FRICTIONAL HEAD LOSSES OF THE FLOW OF SLUDGE IN VARIOUS SIZES OF PIPES

Thesis for the Degree of B. S.

MICHIGAN STATE COLLEGE

James N. Carlisle

1949

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A

THESIS

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INTRODUCTION

The problem of functional head losses of sludge flowing in various sizes of pipes has long been a perplexing one to the design engineer, due to the varying nature of the sludge itself. It has been definitely established that no two samples of sludge are alike in water content, specific gravity and other such properties. Emperical formulas have been devised but their use is mainly for sludge flowing at velocities in the near turbulent region. Therefore in the recent years an attempt has been made by experimentation to find a solution which would standardize in some manner the design of sewage sludge pumps and sludge lines.

It was the intention of the author, in some way, to add additional information to the exhaustive research of Mr. Harold E. Babbit and Mr. David H. Caldwell of the University of Illinois Experimental Station. There were, however, numerous obsticles in the way, mainly the time element and the lack of experimental equipment at Michigan state College.

Through the cooperation of the officials at the Jackson Sewage Disposal Plant at Jackson, Michigan, a set of data was taken and compared to data obtained from the ~~Ameuior~~ American Well Works, Aurora, Illinois, and the Illinois Experimental Station.

It is with deep regret that a more extensive research effort could not have been made, However, as it was stated previously ~~stated~~ the time element was an important factor.

The author wishes to express sincerist appreciation to Professor Frank Thoreaux of Michigan State College for his time and professional assistance.

PART I

The amount of information concerning sludge is limited and insufficient when attempting to estimate the head losses due to friction caused by sludge flows in pipe lines. In the flow of sewage sludges it has been assumed that the formula usually applicable to water may be applied to sludge provided the velocity of the flow is great enough to cause turbulence. Problems envolving the laminar flow of fluid in various sizes of pipe can be solved by means of Poiseuilles's equation which is:

$$\frac{H_f}{L} = 0.00136 \left(\frac{\mu}{\omega}\right) \frac{Q}{D^4}$$

where H_f = head losses in feet

L = length of pipe in feet

Q = rate of flow in cubic feet per second

μ = absolute viscosity in poises

ω = weight in grams per cubic centimeter

D = diameter in centimeters

Q = discharge in cubic feet per second

Turbulent flow frictional losses are determined by means of the Reynolds-Stanton diagram. At present emperical formulas are being used to determine the laminar flow frictional losses of plastic or pseudo-plastic materials which are flowing in circular pipes. This means that not only are these loses evaluated for sludge but for other fluid as well, such as suspension of clay, need from drilling processes, and wood pulp suspensions.

In carrying on from this point it would undoubtedly be clearer to discuss the investigations of other experimenters, notably Babbitt. Professor Babbitt has been responsible for a number of the emperical formulas in use today. Professor Babbitt is also noted for his studies of the properties of the so-called plastic fluid which upon examination gives a much better understanding of the actions and reactions of sludge under varying conditions. It would be nearly impossible to discuss in detail these properties, however, the author will present the most important of the characteristics which it is hoped will leave any reader's mind open to individual examination and experimentation.

One of the properties which varies considerably in all sludges is viscosity, which is defined as <u>the measure of the resistance to flow or deformation of a fluid</u>.

The rate of deformation is a linear function of the deforming force. The coefficient of viscosity of a fluid is equal to the tangential force on a unit area of either of two horizontal planes at a unit distance apart required to move on plane with a unit velocity with reference to the other plane, the space between being filled with the viscous substance. Therefor it follows that:

$$\mu' = \frac{Sx}{V} \qquad (1)$$

where μ' = coefficient of viscosity

S = tangential unit shearing force

x = distance between the planes

V = velocity of one plane with respect to the other.

In the C.G.S. system the unit of viscosity is called the poise, or the centi-poise, which is one one-hundredeth of a poise. There is no name given to the coefficient in the F.P.S. system.

The next important property which varies considerably is plasticity and plastic flow. Plasticity is defined as the propesty of a substance which enables it to be continuously and permanently deformed in any ddirection without rupture under a stress exceeding the yield value. After deformation has started, equal increments of stress will produce equal increments of velocity. Since a part of the applied force S is used up in overcoming the yield value of S_y, the equation for plastic flow becomes:

$$\eta = \frac{(S-S_y)\,x}{V} \qquad (2)$$

where η is the coeffieient of rigidity of the ~~motival~~. material.

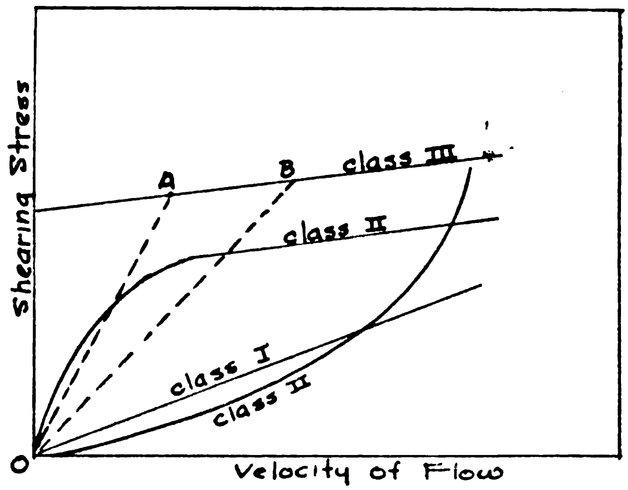


Fig. 1

Class I	True Liquid
ClassII	Pseudo-plastic
Class III	True Plastic
Class IV	Inverted Plastic

Figure 1, is a representation of 4 recognized types of flow. Curve I represents the flow of a true liquid, the slope of the line is proportional to the coefficient of the viscosity. Curve II represents the flow of a pseudo-plastic material. This curve does not follow the equation of a plastic flow since the line bends toward the origin at low rates of flow. Curve III represents a true plastic and is a graphical representation of equation (2). The apparent viscosity of the plastic at any point A on Curve III is proportional to the slope of the line OA. Therefore the apparent viscosity is not constant for different velocities and stresses. The two different velocities such as A and B, correspond to different viscosity lines OA and OB, the slopes of which are proportional to the apparent viscosity. Curve IV represents the flow of an inverted plastic material. This substance is thin at low rates of flow but becomes increasingly thicker as the force increases.

It was found by Babbitt, the flow of sludge and clay followed Curve III and were therefore classified true plastics.

In an attempt to formulate the factors affecting the friction resulting from the steady , uniform flow of sludge in a circular pipe, certain assumptions were made by Babbitt and then checked by certain tests. It was assumed that the conditions affecting the friction resulting from the laminar flow of sludge in a cirdular pipe were the velocity of the sludge, the diameter of the pipe, the length of the pipe and the characteristics of the sludge such as density, rigidity and yield value. The pressure and temperature were assumed to affect the friction only through their effect on the characteristics of the sludge. Another facto which was assumed to possibly affect the friction was the roughness of the pipe wall. However, it is known that, in the laminar flow of fluids, , pipe wall roughness does not affect the friction loss. . Therefore, it was assumed that the pipe wall roughness will not affect friction loss in the laminar flow of sludge. The friction loss was assumed to result only from the rubbing of the sludge layers past each other and not from kinetic energy losses.

Bingham presented by a complicated mathematical analysis a formula for the mean velocity of flow.

$$V = \frac{4D}{\eta}\left(S_p - \frac{4}{3}S_y\right) \quad (3)$$

where

D = diameter of pipe in feet

η = coefficient of rigidity, pounds per foot per second

S_p = shearing stress in a flowing material at the boundary or pipe wall, pounds per square foot

S_y = shearing stress at the yield point of a plastic material, called yield value, pounds per square foot.

