figure 13.

It is of interest to note that at an emergency cooling flow of 12,000 gpm the head beneath the top shield will be 23.3 feet of D_2O from Figure 13 due to friction losses and to this must be added the static head due to ~14 feet of D_2O. This gives a pressure beneath the shield of 16.0 psig. For a light reactor charge such as Mark VI-B[3] or Mark 22 a stress analysis of reactor components indicates that the roll-anchors will fail and the bolted-together plenum-top shield combination will rise up at 12.1 psig in P-reactor.

One solution to this problem would be to add more gas relief tubes. As can be seen from Figure 11 a significant portion of the vent flow can be made to go through this exit path. Another possible solution is to add two more vacuum breakers or to reduce in resistance to flow in the present vacuum breakers. The increased flow capacity would be compatible with pending Plant plans to change out the Cameron valves in the H_2O addition systems. A third solution might be to build a type of "blow-out" hood at the other two lifting lug positions.

E. SPECIAL CONSIDERATIONS

A number of less general facts can be listed about reactor vent paths.

Temperature Effects

Several incidents have been considered which would impose temperatures other than operating temperatures on the top shield and other reactor hardware subject to the expulsion of fluid from the reactor tank. In general, either of two situations prevails;

(1) emergency cooling water (H_2O) comes out of the system in the temperature range (20°C to 50°C) or

(2) steam at a maximum temperature of 123°C is blown through the system.

The former temperature range is based on the removal of decay heat at one minute after initiation of a combination scram-emergency cooling water incident and an ECCW flow of 12,000 gpm. The latter steam temperature is based on a system pressure which would just preserve the integrity of the reactor (i.e., not rupture the plenum skirt seal until the top shield is lifted).

Thus, conditions envisioned for any transient incident are not severe enough to cause thermal expansions which will affect the geometry of the exit paths to a large extent. Because the shield remains cool, hot water flowing through the shield annular space would tend to decrease the flow resistance.

C-Reactor

Several structural differences exist between C and P-K reactors. These need to be accounted for in any analysis involving the venting paths of C-reactor. Most of the differences can be considered by simply scaling up the flow rates presented in the foregoing sections. The following Table gives the number of components in the different areas.

Table I. Component Differences Between P-K and C

	P-K	C
Septifoils	61	73
Safety rods	66	79
One inch positions in top shield	166	178
Standard positions in top shield	673	667

JWR:vpb

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1. Engineering Department Drawing #W 134421

2. Gooden, D. R., letter to R. H. Cornwall, August 5, 1963.

3. Cornwall, R. H., Containment Incident Analysis Investigation of Main Tank Stresses, Engineering Department, DPE-2162, October 26, 1961 (Revised 3/61, 8/61, 9/61, 10/62). (Secret).

