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AIR in WATER PIPES

by Gilles Corcos

A Publication of

AGUA PARA LA VIDA

AIR

IN

WATER PIPES

A Manual for Designers of Spring Supplied Gravity-Driven Drinking Water Rural Delivery Systems

by

GILLES CORCOS

AGUA PARA LA VIDA is a California non-profit organization whose purpose is to help remote rural communities aquire enough water: safe drinking water first, and whenever possible a modicum of irrigation water. Our members are active in Nicaragua where we have designed and helped build drinking water supply systems for the last six years. We expect to participate in answering this primary need in other countries as well, including Bolivia and El Salvador.

If you wish to help or to find out more, get in touch with us

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GILLES CORCOS is one of the founders of Agua Para La Vida. He has been a Professor of Engineering at the University of California, Berkeley, specializing in the mechanics of liquids and gases for thirty-two years. His first drinking water project dates back to 1962.

The material for this manual was gathered in the field in Nicaragua and in the Laboratory in Berkeley. Dan Mote, then Chairman of the Mechanical Engineering Department supported the work. Several classes of Engineering Seniors chose this very topic for their senior laboratory class and contributed useful data. The author is grateful to all of them.

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Please feel free to send your suggestions and comments to us.

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INTRODUCTION

When you design a pipeline for a gravity flow water system you usually assume that the water flow will fill the pipe. In this case the flow rate out of the pipe is controlled by the available head, the length, diameter and roughness of the pipe and the so-called minor losses due to various obstructions (contractions, elbows, expansions, tees and especially valves). We will call this the full-pipe or friction controlled case. It is adequately explained in many textbooks and manuals *. But if for some reason the pipe is not completely full of water, the relation between head available and flow rate is very different. This will happen in several cases. For instance:

> -When you first turn on the water in a new installation with dry or partially filled pipes.
>
> -If you have cavitation somewhere in your circuits (too much suction).
>
> -If the pipe is fed by a spring through a spring box and the output of the spring is less than that for which you designed the pipe system.

Now the general belief is that if you have air in the pipes you need to get rid of it so that the pipes will run full. This is because the presence of air often increases the head required for a given flow. In fact it is not at all rare that this air acts as a block so that no water at all comes out at the end of the pipe. The presence or the ingestion of air in pipes can also cause the flow rate to change over time intervals from a few minutes to a week. For large pipes and high water velocities this unsteadiness frequently causes important damage. For small pipe diameters and the small water velocities typical of gravity flow systems for small communities, the pulsations

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* See for instance: **A Handbook of Gravity-Flow Water Systems** by Thomas D. Jordan, Intermediate Technology Publications, 1984. This handbook covers an extensive list of topics~~ including "air blocks". While incomplete for ou~~r purposes, Jordan's discussion of air in pipes is nevertheless a valuable start.

generally do no harm but they introduce much uncertainty in the operation of the system: I knew a gravity flow pipeline which turned on and off at irregular intervals- off when I had no chance to intervene and on as soon as I had decided to fix it!

On the other hand it turns out that very frequently, in systems with springs of uncertain or variable output, there is a big advantage in operating with air in the pipes. The advantage is that you can design such a system so that it will operate like a canal instead of a pipeline: within limits which you can easily calculate it will deliver to the end of the line whatever flow rate is provided by the spring and this without having to adjust a valve- without controls. For this reason at least it is desirable to understand more thoroughly the nature of the flow of water in the presence of air in pipes, rather than simply devise rules to get rid of it.

This manual is written for this purpose. In particular it will make it possible for you to :

- Understand the problem of starting with dry pipes.
- Predict what will happen if your water supply is or becomes smaller than you assumed in your calculations (for a friction-controlled system).
- Design deliberately smoothly operating systems which can deliver a chosen range of flow rates automatically and such that air is almost always present in the pipes.

Throughout this manual we assume that, even though the spring output may vary in time, one of your primary objectives is to convey it whole to the distribution tank at the end of the pipeline, without any overflow at the spring.

First the hydraulic background necessary to understand this subject is presented. Then the method for predicting and designing with air in the pipes is given. Finally the manual presents a number of examples that will help you use this material and get on top of the subject.

You will find among these examples some friction-controlled designs which get in trouble when the flow rate of the spring is only a little bit less than the design value, as well as cases in which there is no air trouble no matter how small the flow supplied to the pipe. After you have followed these examples you will be able to predict whether your friction-controlled design will give you trouble in a specific case. You will also be able to modify your designs so as to eliminate problems with air in the pipes.

The examples make it clear that the problem is not to choose between a friction-controlled full pipe design and a mixed air-water design but rather to adapt the design to the probability that air will be present in the pipes some of the time.

The material which follows is arranged so that the foundations are given in Chapter I. The way to proceed in a design is given in Chapter II. This chapter is the one that tells you how to deal with air. In other words Chapter II is the "how to" part of the manual, while Chapter I is a reference "why" chapter. Any supplementary information required for the design is found in Appendix A, whether it is new information or even if it is available in other books or manual. Chapter III presents the examples that illustrate the material. Appendix B makes a few more specialized points which would perhaps be confusing in the main text. But these can be read later.

The solutions suggested in Chapters II&III are, of course, not the only ones, perhaps not even the best ones. After you have examined this materiel, no doubt you will choose your own. The important thing is to have in hand enough elements to make an enlightened choice.

<u>Note:</u> It is possible for you to carry out a suitable design <u>without using the equations</u> which appear in the text, i.e. <u>by only adding</u>, <u>subtracting</u>, multiplying, dividing and using the tables. This is shown in chapters II & III.

SYMBOLS

h= head (meters)

H= height (meters); H_{AB}=height difference between points A and B (meaning H_A-H_B); Q =flow rate (m^3/s unless otherwise specified).

Q_c= critical flow rate. Its value depends only on pipe-diameter (see equation 2 and table A2).

Q_{max}= maximum expected output (flow rate) of the spring.

$Q_{min.}$=minimum expected output of the spring.

$Q^*=Q/Q_c$

h_a= head available = H_S-H_T.

h_t= trickle height defined in the text. Appendix A shows you how to calculate it.

h_f= friction head loss. You can use table A1 or the formulas in Appendix A to calculate it.

h_{f1}= friction head loss for $Q=Q_c$ ($Q^*=1$).

h_r= maximum head required. $h_r= h_f+h_t$ if Q is smaller than Q_c and $h_r= h_f$ if Q is greater than Q_c.

L= length of a pipe line. L_{ST} length along the pipeline from the spring to the distribution tank. L_{AB}= length of pipe between points A and B ...etc.

Subscripts 1&2 refer to two points along the pipe with 1 upstream of 2. Letter S refers to the spring or spring tank. Letter T refers to the pipe outlet or distribution tank. Other points along the pipe are indicated in the sketches.

V= (section-averaged or discharge) water velocity; m/s.

g= acceleration of gravity (9.81 m/sec^2).

CHAPTER I

AIR IN THE PIPELINES

Air may be found in water pipelines mainly as large, stationary pockets, or as large or small moving bubbles.

When air collects in parts of the pipeline, without moving, the water may be blocked by the air so that no water flows or it may circulate past the pockets of air by flowing underneath these pockets. You will learn to figure out which will happen in a particular case.

When water flows sufficiently fast, air pockets are not able to remain still and they will be chased down the pipe along with the water. Then the presence of air in the pipe will not affect the delivery of the water. You will also be able to determine when that happens in any particular case.

Stationary Air Pockets. You may first run into this problem when you fill for the first time a newly constructed gravity flow pipeline since this pipeline starts out full of air.

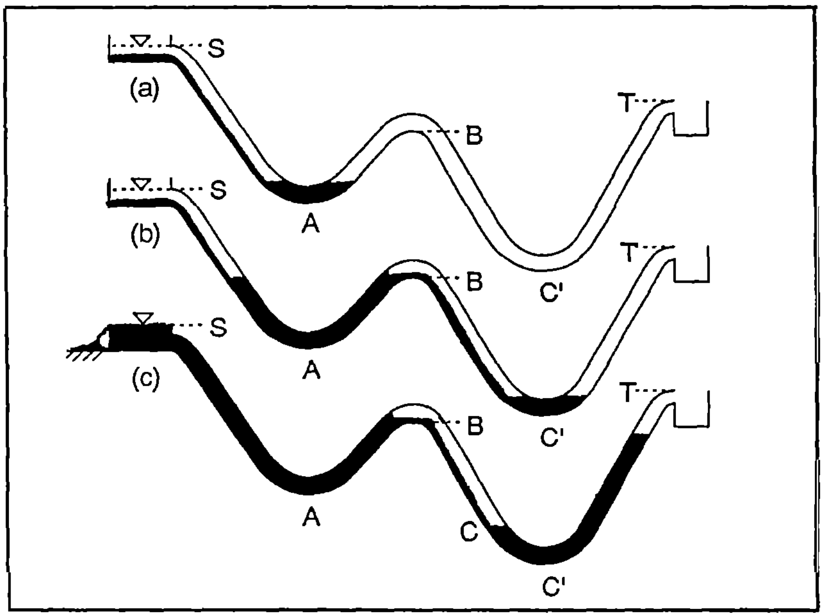

Figure I-1

If, as in figure I-1, **the profile has a local maximum** (point B) between spring S and tank T, as you allow a small flow of water out of S, the water will accumulate at the low point A, then fill the pipe on both sides of A (Figure I-1a). Progressively air is chased out of this section of the pipe until there is no more air between A and B and the water reaches the level of the bottom of the pipe at B (Figure I-1b). The section BC' is still full of air and the water will now trickle down towards C' below the air. This air will not be flushed out by a small water flow rate. We will call the stationary air pocket above the trickle of falling water an air **sock.** The trickle of water below the air sock soon fills the bottom of the pipe at C' so that the air between B and C' is now trapped and isolated from the atmosphere: the sock is closed (Figure I-1b).

A Sock Causes A Head Loss Equal To Its Height. The sock is a **constraint** responsible for a new head loss: The pressure throughout the sock downstream of B has to be uniform (because hydrostatic pressure variations are negligible in a gas), and this forces a uniform pressure in the thin stream of water flowing below the air sock. This is the origin of the head loss due to the presence of the sock: Between B and the end of the sock, the water loses potential energy (height), there is no corresponding increase in pressure head since the pressure remains the same in the stream below the air sock, and the kinetic energy (velocity head) is the same at the beginning and the end of the sock.
This head loss is equivalent to a loss in mechanical energy. It can be ascribed to two agents which conspire to dissipate the potential energy corresponding to the height of the sock:

1) As the water rushes downstream underneath the sock it becomes a thin stream with an enhanced velocity. This increases the friction between the stream and the pipe.

2) At the end of the sock, as the thin water stream hits the slower water in the full part of the pipe, none of its remaining excess energy is recovered. The situation is analogous to that of a waterfall impacting on a pool of water or, with some qualifications to that of a hydraulic jump.

The head loss caused by the presence of the sock is the difference between the elevations of the beginning and of the end of the sock.

Two Or More High Points. If there are several local high points as in Figure.I-2, as you continue to fill the pipe, more air socks appear downstream of these high points so that more head is lost. The total head loss due to all the socks is the sum of the individual sock head losses.

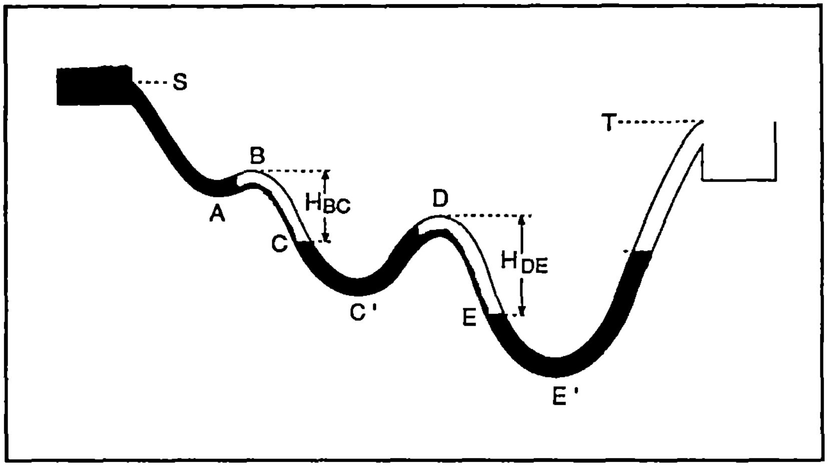

Figure I- 2

The Effect Of The Head At The High Points. In Figures I-1c and I-2, note that while the top of the air socks remains at the level of the local high points such as B or D, the bottom does not have to remain at the local low points because as you keep filling the pipe the hydrostatic pressure in the socks increases. This compresses the air in the socks which causes the volume of the socks to decrease and so, the socks become shorter and the level of the sock bottom rises from C' to C and from E' to E.

As You Fill The Pipe Will The Water Flow Out At All? If you keep releasing water slowly from the spring the water level in the pipe below the spring may reach the spring tank level S before it comes out at the end of the pipe at level T. This is the case shown on Figure I-1c. In that case no water can be delivered to the downstream tank until some air has been purged out of the socks. **This will happen if the available head, $h_a = H_S - H_T$ is smaller than the sum of the heights of the socks.**

Or the water may come out at T before it has backed up to the level of S. In this case you may still want to purge the air out of the socks but even before you do so, some water will flow out the end of the pipe. **This will happen when $h_a = H_S - H_T$ is larger than the sum of the heights of the socks.**

This brings out the importance of figuring out the sum of the heights of the socks. The way to do that is given in Appendix A-II.

<u>Now The Water Flows: Two Ways To Limit The Discharge.</u> So far we have imagined that only a very small quantity of water is released at the spring. Now we imagine that the spring output is larger, though always limited. In other words we don't have a large reservoir or lake at the spring site. We can see that the flow of water and the discharge at T can be limited in one of two ways:

It can be limited by the head loss in the pipe. This head loss increases with the flow rate so that there is a flow rate for which the head loss is equal to the head available and clearly no matter how much water comes out of the spring the amount that flows through the pipe cannot exceed the flow rate for which the head available is equal to the head loss. The rest of the spring output merely overflows at the spring tank. (From a practical standpoint, we will view this as undesirable because we rarely encounter springs whose output exceeds the present or future needs of the community and so, we view overflow at the spring as a loss, even when the supply to the distribution tank meets the minimal requirements: the community can always make good use of additional water).

Or the discharge may be limited by the output of the spring. This happens whenever this output is smaller than the flow rate for which the head losses equal the head available.

In the first case (flow rate limited by the head losses) the section of pipe below S is full of water.

In the second case (flow rate limited by the spring output) the flow out of the spring tank does not fill the pipe and we start below S with what is roughly speaking a waterfall. This is important because in general, air bubbles are created by the waterfall and they are carried (to a greater or lesser extent) by the water down the pipe so that in this second case air is supplied to the pipe along with the water. Sometimes this does not matter but we will soon see that there are frequent cases for which this new source of air causes problems.

<u>The Critical Flow</u>.

We now return to the air socks which we assume we have not purged out. It turns out that there is a special flow rate called the <u>critical flow rate</u>, Q_C, which is fixed by the pipe diameter in the region of the socks.

The system may only be capable of a flow rate less than the critical flow rate Q_C either because the flow out of the spring is less or because the combined losses due to friction at $Q=Q_C$ and the air in the socks, if any, exceed the available head.

Or the system is capable of a flow rate larger than Q_C because the flow out of the spring is larger <u>and</u> the head available is larger than the sum of friction head required for $Q=Q_C$ and whatever head loss is due to air in the pipe.

