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THE MEDIUM IN CONTINUOUS-VACUUM FILTRATION

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Abstract

The Medium in Continuous-Vacuum Filtration

by

N. Nemeth* and L.L. Sirois*

The filter is an apparatus designed to hold the filter medium. At such a medium takes place the entire liquid-solid or gas-solid separation process. Hence, the medium is really the essence of filtration. Yet, the medium, an originally clean porous substance with trapped solids in it, is perhaps the most neglected part of filtration research.

Basically three problems prevail at the medium:

i) Penetration of solids and their blinding of the medium and the influence of such blinding on the resistance to flow.

ii) The behavior of the medium in long-term repetitive filtration.

iii) The filter effect phenomenon whereby the flow rate, on filtering an apparently clear liquid through a medium, decreases with time.

This study undertakes to investigate these fundamental processes.

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THE MEDIUM IN CONTINUOUS-VACUUM FILTRATION

Introduction

Filtration is a liquid-solid separation process. The separation takes place at a porous medium. Due to a pressure differential, the liquid passes through the medium. The solids are retained as a dewatered cake.

Filtration, by no means, is a simple separation process. Describing it, a wide range of adjectives have been used, ranging from complex to subtle. The lack of a unified theory in filtration is attributed to the wide range of variables encountered in the process. Its general state is aptly summed up by the often heard phrase: "Filtration is still very much an art."

Basic relationships used in industrial filter design are either derived for idealized conditions or obtained from empirical observations. Both types of relationships are usually modified to suit local conditions. In continuous vacuum filtration, non-compressibility of the cake allows the use of theoretically sound, rate equations.

Cake compressibility is one of the great dificulties one must face when applying theoretical relationships to the process. The types of filters and methods used vary greatly in various industries. The mining industry has adopted continuous-vacuum filtration as the process for dewatering its concentrates. These concentrates are made up of fine mineral grains. The physical state of the concentrates and the relatively small order of pressure differentials found in vacuum filtration permits the assumption that the process deals with non-compressible cakes.

Notwithstanding the simplification gained by the non-compressibility assumption, there are other problems that are unique to the application of vacuum in dewatering. They require special attention, but so far have been completely ignored.

The basic problems of filtration, as a whole, are the capture of solids and the flow of the liquid through a porous layer of cake and cloth. In this study the capture is effected by the porous medium. Flow is determined by the structural arrangement of the solids making up the cake. This structural problem - a problem of solid geometry - was said to be insoluble by Hatschek (1) as early as 1907 and by Freshwater (2) as late as 1967. The structure of the cake is determined by the slurry parameters which is a problem far to large for inclusion in this study. Instead, this work concentrates on the contact between the cake and filter cloth and draws attention to the significance of the properly chosen qualities of the filter cloth. The greatest part of total filtration resistance will develop at this cake-cloth contact.

For theoretical treatment it must be assumed that the cake is built up uniformly. For efficient practical operation the medium resistance must be kept constant over long time periods. This can be done by correct evaluation and selection of the filter cloth. This paper attempts to discuss the role of the medium in continuous vacuum filtration and the special circumstances that influence the flow through a porous cake and the filter cloth.

The Fundamental Filtration Equation

All of today's theoretical relationships for filtration are derived from D'Arcy's law. It was published in 1856 (3). Essentially, it relates the flow rate to the other parameters of the system. In a modified form this relationship is given as:

$$\frac{dV}{dt} = K \frac{AP}{\mu L} \qquad \text{(Eq. 1)}$$

where:

V = volume of filtrate
t = time
K = permeability coefficient
L = thickness of bed
A = filter area
μ = viscosity coefficient

From the above relationship a fundamental filtration equation was derived by Carman (4). This equation includes a term Rm for the medium resistance.

$$\frac{dV}{dt} = \frac{PA^2}{\mu(rvV + RmA)} \qquad \text{(Eq. 2)}$$

where:

r = is the specific filter cake resistance
v = volume of cake deposited by a unit volume of filtrate.

Upon integrating, the solution can be rearranged to give the form:

$$t/V = mV + \text{constant.}$$

which is the equation of a straight line. The slope m includes the specific cake resistance r and in determining the slope, a solution can be found for r. The constant term includes the resistance of the filter cloth which must indeed remain constant.

The technical literature is full of a variety of equations that originated from this fundamental equation. Two texts can be consulted to obtain further details on both theoretical and empirical formulae. The first is Dickey's (5) textbook on "Filtration" and the second is Scheidegger's (6) book on "The physics of flow through porous media".

Theoretically, the term: specific filtration resistance presents the greatest difficulty in Eq'n 2. In filter-application, the Kozeny-Carman equation is used more often than any other relationship. Its validity is forever debated but in want of a better relationship it is accepted as the most workable one with or without suitable corrections.

Filter Cloth Resistance

1. The nature and origin of the resistance

Filter cloth resistance is lowest at the beginning of the first cake-forming cycle. If ideal conditions could be secured for a cloth then its resistance should remain at this level during its entire operating life. However, optimum conditions should be maintained somewhere in the range of the resistance of a clean cloth. If it were economically feasible and technically possible to discard the medium with each cake there would not be any problem with the resistance of filter cloths.

Repetitive use of a filter cloth will unavoidably result in the trapping of particles by the fibres. The purpose of the discharge cycle, besides removing the cake, is to dislodge the trapped particles and free the cloth from them before the next cycle.