4. Personal communication S. D. Harris with H. Brewer.

5. F. B. Christensen logbook.

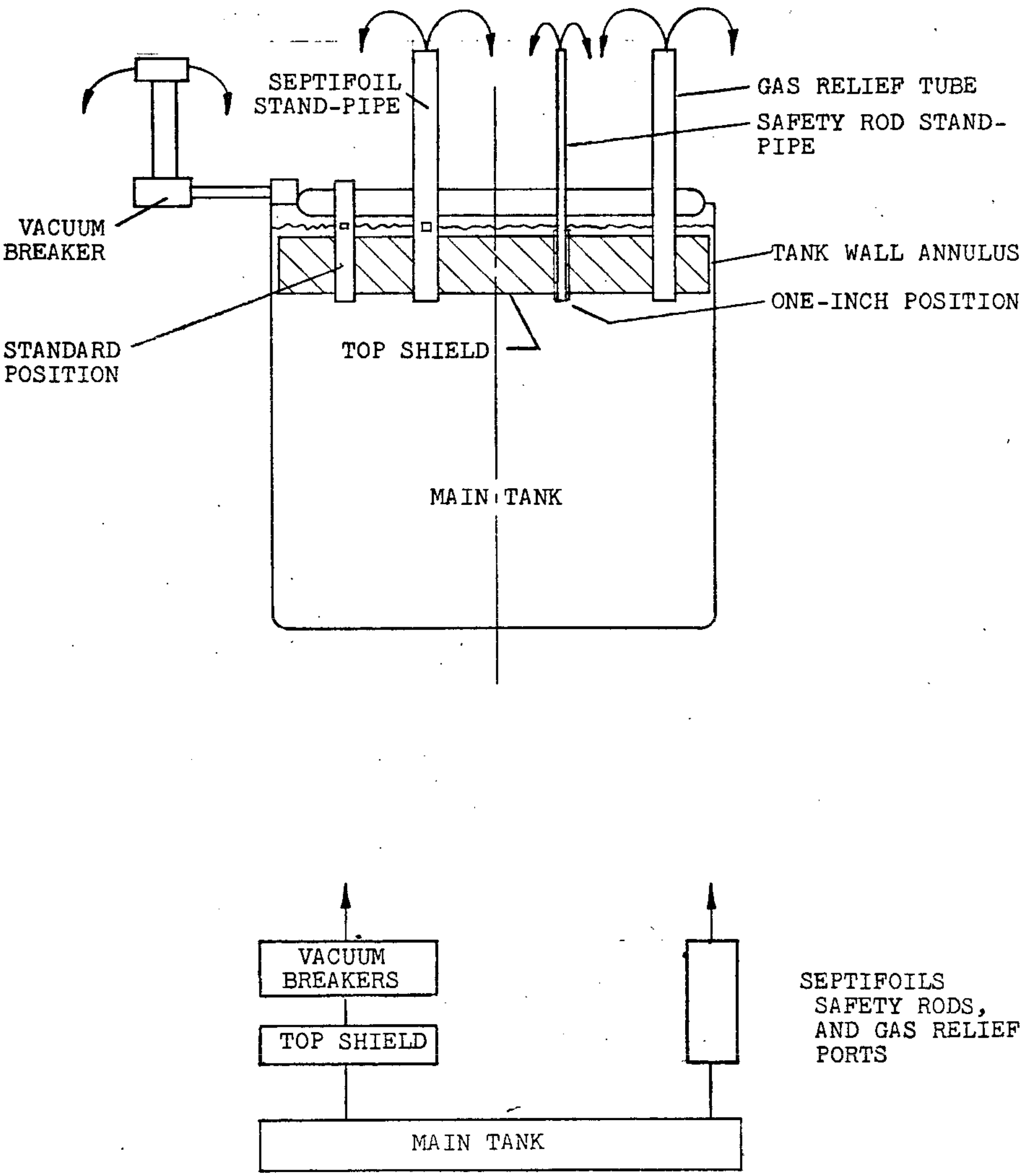


Figure 1. Reactor Exit Paths

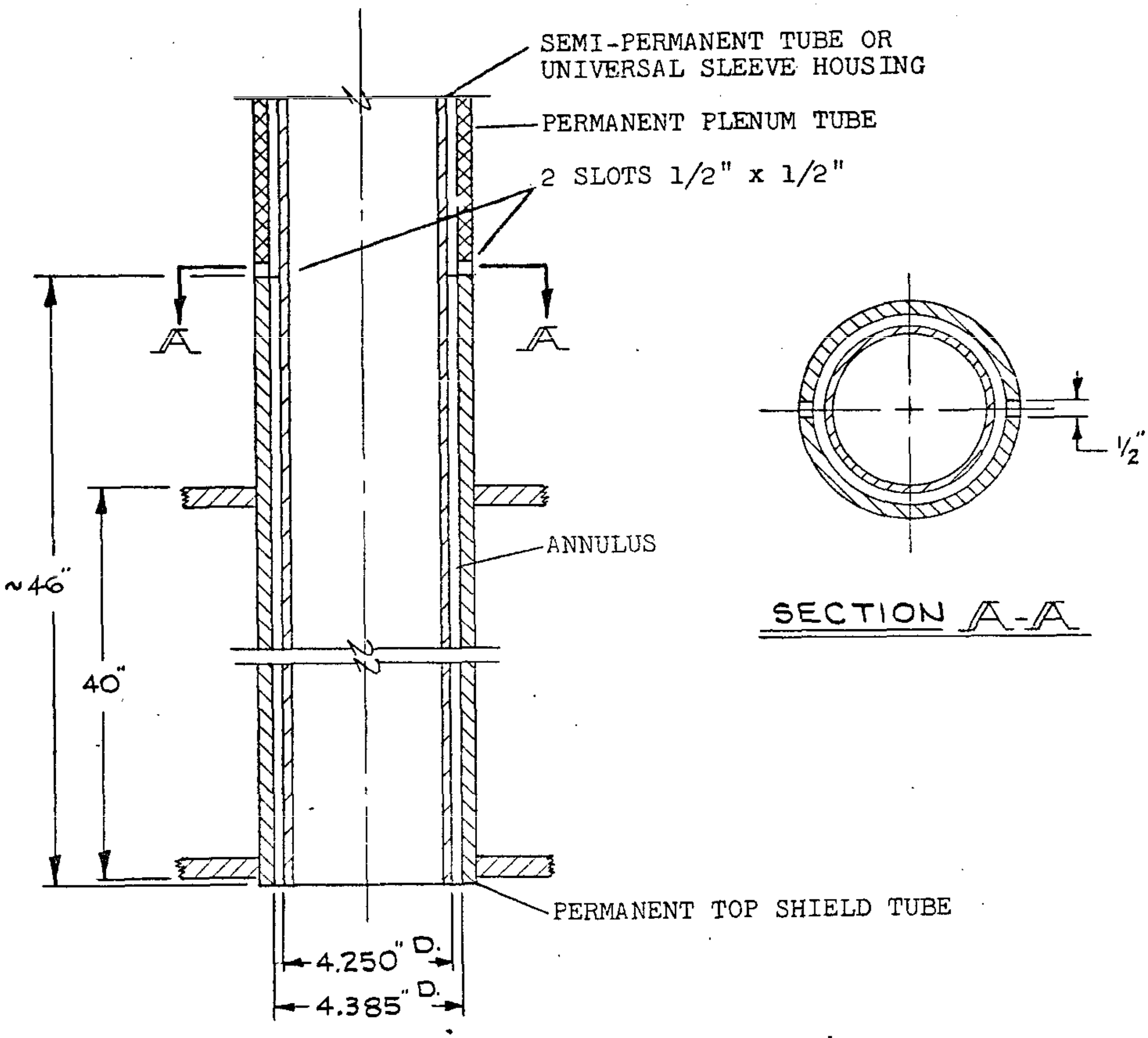