Bingham also showed that the coefficient of rigidity η and the yield value S_y were independent of the characteristics of the measuring apparatus, but dependent only on the nature of the sludge. Investigation showed that by plotting S_p as ordinate and $\frac{V}{4D}$ as abscissa the slope of the resulting line represents the coefficient of rigidity and for a given sludge, the same line represents the flow of the sludge in a pipe of any diameter. For industrial piping and with sewage sludges, clay slurries and drilling muds, the following equation was found applicable:

$$\frac{H}{L} = \frac{16 S_y}{3\rho D} + \frac{\eta V}{\rho D^2} \quad (4)$$

where H = head loss

L = length in feet

ρ = density, pounds per cubic foot

The critical velocity was considered as that velocity below which the friction loss is directly proportional to the velocity and above which the friction loss is directly proportional to some power of the velocity between 1.7 and 2.0.

Reynolds showed that the critical velocity occured at a definite value of the Reynolds number. It has been recently shown that in industrial piping the value of the Reynolds number at the critical velocity is approxamately 2300. For circular pipes the flow will be liminar when the Reynolds number is less than 2000, but in industrial installations the flow will usually be turbulant above Reynolds number of 3000.

In order to determine Reynolds number it was necessary to know the viscosity of the flowing material. Since sludge possesses no definite viscosity but a varying apparent viscosity, Reynolds criterion for critical velocity cannot be directly evaluated for sludge. However, by refering to Poisevilli's expression of viscosity

$$\mu = \frac{4DS\rho}{V} \qquad (5)$$

formulas for both the lower critical velocity V_{lc}, and the upper critical velocity V_{uc}, were derived, giving

$$V_{lc} = \frac{1000\eta + 103\sqrt{94\eta^2 + D^2 S_y \rho}}{D\rho} \qquad (6)$$

$$V_{uc} = \frac{1500\eta + 127\sqrt{140\eta^2 + D^2 S_y \rho}}{D\rho} \qquad (7)$$

Actual experiments showed a high degree of correlation between observed and computed values.

Among the important factors to be considered in sludge are the factors affecting yield value, and the coefficient of rigidity. The most important of these factors are concentration of suspended matter, size and character of particles of suspended matter, temperature, thexotrophy, slippage and seepage, agitation and gas content.

In Babbitt's investigation, the concentration of suspended matter was taken as the ration of the weight of dry solids to the weight of the mixture of dry solids and liquid. According to the test made showed that the concentration of suspended matter greatly affects the yield value and affects the coefficient of rigidty to a lesser degree. Further tests were interpreted to mean that the net effect of an increase in solids concentration was to increase the resistance to the flow of the material.

Bingham stated that as the diameter of the solid particles is decreased the resistance to flow increases. This is not considered as reliable information however, since the size of the particles may be change by chemicals present, agitation or temperature changes.

Temperature has a marked effect on the viscosity of fluids. In the case of liquids a rise in temperature lowers the viscosity while in the case of gases the reverse is true. In Babbitt's investigation no attempt was made to formalate the effect of temperature on the yield value in the case of sewage sludges. Hatfield found a decrease in resistance to flow of sewage sludge with an increase in temperature.

Thixotrophy is the property, or phenomenon, exhibited by some gels of becoming fluids when ~~broken~~ shaken. This change may also be reversible. It may be readily seen th t erroneous data may be acquired if the property is not taken into consideration and possibly overcome. These thixotropic properties greatly affect the viscosity of fluids thereby giving erroneous observations.

Agitation may change the resistence to flow of a sludge in a given pipe line by changing both the yield value and the coefficient of rigidity. Agitation may change the size of the particles, rearrange or redistribute the particles or produce a form of thixotrophy. One of the commonest means of agitation is pumping the sludge through reciprocating, centrifugal or rotary pumps. This very definitely affects the sludges flow characteristics. The theory has been advanced that possibly the flow of sludge in long pipe lines may so change the values of η and S_y that the resistance to flow near the end of the line is less than at the beginning.

Bubbles of gas so finely divided as to be unable to rise and escape can occure in sludge through bacterial fermentation or as a resutl of mechanical stirring. This gas lowers the density and even though, theoretically, density has not effect on the laminar flow of sludge, it was observed that, when the velocity of flow was large enough to cause turbulence, the head loss due to friction is proportional to the density.

Although the investigations of sludge and its flow are limited, there have been a number of other investigations by experimentors who have had a primary interest in the problem. The results and conslusions they have drawn with regard to sludge are interesting and somewhat based on assumptions which do seem logical. The following is a list of a number of these investigators and their conclusions.

1. Gregory, W. B.
   (a) The most economical velocity for pumping is the critical velocity.

   (b) The apparent viscosity of slurry at the critical velocity varied from 24 to 85 times that of water, depending on the concentration of solids.

2. American Society of Civil Engineers
   (a) Sludge is neither a viscous nor a homogenous material but variable in character.

   (b) The usual analytical tests do not define its physical qualities, but it seems to behave more like suspended material.

(c) Below the critical velocity sludges have a different friction factor from that found above the critical velocity.

(d) Sludge friction increases with decrease of moisture content.

(e) Sludge friction losses tend to increase with lower temperatures.

(f) Sludge friction losses ~~fro~~ for high velocities from about 5 to 6 feet persecond or more, tend to follow more closely the characteristics for the law for the flow of water.

(g) Friction losses ~~fro~~ for fresh or undigested sludge and for sludge from combined sewage are more e ratic and the determination of the friction factor is more different.

(h) Within the limits of investigation, no law of flow was found.

3. Hatfield, W. D.

(a) The viscous properties of sewage sludge have been shown to be pseudo-plastic, that is, the apparent viscosity decreases as the rate of shear and the shearing stress increase.

(b) Sludge is thixotropic, the pseudo-plastic resistance and, therefore, the apparent viscosity being greatly reduced by stirring and shaking.

(c) The apparent viscosity when plotted a ainst the rate of flow or the percentage of solids produces a straight line on logarithmic coordinates.

It can be readily seen that much is left to be uncovered and that sludge pumps and sludge lines are a long ways from perfection. In spite of the amount of experimentation that has been done there is still room for improvement for the number of variable conditions are difficult to control. At the present the only anser to the situation appears to be, not in emperical formulas, but in data taken under actual field conditions where the varisble properties of the sludge and the effect of the various distribution systems can be recorded as they really are. When that day comes, there will undoubtedly be a considerable sabing in the expense of design, construction and maintainence of sewage disposal units.

PART II

Although the time element for this thesis was short, the author was able to obtain a set of data from the sewage plant of Jackson, Michigan with the intent of comparing the data to the results of other investegators. Included in the data obtained from other data are the charts which were drawn up from curves developed by the American Well Works of Aurora, Illinois. The results of these curves are shown in Fig. 2. The chart gives the head losses in various sizes of pipes under varying rates of flow, velocities and moisture content. The value listed under sludge friction factors are the percentage that the head losses are of the 100% water. By multiplying these percentages times the various head losses for 100% water the head losses under the various moisture contents are found. The frictional head loss values are plotted in Figure 3 through Figure 10 where it will be noted that they give a clearer picture of the behavior of sludge under the varying moisture contents.

In all cases the sludge curves are by no means comparable to the curve for 100% water. They do however seem to approach the trend of the 100% water in the upper values of velocity and rate of flow. This is particularly noticable in Figure 6 and Figure 10 for the 8" pipe. In the case of the smaller pipe the values are extremely high and run off the diagram.