Now the critical flow rate Q_C has the following physical meaning:

If the flow rate Q of which the system is capable is smaller than Q_C, air socks will remain in fixed locations downstream of the high points. Their tops will remain level with the high points. Their bottoms will have a level which depends on the mass of air which has found its way to the sock and on the pressure within the sock. The loss of head they will cause is still the sum of the heights of the socks.

If the flow rate Q of which the system is capable is greater than Q_C, the air will be chased out of the socks and any additional air coming from upstream will also circulate through the sock zone without stopping there.

The critical flow rate only depends on the diameter of the pipe in the region of the sock:

$$Q_c = 0.5\, d^{5/2} g^{1/2} \qquad (1)^*$$

where d is the inner diameter of the pipe at the location of the sock and g is the acceleration of gravity. If Q_c is in cubic meters /second , Equation (1) can be written, with d in meters:

$$Q_c = 1.57\, d^{5/2} \qquad (2)$$

Q_c is given in table A2, Appendix A for a few pipe diameters. Flow rates larger than Q_c are called supercritical, and those lower than Q_c are called subcritical.

Can We Evaluate the Additional Head Loss Due to the Socks?

In full pipes with no air socks a familiar energy equation (written in units of height) allows us to determine the evolution of the flow. It is:

$$\underset{1}{8Q^2/\pi^2 d_1{}^4 g} + \underset{2}{h_1} + \underset{3}{H_1} = 8Q^2/\pi^2 d_2{}^4 g + h_2 + H_2 + h_f$$

The first term on the left is the "kinetic energy" (velocity energy). The second is the pressure energy. And the third is the "potential energy" (energy due to height). The subscript 1 refers to a section upstream and the subscript 2 to a section downstream. The equation says that the sum of the three energy terms at the downstream section is less than the sum of the three energy terms at the upstream section because there is a loss h_f, due to friction between 1 and 2. This loss is always positive. You can calculate h_f if you know the values of Q, d, and the distance between 1 and 2, (see Appendix A). Now as we have just seen, when there are air socks between 1 and 2 the energy equation must include an additional loss term on the right hand side of the equation. This term can be calculated only when the difference between the elevations of the beginning and the end of all socks are known. But this is the case only when you fill dry pipes (see Appendix A), and not later because air can leave the air

*The origin of Equation (1) is given in Appendix B-VII.

pockets as bubbles and also come in from upstream to replenish them, so that in general you won't know how much air there is in the pipe. What is known is that the initial head loss due to the socks which is found when you first fill the dry pipes and which you will calculate at the critical flow (this head loss, we will later call **the trickle height, h_t**) is the maximum air sock head loss you will encounter. You will usually design for this worst case situation.

You should keep in mind that: **The head loss due to an air sock containing a given mass of air will not change much, whether the flow rate is very small or not, as long as the flow rate is less than the critical flow rate, Q_C. For Q larger than Q_C, that head loss disappears because the air is chased out.**

The Sock Head Loss is not Just A Starting Problem: Whether the flow is subcritical or supercritical air bubbles and air pockets can be carried from the area of the pipe below the spring towards the location of the air socks **as long as the head required is less than the head available.** If the flow is subcritical this means that air socks can be replenished with air after they have been flushed out manually.

Moving Air Pockets And Bubbles. What happens when Q exceeds Q_C is that since the water flow is now large enough to flush out the air sock, the head required suddenly decreases (h_t disappears). Now, if the head available is enough to cause Q to exceed Q_C before the sock is chased out, an even greater flow rate will occur afterwards. This flow rate is now determined by the head available and ordinary friction losses. If the output of the spring is sufficient to keep up with this greater flow rate the pipe will fill up with water and remain full. But if not, i.e. if the output of the spring falls short of the flow rate which the pipe can sustain in the absence of air, it is almost always the case that air will be entrained by the water at the beginning section of the pipe and this air will travel down the pipe. Some details of this entrainment will be given presently. But from a practical point of view you should keep in mind the fundamental distinction between subcritical and supercritical flow: While supercritical flow may look very complicated, unsteady, and unpredictable, with *shifting and* merging bubbles, <u>as long as Q remains larger than Q_c, the head requirement becomes the one you would calculate for the same Q if the pipe were full.</u>

<u>**Entrainment Of Air In Subcritical And Supercritical Flows When The Spring Output Limits The Flow Rate.**</u> One might think that after one had flushed out of the pipe the air which was originally in it, the level of the water in the pipe below the spring box would simply adjust itself so that the head of water just balances the friction head for the water flow available. But this happens only when the flow rate is extremely small (compared to Q_c). Instead, if the pipe is not full below the spring(because the head available h_a is larger than the friction head h_f), the current is able to carry air bubbles (created by the fall of water from the spring) downstream with the water. For very small flow rates, the water carries only small bubbles and entrains little air. For flow rates which are a good fraction of Q_c, larger bubbles (and a larger volume of air) are carried downstream. Both can replenish air socks after these had been bled out.This normally takes a long time-up to many days. When Q is larger than Q_c, air will still be brought in from below the spring but it will not remain in any fixed, stationary sock. Instead it will be flushed out either periodically(when Q is only a little larger than Q_c) or more steadily (for greater flow rates). Now the flow down the first section of pipe is very complex, full of shifting pools and cascades. Air bubbles or pockets of various sizes circulate through the pipe with the water.This has no adverse effect on the operation of the pipeline <u>as long as the spring is able to supply a flow rate larger than Q_c</u>. But If the spring output decreases below Q_c, the air in transit through the pipe will accumulate again in the sock areas downstream of the local highs and contribute a new head loss. So:

The most frequent way to get In trouble with air socks after the system has been started is for the flow to decrease from supercritical to subcritical as a result of a decrease in the output of the spring. In this case your flow may be completely shut off.

Another, though rarer source of trouble is subcritical flow which has been started by bleeding the air socks once: Air slowly returns to the sock area without decreasing the flow rate but the system will not track well variations in the spring output , if this output decreases and then increases again.

The Head Required.

a) The Pipe Diameter Is The Same For All Sock Sections.
The head requirement (if you start with empty pipes) is made clear in figure I-3.

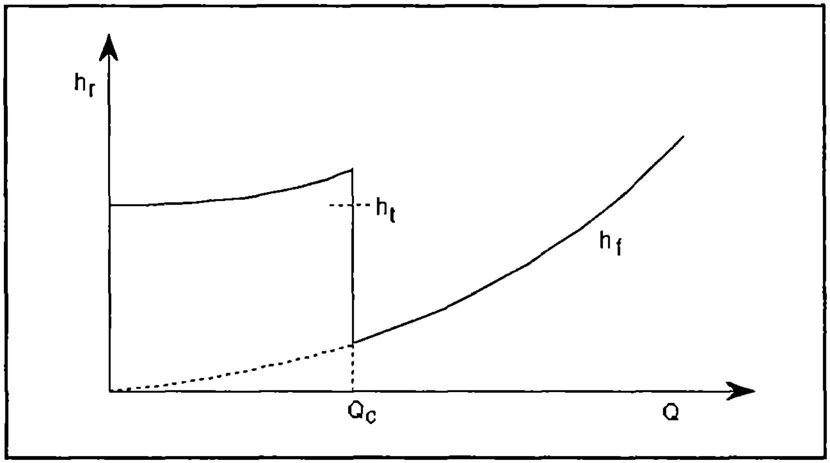

Figure I-3

This graph is appropriate even when there are several local maximae in the pipe profile as in Figure I-2, but only if the pipe diameters downstream of the several maximae are all the same. It shows the maximum head required on the vertical axis and the flow rate on the horizontal axis. When Q is less than Q_C, this head required is the sum of two terms: The trickle height h_t, and the friction head loss h_f. h_f is the curve which starts as a dotted line and which rises steadily. It increases with flow rate. When Q is larger than Q_C, h_r is equal to h_f because h_t has disappeared, (no sock losses).

b) Different Pipe Diameters At Different Sock Sections.
When there are several socks and downstream of the high points the pipe diameters are not the same, the sudden decrease in h_t as Q increases occurs in steps as in Figure I-4. The first step occurs at the value of Q equal to the value of Q_c for the smallest pipe diameter: The sock with the smallest diameter looses its air first.

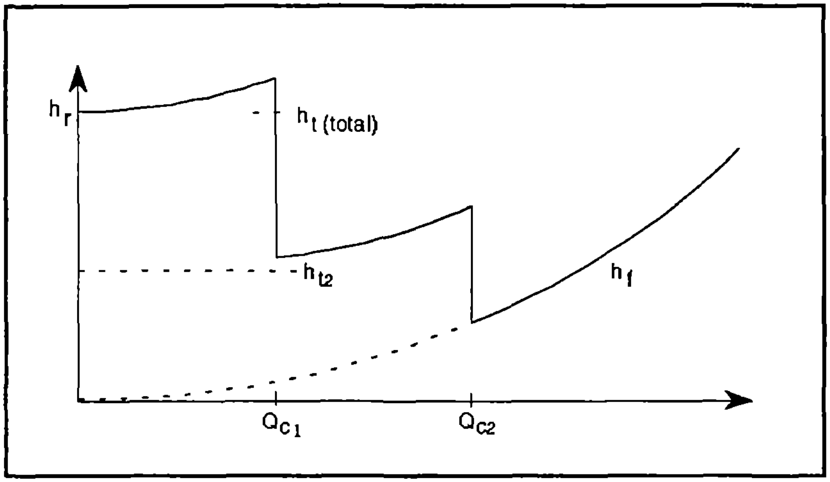

Figure I-4

Head Available And Head Required: The Operating Point.
Now we return to the case of a single pipe diameter as in Figure I-3.
Let us indicate the head available , $h_a = H_S - H_T$ as a horizontal line on the same graph, (Figures I-5ab).
The smallest value of Q for which this line crosses the head required curve is the maximum flow rate which the pipeline can deliver.
If as in Figure I-5a, the horizontal line h_a lies above the curve h_r for low values of Q,and crosses it only once, the situation is simple: the pipeline will deliver the flow rate of the spring from Q=0 to Q_1, the crossing point, and if the spring output is larger than Q_1 the excess will spill at the spring.

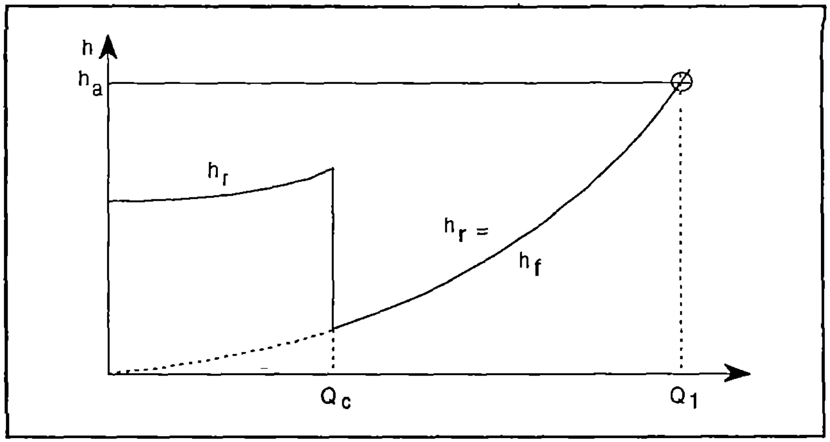

Figure I-5a

If as in Figure I-5b, the horizontal line h_a is lower than h_r even at Q=0, water will not flow at all **unless enough air is first bled out of the socks so that the curve h_r falls below h_a.** If you do bleed the air, you will be able to have a supercritical flow up to Q_2, provided of course that the spring output is sufficient.

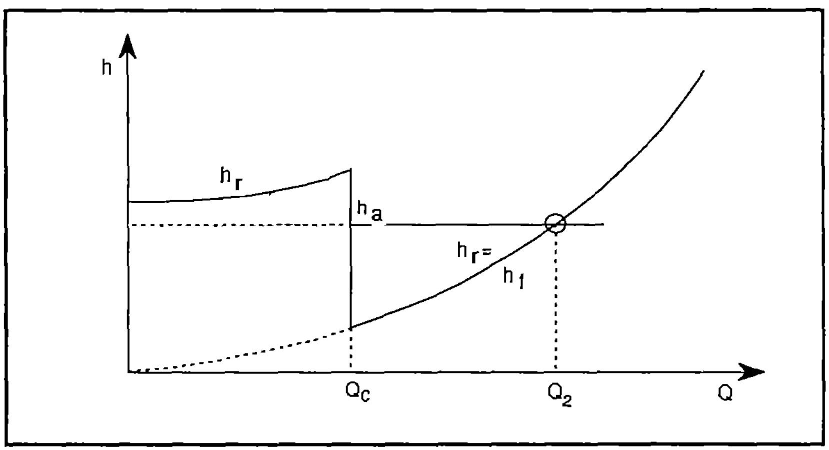

Figure I-5b

These are only two possible situations used to illustrate the meaning of these curves. In Chapter II you will learn that there is a total of 4 different cases which lead to 4 different

designs. Whether a particular installation belongs to case 1,2,3 or 4 depends on the relative magnitude of the head available h_a, the trickle height h_t, and the value of the friction head loss when $Q=Q_c$,i.e. h_{f1}. So the first step in the design of a specific case will be to classify that case as a case 1, 2, 3 or 4 problem.
Here we run into a difficulty which may have already started to confuse you: Both h_f and Q_c depend on pipe diameter which cannot be chosen before we classify our case. So how are we going to proceed? Here goes!

The Universal Curves

To classify your cases you will be interested in the value of the friction losses at a flow rate near the critical flow rate $Q=Q_c$ rather than at a fixed flow rate. If you plot the friction head loss versus Q, you will find that this curve changes a lot with pipe diameter. But if you plot it versus the ratio Q/Q_c the result almost does not change with pipe diameter. This is the origin of what I call the Universal Curves. These are approximate friction curves which allow the classification of your case before the diameter has been chosen.

For these graphs you plot on the vertical axis h_r/h_t or h_a/h_t, (head required or head available divided by trickle height) and on the horizontal axis, the ratio, $Q^* = Q/Q_c$, of flow rate to critical flow rate. The friction losses naturally depends on the length of the pipe so that there is a family of friction curves and you have to choose the one appropriate to your case. How to do this is explained in Chapter II. On figure I-6 is shown this family of friction curves which you get if the diameter of the pipe does not change along the pipe. To obtain it we have made the approximation that the so-called friction factor f is constant. In this case the friction curves plotted as in figure I-6 do not depend on the pipe diameter . In fact the factor f varies a little with pipe diameter for a given flow rate. But this does not matter for the purpose of deciding how to design your case. For this purpose, assume also that the pipe diameter does not change along the length of the pipe.*

* If you wish you will be able to vary your pipe diameter later

Then, all you need to determine the friction curve on a graph like figure I-6 is the length of the pipe and the value of the trickle height . The curves shown are described by:

$$h_f / h_t = 0.00568Q^{*2}(L/h_t) \qquad (3)$$

for the average value f=.028. In particular the value h_{f1}/h_t,(for $Q=Q_c$) is given simply as

$$h_{f1}/h_t=0.00568(L/h_t) \qquad (4)$$

Here L is L_f, the length of the pipe where the water runs full, (the total length minus the length of the air socks). Therefore the friction calculation is done after the calculation of h_t.