Figure 2. Standard Position Through Top Shield

Figure 3. Friction Loss Vs. Flow Rate for Low Capacity Paths in Top Shield

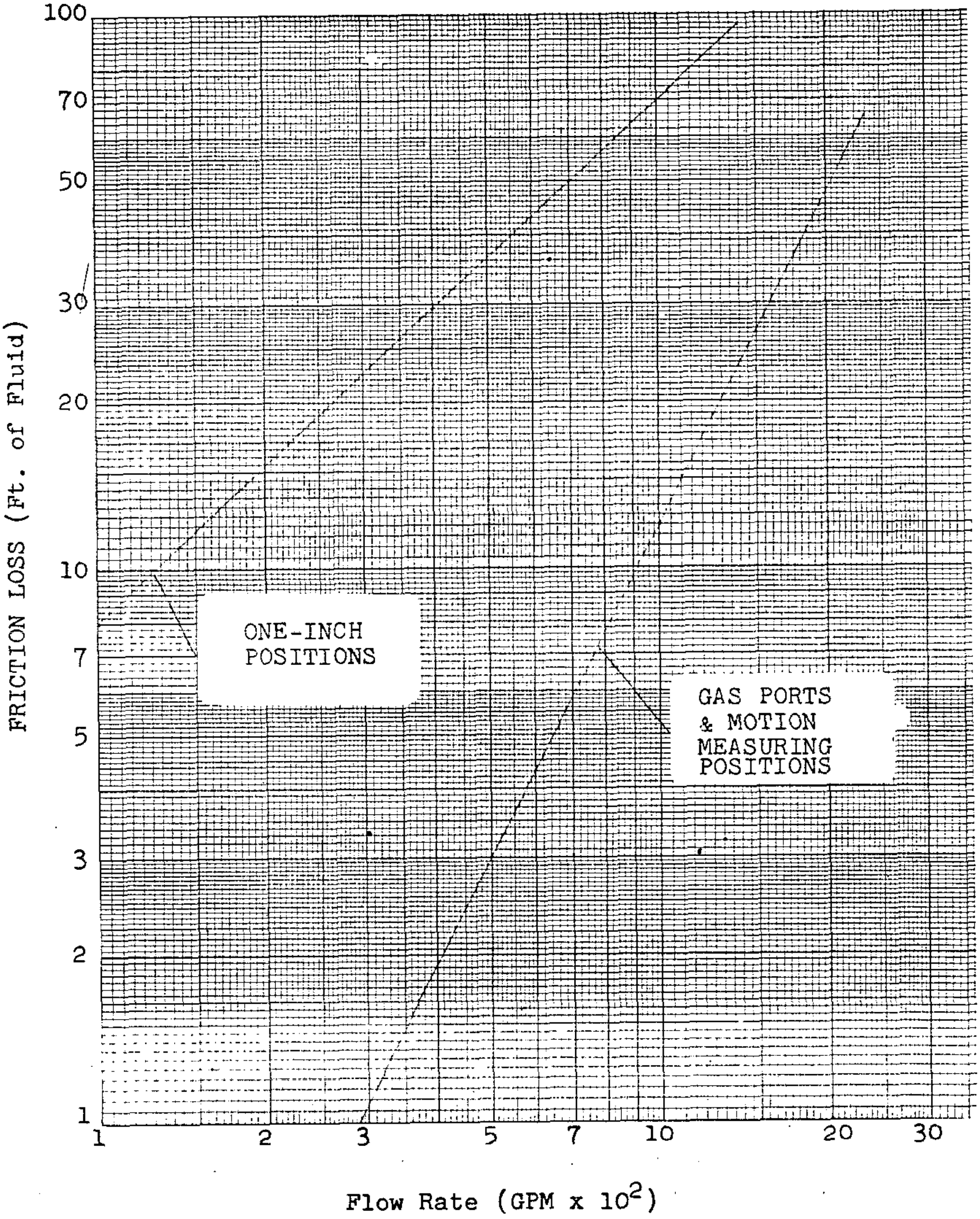


Figure 4. Friction Loss Vs. Flow Rate for High Capacity Paths in Top Shield