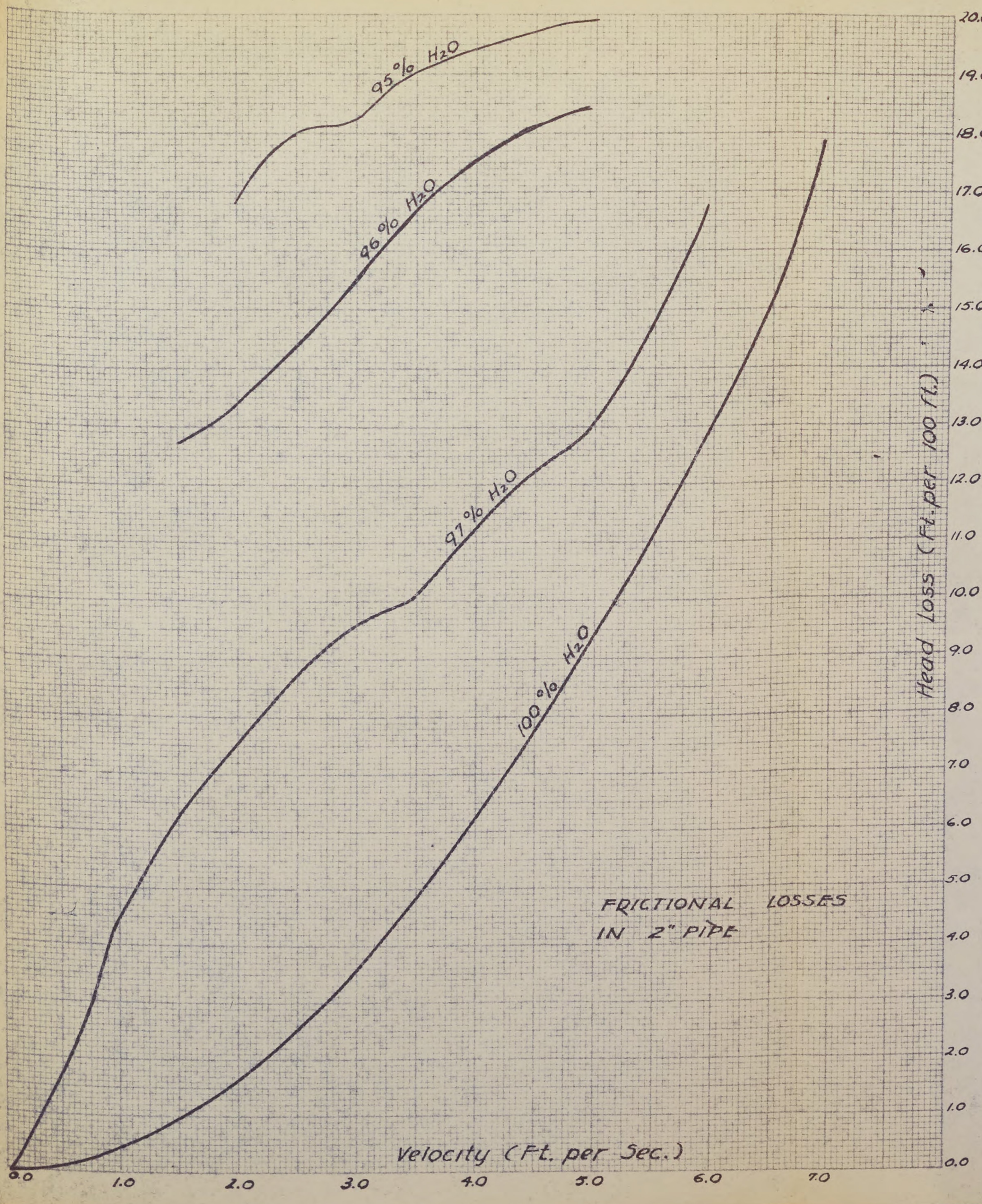
In all cases it can be plainly seen that for all moisture contents, with the exception of the curve for 100% water, there is a sharply defined hump in the curves at velocities varying between 1 and 3 feet per second. What really happens at those points can only be left to the imagination. It could be assumed