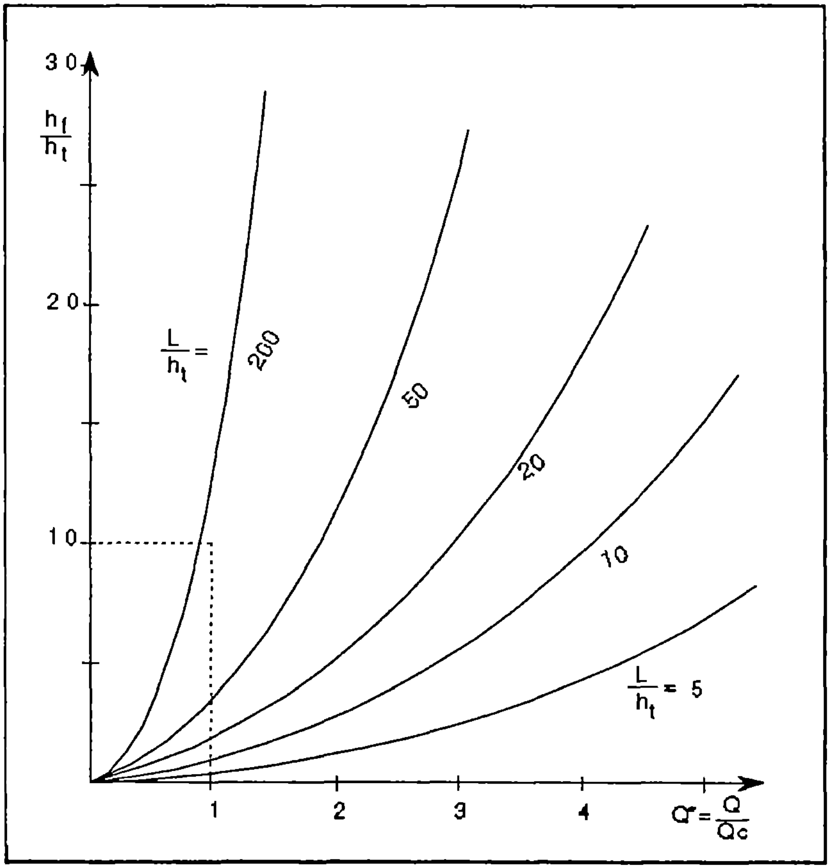

Figure I-6

CHAPTER II

DESIGNING WITH AIR

A) Required Design Data: H_S, H_T, L, the maximum and minimum estimated values of the spring flow rates, Q_{max} and Q_{min}, and the heights and location along the ground of the spring S, tank T, and local low, (A, C', E'....etc,) and high points, (B, D.....etc,) of the pipeline. A pipeline profile should be drawn to scale with the distance along the pipeline as the horizontal scale.

B) Design: (Spring-Limited Flow Rate). This is the design which allows the system to deliver automatically a variable spring flow rate. It avoids systematically trouble with air in the course of the system operation. Such a design (in one of its 4 versions) is always possible if the spring tank is higher than any other point of the pipeline.

Let us use Figure II-1 as a reference:

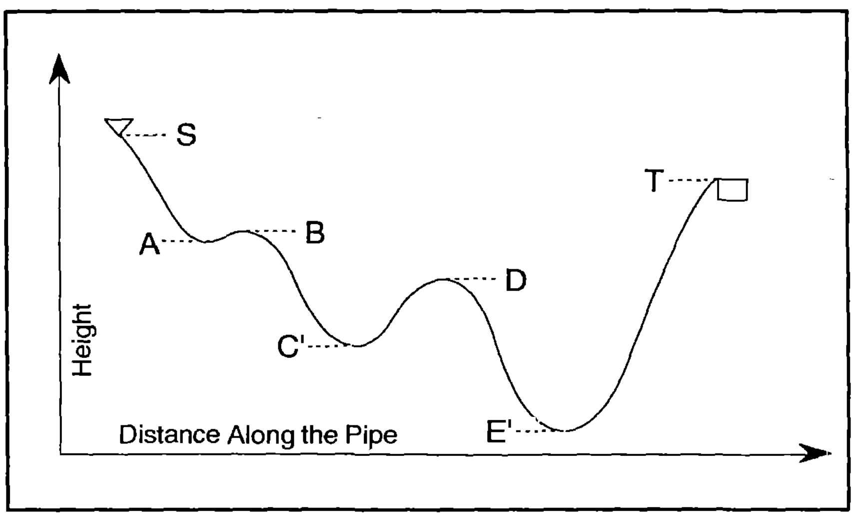

Figure II-1

To start with, record the number of local highs if any, between the spring tank S and the end point,(usually the distribution tank) T. Note also whether the point T is higher or lower than any of the intermediate high points.

Can You Avoid The Problem?

If there is no intermediate high point there will be no air blockage and whatever the flow rate out of the spring, you may proceed as if the pipe were always full. You should use Q_{max} as Q, L_{ST} as L and h_a as h_f in the friction tables A1. But make sure that your design does not cause a negative head anywhere along the line.

If the vented point T is lower than a local high you can eliminate the sock downstream of this high if you wish by venting the pipe there with a small break-pressure tank. This has the effect of moving the point S to that high point. But this may not be desirable; see, e.g. Example 6, Chapter III.

If Not: The next steps are these:

1) Calculate the head available, h_a, from $h_a = H_S - H_T$

2) Calculate the trickle height, h_t. The trickle height is the largest head loss due to the greatest possible amount of air trapped in a pipeline when the flow rate just reaches the critical flow rate Q_c. This calculation is described in Appendix A-II. Then calculate h_a/h_t.

3) Calculate h_{f1}/h_t. A sufficiently accurate method is to use the simple formula:

$$h_{f1}/h_t = 0.00568 \times \{L_{ST} - L_{BC} - L_{DE} - \ldots etc\}/ h_t$$

Recall that if you call h_r the head required,

$$h_r/h_t = h_{f1}/h_t + 1 \quad \text{if } Q^* \text{ is smaller than 1}$$

$$h_r/h_t = h_{f1}/h_t \quad \text{if } Q^* \text{ is larger than 1}$$

4) **<u>You Are Now Ready To Classify And Then Design Your Case:</u>** It is one of the following four. Generally speaking cases 1 and 2 occur with shorter pipeline reaches and larger ~~altitude variations~~, cases 3 and 4 with larger reaches and shallower profiles.

Case 1: h_a/h_t is larger than $\{h_{f1}/h_t + 1\}$

This is the most frequent case. The system will deliver whatever flow comes out of the spring up to the flow which will fill the pipe. Select the appropriate pipe diameter this way:

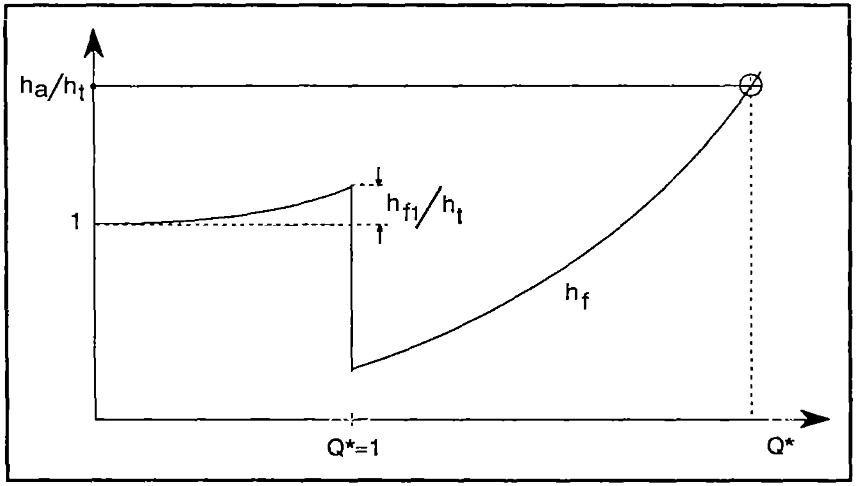

Figure II-2

Calculate or recall the value of h_a/L_{ST}. Then, in Table A1, Appendix A-I, select the row and the column which give a value of h_f/L most nearly equal to your h_a/L_{ST} for a value of Q most nearly equal to your Q_{max}. The diameter of the pipe is at the head of that column. For example if $h_a/L = .0015$ and $Q_{max}=0.05$ l/s, the nearest choices are $h_f/L = .00137$ and Q=0.05 which belongs to the column d= 3/4 inch (SDR 17).

This diameter will cause the pipe friction to limit the flow rate near your chosen maximum flow rate. If you prefer the limit to be slightly above rather than slightly below the estimated Q_{max}, choose a value of h_f/L slightly smaller than your h_a/L_{ST}.

In Case 1 you need not worry about air in the pipeline either as you start by filling them or during later operations no matter how much the output of the spring varies.

Case 2. (h_{f1}/h_t) smaller than (h_a/h_t) but $(h_{f1}/h_t)+1$ larger than h_a/h_t. In this case (Figure II-3) you will need to start the flow by letting air escape from one (or more) of the socks just downstream of its high point. You can do this by providing either a T or a manual valve just downstream of the high points. Either one should then be closed and buried. Start by bleeding the sock whose contribution to h_t is largest. Do not use automatic float-type air-bleeding valves in Case 2. The reason is that you will be operating supercritically and as a result air in transit will continually actuate your valve which will turn on and off abruptly and all the time. This risks wearing out the valve shut-off mechanism.

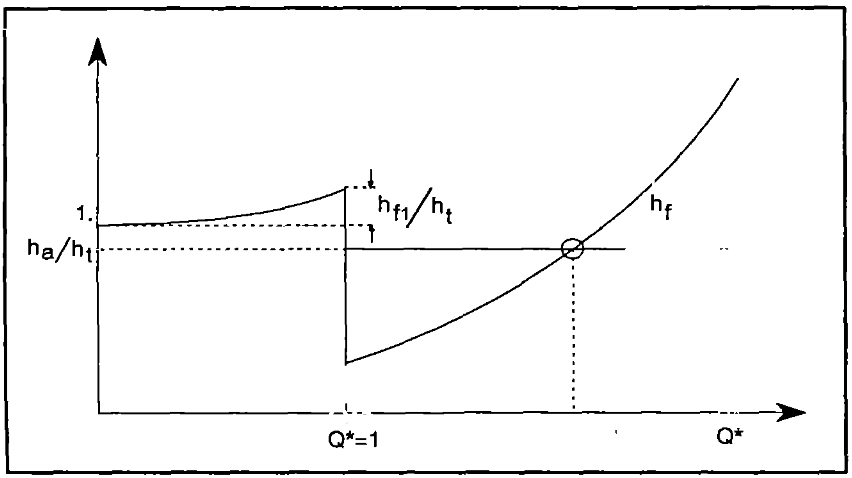

Figure II-3

Choice of the diameter: In case 2 generally plan on operating with flow rates between Q_c and the friction limit Q_f. In other words you choose $Q_{min} = Q_c$. You do this by choosing the diameter d equal to (or slightly smaller than):

$$d = \{2Q_{min}/g^{1/2}\}^{2/5} \qquad \text{(II-3)}$$

(or use Table A3 in Appendix A)

This is the choice that guarantees that you will *always operate* at a flow rate larger than Q_c. The reason to make this choice is that in this case the head available is not sufficient to make the water flow slowly past the largest possible air socks. But for Q larger than Q_c, no air sock can stay put.

You may select the nearest choice to the value of d given by equation II 3 from table A2 which is calculated from this equation. But choose a value of Q_c lower than Q_{min} rather than higher.

So far you have not insured that the pipe will be able to accommodate the maximum spring flow rate Q_{max}. Indeed it may not be possible. Proceed as follows:

From Table A1, entering the diameter you have just selected as d and h_a/L_{ST} as h_f/L find the approximate value of Q. This is the Q which pipe friction will allow, the maximum value of Q that the pipeline can deliver if the whole pipe length has the diameter selected. If this value is smaller than your desired Q_{max} you can increase it by increasing the diameter of the pipe wherever air cannot accumulate i.e anywhere except in the downhill parts of the pipe which are downstream of high points. The details are given in Appendix A-III and examples 2 (remark), 3 and 4 in Chapter III.

Remarks:

a) If h_a/h_t is only slightly less than $(1+ h_{f1})/h_t$ and much larger than h_{f1}/h_t, using the procedure of Case 1 is usually satisfactory because it is exceptional that after the system has been started as much air can be reintroduced in the socks as was there at the start (fill up operations). But this should not be done if h_a is smaller than, say, $0.7x(h_{f1}+h_t)$. Also you will of course still have to bleed air out of the socks as you start the system.

b) If you don't know the minimum flow rate and if you have reasons to suspect that it may be very low, you should probably prevent supercritical flow by choosing for the downhill sections of pipes, downstream of the high points, a diameter large enough to insure subcritical flow for Q_{max}. This changes a Case 2 to a Case 4 (see below).

Case 3. h_a/h_t is smaller than h_{f1}/h_t, but larger than 1

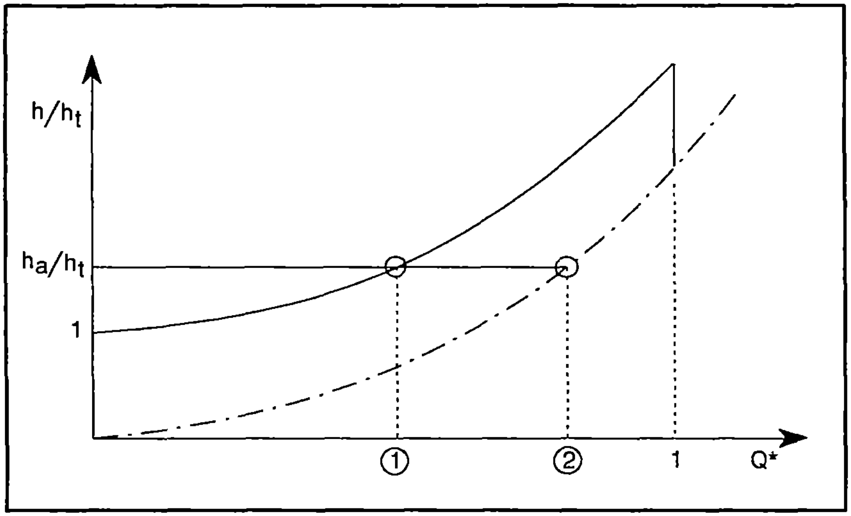

Figure II-4

There are two different ways to deal with this case. The first one requires an automatic air bleeding valve, the second does not, but requires in general a larger diameter pipe:

According to the first method, you provide one (or several) air-bleeding float valves (these are valves which open the socks to the atmosphere when they contain air but which are closed when the sock area is full of water). These valves should be located just downstream of each of the local highs. The diameter of the pipe is selected by using Table A1 in which you enter Q_{max} as Q and h_a/L_{ST} as h_f/L. You should choose the available diameter which gives an h_f/L smaller(not larger) than the one you desire. In other words except for the necessity to bleed the pipes permanently the first method handles this case in the same way as Case 1.

According to the second method for Case 3 you subtract from the head available the trickle height h_t and determine the diameter required by looking up in Table A1 the h_f/L which equals $(h_a-h_t)/(L_{ST}-L_{BC}-L_{DE}-$ etc...) *for the* required maximum flow rate ($Q=Q_{max}$). This is a larger pipe diameter than for the first method, because it assumes that the air socks are always there but it has the advantage that with it your system does not require an air-purging float valve. No initial purging of the air in the system is necessary.

<u>Case 4.</u> h_a smaller than h_t and smaller than h_{f1}.