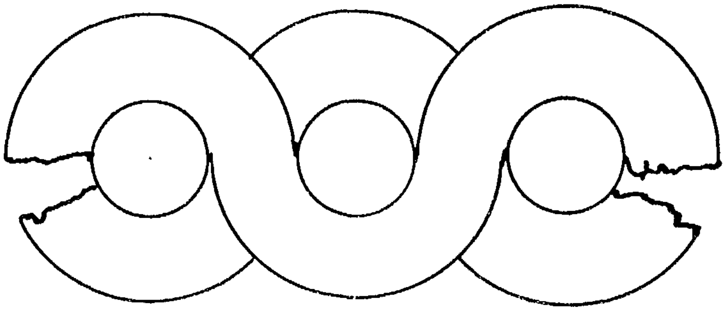
The first model of the cake-medium contact was proposed by Hixon, Work and Odell (8). The diagram of an arch made of granular particles at the end of a capillary tube has been reproduced in practically every Mineral Processing textbook published in this century. In this model, the coarser grains form a real arch over the circular capillary opening and trap the finer particles that are brought to the surface subsequently.

This model over-simplifies the situation that exists at a cloth-cake contact. The first fallacy is that in a uniform slurry there are always some fines in the minus-10-μ range that reach the cloth simultaneously with the larger grains. The second fallacy is that regardless of the type of weave, the openings of pores or channels in a filter cloth are funnel-shaped - not necessarily circular but elongated and twisted as well. Unfortunately, the formation of these arches that aid filtration will be minimized in such entrance "funnels". In addition to this, particles that have embedded themselves in the cloth will be more difficult to remove. In an ideal cloth the surface openings on the cake side should be as small as possible and the filtrate discharge openings as large as possible.

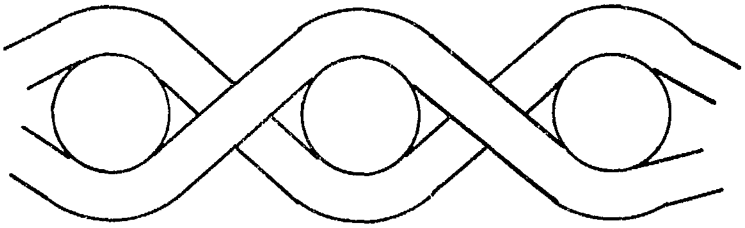
The degree of particle trapping is further facilitated by a loosely twisted yarn. Particles trapped in the yarn will be practically impossible to remove. Furry yarns like those found in cotton cloths are extremely easily loaded with solids. This is the reason that, other conditions permitting, a monofilament cloth will always have superior medium-resistance characteristics.

Figure one indicates some weave types.

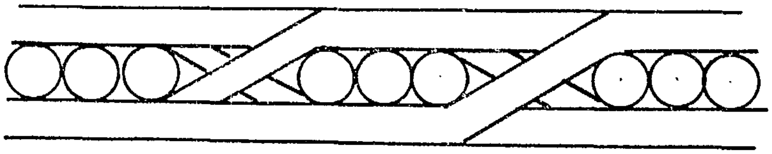
Figure I.



a) Duck weave.



b) Plain Dutch weave.



c) Twilled Dutch weave.

It is an undisputed fact that filter media will be penetrated by the particles that are to be dewatered. In France, Le Goffe and Delachambre (7) are presently working on the mechanism of medium clogging. In their system they are using a slurry in which microspheres are suspended. The flow is through a bed of macrospheres. Although the system is highly idealized it may allow the establishment of some fundamental mathematical relationships.

2. Experimental Procedure and Determination of the Resistance

In the experiments carried out to establish the characteristics of filter-cloth resistance, filter cakes were formed by vacuum on a 1-cm-diameter circular area of various cloths. The slurry concentration, cycle times and cake discharge resembled the actual conditions of an industrial filter as closely as possible. Ten cakes were formed in succession and then the cloth rinsed to remove the loosely connected particles. The resistance of the cloth after each set of experiments was evaluated as the time required to pass 10 ml of clear water through the cloth. These filtering times indicate the changes in resistance with the number of cakes produced on the cloth. This is often also a measure of the ease with which the cloth can be cleaned after each filter cycle.

The slurry used for the tests was a composite sample made up of the products of various bench-scale flotation tests. Ninety per cent of the material was less than 40μ and over 30% was below 10μ. Approximately 18% was less than 4μ. While such an ore would not necessarily be typical of all filter feeds it is representative of material that will be faced by operators in plants.

The following microphotographs, Figure 2, show some of the cloths tested with this sample. Unfortunatley the soiled cloths cannot be compared with the original clean material, because the all-white cloth showed no contrast under the microscope.

The following microphotograph, Figure 3, shows a cotton cloth that was used to filter a copper-nickel concentrate. Only 5 cakes were made on this cloth. Before taking the picture, the cloth was thoroughly washed under a tap with running water. As the picture indicates, a rather heavy layer has been trapped by the surface of the cloth. Other tests, of course, indicated rather rapidly decreasing filtering efficiency with this cloth.

Figure 4 shows the so-called resistance curves for 5 different cloths tested. Table 1 lists the physical properties of the cloths tested.