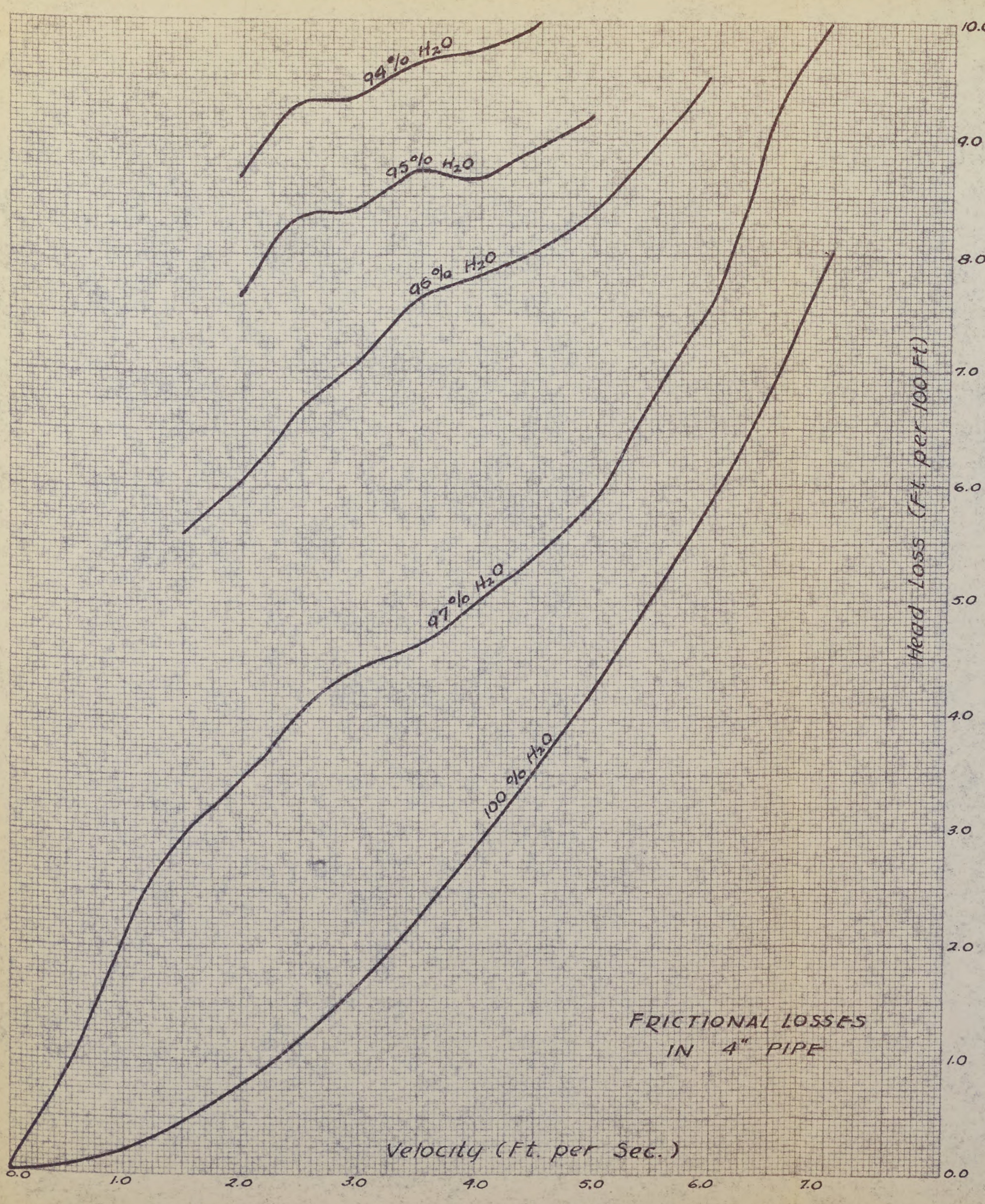
FRICTIONAL LOSSES IN PIPES

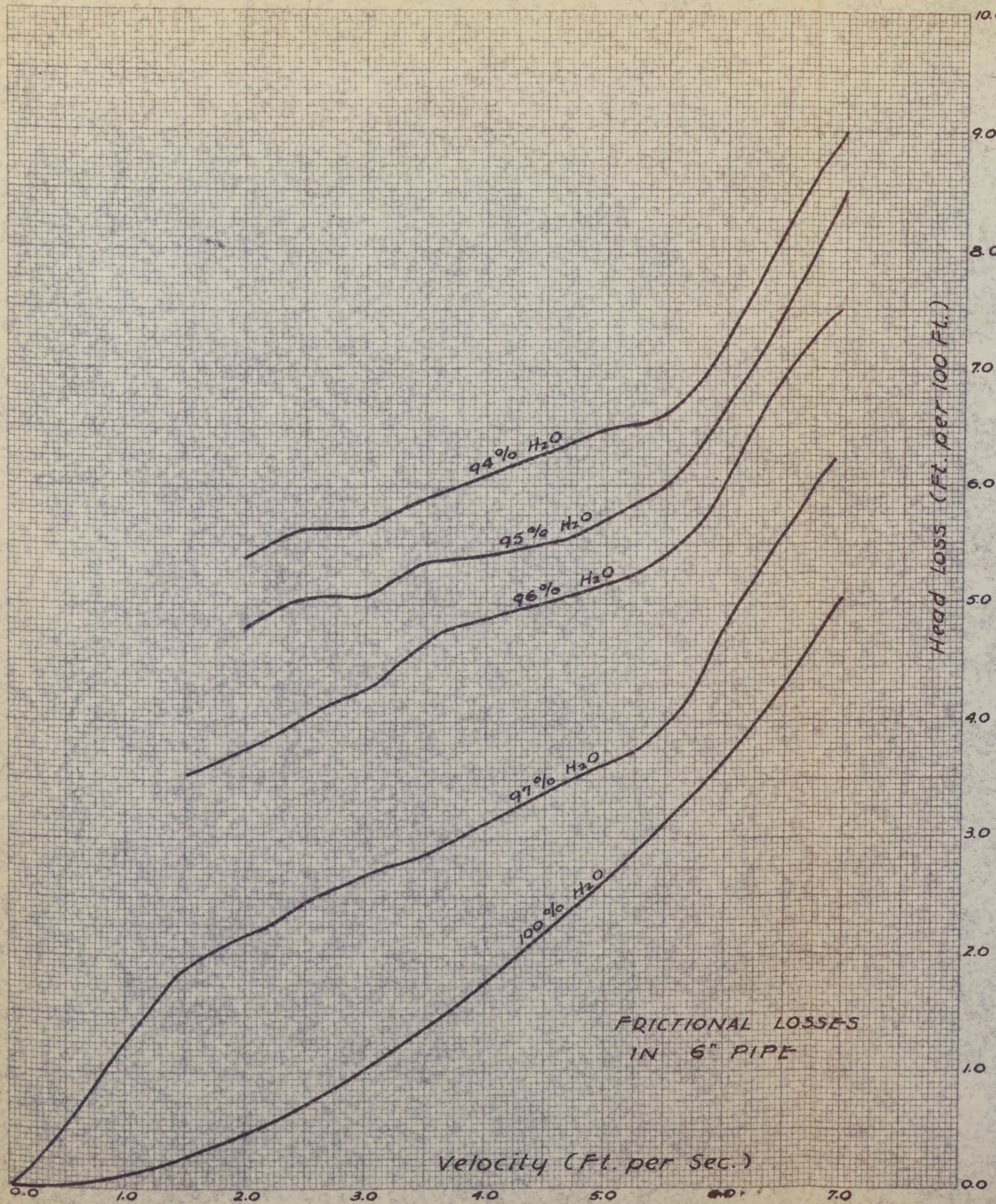
Vel. ft per Sec.	**Sludge Friction Factors				Ft. Friction per 100 ft 2-Inch Pipe						Ft. Friction per 100 ft 4-Inch Pipe						Ft. Friction per 100 ft 6-Inch Pipe						Ft. Friction per 100 ft 8-Inch Pipe					
	Sludge				Water		Sludge				Water		Sludge				Water		Sludge				Water		Sludge			
	97%	96%	95%	94%	Q g.p.m.	*h_f	97%	96%	95%	94%	Q g.p.m.	*h_f	97%	96%	95%	94%	Q g.p.m.	*h_f	97%	96%	95%	94%	Q g.p.m.	*h_f	97%	96%	95%	94%
0.5	14.5				4.58	.13	1.89				19.0	.06	.870				44.0	.037	.54				78.0	.026	.377			
1.0	9.1				10.0	.50	4.05				40.0	.22	2.0				84.0	.136	1.24				160.0	.097	.885			
1.5	6.2	12.3			14.9	1.05	6.30	12.9			58.0	.46	2.99	5.66			132.0	.29	1.89	3.57			235.0	.210	1.37	2.58		
2.0	4.5	7.9	10.0	11.3	19.0	1.70	7.65	13.9	17.0	19.2	77.0	.77	3.46	6.09	7.70	8.70	175.0	.48	2.16	3.80	4.80	5.93	310.0	.345	1.56	2.72	3.45	3.90
2.5	3.4	5.6	7.0	7.8	24.0	2.6	8.84	14.6	18.2	20.3	97.0	1.20	4.08	6.72	8.40	9.36	220.0	.73	2.48	4.09	5.10	5.69	400.0	.53	1.80	2.97	3.71	4.19
3.0	2.7	4.3	5.1	5.7	29.0	3.6	9.72	15.5	18.4	20.5	115.0	1.65	4.46	7.10	8.41	9.40	260.0	1.0	2.70	4.30	5.10	5.70	460.0	.73	1.97	3.19	3.72	4.16
3.6	2.1	3.5	4.0	4.4	34.0	4.8	10.1	16.8	19.2	21.1	132.0	2.20	4.63	7.70	8.80	9.70	310.0	1.35	2.84	4.72	5.40	5.94	540.0	.95	2.00	3.32	3.80	4.18
4.0	1.8	2.8	3.1	3.5	39.0	6.3	11.35	17.6	19.5	22.0	155.0	2.80	5.09	7.84	8.68	9.80	350.0	1.75	3.15	4.90	5.40	6.13	620.0	1.25	2.25	3.50	3.88	4.38
5.0	1.4	2.0	2.2	2.5	47.0	9.3	13.0	18.6	20.5	23.2	190.0	4.20	5.88	8.40	9.25	10.5	440.0	2.60	3.64	5.20	5.73	6.50	770.0	1.85	2.59	3.70	4.06	4.63
6.0	1.30	1.65	1.85	2.0	58.0	13.0	16.9	21.9	24.0	26.0	230.0	5.80	7.55	9.60	10.7	11.6	520	3.60	4.70	5.95	6.66	7.20	920	2.60	3.38	4.30	4.80	5.20
7.0	1.25	1.50	1.70	1.80	69.0	18.0	22.5	27.0	30.6	32.4	270	8.0	10.0	12.0	13.6	14.4	620	6.0	6.25	7.50	8.50	9.00	1100	3.60	4.50	5.90	6.13	6.49