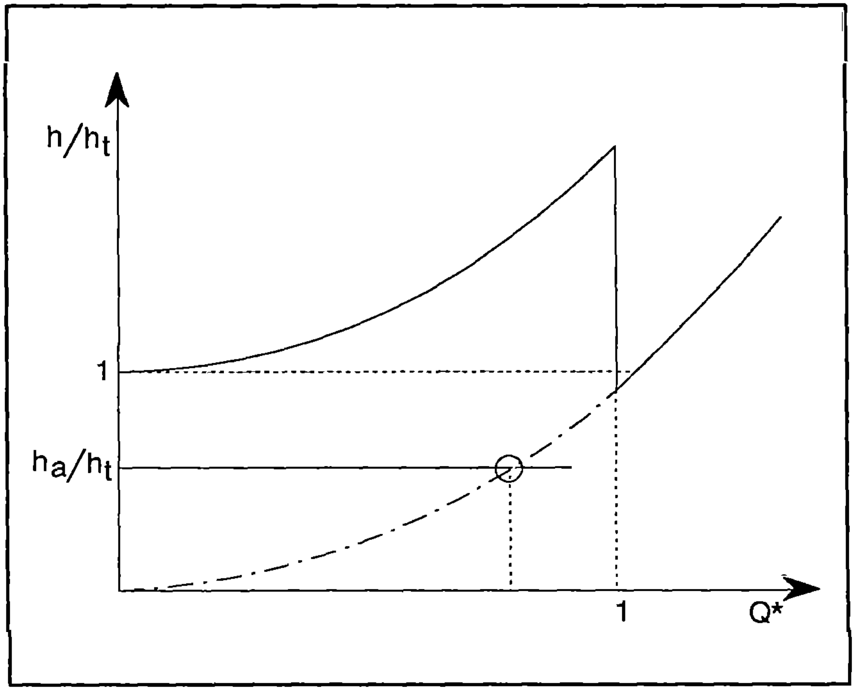

Figure II-5

In this case, (Figure II-5) there is only one good way to proceed: the same as the first method in Case 3. So, plan on installing air-purging valves and determine d by calculating h_f/L_{ST} and using that value as h/L and Q_{max} as Q in Table A1. If you do this without the valves and start the water going by purging the air only once with a T at the socks you will construct the typically unreliable system which will stop on its own at unpredictable times.

5) **Check your pressures.** No matter which design you have been led to, you now need to check the pressure along the pipe:

a) Check the pipe for pressures which fall below atmospheric pressure. This is done by drawing the hydraulic grade line on top of the pipe profile: Where the profile rises above the hydraulic grade line (HGL), you've got a negative gage pressure (pressure less than atmospheric). This needs to be avoided since in general it will lead to cavitation (the vaporizing of the water) and so you will have to modify your choice of pipe diameters to avoid it. Some manuals recommend that your HGL remain a fixed distance above the pipe profile. My opinion is that this is not necessary.

<u>Note:</u> If you have built into your design, regions where socks remain such as in Case 3, (second method), you will have to calculate you HGL as indicated at the end of Appendix A-II, for the **maximum** (subcritical) flow rate you expect. The idea is that wherever the pipe is full, the hydraulic grade line height falls in the downstream direction by h_f/L times the length of full pipe and wherever there is a sock, the hydraulic grade line follows the profile, remaining above it at the fixed height it had at the high point which is the beginning of the sock. Since in general you won't know the length of the sock you'll have to use the length which you determined in the trickle height calculation- a conservative estimate. If no sock remains in your design you should calculate and plot the HGL as indicated in the first part of Appendix A-I (full pipe).

b) Check the pipeline for excessive pressure: To do this you use the hydaulic grade line also: Spot the locations where the HGL is highest above the pipe profile and make sure that the SDR classification (or the schedule number, for US-made pipes) is adequate for these pressures.

<u>Note:</u> For a pipe from the distribution tank to tapstands, the HGL you should use is the one for zero flow, a horizontal line from the tank. But for the pipeline from the spring-box to the tank, this is indicated only if you include a

valve near the tank that can be used to shut-off the flow out of the pipeline. Such a valve is not necessary since it is always possible to shut-off the flow at the pipe intake in or at the spring-box. If the water in this pipeline is never shut-off from below, the maximum pressure will generally be found for the flow rate that fills the pipe.

CHAPTER III

EXAMPLES

The examples which follow have been chosen to illustrate various aspects of the material just presented.

Example 1

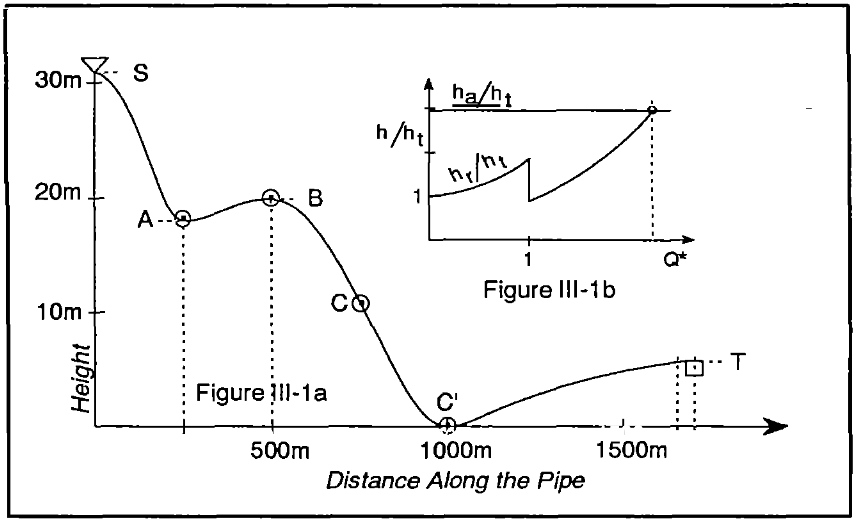

Figure III-1

L_{ST}= 1700m L_{SB}=480m $L_{BC'}$=475m
H_S=31m H_A=18m H_B=20m $H_{C'}$=0 H_T=6m
Q_{max}=0.3 lit. /sec.

Therefore: $h_a=H_S-H_T$=25m. H_{SB}=11m.

There is one local high point at B and so there will be one sock with a trickle height.This high point is higher than the next vented point (Tank T) so that you could if you wished eliminate the sock by designing a break-pressure tanklet at B. You should always check for this possibility. But in this example it will turn out that there is no advantage in using it.

<u>Calculate the trickle height.</u> When the pipe upstream of B is full up to S, the static head at B is H_S-H_B=11m. Therefore (see Appendix A-II)

$$h_1=H_S-H_B-.00568L_{SB}= 11-(.00568x480)=8.27.$$

So the volume of the sock after compression is

$$10.4/(10.4+8.27)=0.556$$

times the volume before compression. If the pipe diameter is uniform along the sock the length of the sock after compression will also be 0.556 times what it was originally. Assume that after you measure off the length $L_{BC}= L_{BC'}$ x 0.556= 264m (downstream of B) you find on the pipe profile that the height H_C=11m. Then:

$$h_t=H_B-H_C=9m.$$

Note that h_a is larger than h_t so that water will flow when you first fill the pipe.

Next calculate $h_{f1}+h_t$ approximately:

h_{f1}=0.00568x(The length of the part of the pipe that is filled)= 0.00568x(1700-264)=8.16m

so that $h_{f1}+h_t=8.2+9=17.2m.$

So h_a/h_t= 25/9=2.78 is larger than h_{f1}/h_t+1=17.2/9=1.91. So this is **Case 1.** (Figure III-1b)

In this case we use Table A1 to determine d after having determined h_f/L. We calculate the $h_f/L=(h_a/L_{ST})$ where h_a=25m, and L= L_{ST}= 1700:

$$h_f/L=25/1700=0.0147$$

We enter this value and our **maximum** flow rate= 0.30 lit./sec.in the table. We find that for a diameter of 1", and Q =0.30 lit./sec., h_f/L=0.0091,(less than the friction we can afford) but for d=3/4" and Q=0.30 lit./sec, h_f/L= 0.0315, (much more than what we can afford). We therefore choose D=1" and check that this will allow us to get almost 0.40 lit./sec.if it turns out that the spring output is that high.

Alternatively we can use a combination of 3/4" and 1" pipe lengths to get the system to limit the flow rate to be exactly the maximum flow rate that we were given. You proceed as indicated in Appendix A-III:

With L_l= length of 1" pipe and L_s= length of 3/4" pipe in the formula of the appendix, and $(h_f/L)_s$=0.0315, (the value for d=3/4" and Q= 0.30 lit./sec, taken from the table), while $(h_f/L)_l$= 0.00909, (the value for d=1" and the same Q):

$$L_{1"}=\{(0.0315\text{x } 1700)-25\}/\{0.0315-0.00909\}=1274\text{m}$$
$$L_{3/4"}= 1700\text{m}-1274\text{m}=426\text{m}.$$

Now we check our calculation by finding the total head loss for maximum flow which should match the head available:

$$h_f=(426\text{m x } 0.0315) +(1274\text{m x } 0.00909)=24.99\text{m}$$

which matches our h_a=25m.The 426m of smaller pipe diameter is best placed downstream of C' to keep the hydraulic grade line sufficiently high up to point B.

<u>To summarize:</u>

The system is now designed so that it will deliver without fail any amount of water supplied by the spring up to a maximum of 0.30 lit./sec. It is not necessary to bleed the pipes of air as you start the water going in the empty pipes.

<u>Example 2</u>. The profile is given below.

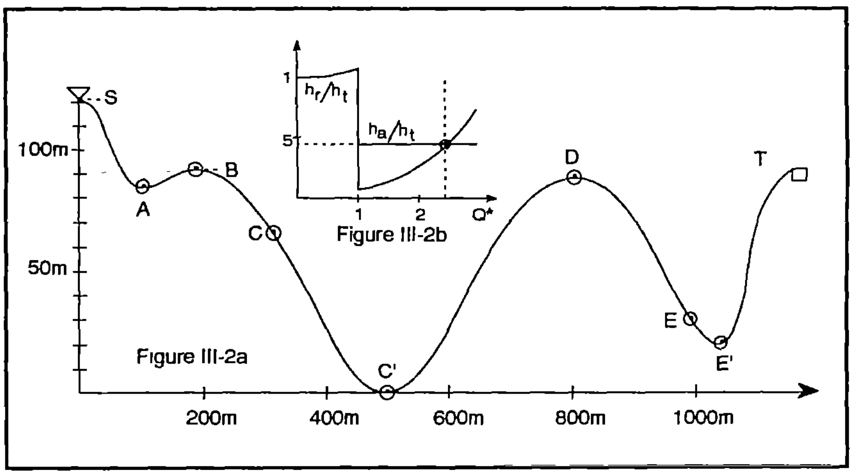

Figure III-2

The data are:

H_S=121m H_T=93 H_A=85m H_B=91m $H_{C'}$=0
H_D=89m $H_{E'}$=21m L_{ST}=1150m L_{SB}=150m
$L_{C'D}$=265m $L_{BC'}$=383m $L_{DE'}$=241m
Q_{min}=0.13 lit./sec Q_{max}=0.260 lit./s.

From which we calculate:

$h_a = H_S - H_T = 28m.$ $H_{BC'}$=91m $H_{DE'}$=68m

We first note that there are two local high points and that we cannot eliminate either one of them with a venting (break pressure) tanklet since they are both lower than T. We proceed to calculate the trickle height h_t. For the sock between B and C' the head at B is

$$h_1=H_S-H_B-(.00568x150m)=29.1m$$

Therefore, according to Appendix A-II:

$$L_{BC} / L_{BC'}=10.4/\{10.4+29.1\}=0.263$$

so that L_{BC}=383x.263=100.7m On the profile the point 100.7m downstream of B is found to be at a height H_C= 67m so that H_{BC}= 91-67=24m.
We will now need L_{CD}:

$$L_{CD}=L_{BC'}+L_{C'D}-L_{BC}=383+265-100.7+=547m$$

We now calculate the head a the next high point D.

$$h_2=h_1+H_C-H_D-.00568L_{CD}=29.1+67-89-(.00568x547)=4m$$

So the volume compression ratio in the second sock is:

$$v_{DE}/v_{DE'}=L_{DE}/L_{DE'}=10.4/\{10.4+4\}=0.722$$

Therefore L_{DE}= 241x 0.722= 174m.

On the profile the point 174m downstream of D is found at a height H_E=30m so that H_{DE}=38m. The trickle height is therefore

$$h_t=H_{BC}+H_{DE}=24+38=62m$$

If we wish we can now draw the universal plot, (*equation* A3 from Appendix I):

$$h_f/h_t = .00568Q^{*2}x\{L-L_{BC}-L_{DE}\}/h_t$$
$$= .00568x\{1150-100.7-174\}/62=.0802Q^{*2}$$

Q *	.6	.8	1.0	1.4	1.8	2.2	2.5
h_f/h_t	.0288	.0512	.0802	.156	.259	.387	.501

We note that: h_a/h_t=28/62=0.452

so that h_a/h_t is larger than h_{f1}/h_t (=.0802) but smaller than $(1+h_{f1})/h_t$. Our case is therefore **<u>Case 2</u>** (See figure III-2b above). We therefore select the pipe diameter on the basis that Q_c should be equal to Q_{min}. From Table A2 in Appendix A-IV we find that a 3/4" pipe has a critical flow rate Q_c=0.127 lit./s, slightly less than our Q_{min}, and therefore suitable. We then check what maximum flow this choice allows us

$$h_f/L=h_a/L_{ST}= 28/1150=.0243$$

In Table A1 we find that this allows us a flow slightly less than 0.275 lit./s and slightly more than 0.250 lit. /s. This is very close to our Q_{max}. So a single pipe diameter of 3/4" is acceptable and will allow us to operate without fail between our designated Q_{max} and Q_{min}.
Naturally, since this is a Case 2, you will have to purge air out of the two socks as described in Chapter II before the water can flow as you start the system.

<u>Remark:</u> Many times in Case 2 problems, proceeding as we have just done does not allow us to reach the desired maximum flow rate. In this case while you still may not reach the desired maximum, you can increase it over the amount given by the procedure we just used by adding one extra step at the end. That is by replacing all the pipes which are not between points like B and C' and D and E' ($L_{BC'}$, $L_{DE'}$, ...etc.) by pipes of larger diameter. This is because only those sections of pipe which are located between the local high points and the next low points downstream determine what the critical flow is. For

instance if we replace all sections except $L_{BC'}$ and $L_{DE'}$ in this example by 1" pipe, we find the following:
The remaining length is L_{ST} - ($L_{BC'}$+$L_{DE'}$)= 1150 -(383+241)= 526m. This is the length for which we might choose a 1" (or 1.5") pipe while we would keep 3/4" for the sections downstream of the two highs, i.e a combined length of 383+241= 624m. If we now calculate the head lost by the two sections separately, by multiplying the h_f/L (taken from Table AI) for the 3/4" pipe by 624m and the h_f/L for the 1" pipe for the 526m for a few flow rates Q and add them up for each Q, we find that the total h_f adds up to 28m for a Q= 0.31 lit./s. So we have increased the maximum flow allowed by the pipe from about 0.26 lit./s to 0.31 lit./s.But our minimum flow rate of 0.13 lit../s. remains above Q_c (which has not been altered) and so we cannot form new socks if the flow does not decrease below that value.