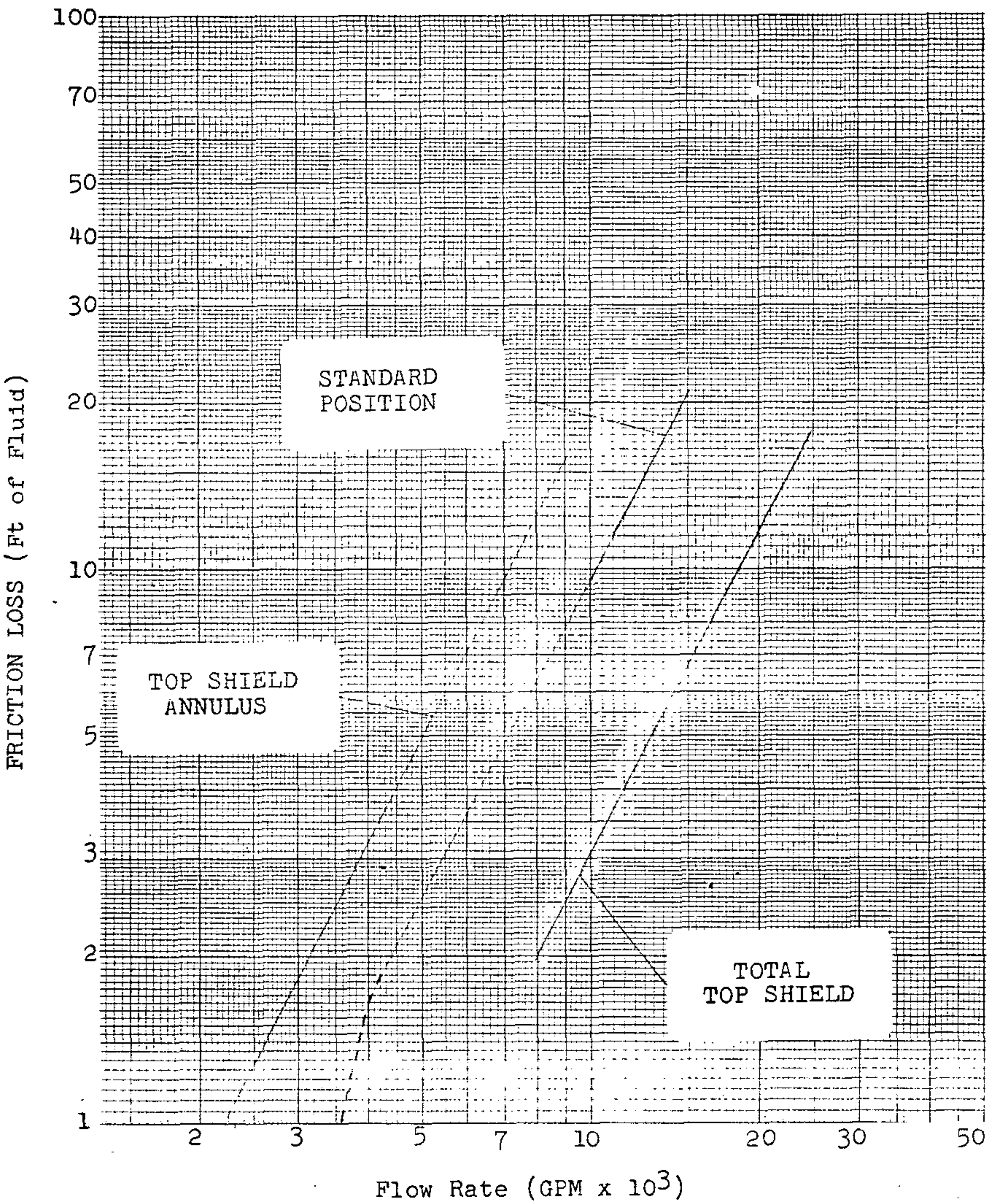


Figure 5. Vacuum Breaker Model

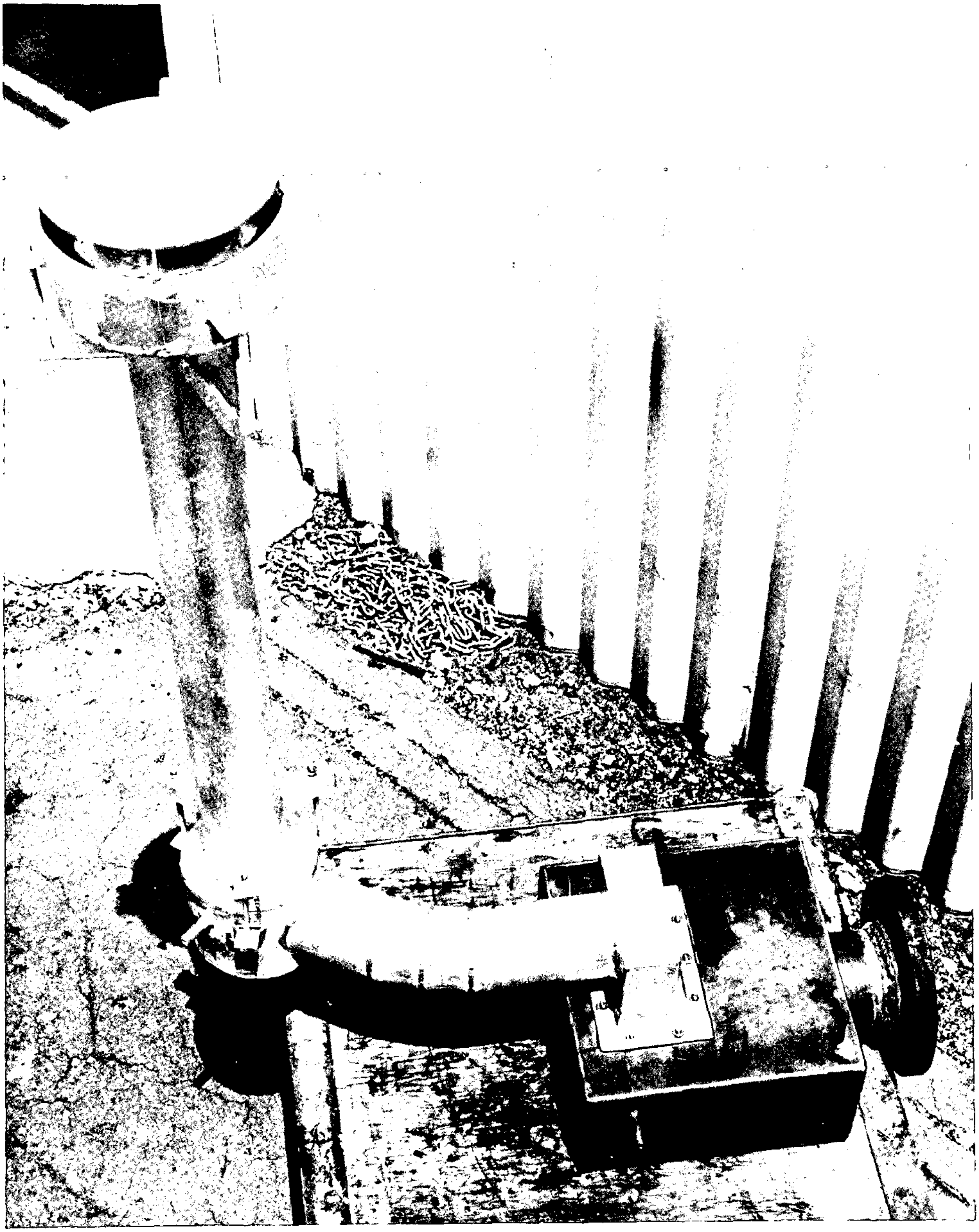


Figure 6. Plexiglass Top Shield Lifting Hook in Place