Table 1

	Weave	Yarn	Wt.oz/yd^2	$\frac{\text{Cuft}}{\text{min}}$/sq ft	Filtrate
Cotton 1	2x2 Twill	Spun Staple	17.5	2.9	clear
Cotton 2	2x2 Twill	"	17.5	12.63	clear
Nylon 1	1x1 Plain	Multi Filam.	9.0	6.0	clear
Nylon 2	7x1 Satin	Fil-warp	12.0	not given	foggy
Dacron	3x1 Chain	Multi-fil	4.5	0.5-1.0	very clear

The curves indicate the drastic changes that may occur in cloth resistance if the initial selection is poorly made. It also brings to light the necessity of extensive testing before selecting cloths. The fuzzy structure of cotton fabrics is ideal to trap the particles permanently and it is well illustrated by the microphotographs.

Figure 2

All magnifications are: 48 unless otherwise indicated

Figure 2a) Co-1, Cotton cloth after 50 cakes and thorough rinsing.

Figure 2b) Co-2, Cotton cloth after 50 cakes and thorough rinsing

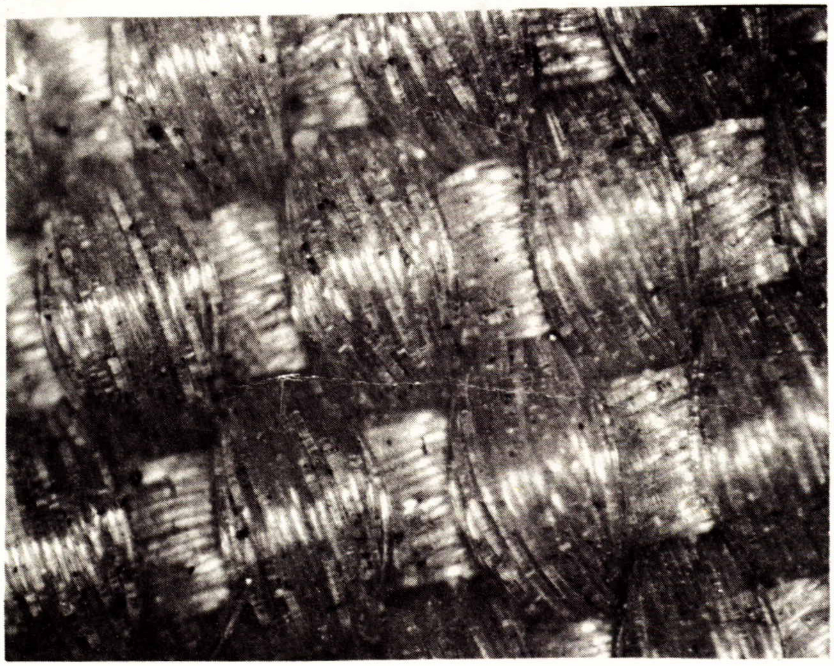


Figure 2c) NY-1, Nylon cloth after 50 cakes and thorough washing. As the photograph indicates, it was an easy cloth to clean, yet the flow results indicated a **relatively** high resistance.

Figure 2d) NY-2, Nylon Cloth after 50 cakes

NY-2, Nylon cloth after 200 cakes. This cloth has identical flow characteristics after 200 cakes as it did after 50. The lack of loose fiber ends accounts for the lack of a permanently trapped layer.

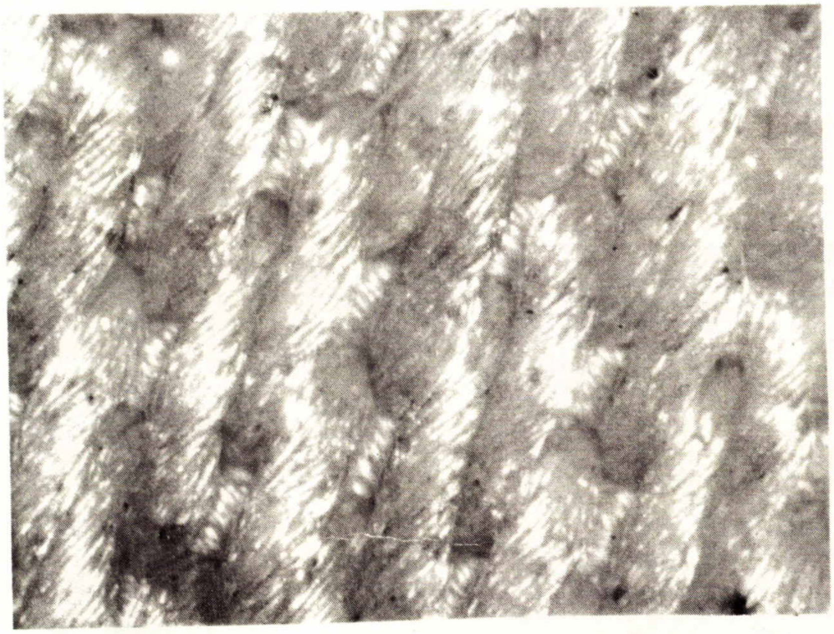
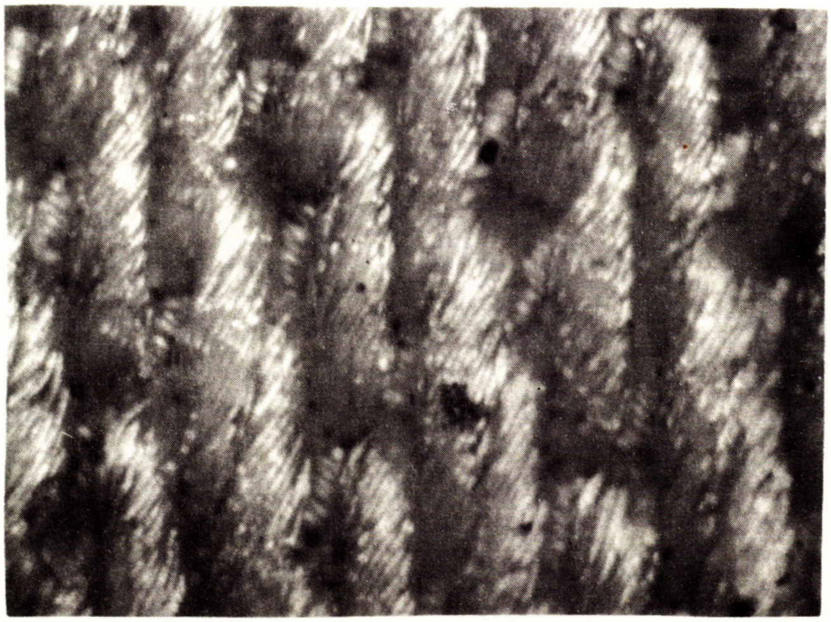