*Based on C=100 in Hazen & Williams Formula

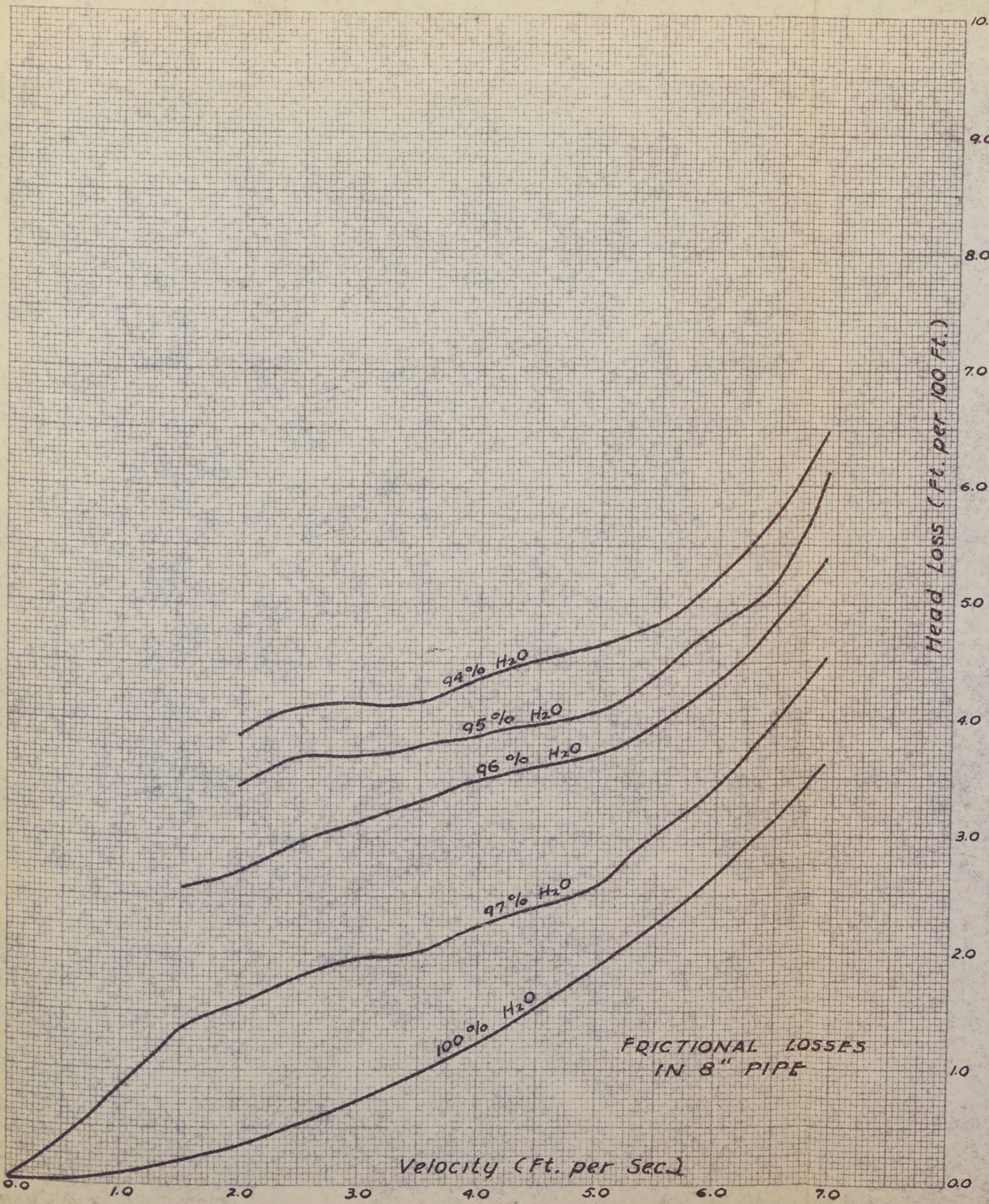
**From American Well Works Sludge Friction Curves


95% H_2O
96% H_2O
97% H_2O
100% H_2O
FRICTIONAL LOSSES
IN 2" PIPE
Velocity (Ft. per Sec.)
Head Loss (Ft. per 100 ft.)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
20.0

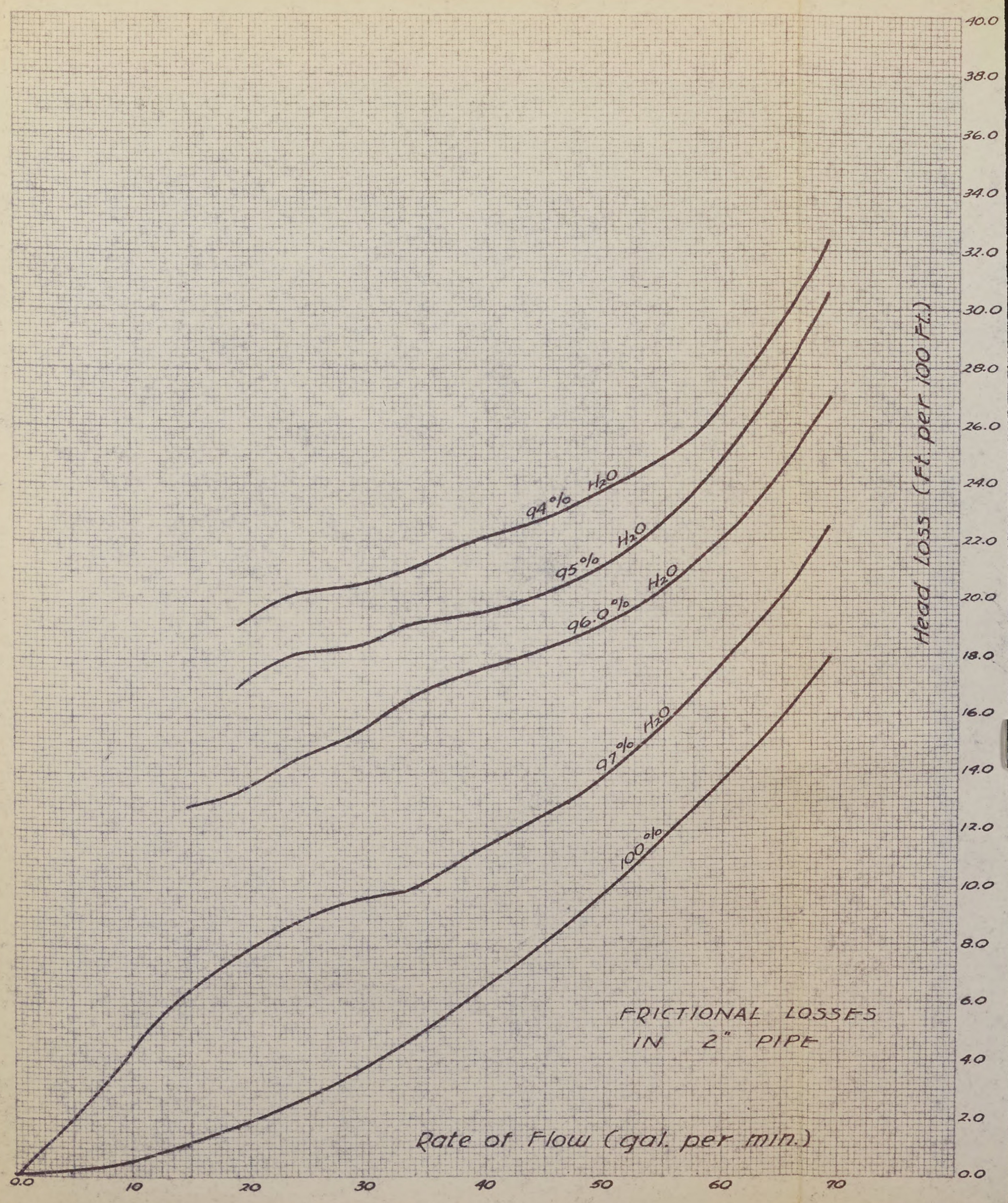

94 % H_2O
95 % H_2O
96 % H_2O
97 % H_2O
100 % H_2O
Head Loss (Ft. per 100 Ft.)
Velocity (Ft. per Sec.)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
FRICTIONAL LOSSES
IN 4" PIPE