Example 3:

The profile is sketched in Figure III-3a.The geometric data is:

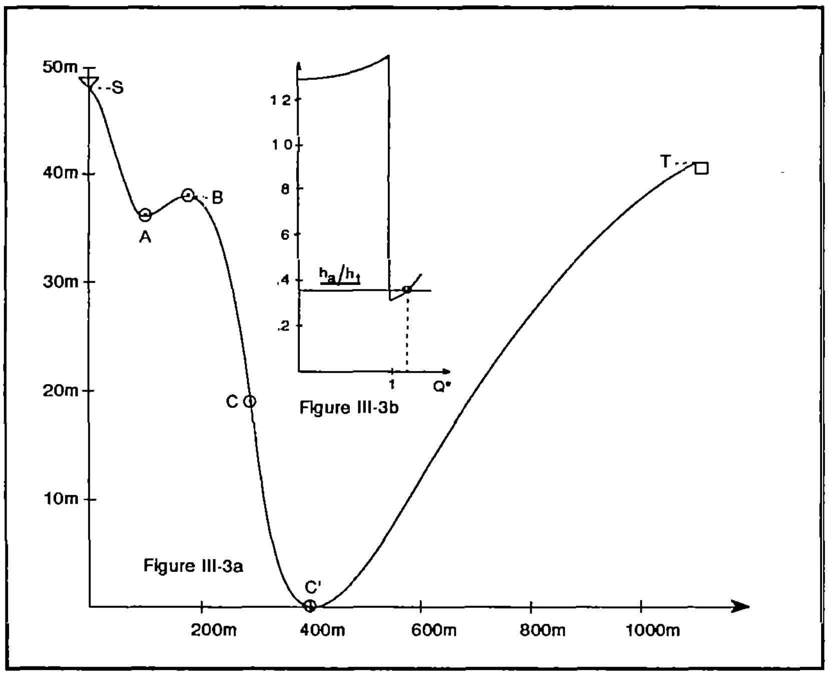

Figure III-3

H_S =48m $H_{C'}$=0 H_A=36m H_B=38m H_T=41m;

L_{ST} = 1100m L_{SB}=145m $L_{BC'}$=267m

The available and desired flow rate is estimated as 15 lit./min.

Here we first ignore what we have learned above and design without paying attention to the possibility of air trouble.

Standard Friction Design. The available head, h_a is:

$$h_a=H_S-H_T=48-41=7m$$

We calculate the average slope, h_a/L:

$$h_a/L=7/1100=0.00636$$

This is very close to the friction slope for the desired flow rate (0.25 l/sec.) for a 1" PVC pipe, SDR 26 (see table A1) or carry out the calculations in Appendix A for a pipe with diameter=0.0300m). So, if we use a 1" pipe from S to T and if the pipe is full of water we should be able to get the flow rate that we desire. Furthermore the maximum pressure head is about 43m (well within the rating of SDR 26) and there is no negative pressure anywhere, so a single diameter pipe seems appropriate.

How well will it work? Now we worry about starting the system and about what happens if the output of the spring falls below 15 l/min.

We note first that from the profile (only one local maximum), only one air sock is possible. We notice also that we cannot use a simple break-pressure tank at B, since B is lower than T. We calculate the trickle height h_t, i.e. the height of the air sock when the water in the pipe backs up to the level of S. In this case the pressure head at B is

$$h_1=H_S-H_B-.00568L_{SB}=9.2m$$

So

$$L_{BC'}/L_{BC}=10.4/\{10.4+9.2\}=.531$$

Then,

$$L_{BC}=267X.531=142m \text{ and } L_{SC}=145+142=387m$$

Here, on the scale drawing of the pipe, measure off the distance BC of the sock once compressed and read the height of point C. Suppose that this gives H_C=19m so that

$$h_t=H_B-H_C=38-19=19m$$

This is a large potential trickle height since h_a is only 7m. And this raises two problems:

Starting: Now since h_t is larger than h_a you will have to bleed the air out of the sock before any water will flow out at T. You can do that with a T or a valve just downstream of B. If you bleed all the air out, the system will deliver the design flow rate as long as it is provided by the spring.

Sustained Operation: But now suppose that the spring output decreases during the dry season: suppose for instance that it is or becomes only 13.5 lit./min.(or less). This is a very small, (10%), decrease of the estimated flow rate. However the new amount is also less than the critical flow rate, Q_c for this size pipe, since Q_c= 14.7 lit./min. for a 1" pipe (see Table A2, Appendix A). With a spring flow rate less than both the critical flow rate and the flow rate that your chosen pipe friction calls for, air in the form of small or medium size bubbles will travel from the spring exit downstream and keep accumulating in the sock . This is serious. For instance by the time the sock height is 1/3 of its maximum height , you would only have 0.65m of head left to overcome pipe friction which would reduce your flow to 0.018 lit./s.=1.3 lit/min. instead of 15. In fact if the decrease in the spring output occurs fairly rapidly, enough air will accumulate in the sock to block the flow completely.

Cure: You may install a float-type air purging valve downstream of B. In general this is not a good idea for flow rates which are supercritical, as explained in Chapter II because these flows tend to cause the valve mechanism to turn on and off abruptly and all the time- a source of wear. A better idea is to:

Follow the procedure recommended in this manual!

The first step since we have already calculated h_t is to draw the universal curve. Following the procedure outlined in Chapter II and used in the first example we get

Q	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.2
h_f/h_t	.046	.072	.103	.140	.183	.286	.346	.412

Now, h_a/h_t=7/19=.368. Since h_a/h_t is larger than h_{f1}/h_t but smaller than $1+h_{f1}/h_t$, we recognize that this is a Case 2, (although very close to a case 4, see, Figure III-3). The figure makes it clear that as we have already found out a very small decrease in flow rate out of the spring leads to the possibility of an air sock. Also we have not been given a minimum flow rate out of the spring, so that we cannot follow the instructions of Chapter II for this case which recommend that you set $Q_c=Q_{min}$. . We don't either know the value of Q_{max}.! This is life! We do our best: For this we make use of Chapter II in which it is shown that you can usually modify the situation (as in the preceding example) by using a pipe of smaller diameter only in the sections where air might accumulate and compensate with a larger pipe elsewhere.

We shall assume that the maximum flow rate Q_{max} is 15 lit./min. since it was said to be the desired rate. And we will endeavor to protect the system against a flow rate less than expected.

We first find out what length of 3/4" pipe we can use in conjunction with a 1.5" pipe elsewhere to get a friction head loss $h_f= h_a$.The procedure is exactly the same as described in Appendix A-III. But here the pipe diameters are 3/4" and 1.5". From Table A1 with the desired flow rate, and d_s=3/4", d_l=1.5", we get $(h_f/L)_s$= .0229, $(h_f/L)_l$= .00102. Therefore:

$$L_{1.5"}=\{.0229x1100 -7\}/(.0229-.00102)=831m$$

$$L_{3/4"} = 1100-831=269m$$

So, since the section from B to C' is not longer than 269 m we can replace the 1" pipe there by a 3/4" pipe section provided we replace the rest of the line by a 1.5" diameter pipe.This has the effect of reducing Q_C (see Table A3) to the value Q_C=0.127lit./s or 7.62lit./min so that no air can now accumulate downstream of B unless the flow rate out of the spring falls below 7.62 l/sec or about 51% of the expected value.

To summarize: 1100m of 1" pipe have approximately the same friction at 15 lit./s. as 269m of 3/4" and 831m of 1.5" pipe so that the new combination will give the same flow rate when the pipe is full as the original design. But the new design will not get into air trouble until the flow rate has fallen below 51% of the expected flow rate provided the smaller pipe is positioned where the air socks might form.

You would still need to bleed the pipe as you fill it initially of course , and for this you could use a simple T which you could cap after the start. The 1.5 " section, you would locate anywhere except between B and C'.

The additional cost of the modification at present pipe prices is approximately $350.

Remark: It is also possible to increase the diameter of the pipe section between B and C' which would guarantee that the flow is always subcritical. In other words this modification would turn it into a Case 4. The system operation would then necessarily require an air float valve at B to purge the sock downstream of B. The details are left as an exercise to the reader.

Example 4

This example is an adaptation of a completed project in Cerro Grande, San Ramon, Nicaragua, 1991. The water is drawn from two springs near each other. It is delivered to a small compact community (50 persons) near the springs and to a larger community (300 persons) at a large distance, much lower and so dispersed that it requires 18 waterstands.

Two additional facts need to be noted:

Spring A (variable output with a maximum of 7 lit./min. and a minimum of 3 lit./min.) belongs to the small upper community so that in the agreement giving permanent water rights of this source to the lower community it is specified that the upper one has priority for its use. This means that it gets water first from its own spring up to a daily consumption of 40 l/ inhabitant (or 2 m^3/day, total).

The lower community is so much lower than the upper one that the pipeline will require the use of break-pressure or venting units in between. The data is:

Springs output: Spring a: 3 to 7 l/min. Spring b : 6 to 8 l/min

Head available 17.4m Trickle height 7m.
L_{ST} = pipeline length between upper tank and a lower tank located just above lower community = 9000m.
L_{BC}=400m.

<u>Preliminary Discussion</u> . It is not a good idea to make the supply to the lower community too dependant on the water use from the top one. Hence there should be at least two tanks, one with a capacity of $2m^3$ fed by the first spring, for the upper houses and a second to supply the rest of the houses. The question is : where should that second tank be located? The minimum flow from the two springs at the end of the dry season is marginally sufficient to supply the two communities. This means that it is especially important not to spill overflow water anywhere. A sensible plan is to use the excess water from the overflow of the first (upper) tank into the lower supply system. Now compare two choices: a second tank near the first one with overflow of tank 1 directly into tank 2 -or a second tank immediately above the lower community. In the first case we shall need one or several break-pressure units and since we can't have spilling, we'll have to install a float valve in these units. But in addition, there is a minimum desirable flow rate out of a faucet (if the

flow rate is too slow users tend to leave the faucet open). Let us say that this minimum is 5 lit./min. This means that even three faucets will draw more water through the long pipeline in the first case (tank above) than can be fed by the springs through the pipe line in the second case. In other words we are going to need a much larger pipe diameter in the first case than in the second if we want a reasonable fraction of all the faucets to draw water simultaneously. Finally if we use choice 1 we may run into trouble whenever the second tank runs out even before the pipeline has been emptied so that the capacity of the pipeline itself would not be utilized properly. Below we calculate the sizes and costs of the two choices. But it is already clear that it is much cheaper and also better for the tank to be as low as possible. This requires that the pipeline be able to accommodate a variable flow rate not only from the variable output of spring b but also from the on or off output of the overflow of tank#1. This means of course that <u>the pipeline must be able to operate with air in the pipe most of the time.</u>

For calculation purposes, we estimate that half of the faucets available to the lower community need to be usable simultaneously with a minimum flow rate of 5 lit./min. each. Hence we require (18/2)x 5= 45lit./min. of flow out of the pipe if the second tank is located next to the first. But if the second tank is located at the end of the pipeline, the maximum flow rate is the maximum combined spring output= 7+8=15 lit./min.

Calculations:

We first classify our case: From Equation A-4:

$$h_{f1}/h_t=0.00568(L/h_t)$$

Where <u>L is always the length of water-filled pipe</u>. This means 9000m if there is no sock, 8600m if there is a full sock.

So, for the full pipe case

$$h_{f1}/h_t= .00568x9000/7= 7.30$$

and for the other case ,

$$h_f/h_t = .00568 x 8600/7 = 6.98$$

Since h_a/h_t= 17.4/7= 2.48, in either case, h_t is less than h_a which is less than h_{f1}.

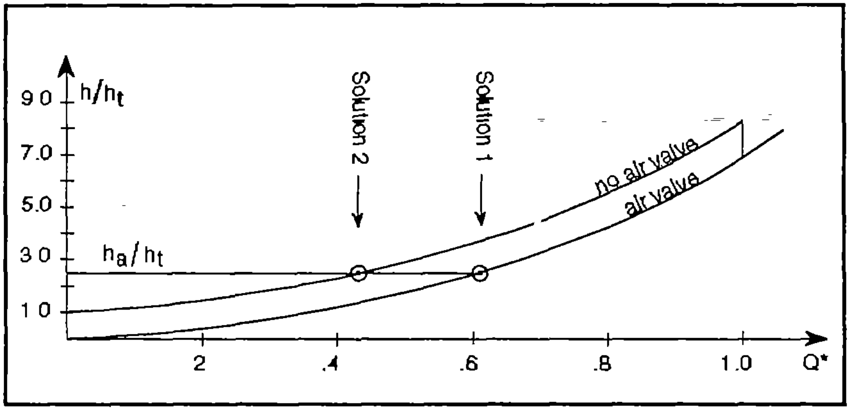

Figure III-4

<u>This is a Case 3</u> (see figure III-4). According to Chapter II, we can design this case following one of two methods, when tank 2 is at the end of the pipe, and with a maximum flow rate of 15 lit./min. When the tank is at the top of the pipeline, Q=45 lit./min, as long as the tank supply holds up. During that time no air can be ingested from the tank but whenever the supply from that tank is exhausted-which could be a daily event-air will be resupplied to the sock so that an air sock needs to be taken into account in this case also: Consequently the two methods of Case 3 can be examined also when the tank is placed next to tank I.

<u>Solution 1: Full pipe with an air-bleeding valve at the sock:</u>

In this case, the allowable friction losses $h_f = h_a$= 17.4m. The average friction slope is

$$h_f/L = 17.4/9000 = .00193$$

For Q=15 lit.min. the two pipe sizes which straddle this value (Table A1) are

d= 1", h_f/L= .006617 & d=1.5", h_f/L=.00102 and for Q=45 lit./min., they are:

$$d=2", h_f/L=.00239 \ \& \ d= 2.5", h_f/L= .00100$$

Now we use equations A-6 and A-7 to find the right combination of lengths

For Q=15 lit./min,

$$L_{1.5"} =\{9000x .00661-17.4)/ (.00661-.00102)=7530m$$
$$L_{1"}=9000-7530=1470m$$

And for Q=45 lit./min.,

$$L_{2.5"}=(.00239x9000-17.4)/(.00339-..00100)=2957m$$
$$L_{2"}=9000-2957=6043m$$

Solution 2: allows for the trickle height; no air-bleeding valve:
Here $h_f= h_a-h_t$=10.4m. Also L=9000-400=8600m. The diameter of the pipe along the 400m of possible sock does not influence the friction calculation and can be chosen for convenience For the remaining. 8600m:

$$h_f/L=10.4/8600=.00121$$

which is straddled by the same pipe sizes as in Solution 1.

With the tank below, (Q=15 lit./min.):

$$L_{1.5} =(.00661x8600-10.4)/(.00661-.00102)=8309m$$
$$L_{1"}= 8600-8309=291m$$

and for the sock area we should use 1.5" to avoid that the flow become supercritical at maximum flow rate(Q_c=14.7 lit./min.for d=1"), So the total length of 1.5" pipe is 8709m.

With the tank above, (Q=45 lit./min.):

$$L_{2.5"}=(.00661x8600-10.4)/(.00661-.00102)=7305m$$
$$L_{2"}=8600-7305=1295m.$$

Since Q_c =69 lit./min. for d=2",we can use that diameter for the remaining 400 m of pipe along the sock, so that the total length $L_{2"}$=1695m. The results are tabulated below together with the cost of each option which is based on the following unit prices for PVC, SDR 26:

diameter	1"	1.5"	2"	2.5"
price/m	$0.79	$1.27	$1.65	$2.20

	Solution 1. Air valve	Solution 2. No air valve
Tank II above	2957m@2.5"	7305m@2.5"
	& 6043m@2	& 1695m@2"
Cost	$17,333.00	$18,859.00
Tank II below	7530m@1.5"	8709m@1.5"
	& 1070m@1"	& 291m@1"
Cost	$10,372.00	$11,247.00

It is clear that placing the tank near the lower community saves roughly $7,000, a large fraction of the total cost, no matter which solution is chosen. It also makes the outlet of the individual faucets far less dependant on the number of faucets used at the same time. Finally it makes it unnecessary to provide shut-off valves in the break-pressure tanks. These would be necessary if the second tank were placed next to the first.

Wrap up: This example was included to show that if you know how to deal with air in pipes your designs will not only be trouble-free but also occasionally much cheaper.

Example 5a

This example is adapted from a case near Quolga Khoya, in the Cochabamba region of Bolivia. A community of 16 families has access to water for washing and cattle from a canal but this water is not suitable for drinking. About 1 km away from the village and 4m above a possible distribution tank is a small spring through broken rock on a steep slope. An unlined earth canal with a very small slope used to bring the water to the village (presumably when it was more abundant). The campesinos have now dug the canal deeper and intend to place a PVC pipe at the bottom of the trench and bury it to protect the small water supply and prevent seepage losses.