Figure 2e) Dacron cloth after 50 cakes



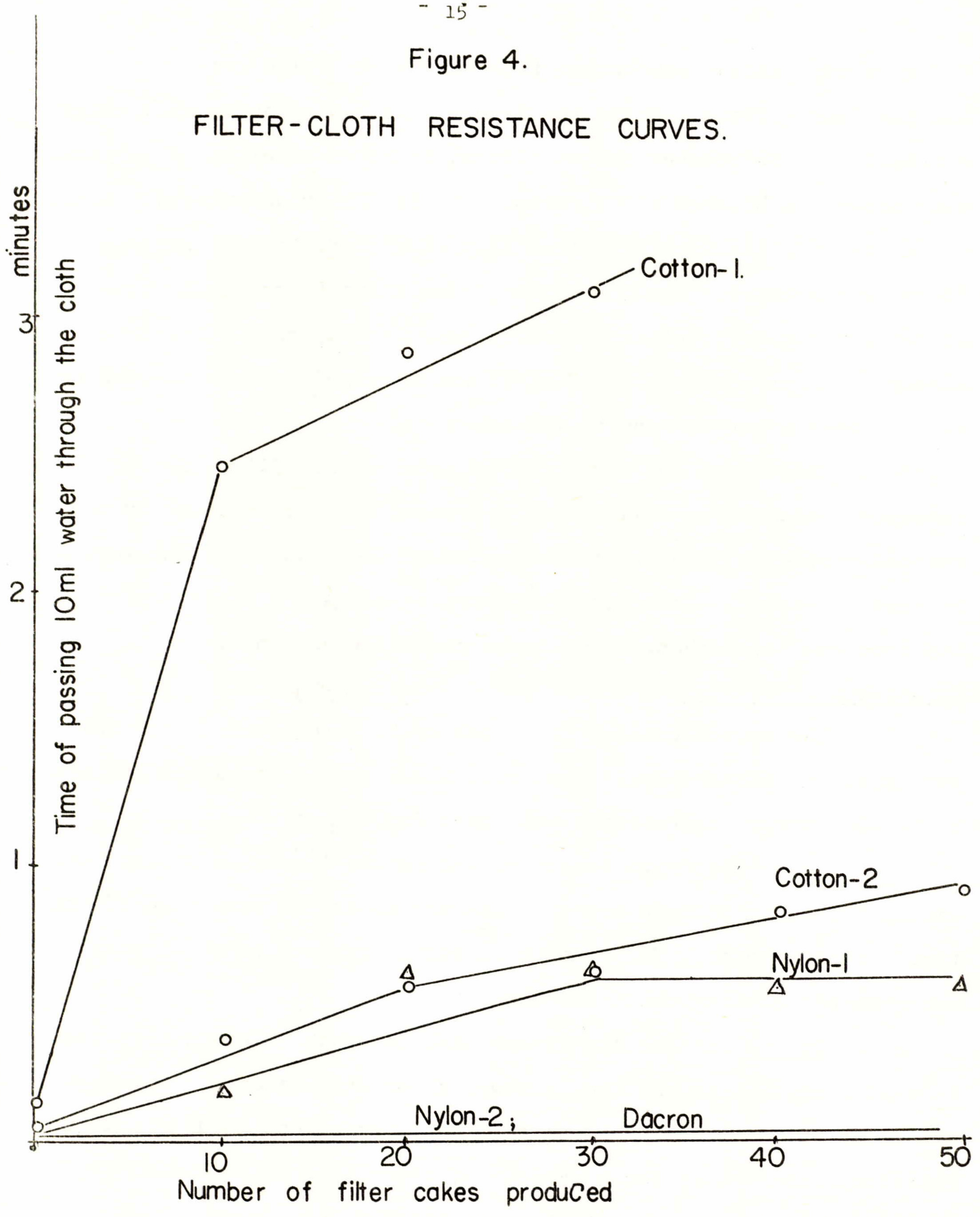
The same dacron cloth after 200 cakes
(magnification on these two microphotographs is: 63

Figure 3

Microphotograph showing a cotton filter cloth used for copper-nickel concentrate. Five cakes were formed and before photographing it, the cloth was rinsed under a tap with running water. The loose fibers trap the solids permanently. They serve as reinforcements in retaining these solids. With today's finer and finer grinds this is a definite disadvantage, since the greatest loss of driving force is caused by it. Magnified (48) times.