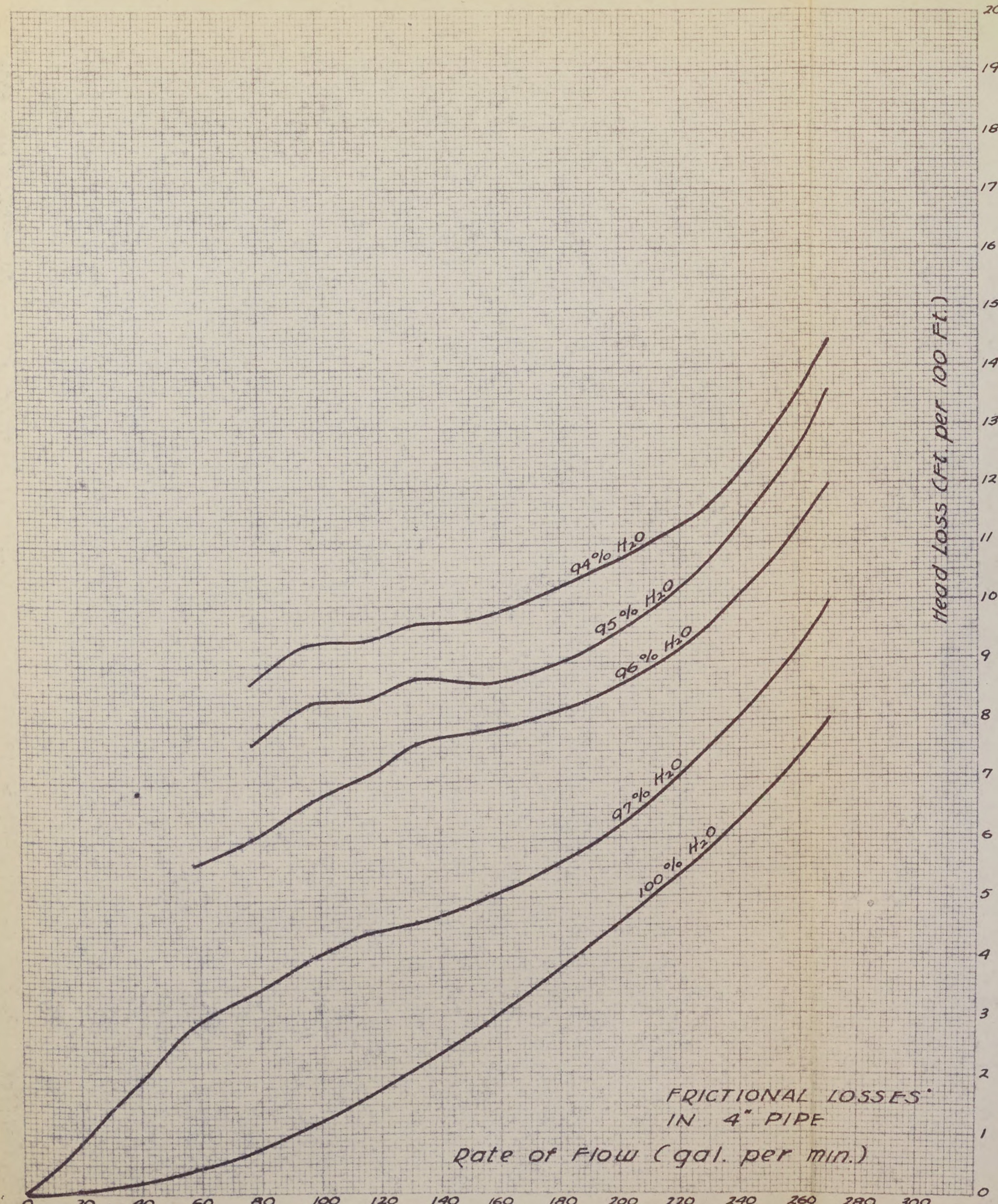
FRICTIONAL LOSSES
IN 6" PIPE
94% H_2O
95% H_2O
96% H_2O
97% H_2O
100% H_2O
Velocity (Ft. per Sec.)
Head Loss (Ft. per 100 Ft.)
0.0
1.0
2.0
3.0
4.0
5.0
7.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0



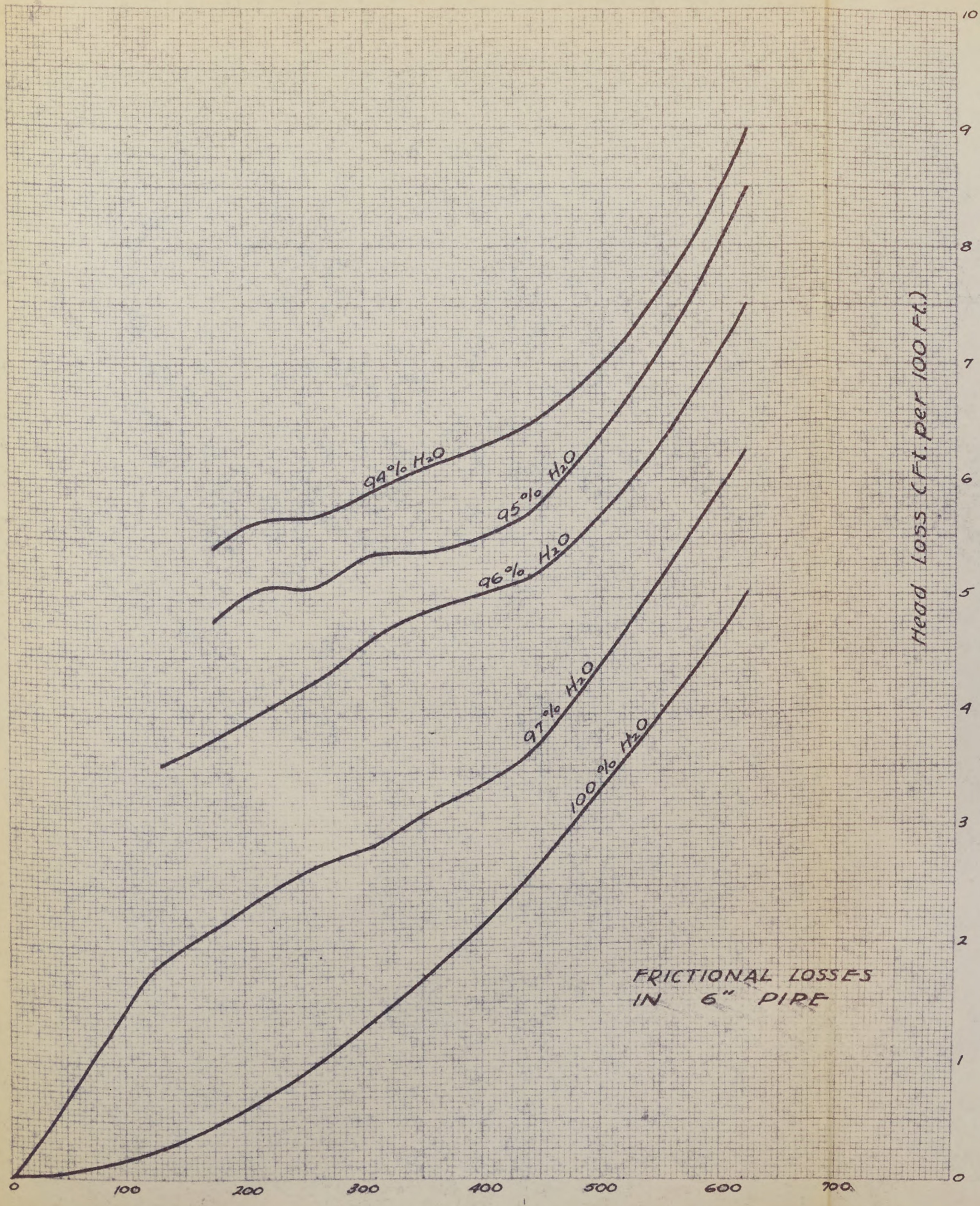
FRICTIONAL LOSSES
IN 8" PIPE
Velocity (Ft. per Sec.)
Head Loss (Ft. per 100 Ft.)
94% H_2O
95% H_2O
96% H_2O
97% H_2O
100% H_2O
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0