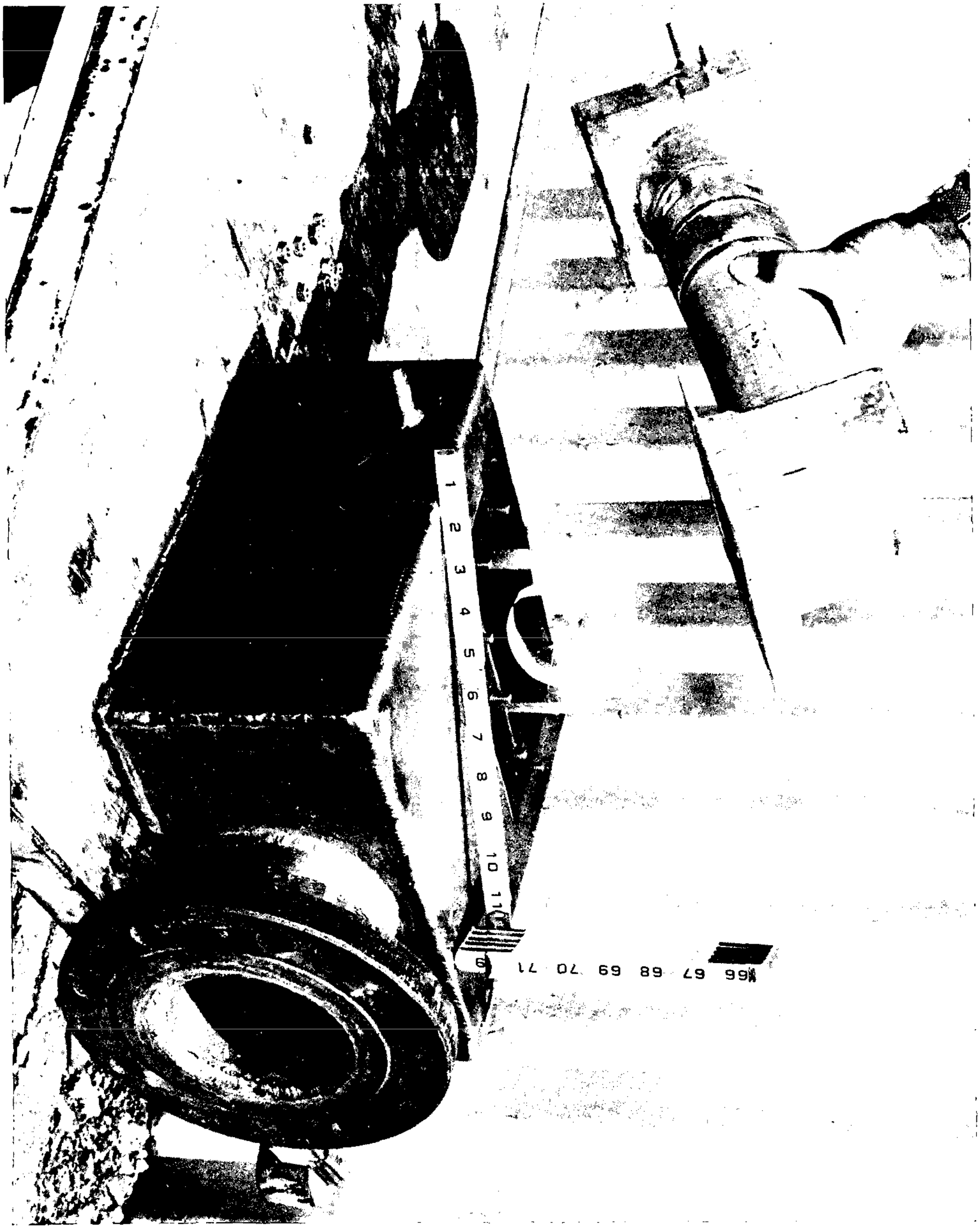


Figure 7. Water Discharge from Top of Vacuum Breaker During Testing.

Figure 8. Friction Loss Vs. Flow Rate Scaled to Reactor Proportions (from the Plenum Skirt to the + 14 foot Level)