Figure 4.

FILTER - CLOTH RESISTANCE CURVES.



The most interesting comparison is given by the Nylon 2 cloth and the Dacron cloth. While the former is a loose fabric with weights comparable to the tested cotton cloths, it gives excellent flow results even after two hundred (200) cakes. The latter is an extremely tightly woven, thin fabric with excellent flow characteristics as well as cleaning characteristics. Both the Nylon 2 and Dacron cloth have almost identical flow-time curves as shown in Figure 4. The times measured for the passage of 10 ml of water ranged between one and two seconds even after as many as 200 cakes.

While from the foregoing it appears that filtration of suspended solids from a liquid is a process that is retarded by the trapped particles, the actual mechanism of flow and the final separation is much more complex than that. In trying to gain a clear insight into the process, the mechanism has to be carefully examined.

The Mechanism of Flow

The hydromechanics in porous media is concerned with the pore space of the medium, filled with the liquid. There are two aspects to be considered: macroscopic and microscopic.

The macroscopic aspect refers to the liquid as a continuous entity. The microscopic aspect takes the molecular structure of the liquid into account. This latter aspect is assumed to be of minor importance regarding continous flow.

Fluids and solid surfaces also interact. This interaction is very important to the flow through a porous substance. Although the order of magnitude of these surface interactions is difficult to establish unanimously for a variety of materials, it is easier to appreciate its hindering effect qualitatively.

Theoretically 3 kinds of physical conditions determine the flow of a fluid:

1) The continuity condition,
2) The rheological equation of state,
3) Newton's Law of motion.

The first and the third conditions are well worked out by Lamb (9). The rheological condition relates the stresses and strains within the fluid itself.

There are mathematical expressions for the above physical conditions.

1) The Navier-Stokes equation. It is very difficult to solve because of its structure and its boundary conditions. By setting the viscosity equal zero, and approximation can be reached which is really Euler's equation for non-viscous flow.

2) The Hagen-Poiseuille equation which gives the exact solution for the Navier-Stokes equation for a straight circular tube of radius α and length L. According to the Hagen-Poiseuille equation the flow Q will be equal to: $\frac{\pi}{8} \frac{DP}{L} \frac{\alpha^4}{\mu}$ where DP represents the pressure drop over length L.

These two expressions are the classical relationships of flow through a porous medium.

Somehow, these expressions give an incomplete picture of the complete flow mechanism. First of all they are fitted to idealized situations. They neglect the driving force by assuming that the system is independent of the nature of the pressure differential. To show that it is an incorrect assumption the following photograph is used for illustration.

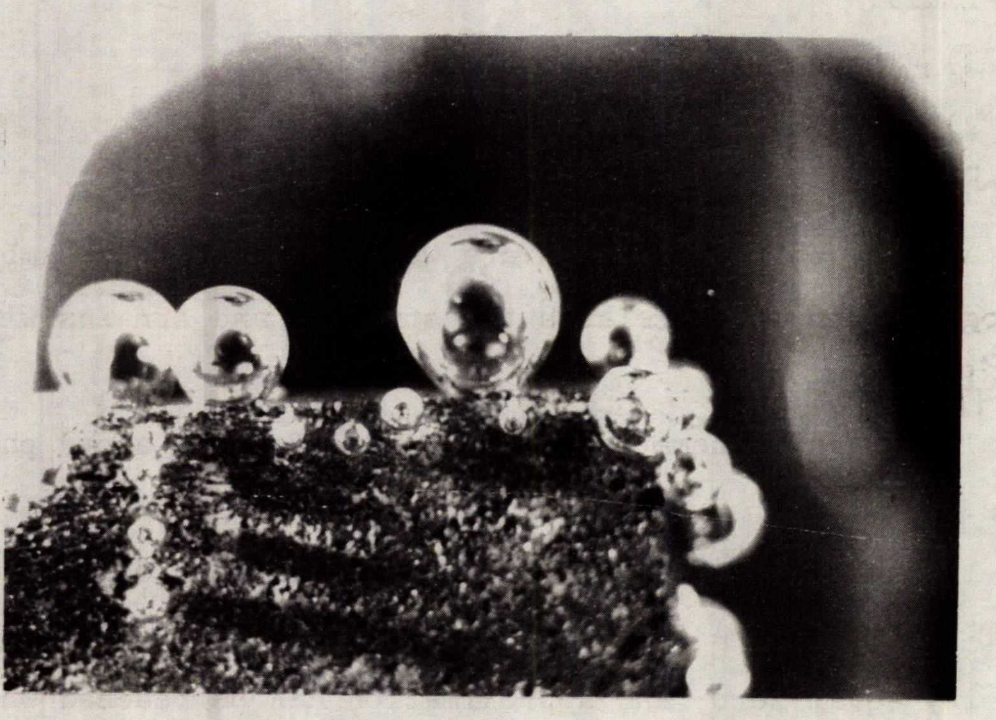


Figure 5

Photograph showing the bubles on a small piece of hematite ore in water under vacuum.