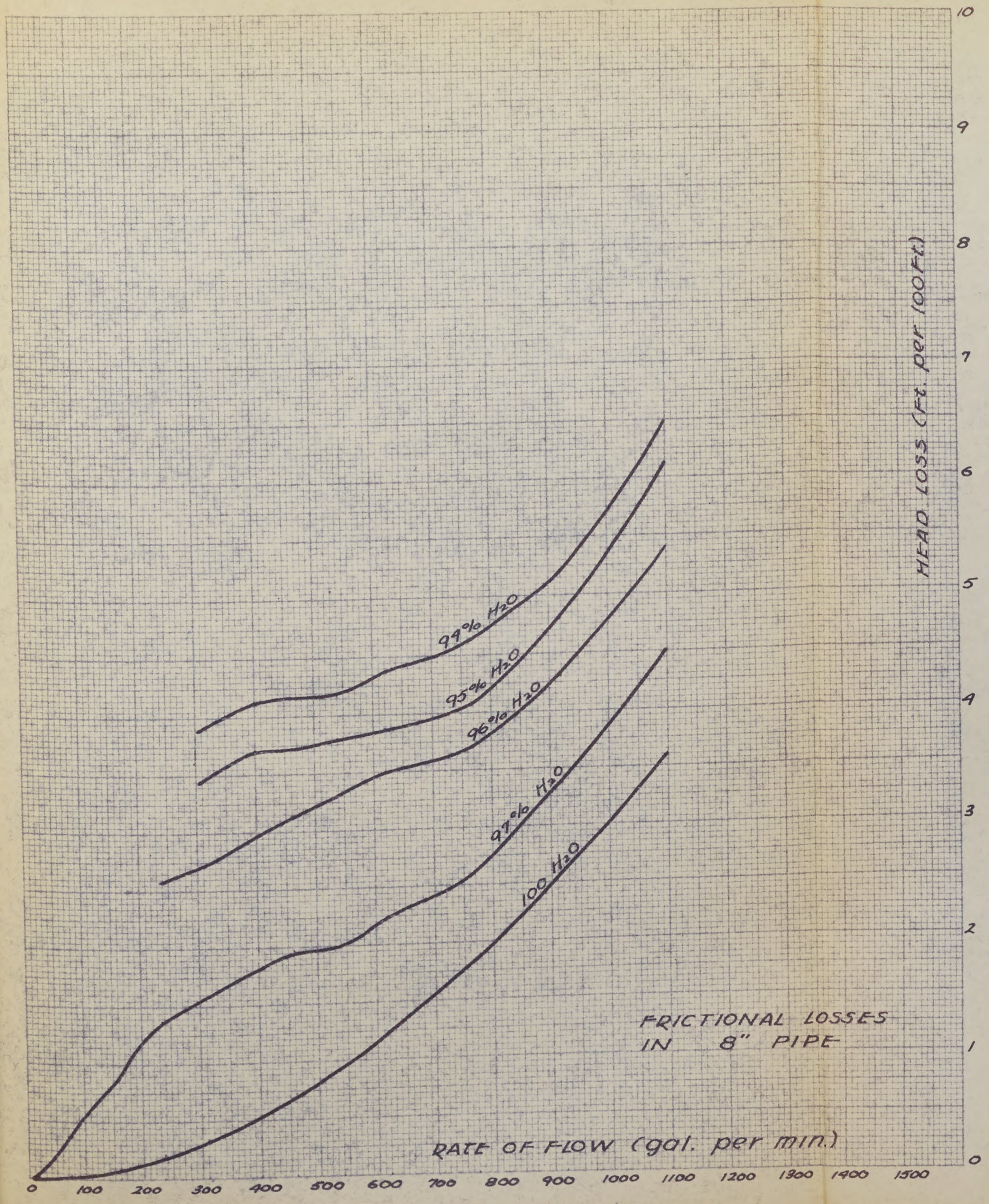
FRICTIONAL LOSSES
IN 2" PIPE
Rate of Flow (gal. per min.)
Head Loss (Ft. per 100 Ft.)
94% H_2O
95% H_2O
96.0% H_2O
97% H_2O
100%
0.0
10
20
30
40
50
60
70
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
36.0
38.0
40.0



94% H_2O
95% H_2O
96% H_2O
97% H_2O
100% H_2O
FRICTIONAL LOSSES
IN 4" PIPE
Rate of Flow (gal. per min.)
Head Loss (Ft. per 100 Ft.)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20



94% H_2O
95% H_2O
96% H_2O
97% H_2O
100% H_2O
FRICTIONAL LOSSES
IN 6" PIPE
Head Loss (Ft. per 100 Ft.)
0
100
200
300
400
500
600
700
0
1
2
3
4
5
6
7
8
9
10


FRICTIONAL LOSSES
IN 8" PIPE
94% H2O
95% H2O
96% H2O
97% H2O
100 H2O
RATE OF FLOW (gal. per min.)
HEAD LOSS (Ft. per 100Ft.)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
0
1
2
3
4
5
6
7
8
9
10

that the sludge is either entering or has entered the turbulant reqion and is slowly approaching values more comparable to water even though they are much higher. It is also possible that agitation at this point has reached its maximum and has changed the particles to a more uniform size and shape, thereby causing the flow to even out. It does indicate that the best velocities at which the ~~the~~ operation would be most successful would be between 5 and 7 feet-per-second.

It cust be understood that the American Well Works did not publish in the paper the conditions under which the tests were run. This would have a decided effect on the final analysis. It would be assumed that conditions were as ideal as possible and if they were as such, the curves would in some ways substantiate the results of other investigators (See Part I). First, the sludge friction losses increase with a decrease in moisture content. Second, the small solids ~~sloids~~ content does increase the head losses as compared to 100% water approaimately $1\frac{1}{2}$ to $4\frac{1}{2}$ times depending on the velocity and moisture content. Third, the values give a curve of nearly the same slope as 100% water in the higher ranges of velocity and rate of flow. In basing a design on the above facts and the American Well Works curves, it would have to be done with the greatest of care since a smooth curve would have to be superimposed on those curves. It is believed that in this way a slight safety factor would be introduced which would compensate to a certain extent for the varying properties of the flowing sludge.

At ~~And~~ this point let us examine a few of the formulas which may be used under certain conditions where sludge is concerned. It must be noted that in most cases certain assumptions must be made which must be taken with questionable value. However, the values do give interesting results which do give an indication of the variability of sludge.

According to Babbitt and Doland (Sewerage and Sewage Treatment), if velocities above critical are used the friction loss in the sludge pipe can be estimated by the application of the Hazen-Williams formula $V=1.31\,C\,R^{.63}S^{.54}$, using values of C 20% to 40% less than the values that have been established for the flow of water in pipes of the material to be used for conveying the sludge. This means that, since,

$$V=1.31\,C\,R^{.63}\,S^{.54}$$

$$S=\left(\frac{1}{1.31C}\right)^{1.85}\left(\frac{V}{R^{.63}}\right)^{1.85}$$

$$\text{or}\quad S=\left(\frac{.764}{C}\right)^{1.85}\left(\frac{V}{R^{.63}}\right)^{1.85}$$

By considering only $\left(\frac{.764}{C}\right)^{1.85}$ this gives for values of:

C 20% less
$\left(\frac{.764}{C}\right)^{1.85}=.834$ or 83.4% which is 16.6% less than values for water

C 30% less
$\left(\frac{.764}{C}\right)^{1.85}=1.153$ or 115.3% which is 15.3% more.