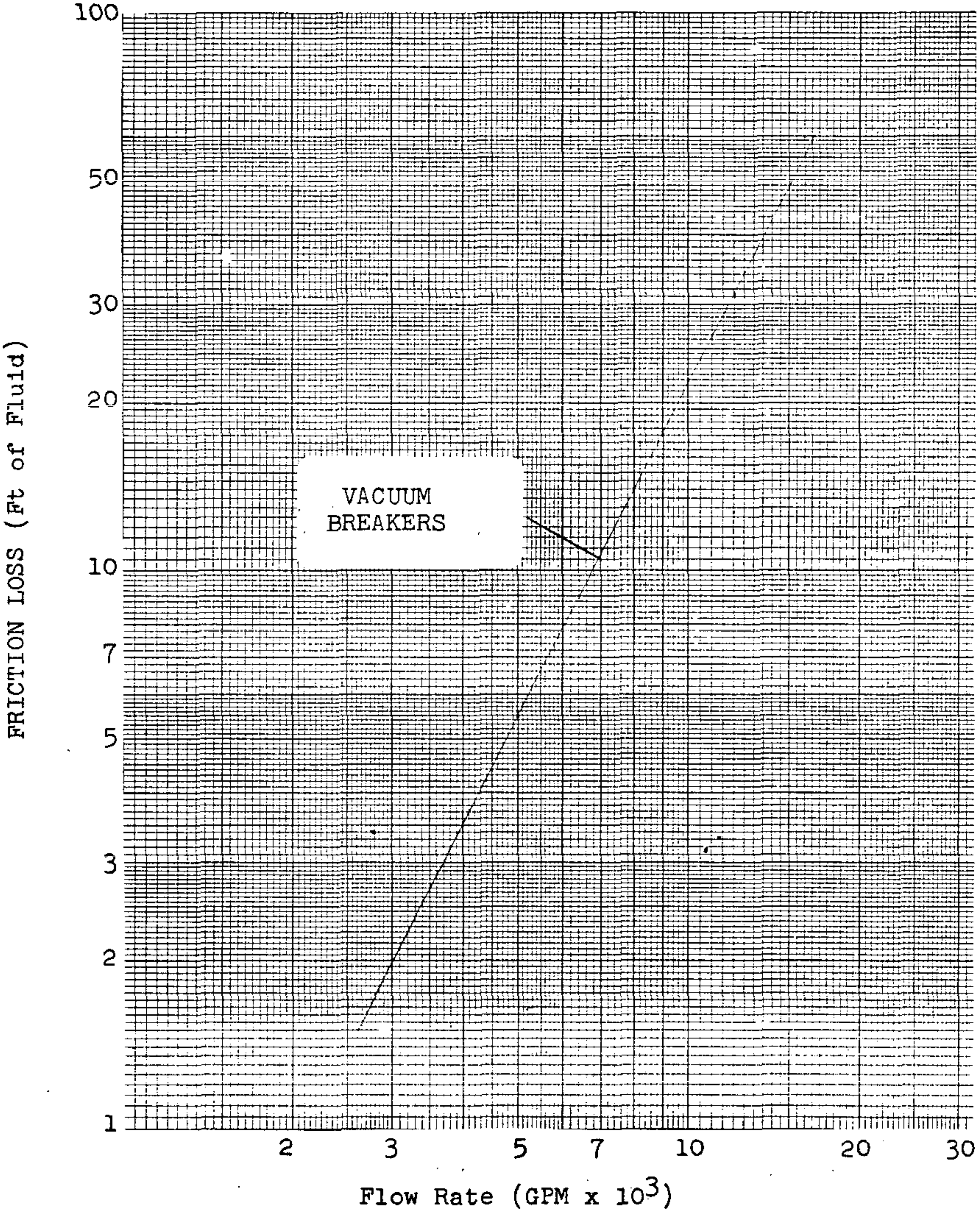
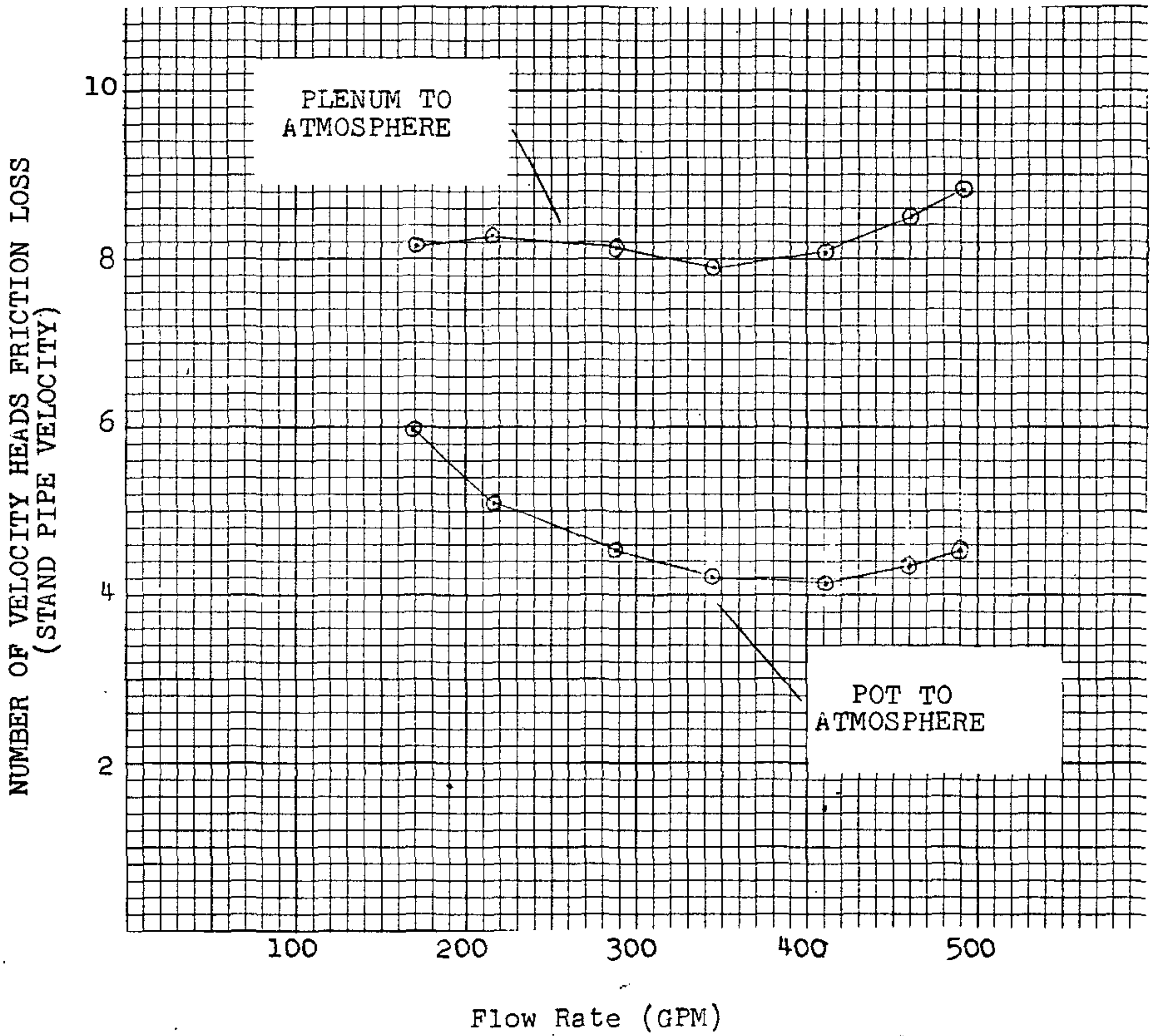


Figure 9. Number of Velocity Heads of Friction Loss Vs. Model Flow Rate.