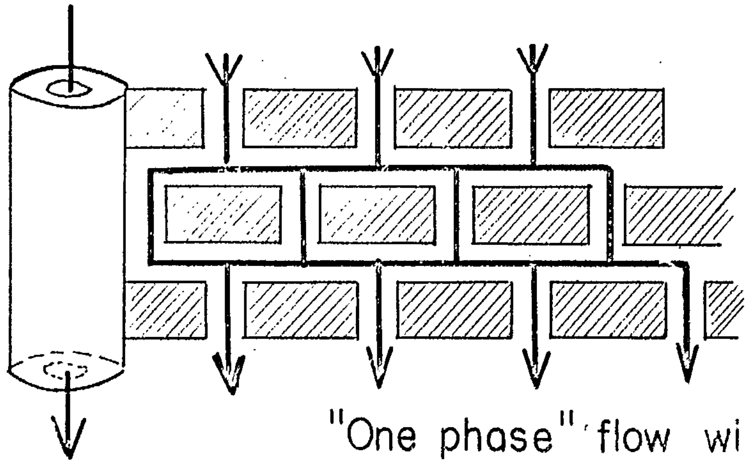
The photograph shows a small piece of hematite in distilled water. Exposing this system to vacuum, bubbles formed on the surface of the particle. Two interesting points were observed here. First, if the vacuum source was open to the system and maintained at a high level, the bubbles formed and departed from the surface at a very high rate. Secondly, if the vacuum was opened very gradually and closed when the first set of bubbles formed, a reasonably permanent state could be reached; this state could be maintained for hours.

This phenomenon must be now superimposed on the filter-cake-and-medium system. However, it should be noted here that such bubble development is not unique to hematite or to oxide ores. The solid particles that make up the filter cake will be particles very similar to the ore picture in Fig. 5. When the flow under vacuum begins through the channels and the voids of a filter cake, similar occurrence of bubbles will take place. The kinetic movement of the flow will shear these bubbles off and from that moment the flow will consist of a two-phase system. The situation has a certain physical resemblance to the streaming-potential phenomenon where charges are sheared off by the flow from the diffused double-electric layer.

The bubbles come in a variety of sizes. In a cake it would be perhaps at the limit where they could be barely seen with the naked eye. Due to the existing negative pressure the bubbles have a tendency to grow in size. However, the physical limitation of available pore space tends to restrict their growth. This is a complimentary situation. The permanency of bubbles then is governed by the interfacial tension ie. the strength of the skin of the bubble. This, combined with the extremely tortuous path of flow within the cake and through the medium can create the situation whereby the rate of flow is significantly reduced.

This can be illustrated by the following schematic diagrams of Figures 6 and 7. Flow caused by a positive pressure differential will take place according to the mechanical resistance offered by the shape of the particles and restrictions caused by the special arrangement of the solid structures of cake and medium. Figure 6 is perhaps the simplest illustration of such mechanical resistance due to the sharp changes of flow directions and the sizes of channels. When bubbles are present in a flow under vacuum it is easy to visualize the difficulties created by their presence. From the moment

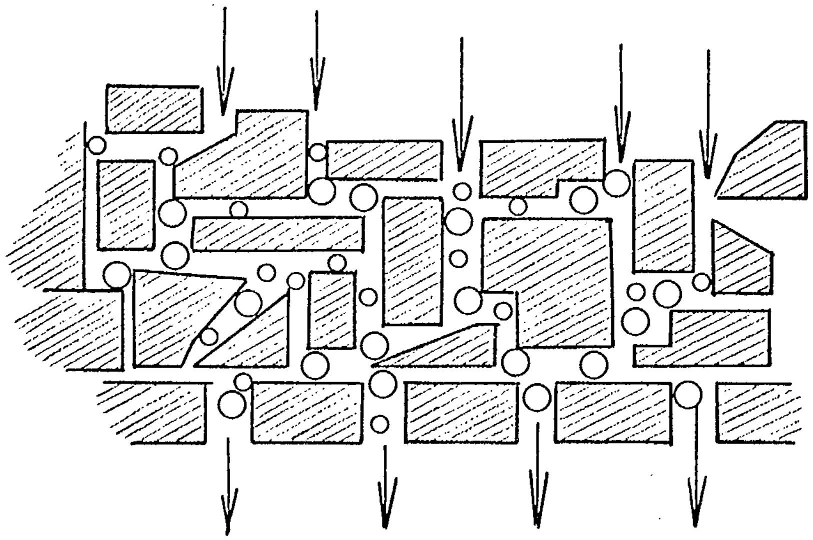
FIGURE 6.



"One phase" flow with changing flow direction.

The Hagen-Poisseuille flow through straight cirular channel.

FIGURE 7.



"TWO PHASE" flow through an irregular channel system.

of their formation, they tend to increase in size because of the negative pressure. This situation is further complicated by the restrictions that exist in a flow-path. Figure 7 illustrates such a situation. Those surfaces that will be in the way of a straight-line flow will be bombarded by the bubbles. Narrowing channels, that are paths of greater resistance will now be blocked by bubbles, because they represent a more quiescent region. With the gradual bubble evolution such a blocking can expand into other channels that at positive pressures would otherwise be open to flow.

The presence of the filter cloth with its trapped solids in the pores will represent the final obstacle in the way of the two-phase flow. At the cloth surface the permeability of the combined cloth-cake system will be at its lowest. The thickness of the cloth is, therefore, of great importance. Those bubbles that reached this region will have to move through the cloth. Fabrics woven of smooth, thin filaments can therefore permit a faster passage of such a water-bubble mixture than dense furry thick cloths.