The spring output is about 1.5 lit./min. Will the system work?

This example illustrates one important practical consideration in the construction of gravity flow systems: It is easy to introduce unintentionally local high points which create unexpected trickle height losses. This is a particular danger when the desired profile is almost horizontal at sections where the head is small: in this case the high points may even be higher than spring level.

For the present case we first calculate the friction head required. Even with the smallest easily available PVC pipe diameter d= 1/2", this friction loss is small:

For this very small flow rate, Table A1 gives approximately for d=0.0173m, $h_f/L=0.0016$ or $h_f=1.6$m, so that the available head , 4m, is more than adequate for the friction head loss. But even for d=1/2" the flow will always be subcritical, (see table A-3). Since the trench follows a canal , there are no intended local high points in the profile. But normally as the workers lay and bury the pipe at the bottom it will not be perfectly straight.This is particularly true of pipes which are manufactured in rolls. But even with PVC, the pipe can be expected to go up and down an inch or two several times for each pipe section. Yet a single high point at the beginning will cut down to almost nothing the already miserably small flow rate. The remedy is time-consuming: the workers need to insure that everywhere the pipe as laid has a downstream slope. This has to be done with a carpenter's level or by trying the pipeline before the trench is filled. Also the trench filling needs to be done with great care.

<u>Example 5b</u>

Similarly in the actual construction of the system small deviation from an intended profile can occasionally cause serious problems. Consider the following intended (III-5a) and actual (III-5b) profiles inspired by a case near Rio-Blanco, Nicaragua:

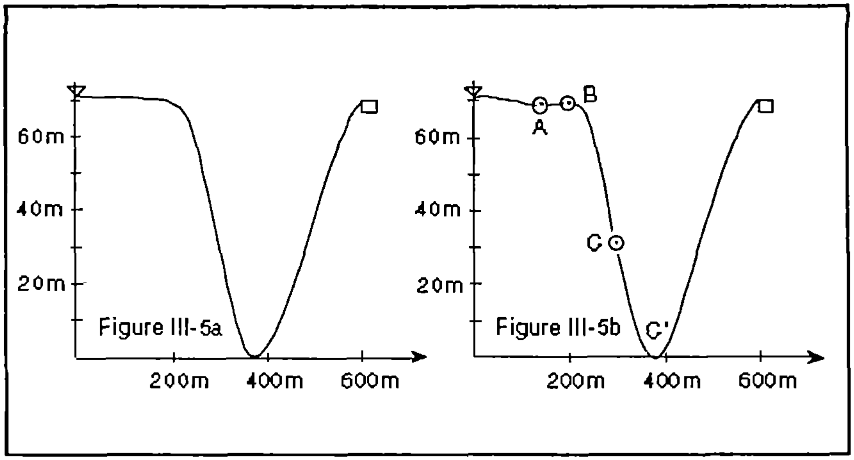

Figure III-5

H_S-H_T=6m; H_S-H_B=7m; H_B-$H_{C'}$= 70m; H_B-H_A= 0.30m.

L= 600m. Q between 8 and 18 lit./min.

In the design there is no trickle height at all and the pipe diameter has been chosen on the basis of friction losses. The available head allows a h_f/L= 6/600=0.01 For a maximum flow rate of 18 lit./min. = 0.3lit./s. a 1" pipe (SDR 26) has a h_f/L= 0.0091. It is therefore suitable and if the construction conforms to figure III-5a. all is well. But if the profile turns out to be as in figure III-5b, (a very minor change in height which is hard to avoid especially when the spring is found within a ravine) there is a considerable trickle height whose maximum value needs to be computed for a specified profile between B and C' but which is likely to be about 40 meters - much more than the available head. With the trickle height you can expect complete blocking, a situation which clearly needs to be avoided. In this case it is far better, if at all possible, to get rid of the low point at A than to add a float-type air valve beyond B because the system operates supercritically a good deal of the time (Q_C= 14.7). Anyway <u>always strive for the simplest installation, the one which requires the fewest number of moving parts.</u>

Example 6

H_S=40m H_A=21m $H_{C'}$=0 H_T=20m
H_B=26m
L_{ST}=4700m L_{SB}=200m $L_{BC'}$=786m
Q_{min}=0.10 lit./s. Q_{max}=0.15 lit./s.

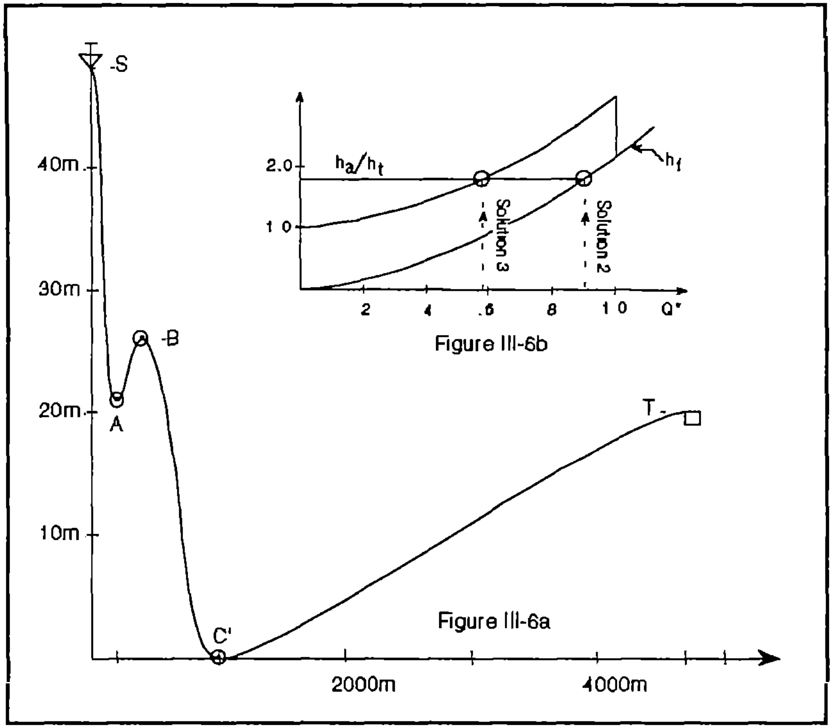

Figure III-6

This is an example for which there are three possible solutions. We will explore all of them.

Solution 1: There is one high point (one possible sock) at B. Since B is higher than the tank at T we can get rid of the sock problem by placing a break-pressure tanklet there. Then we can accommodate any flow up to the maximum by equating the head available between S and B to the friction head loss between these two points at Q_{max} and doing the same for the section BT.
For SB the head available is H_S-H_B=14m and the length is

L_{SB}=200m. So the maximum friction loss ratio h_f/L =14/200=0.070. Table A1 gives h_f/L =0.0369 for Q= 0.15l/sec. and d=1/2". We shall therefore use 1/2" pipe for this first section and remember that it will not limit the flow rate unless the spring output increases beyond expectations to Q=0.21. For the section BT, L_{BT}=4700m-200m= 4500m and H_B-H_T=6m. So the maximum friction ratio allowed for this segment is 6m/4500m=0.00133. According to Table A1 for a Q =0.15 a 1" pipe has a h_f/L=0.00270 and a 1.5" pipe has a h_f/L= 0.00042. So we need a mix of these two diameters. Turning to Section A-III we find that :

$$L_{d=1.5"}=L_l=\{(0.00270x4500)-6\}/(0.00270-0.00042)=2697m$$
$$L_{d=1"}=L_s=4500m-2697m=1803m$$

Check: (2697x0.00042)+(1803x0.00270)= 6.001m

<u>Summary of solution 1:</u> From T to B, 200m of 1/2" pipe. From B to T first 1803 m of 1" pipe then 2697 m of 1.5" pipe. A break pressure unit at B. Water will spill at B if Q is greater than the expected maximum unless a partially closed valve is inserted between S and B.

<u>The two other solutions:</u>

Without a break-pressure unit at B we have to allow for a sock after B.

Calculate h_t:

$$h_1=H_S-H_B-.00568L_{SB}=14-(.00568x200)=12.9m$$
$$L_{BC}/L_{BC'}=10.4/(10.4+12.9)=0.446,$$

so, L_{BC}=0.446x786m=350m. On your profile of the pipeline, you find that the height of point C is 14.9m so that h_t =11.1m. $h_a=H_S-H_T$=20m and from equation A4 :

$$h_{f1}=0.00568x(4700-350)=24.71m.$$

From this we get:

$$h_a/h_t=1.80 \qquad h_{f1}/h_t=2.23$$

So h_a is larger than h_t but smaller than h_{f1}. This is a **Case 3** (Figure III-6b). Case 3 has two solutions(solutions 2 & 3).

for simple friction with Q_{max}.
The friction ratio or slope is $h_f/L=h_a/L_{ST}=20/4700=0.00426$. At $Q_{max}=0.15$l/sec. as we have just seen, h_f/L is .00270 for a 1" pipe and it is 0.00936 for a 3/4" pipe. The proper combination of these is, following Section A-III,

$$L_l=L_{1"}=\{(0.00936x4700)-20\}/(0.00936-0.00240)=3447m$$
$$L_s=L_{3/4"}=4700-3447=1253m$$

Check: (3447x0.00240) +(1253x0.00936)=20m.

Summary of Solution 2: With an air-bleeding float valve at B the right maximum flow rate is achieved with 1253 m of 3/4 " pipe and 3447m of 1" pipe. The order in which these diameters are chosen is not important in this particular case because the hydraulic grade line will remain above the pipe profile for any order.

Solution 3: In this one, (See Chapter 2, Case 3, second solution) we do not install an air bleeding valve or a break-pressure tank at B. Instead we assume we will be permanently losing as much as 11.1m of head at the sock so that we have 20-12.9=7.1m of head available to overcome friction losses over a length which is L_{ST}- L_{BC}=4700-350=4350m. Thus the friction slope,h_f/L is 7.1/4350=0.00163.This can be achieved by a combination of 1" and 1.5 " pipes. Using Section A3 as before, we deal first with the full part of the pipe-4350m we find that in this case:

$$L_l=L_{1.5"}=\{(0.00240x4350)-7.1\}/(0.00240-0.00042)=1687m$$
$$L_s=L_{1"}=4350-1687m=2663m$$

To this we need to add the section BC= 335m whose friction is not counted and which could be either 1" or 1.5" diameter. Naturally we choose 1" in this case.

Summary of Solution 3: With no special vent or valve at B we can achieve our flow rate with 1687m of 1.5" pipe and 2663+350=3013m of 1" pipe.

The results for the three solutions are summarized below:

diameter	solution 1	solution 2	solution 3
1/2"	200m	0	0
3/4"	0	1253m	0
1"	1803m	3447m	3013m
1.5"	2697m	0	1687m
Device	Break-pressure tank	Air-bleed valve	none

From this table it appears that solution 2 would be the cheapest if the air-bleeding float valve installation is not especially expensive. But it requires a device with moving parts. Note that solution 3 is likely to be cheaper than solution 1.

<u>Example 7.</u> For our final example we use the same profile as for Example 6 but raise the height of the end tank T to 31m. This only changes h_a. We have:

h_a= 9m. h_t= 12.9m h_{f1}=24.71m

Note that T is higher than B now so that solution 1 of the previous example cannot be used. Since h_a is smaller than h_t and also smaller than h_{f1}, this is a **Case 4** (Figure III-7). This means that we will have to use an air bleeding float-valve at B and that we evaluate;

$$h_f/L = h_a/L_{ST}.=9/4700=0.00191$$

For Q=Q_{max}=0.15 l/sec.Table A-1 gives us:

h_f/L=0.00270 for d=1" and h_f/L= .00042 for d= 1.5".

So, according to Section A-III:

$$L_{1.5"}=L_l=\{(0.00270x47000)-9\}/ (0.00270-0.00042)=1618m$$

$$L_{1"}=L_S=4700-1618=3082m$$

Check: 1618x0.00042 +(3082x0.00270)= 9m.

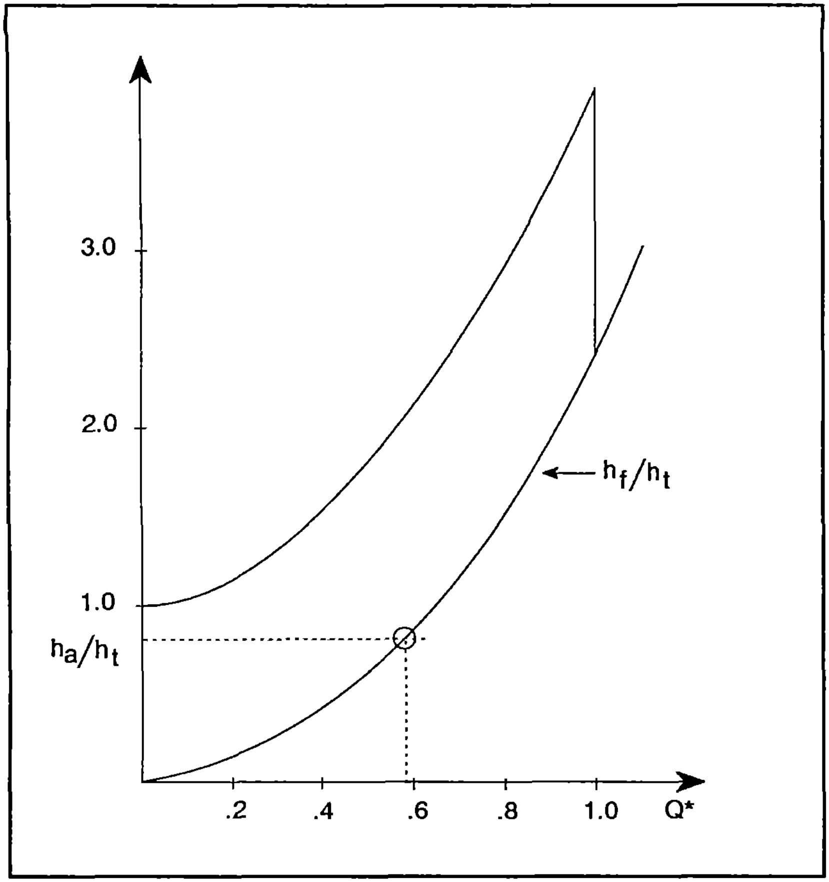

Figure III-7

APPENDIX A

A-I: Summary of Formulas and Tables for Conventional (full pipe) Hydraulic Calculations in Pipes.

These apply where there are no stationary air socks. Stationary air socks will not occur if:

-There is no unvented local maximum in the pipeline profile.

-Or the pipe runs full

-Or the pipe runs with a flow rate Q greater than the critical flow rate Q_c.

One exception: If the hydraulic grade line is locally sufficiently below the pipe line elevation to cause cavitation(8 to 9 meters), there will be not air but water vapor there and also a great deal of shocks and knocks caused by the collapse and reforming of vapor bubbles. This will damage the pipe and should be avoided.

The basic equation for a single pipe (without branching) between an upstream point 1 and a downstream point 2 is:

$$.0826Q^2/d_1{}^4 + h_1 + H_1 = 0.0826Q^2/d_2{}^4 + h_2 + H_2 + h_{f12} \quad \text{(A1)}$$

In this equation h is the pressure head in units of meters; (the pressure head is the pressure above atmospheric pressure divided by the weight of a m^3 of water), H is the height of the pipe line at any point (with respect to any fixed datum) and h_{f12} is the friction head loss between any two points 1 and 2. The flow rate Q is in m^3/sec.and the diameter d in meters.