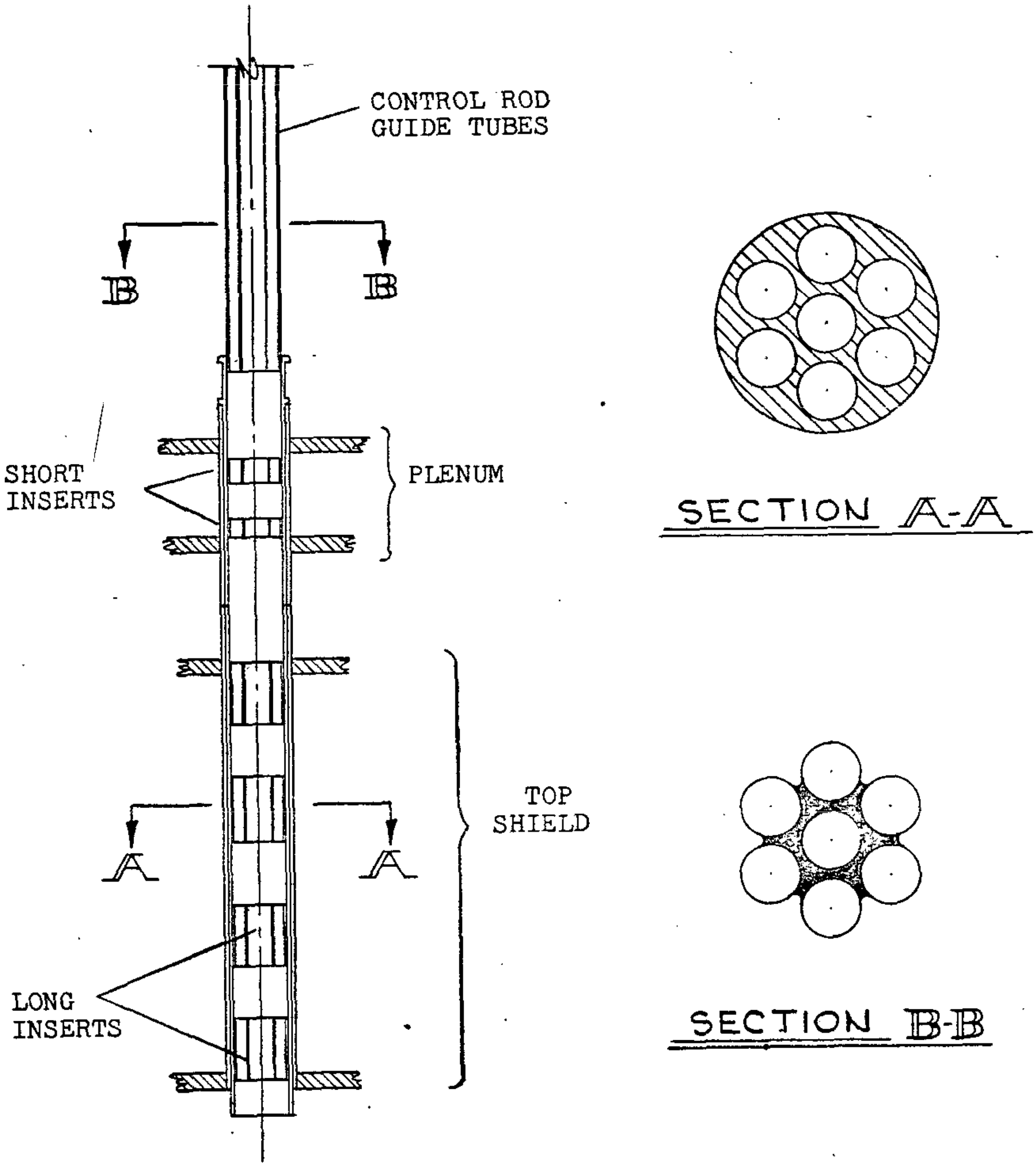


Figure 10. Components in a Typical Septifoil Position

Figure 11. Friction Losses Vs. Flow Rates for Septifoils and Gas Relief Tubes

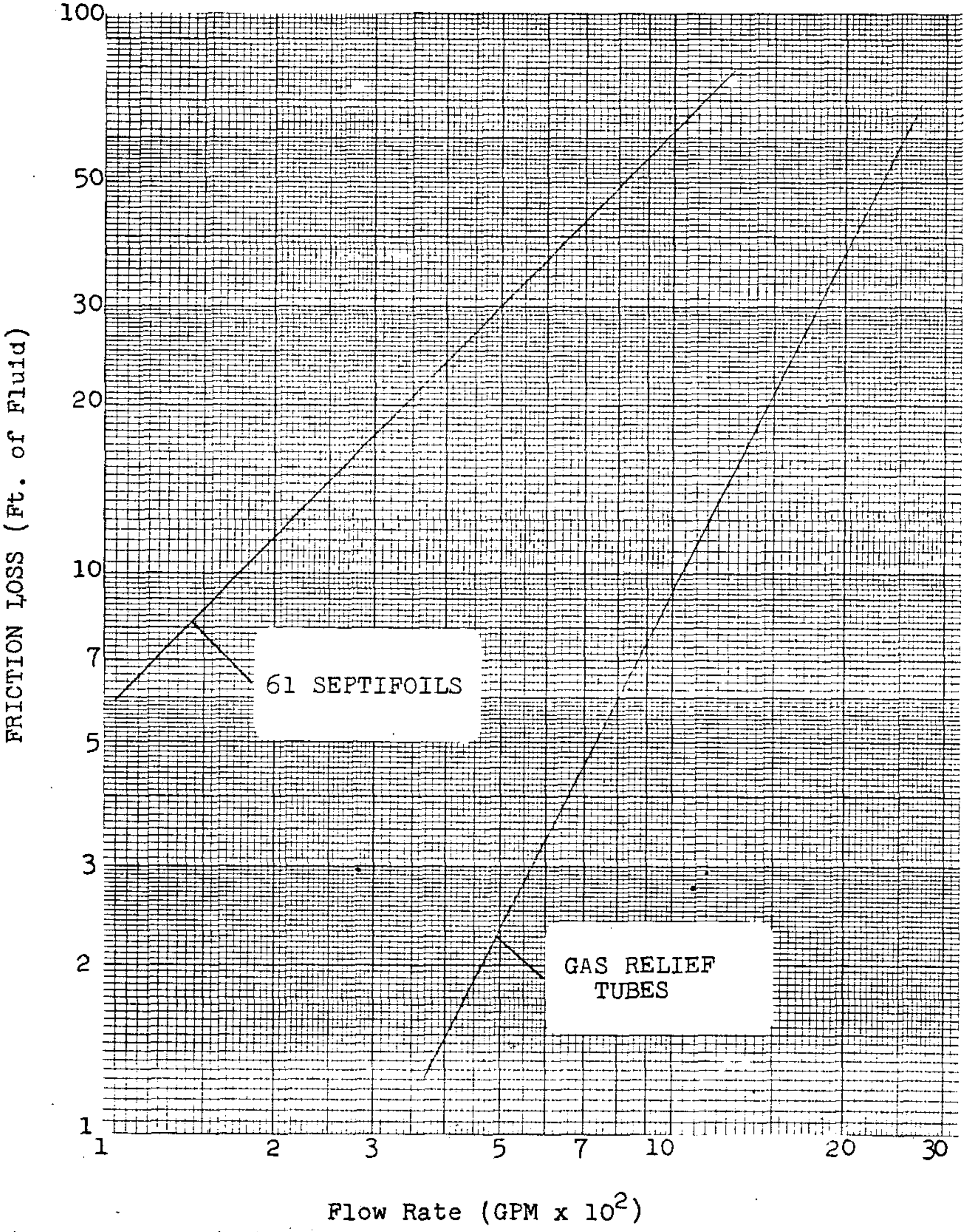