Figures 8 and 9 show the bubbles developing in flow through a capillary tube that has successive spherical enlargements and through a layer of crushed minerals. Carman (4) mentions that gases in flow may be influencing the resistances with other factors like adsorption and surface electrokinetic effects. However, he dismisses it as insignificant when compared to the mechanical resistance offered by the cake build-up. This has been contradicted by the experiments illustrated in Figures 8 and 9. The evolution of bubbles increased significantly when one or two layers of filter paper were placed at the intake end of the capillary tubes. Therefore, as the

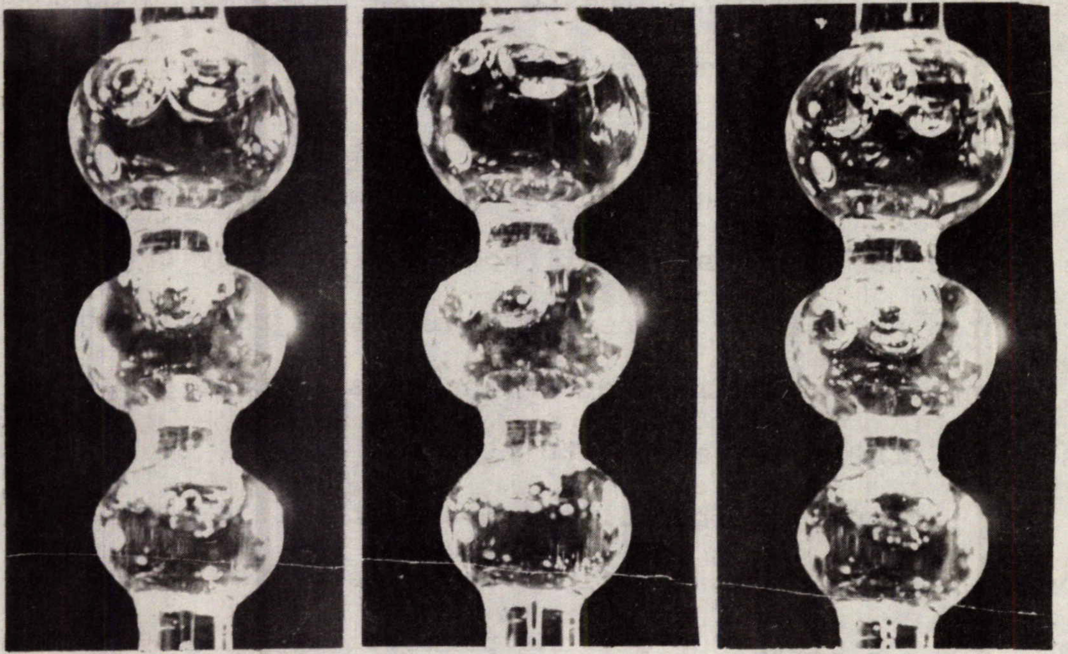


Figure 8 Photographs showing air bubbles in the spherical enlarged sections of a capillary tube.

Figure 9 Filter-effect phenomenon in a layer of crushed ore. Pictures show the development of bubbles and complete filling of a pore space. (Lower right corner) Arrows indicate other bubbles.

mechanical resistance increases due to the increase in cake thickness the evolution of bubbles also increases. This is similar to a substance being in tension. With solids, the response is elongation and then failure; in liquids under vacuum the response is the development of bubbles.

In a mineral slurry the situation is extremely complex. The magnitude of this bubble-effect was investigated also in a simple liquid system where clear distilled water was allowed to pass under vacuum through three layers of a cotton filter cloth.

The Filter-Effect Phenomenon

When clear liquids are filtered, a gradual decrease in their flow rate can be observed. Initially this was attributed to possible changes in the medium, but subsequently it was also observed with such rigid media as sintered glass. Simon and Neth (10) and Mehner (11) were the first to recognize the phenomenon and named it the filter-effect phenomenon.

The belief that it is not caused by changes in the filter medium was proven by refiltering the filtrate. The flow rates always increased again when this was done. This phenomenon was observed for a very wide range of liquid. Finally the cause was pinned down to be the evolution of gas bubbles from the water and from the solid surface of the medium. Wrobel (12) discusses the sources of air bubbles and the form in which they are present in the liquid phase.

Figure 10 shows the effect of evolving bubbles on the flow of distilled water through a bed of cotton cloth. The time required for the passing of 10 ml of distilled water is plotted against the number of tests. The first part of the curve shows the