A hydraulic grade line, (HGL) is a line which plots the height of the sum (h+ H) as a function of position along the pipe. One usually plots also the height H of the pipeline on the same graph. In principle there should be one more line. the Energy line whose height represents the sum of all three terms in the equation. But for drinking water designs, the first term on the left of either side of the equation is quite small compared to the others so that the hydraulic grade line and the energy line are almost the same. This is because the recommended velocity in drinking water systems does not exceed 3m/s. This gives a maximum difference in levels between the energy and hydraulic grade line of less than 50 cms. For pipelines leading to and from pumps and turbines and for penstocks this is far from true and the energy line should always be shown.

Since the height of the pipe is H, the vertical spacing between the hydraulic grade line and the pipe height is the pressure head h. If the HGL falls below the pipeline height the pressure head is negative (i.e. less than atmospheric).

Wherever the pipe is vented (spring, breakpressure tank, distribution tank, valve opened to the atmosphere) the HGL and the pipe profile have the same height.

The energy line and so also the HGL in our case, always decrease downstream because h_f is always a loss of head.
The calculation of the HGL starts at the spring tank. There the HGL height is the height of the tank since the spring is vented (gage pressure =0). Downstream of the spring its **slope** is the h_f/L appropriate to the flow rate and pipe size of the section considered (See the friction head loss tables below). So the slope does not change for a given flow rate and for a pipe without any branches unless the pipe diameter changes. The flow rate you select to draw the HGL depends of course on what use you make of it. For instance to check for negative gauge pressures you would use the highest value of Q that you expect.

Friction Losses: The equation you can use instead of Table A1 to calculate h_f or to determine the hydraulic grade line, given d & Q and in the absence of air socks is:

$$h_f / L = 7.76 \times 10^{-4} Q^{7/4} / d^{19/4} \qquad \text{(A2a)}$$

If you know Q and h_a instead, you get d from:

$$d = 0.222\, Q^{7/19} (h_f/L)^{-4/19} \qquad \text{(A2b)}$$

And if you know h_a and d, you can get Q from:

$$Q = 59.9\, (h_f/L)^{4/7} d^{19/7} \qquad \text{(A2c)}$$

where Q is in m^3/sec. and d in m.

Equation (A2a) was used to calculate h_f/L in the tables A1 which are found on the next pages.
Equations 3 and 4 of Chapter II, the approximate equations used to classify your cases are reproduced here for convenience:

$$h_f/h_t = 0.00568\, Q^{*2} (L/h_t) \qquad \text{(A3)}$$
$$h_{f1}/h_t = 0.00568\, L/h_t \qquad \text{(A4)}$$

The length L here does not include the length of the socks.

Note: In Chapter III & in the tables the inner diameters assumed are as follows:

Nominal d	SDR#	Diam
1/2"	13	0.0173m
3/4"	17	0.0231m
1.0"	26	0.0300m
1.5"	26	0.0444m
2.0"	26	0.0557m
2.5"	26	0.0674m
3.0"	26	0.0821m

Table A1 was prepared by using Equation A-2. It can be used instead of A2.

TABLE A1: FRICTION HEAD LOSSES

d= 1/2"= 0.0173m		d=3/4"=0.0231m		d=1"=0.0300m	
Q, l/sec	h_f/L	Q, l/sec	h_f/L	Q, l/sec	h_f/L
0.010	.000323	0.01	.000082	0.03	.00016
0.015	.000657	0 02	.000275	0.05	.00040
0.020	.00109	0.03	.00056	0.075	.00080
0.025	.00161	0.05	.00137	0.10	.00133
0.030	.00221	0.075	.00278	0.125	.00196
0.040	.00365	0.10	.00460	0.150	00270
0.050	.00540	0.125	.00680	0.175	.00353
0.075	.0101	0.150	.00936	0.200	.00447
0.100	.0182	0.175	.0122	0.225	.00550
0.125	.0268	0.20	.0158	0.250	.00661
0.150	.0369	0.225	.0190	0.275	.00780
0.175	.0483	0.250	.0229	0.300	.00909
0.200	.0611	0.275	.0270	0.325	.0105
0.225	.0751	0.300	.0315	0.350	.0119
0.250	.0903	0.325	.0362	0.375	.0134
0.275	.106	0.350	.0412	0.400	.0150
0.300	.124	0.375	.0465	0.425	.0167
0 325	.143	0.400	.0521	0.450	.0185
0.350	.163	0.425	.0579	0.475	.0203
0.375	.184	0.450	.0640	0.500	.0222
0.400	205	0.475	.0703	0.525	.0242
0.425	.228	0.500	.0769	0.550	.0263
0.450	.252	0.525	0837	0 575	.0284
0.475	.278	0.550	.0909	0.600	.0306
0.500	.303	0.575	.0982	0.625	.0328
0.525	.330	0.600	.106	0.650	.0352
0.550	.359	0.625	.114	0.675	.0376
0.575	.388	0.650	.122	0.700	.0400
0.600	.418	0.675	.130	0.725	.0426
		0.700	.139	0.750	.0452
		0.725	.147	0.775	.0478
		0.750	.156	0.800	.0506
		0 800	.175	0.825	.0534
		0.825	.185	0.850	.0562
		0.850	.195	0.875	.0592

TABLE A1: FRICTION HEAD LOSSES
(continued)

d=1"=0.0300m (cont.)		d=1.5"=0.0444m		d=1.5"=0.0444m	
Q, l/sec	h_f/L	Q, l/sec	h_f/L	Q, l/sec	h_f/L
0 900	.0622	0.10	.00021	1.90	.0357
0 925	.0652	0.15	.00042	1.95	.0374
0.950	.0684	0.20	.00069	2.00	.0390
0.975	.0715	0.25	.00102	2.05	.0408
1.000	.0748	0 30	.00141	2.10	.0425
1.025	.0780	0.35	.00185	2.15	.0443
1 050	.0814	0.40	.00234	2.20	0461
1.075	.0848	0.45	.00287	2 30	.0499
1.10	.0883	0.50	.00345	2.40	.0537
1 125	.0918	0.55	.00408	2.50	.0577
1.15	.0954	0.60	.00475	2.60	.0618
1.175	.0991	0.65	.00546	2.70	.0660
1.20	.103	0.70	.00621	2.80	.0704
1.25	.110	0.75	.00702	2.90	.0748
1.30	.118	0 80	.00786	3.00	.0794
1.35	.126	0.85	.00873	3.10	.0841
1.40	.134	0.90	.00965	3.20	.0889
1.45	.143	0.95	.0106	3.30	.0938
1.50	.152	1.00	.0116	3.40	.0988
1.55	.161	1.05	.0126	3.50	.104
1.60	.170	1.10	.0137	3.60	.109
1.65	.180	1.15	.0148	3.70	.115
1.70	.189	1.20	.0160	3.80	.120
1 75	.199	1.25	.0172	4 00	.131
1.80	209	1.30	.0184	4.20	.143
1.85	.219	1.35	.0196	4.40	.155
1.90	.230	1.40	.0209	4.60	.168
1.95	.240	1.45	.0222	4.80	.181
2.0	.251	1.50	.0236	5.00	.194
2.1	.274	1.55	.0250	5.20	.208
2.2	.297	1.60	.0264	5.40	.222
2.3	.321	1.65	.0279	5.60	.237
2 4	.346	1.70	.0294	5.80	.252
2 5	.371	1.75	.0309	6.00	.267
2.6	.398	1.80	.0324	6.20	.283
2.7	.425	1.85	.0341	6.40	.299

TABLE A1: FRICTION HEAD LOSSES
(continued)

d=2.0"=.0557m		d=2.0"=.0557m		d= 2.5"=.0674m	
Q, l/sec	h_f/L	Q, l/sec	h_f/L	Q, l/sec	h_f/L
0.2	.000236	2.90	.0255	0.40	000322
025	.000300	3.00	.0270	0.50	.000475
0.30	.000481	3.20	.0303	0.60	.000654
0.35	000630	3.40	.0337	0 70	.000856
0.40	.000796	3.60	.0372	0 80	.00108
0.45	.000978	3.80	.0409	0.90	.00133
0.50	.00118	4.00	.0447	1.00	.00160
0.55	.00139	4.20	.0487	1.10	.00189
0.60	.00162	4.40	.0529	1.20	.00220
0.65	00186	4.60	.0571	1.30	.00253
0.70	.00212	4.80	.0615	1.40	.00288
0.75	.00239	5.00	.0661	1.50	.00325
0.80	.00268	5.20	.0708	1.60	.00364
0.85	.00298	5.40	.0756	1.70	.00404
0.90	.00329	5.60	.0806	1.80	.00447
.0.95	.00361	5.80	.0587	1.90	.00492
1 00	.00395	6.00	.0910	2.00	.00538
1.10	.00467	6 20	.0963	2.10	.00586
1.20	.00544	6.40	.1020	2.20	.00635
1.30	.00626	6.60	.1080	2.30	.00687
1.40	.00712	6.80	.1132	2.40	.00740
1.50	00804	7.00	.1191	2.50	.00794
1.60	.00900	7.20	.125	2.60	.00851
1.70	.0100	7 40	.131	2.70	.00909
1.80	.0111	7 60	.138	2.80	.00969
1.90	.0122	7 80	.144	2.90	.0103
2.00	.0133	8.00	.151	3.00	.0109
2.10	.0145	8.20	.157	3.20	.0122
2.20	.0157	8 40	.164	3.40	0136
2.30	.0170	8.60	.171	3 60	.0150
2.40	.0183	8.80	.178	3.80	.0165
2.50	.0196	9.00	.185	4.00	.0180
2.60	.0210	9.20	.192	4.20	.0197
2.70	.0225	9.40	.200	4.40	.0214
2.80	.0240	9.60	.207	4.60	.0231
				4.80	.0249

TABLE A1: FRICTION HEAD LOSSES
(continued)

d=2.5"=.0674m.)		d=2.5"=.0674m		d=3.0"=.0820m	
Q, l/sec	h_f/L	Q, l/sec	h_f/L	Q, l/sec.	h_f/L
5.0	.0267	9.8	.0868	0 50	.000187
5.2	.0286	10.0	.0899	0.75	.000380
5 4	.0305	10.5	.0979	1.00	.000628
5 6	.0326	11.0	.106	1.25	.000930
5.8	.0347	11.5	.115	1.50	.00128
6.0	.0368	12.0	.124	1.75	.00167
6.2	.0389	12.5	.133	2.00	.00211
6.4	.0412	13.0	.142	2 25	.00260
6 6	.0434	13.5	.152	2 50	00312
6.8	.0458	14.0	.162	2.75	.00369
7.0	.0482	15.0	183	3.00	.00430
7.2	.0506	16.0	.205	3.25	.00494
7.4.	.0531	17.0	.228	3 50	.00563
7.6	.0556	18.0	251	3.75	.00635
7 8	.0582	19.0	.276	4.00	.00711
8.0	.0608	20.0	.302	4 25	.00791
8.2	.0636	21.0	.329	4.50	.00874
8.4.	.0662	22.0	.357	4.75	.00960
8 6	.0690			5.00	.0105
8 8	.0719			5.25	.0114
9.0	.0748			5.50	0124
9.2	0777			5.75	.0134
9 4	.0807			6.00	.0145
9.6	.0837			6.25	.0155

TABLE A1: FRICTION HEAD LOSSES
(continued)

d=3"=.0821m		d=3"=.0821m		d= 3"=.0821m	
Q, l/sec	h_f/L	Q, l/sec	h_f/L	Q, l/sec	h_f/L
6.50	.0166	12.00	.0486	18.00	.0988
6.75	.0178	12.50	.0522	18.50	.103
7.00	.0189	13.00	0559	19.00	.109
7.50	.0214	13.50	.0597	20.00	.119
8.00	.0239	14.00	.0637	21.00	.129
8.50	.0266	14.50	.0677	22.00	.140
9.00	.0293	15.00	.0718	23.00	.152
9.50	.0323	15.50	.0761	24.00	.164
10.00	.0353	16.00	.0804	25 00	.176
10.50	.0385	16 50	.0849	26.00	.188
11.00	.0418	17 00	.0894	27.00	.201
11.50	.0451	17 50	.0941	28.00	.214

Correction for slightly different pipe diameters. The friction head losses vary a lot with pipe diameter. For instance with the 1" pipe, if you had used its nominal diameter, 1"=.0254m instead of the S.D.R. 26 diameter of .0300m, say, with Q=0.8 l/sec., equation A2 says that h_f/L would be .111 instead of .0506 (twice as much!). So even pipes of the same nominal diameter but of different thicknesses have different friction head losses and once in a while you might want to correct for that. You can of course use the correct diameter in equation A2a. But if you don't have the right pocket calculator for that, you can correct Table A1 this way:

Call d_t the diameter of the pipe given in the table and h_{ft}, the corresponding head loss at a given flow rate. For a real diameter d at the same flow rate the corrected head loss is given by:

$$h_f=(h_f)_t x\{1+4.75(d_t-d)/d_t\} \qquad (A5)$$

Note that the smaller diameter pipe gives the larger head loss. You should not use this formula for pipe diameters which differ by more than 10% from the ones in the tables: For a 5% change in diameter the correction is given with 3% accuracy, and for a 10% change in diameter the correction is given with 11% accuracy.

A-II: Calculation Of The Trickle Height

The trickle height h_t is the largest head loss due to the greatest possible amount of air trapped in a pipe line when the flow rate just reaches the critical flow rate Q_C. In general this is not precisely (somewhat larger than) the head you have to overcome to start the water flowing with the pipe full of air, because, when the flow rate is Q_C, the friction in the full parts of the pipe line tends to decrease the pressure in the socks so that they expand somewhat. But it is the head loss of importance for our designs. The procedure calculates the vertical extent of each sock and then adds them up.

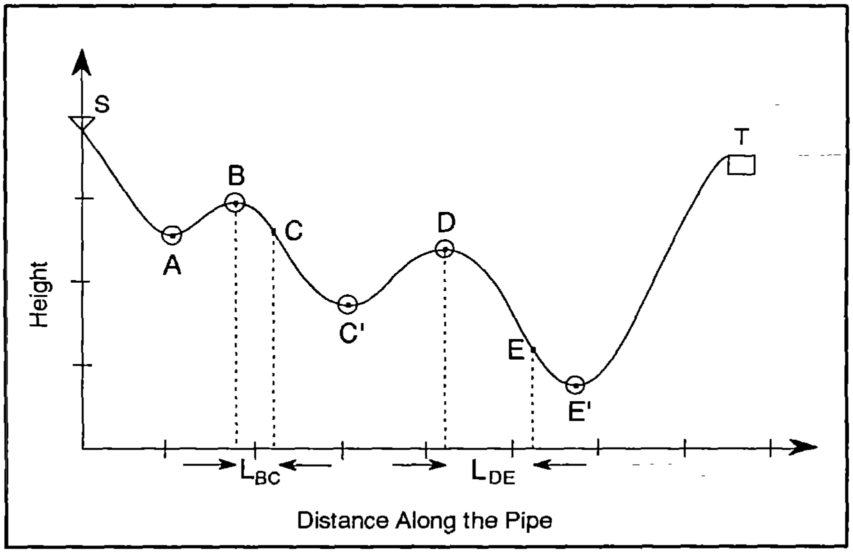

Figure A-1

Draw the pipeline to scale. The only convenient way is to use length along the pipe for your horizontal scale and to exaggerate your vertical scale. Choose a level datum and record the heights of all points such as S,T, A.B,C' etc...with respect to the datum. Record the distance along the pipeline of all these points. Call L_{SB} the length of the section between S and B, etc...