C 40% less
$\left(\frac{.764}{C}\right)^{1.85}=1.558$ or 55.8% more

The value for C 20% less seems erroneous since it gives a result of 16.6% less than the usual values for water. This cannot be according to the observationsof the American Well Works. They have shown that in virtually all cases the values should exceed water, such as, the values of C 30% to 40% is correct or all are incorrect observations.

Another interesting comparison is the comparison of the formulas for lower and upper critical velocity by Babbit and Reynolds number (using Schoder and Dawson as a reference), a Reynolds number of over 63 will give turbulant flow. It will be assumed that the specific gravity is 1.008 (activated sludge) and a pipe diameter of 8". It will also be assumed that the moisture content is 97% and the coefficient of viscosity is 0.02 poises. Therefore:

$$Q_g = \frac{(R)(D)(\mu)}{\rho}$$

where Q_g = rate of flow in gallons per minute

D = diameter in inches

μ = coefficient of viscosity

ρ = specific gravity

By substituting in the formula, $Q_g = 10$ g.p.m. Now let us turn to the formula for upper critical velocity according to Babbit since velocities over this will give turbulant flow. Therefore;

$$V = \frac{1500\eta + 127\sqrt{140\eta^2 + D^2 s_y \rho}}{D\rho}$$

where η = .001

s_y = 0

D = 1/3 feet

ρ = 62.4 lbs. per cubic foot

The above values were taken from Babbitt and Doland, "Sewage and Sewage Design." By substituting in the above formula,

$$V = .071 \text{ feet per second}$$

Therefore, any velocity above this value will theoretically give turbulant flow. Since $V = .071$ feet per second, it equals 4.2 feet per minute.

Since $Q = AV$

$= .35 \times 4.2 = 1.47$ cubic feet per ~~second~~ minute

or $Q = 11$ g.p.m.

If the assumptions are correct or nearly correct, the above results would indicate that the use of empirical formulas will give results accurate enough for practical application. The reliability of these assumptions, however, could be proven only through experimentation with equipment not available at the present time.

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PART III

It was mentioned preciously that a set of data was obtained from the sewage disposal plant in Jackson, Michigan. The following data was recorded:

TRIAL	DEPTH OF WET WELL (feet)	TIME (mins)	PRESSURE (lbs. per sq. in)	FLOW (gal/min)	V ft/sec)	% H_2O	Specific Gravity
1	2.5	2.5	12	540	3.49	90	1.0
2	3.5	4.1	12	470	3.01	90	1.0
3	2.5	3.0	12	450	2.86	90	1.0
4	5.5	7.83	12	380	2.44	90	1.0
5	5.0	8.33	13	324	2.09	93	1.01

Fig. 11

Since the pipe schedule was composed of both straight 8" pipe and various fittings it was necessary to convert the fittings to equivilant lengths of 8" pipe. The following pipe schedale was evolved:

QUANTITY	ITEM	HEAD LOSS IN TERMS OF
1	6"x5" Reducer	.25
1	6" Check Valve	.20
1	6"x8"x8" Tee	1.89
3	90° Bends	1.50
8	45° Bends	2.00
5	22½° Bends	0.50
5	8" Gate Valves	10.00
1	8" Check Valve	0.70
4	8"x8"x8" Tee	0.40
1	8" Cross	1.50
3	Exit Loss	3.00
719'-10"	8" Pipe	Chart

Fig. 12

The above head losses give a total of $21.44 \frac{V^2}{2g}$ where V is the velocity in an 8" pipe. According to Fig. 114 in Schoder and Dawson and using a category between fairly smooth and rough the following equivalent diameters of 8" pipe were determined.

(a) For category between fairly smooth and rough

$21.44 \times 37 = 799$ diam.

(b) For category between rough and extremely rough

$21.44 \times 26 = 558$ diam.

Therefore (a) is equivalent to 530 feet of 8" pipe and (b) is equivalent to 372 feet of 8" pipe. For (a) a total of 530 + 720 = 1250 feet will be considered and for category (b) a total of 372 + 720 = 1092 feet will be considered.

The gas pressure as measured by a monometer at the sludge digest~~ion~~or was 7.5 inches of water. The construction plans indicated a static head of 7.22 feet from the discharge side of the pump to the point of discharge in the digestors. The total frictional head loss involved is $12 \times 2.31 - \frac{7.5}{12} - 7.22$ which equals 1985 feet. Since for category (a) the total equivalent length of 8" pipe is 1250 feet, the loss per 100 feet is $\frac{19.85}{12.50} = 1.58$ feet. For category (b) the length of equivalent 8" pipe is 1092 feet which gives a loss per 100 feet of $\frac{19.85}{10.92} = 1.82$ feet .

It can readily be seen that the result of the Jackson experiment do not follwo the line of reasoning set forth from the results of other experimentors. In the first pla e the above head losses are lower for a moisture content of 90% as compared to the head loss thaken from the curves in Figure 3 through 10. They should be within a range several times higher than a moisture content of 94%. Another point to be considered is that the moisture content for the first four trials remained constant at 90% even although the flow decreased. Also the pressure remained constant; however, the author is of the opinion that the gauge was giving incorrect readings, thereby covering up any fluctuations in pressure. According to the work of other men, there should be a fluctuation in pressure since the flow showed a decrease. Naturally if the flow decreased there should have been a gradual decrease in moisture content. The data obtained at Jackson most certainly doesn't give a true picture of the head losses under the varying flows.

To obtain a clear picture of any head losses, a great many observations should be taken at several different plants. Also a better method of determining the rate of flow should be used, such as a venturi tube ~~tube~~ located on the discharge side of the pump. Any guages that are to be used should record accurate pressure at any reading and should be attached to a short length of rubber tubing to prevent clogging. Any laboratory tests that are to be made should be made if possible immediately following the collection of the data. The authorfirmly believes that if precautions such as these are taken, errors introduced could be kept at a minimum.

PART IV

It is the usual goal of a thesis to either prove or disprove the theory behind a certain thing or things. A practical engineer in many cases, looks toward the person who attempts to seek out the hidden facts that cause a fluid such as sludge to behave so differently under varied conditions. Such was the intent of this thesis. The conclusion to be drawn cannot be based on the proving or disproving of any certain phase of the actions of the sludge, but rather on the general observations of the work of others and to an extent, personal experimentation.

At a first glance, it would seem that the results recorded bythe author are of no value at all, but it is believed that even through experiments that fail, there is always something of value learned. In the author's case, it was what to do, should the occasion everpresent itself, to allow for any erroneous results. To those who may cary on with this work, it must be remembered that dependable equipment is a prerequisite to accurate results. It most certainly does not take a detailed knowledge of fundamentals of the flow of water or sludge or even their behavior, but rather equipment, time and ambition to analize and formulate into a definite pattern the information supplied by other investigators and personal experimentation.

The problem of the frictional head losses in the flow of sludge is far from completion. It is not a problem to which there is no answer. There is no doubt that some day enough information will be supplied to definitely set design standards. It is deeply regretted that a job must be left partially finished but to those who read this paper, it must be understood that the author has attempted to embody the important facts, which are available at the present time. Should it be that these facts and experience are clearly understood then success and not failure shall be the result.

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