TWO STAGE FILTRATION

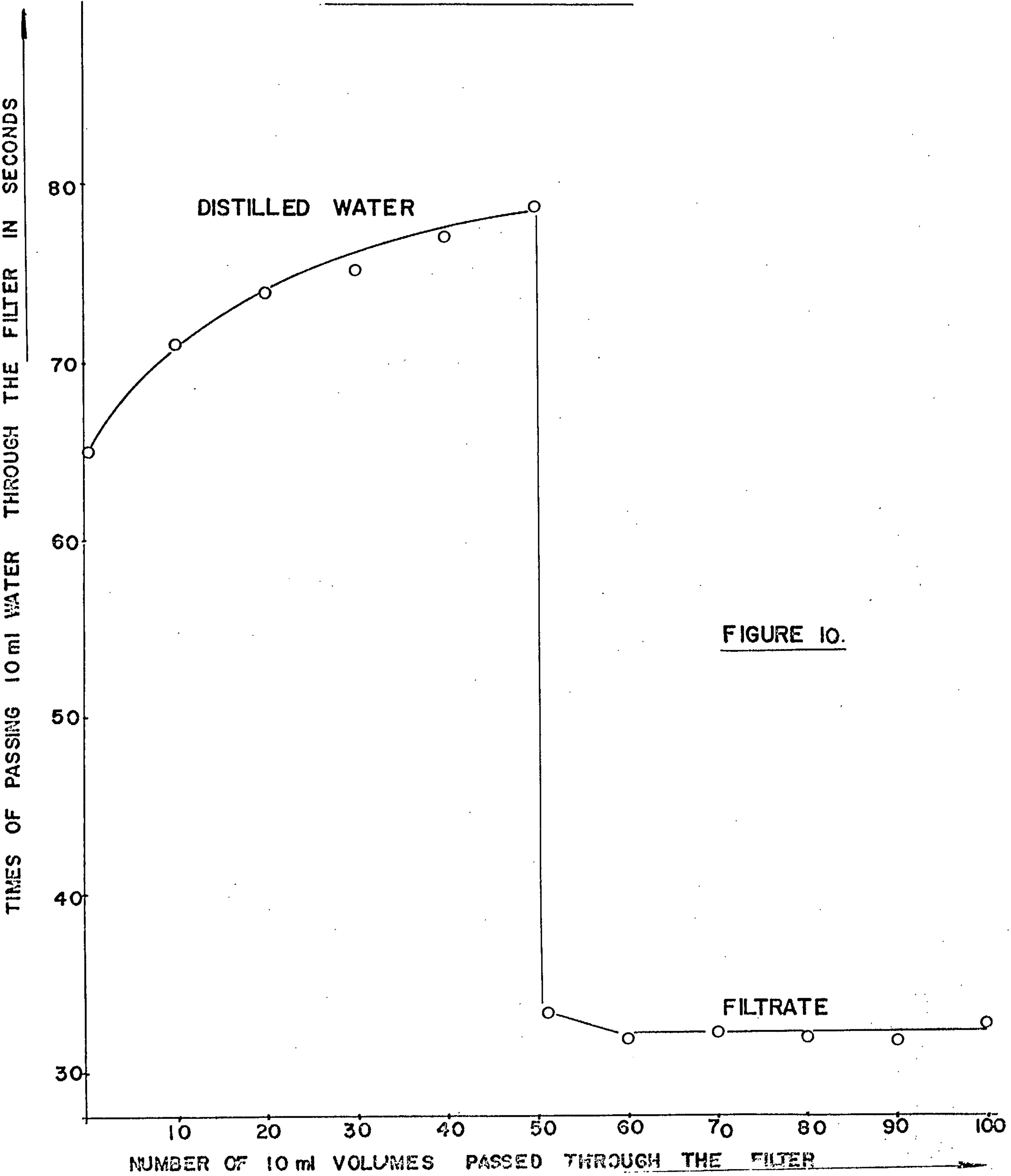


FIGURE 10.

behavior of cloth with distilled water and the second part with the water that was already filtered once and was not again exposed to atmosphere before re-filtration. There is a sudden change of filtration times with this degassed water. Furthermore it is interesting to note that not only have the individual times decreased but they also remained constant for the entire duration of 50 tests. It is also interesting to note that for filter cloths that were very thin, yet very tightly woven, the filter-effect phenomenon was not observed to any significant degree. This indicates that media with greater thickness and therefore longer flow-path through them, are more liable to be blocked by bubbles.

The exact evaluation of the filter-effect phenomenon for continuous vacuum filters is still a long way from completion. It should be noted however that two practices have already been used to minimize or eliminate its effects. The first one was the realization that higher solid-content slurries filtered better. No doubt there are other factors that played a role here. Yet one cannot deny that filtering only half as much water for the same amount of solids will proportionally reduce the amount of bubbles that can block the pores. The second one is steam filtration. While one litre of water has 17 ml of air dissolved in it at room temperature and atmospheric pressure, near the boiling point this amount rapidly diminishes to zero ml.

A motion picture was prepared to illustrate the filter-effect phenomenon. It shows that the phenomenon is very real and very significant in influencing an otherwise homogeneous flow.

SUMMARY

To the already existing complexities of filtration we must add special problems created by vacuum in continuous-vacuum filtration.

Due to the negative pressure differential applied to the slurry, gas bubbles evolve. These bubbles originate from the liquid which keeps a certain amount of air dissolved at atmospheric pressure and from the mineral surfaces that were made hydrophobic for the purposes of flotation. The bubbles can also come from minor cracks in the solid surface. They form on the surface and if the particle is not limited in the liquid, they evolve from it.

In restricted situations such as those found in filter cakes and woven fabrics the bubbles will be hindered in their movement. Those bubbles leaving the surface under such conditions will be restricting the flow through the available channel.

To give this phenomenon a real significant value, valid beyond laboratory conditions, further thorough experimenting is necessary. Only afterwards can steps be taken to eliminate the bubble effect.

In view of this phenomenon the role of the filter cloth should also be re-examined and new types of materials evaluated.

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