In determining the trickle height, assume:

a) that the initial volume of air is that contained in sections such as BC', DE', etc...(as when you start with dry pipe).

b) that all the available head may be used to calculate the pressure within the socks (this means that the reach from S to B is full).

Step 1: Record the quantities: $(H_B-H_{C'})$; $(H_D-H_{E'})$......etc and the length that go with these points: $l_1' = L_{BC'}$; $l_2' = L_{DE'}$...etc.

Step 2: Calculate the maximum head h_1 in the first air sock. This is

$$h_1 = (H_S-H_B) - 0.00568L_{SB}$$

Step 3: Calculate the change in volume of the air sock due to the compression by the head h_1. The calculation assumes that the temperature of the air is the same before and (eventually) after the compression (See Appendix B-I). The ratio of the volume v_1 after compression to v_1' before compression is the ratio of the **absolute** pressure before compression (10.4 m) to absolute pressure after compression (10.4 m + h_1):

$$v_1/v_1' = 10.4/(10.4 + h_1)$$

where h_1 is expressed in meters.

We will assume that the pipe diameter does not change between B and C' So the length of the sock is reduced in the same ratio:

$$l_1 = l_1' \times 10.4/(10.4 + h_1)$$

Knowing l_1, you can lay out the segment BC along the pipe (along the horizontal in your scale drawing) and find the height of the point C on the profile.

Step 4: The head at C is the same as the head at B = h_1. The head in the next pocket (between D and E) is:

$$h_2 = h_1 + (H_C - H_D) - .00568 x L_{CD}$$

If h_2 is a positive number proceed to step 5.

When h_2 is negative: Step 4a.
Once in a while, h_2 will be a negative number, (a pressure less than atmospheric pressure). In this case you should stop you calculation of the trickle height: You have to modify your system. If the point B is higher than T, you may decide to provide a break-pressure tank at B. If you do, you should start the trickle height calculation over but **starting at B as if the point B were the spring tank point S.** Then point D, (the second high point) becomes the first high point with head $h_1 = H_B - H_D - .00568\ L_{BD}$ and a third high point would be treated as the second high point, etc...as explained in steps 5 and on. If you decide against providing a break-pressure tank at B (because the head difference between either S and B or B and T is small enough to require an excessively large pipe diameter in that section, or simply because B is lower than T), you will need to provide an automatic air valve just downstream of B. In this case the air sock between B and C and its head loss will be eliminated: you start you trickle height calculation **from point S but as though there were no high point at B.** So $h_1 = H_S - H_D - .00568\ L_{SD}$ and you follow the rest of the steps in this section to calculate the air head loss for this sock and for the one downstream of the third high point , if there is one, etc...But don't forget to include the automatic air-purging valve at B!

Step 5. The length of the second sock is found in the same way as that of the first:

$$L_{DE} = L_{DE'} x\{10.4/ (10.4 + h_2)\}$$

The height H_E of the point E at the end of that length is again found by laying the segment L_{DE} from D horizontally on your scale drawing of your profile.

Step 6. If you had more socks, you would repeat the procedure used for the second sock for these.

Step 7. Collect and add the (vertical) height of all the socks. This is the trickle height h_t:

$$h_t = \{H_B\text{-}H_C\} + \{H_D\text{-}H_E\} + \text{...etc.}$$

The Hydraulic Grade Line With A Sock. The HGL looks different when there is a stationary sock (See figure A-2). This is a consequence of the fact that the pressure does not change along the length of the sock. From the high point where the sock begins to the end of the sock the HGL is parallel **to the pipe profile**, standing above the high point a value in meters equal to the value of h at that point. This vertical distance between the HGL and the pipe profile remains the same down to the section where the pipe is full again. Downstream of the sock, where the pipe is full the HGL has again a slope equal to the local value of h_f/L.

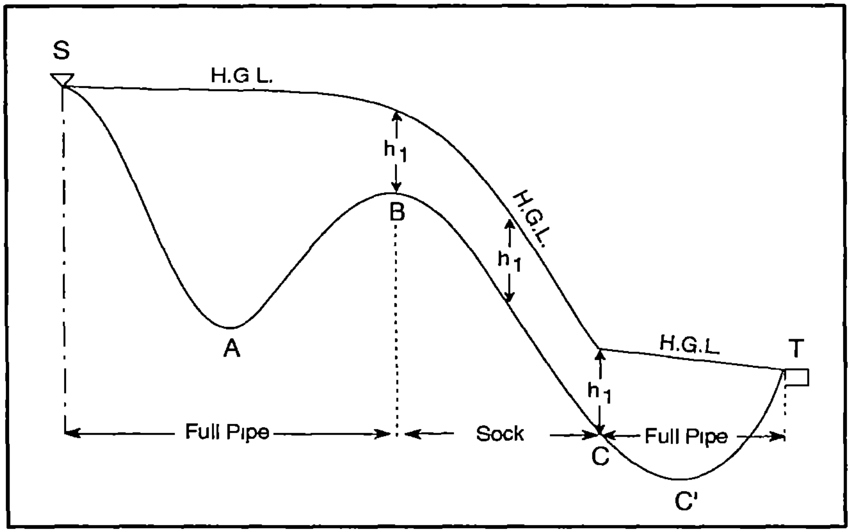

Figure A-2

A-III: How to combine pipe diameters to get a *given* friction head loss over a given length and with a given flow rate.

Let the required head loss be h_a and let the length be L. Divide one by the other to get h_a/L. Let us assume that for some reason you have already selected one of the pipe diameters, but that it is too small to be used over the whole length L of the pipe.Call this diameter d_s and the corresponding friction loss per unit length, $(h_f/L)_s$. For the required value of Q find in table A-1 a diameter d_l which causes a h_f/L smaller than h_a/L. Call this value from the table $(h_f/L)_l$.The two pipe lengths which together will add up to L and cause a friction head loss equal to h_a are given by:

$$L_l = \{L(h_f/L)_s - h_a\} / \{(h_f/L)_s - (h_f/L)_l\} \qquad (A\ 4)$$

$$L_s = L - L_l \qquad (A\ 5)$$

where L_l is the length of the pipe of larger diameter and smaller friction and L_s is the length of the pipe with smaller diameter and larger friction.

<u>Note:</u> The larger pipe diameter does not have to be the size just above the smaller one. For instance,if d_s= 3/4", d_l can be 1.5" instead of 1".

A-IV: The Critical Flow Rate Q_C

This is the flow rate above which air pockets and bubbles cannot accumulate downstream of local highs. Instead they circulate downstream. Q_C depends on the pipe diameter:

$$Q_C = 1.57 d^{5/2} \qquad \text{(A 6)}$$

where d is the inner diameter (in meters) of the pipe at the top of the sock, just downstream of the local high) and Q_C is in cubic meters /sec. Table A-II below can be used instead of equation A-6. But in the table Q_C is in liters per second.

TABLE A2. CRITICAL FLOWS

d	1/2"= .0173m	3/4"= .0231m	1"= .0300m	1.5"= .0444m
Q_C	0.0618	0.1274	0.245	0.652

d	2"= .0557m	2.5"= .0674m	3"= .0830m
Q_C	1.15	1.85	3.02

APPENDIX B

B-I: Why is the volume of a sock inversely proportional to its absolute pressure?
This does not happen right away. As the pressure increases in the sock, the volume decreases but, to start with, less than the formula predicts, because the air temperature increases (the compression is initially close to **isentropic**). After a while the air in the pipe cools off by losing heat to the pipe and to the dirt in the trench so that its temperature is eventually the same as before the compression. Only then does the volume of air follow the law given in Appendix A-II. So for those cases 1 and 3 which are close to cases 2 and 4, you may have to wait a while before water comes out at the end of the pipe.

B-II: An Alternative To Automatic Air-Flushing Valves:
Can't you get rid of the air in a sock permanently with a small hole drilled in the cap of a T?

In the absence of an automatic air-flushing valve it is tempting to drill a small hole in a plastic T cap for instance, because such a hole will let a lot more air escape than water. This solution would surely simplify things. The trouble with it is that the hole has to be rather small not to waste an excessive amount of water in a typical installation. So it has to be made carefully and it is likely to plug up.

The relation between the hole diameter d, the flow rate Q of water through the hole and the head h_1 in the pipe at the hole is approximately, (this formula is not too accurate for small holes)

$$d = 0.56\ Q^{1/2}/h_1^{\ 1/4}$$

where the hole diameter is in meters, the flow rate is in m^3/sec. and the head is in meters. The same size hole will pass a volume of air about 28 times as large. It does not make much difference whether the hole is at the top or at the bottom of the pipe.
Now if for example we want no more than 3% of the water flow rate through the pipe to spill out of it, if the pipe passes 15 lit./min.of water and if the head at the sock is 10 meters

we get for the diameter of the hole:

$$d=0.56x\{15x.03/60x10^{-3}\}^{1/2}x10^{-1/4}=0.00086m=0.86mm$$

This is two thirds of the thickness of a paper clip or of a 1" finishing nail and a hole diameter twice as big will waste 4 times as much water.
So this solution may be handy at times but I would worry about dirt or vegetable matter plugging the hole up. I have not had too much luck in general with small holes passing a reliable amount of water or not plugging up completely.

B-III: More on changing the diameter in the sock area.

a) When the design calls for a smaller diameter pipe along the sock than elsewhere, this manual recommends that the smaller pipe extend to the low point rather than only to the end of the sock. Why?
As Q increases and exceeds Q_c, the top of the sock moves along the downhill leg downstream of the high point. But it does not get chased out of the downhill leg suddenly. This is because for moderate pipe angles the flow rate required to chase the pocket downstream first increases with the slope (from the horizontal to about 35 degrees) then decreases. You need about the same flow rate to chase the top of the sock from a horizontal pipe and from one that has about 65 degrees of downward slope. As a result if the pipe diameter is increased between C and C' for a flow which is supercritical with respect to the smaller diameter, but subcritical with respect to the larger one, you should expect the sock to be trapped at the section where the diameter changes unless that section is at the bottom of the pipe.

b) Start up: Note that to choose a smaller diameter at the lower end of sections such as BC' than at the upper end can help with the starting problem because the compression head h_1 will then shorten the initial sock more than with a uniform diameter(l/l' will then be smaller than v/v' in the calculation of the trickle height). But you also have to take into account the effect of this change of diameter on the steady operation of the system after start up, so that this trick can seldom be used. Anyway you don't really need it.

B-IV. The Pressure Is Negative At The Second (Or Third) High Point In The Trickle Height Calculation:
This may occur if these points are very high. If the negative pressure you calculate exceeds 7 or 8 meters the water will not flow because the low pressure will convert the water to water vapor. For small negative pressures (say less than 5 meters) the suction in the pipe will not necessarily stop the water flow. The length of the next sock will not increase (as you might conclude from carrying out step 5), because all the air which appears beyond, i.e. downstream of the low point will escape to the next sock or to the exit. So E and E' are the same points. But all in all I don't recommend your designing such a marginal case: **Avoid negative gage pressures anywhere.**

B-V How Do I Control The Water Velocity in the Pipe?
The advice commonly given is to keep the water velocity between 0.7m/sec.and 3.0 m/sec. The reason is that if the velocity is too low dirt will tend to deposit on the pipe especially at low points and eventually plug up the pipe and if the velocity is too high, the same dirt will tend to erode the pipe. It is usually easy to keep the water velocity from exceeding the recommended upper limit. But to keep it above the lower limit you will often have to give up other, usually more crucial, constraints. For instance you may not have enough head to allow this velocity.[Note from Table A-3 that **all** subcritical velocities for pipes with diameters up to 3" fall below the recommended lower limit]. The situation is a bit like that which we face with the Ten Commandments: We do our best but sometimes we will sin: Then we make amends: For instance if a short section of pipe passes under a stream you can usually afford a pipe of small enough diameter to keep the velocity high along that short passage. But if the pipe then climbs for a considerable length, you'll need a second amend: you will provide a clean-out near the river crossing, and a third amend: you will make sure that before it gets into the spring box the spring water is forced to filter through an extra thick layer of gravel.

B-VI. Can't One Operate With A Full Pipe All The Time By Adding A Regulating Valve At The Exit Of The Spring? One would then simply purge the air manually, then adjust the valve setting to the spring output.

This sounds great and would make it unnecessary to read most of this complicated manual! But if you try, you will find that it takes **days** to reach the proper valve setting. So the villager will tend to close the valve enough to stay out of trouble and the spring will overflow most of the time.

B-VII: Where does equation (1) page 12 come from?

This is an experimental result of sufficient accuracy for practical use and with some theoretical support. Its origin may only interest Hydraulics specialists but it is given below.

A) The equation applies evidently to air pockets which are **long** compared to the horizontal section of the pipe, not to bubbles such as those found in water levels. For the latter $Q_c = 0$, but h_t is negligible and so they are unimportant.

B) To be perfectly general we should write:

$$Q_c = a d^{5/2} g^{1/2}$$

where the number a depends on

-the surface tension of water,(the Weber number $16Q^2/\pi^2 d^3 \gamma$), and possibly the contact angle.

-the velocity profile, (the Reynolds number, $4Q/d\pi\nu$), where γ =surface tension and ν =kinematic viscosity.

-the pipe slope distribution in the area of the nose of the sock.

Now:

1) <u>For a non-viscous fluid flow with negligible surface tension and a horizontal pipe</u> it is possible to calculate theoretically the velocity of propagation of the nose of a semi-infinite sock into a water filled round pipe, (the water ahead of the sock being at rest).

This gives, (see Brook Benjamin, Journal of Fluid Mechanics, 1968, vol.31,pages 209-248):

$$Q_c = 0.426\, d^{5/2} g^{1/2}$$

2) The real case is of course different because:

-It is the water that flows and the sock does not move.

-Water is a viscous fluid and its velocity far upstream of the sock is not uniform across the pipe.

-There is some,(small) surface tension between the water and the air along the sock-water boundary near the sock nose.

-You want to chase the sock not only from the high points but all the way past the next low points; so, the head of the sock will have to move past inclined sections of the pipe.

3) Experimentally but still for a horizontal section of pipe with typical Weber and Reynolds numbers and with the water flowing, the critical flow rate,(the flow rate for which a long sock remains stationary) is about

$$Q_c = 0.38 d^{5/2} g^{1/2}$$

The sock moves upstream if Q is less (but never if the section of pipe upstream is lower) and it moves downstream if Q is more (but not necessarily if the pipe downstream is lower).

4) Finally, also experimentally, Q_c first increases as the downwards slope of the pipe increases from the horizontal up to a maximum of about 35 degrees and then decreases as the slope continues to increase past 35 degrees.(See Also B-III). The value of the constant chosen, a= 0.5 is slightly larger than that which is needed in equation (1) to flush the sock out of a pipe with the worst slope (35degrees) somewhere along the sock. If the maximum slope downstream of the high point is small, (say 5 or 10 degrees), this constant is a little too large.

The experimental results referred to above are all mine.

AIR IN WATER PIPES

A Manual for Designers of Spring-Supplied Gravity Driven Drinking Water Rural Delivery Systems

This manual is intended as a complement to handbooks on the construction of rural gravity-flow water systems. It focuses on the problems and the opportunities associated with the almost inevitable presence of air in the main pipeline from the spring to the distribution tank. The starting point is the author's opinion that the water output from the source is a valuable and scarce resource which the designer should convey whole to the distribution tank, an objective that is practically impossible to reach with full pipes even with regulating valves, given the variations of a typical spring output with the seasons. But such a goal can largely be achieved when the presence of air in the pipeline is accepted, understood and controlled.

The manual contains new material, that the author has gathered both in the field and in the laboratory and which fits into a relatively simple theoretical framework.

The essential ideas are also applicable to other technical areas, such as drainage, in which pipes are used to convey a liquid at an unspecified flow rate.