Figure 12. Friction Losses Vs. Flow Rates for Safety Rods and Combined Forest Flow.

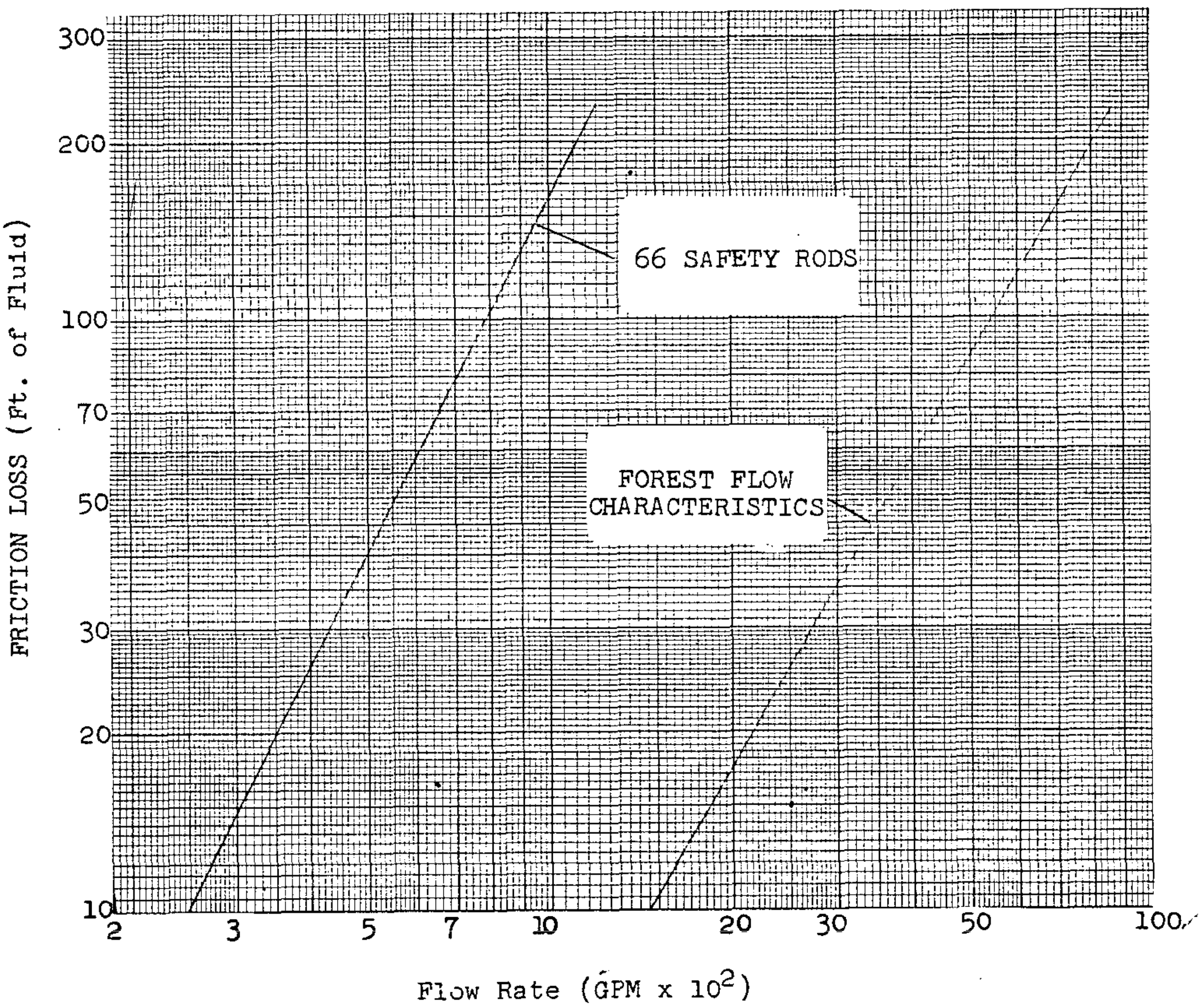


Figure 13. Friction Losses Vs. Flow Rates for Vacuum Breakers and Total Overflow (From beneath Top Shield to +14 foot Level).