Wells

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A HISTORICAL REVIEW OF INVESTIGATIONS OF SEEPAGE TOWARD WELLS[1]

BY HOWARD P. HALL[2]

INTRODUCTION

General

Seepage of ground water toward a well may be idealized as a case of axially-symmetrical three-dimensional flow of a homogeneous fluid through a porous medium.

If the water-bearing stratum is overlain by a relatively impervious stratum, so that the seeping water is subjected at all points to pressures greater than atmospheric, the porous mass is called an artesian[3] or confined aquifer, and the well, an artesian well.

If the water-bearing stratum is not overlain by an impervious layer, the ground water stream is exposed to the atmosphere, and there exists within the ground water stream an imaginary surface at all points of which the fluid pressure is exactly that of the atmosphere. Disregarding capillary water, this imaginary surface constitutes the upper boundary of the ground water stream, and is referred to as the free surface or the phreatic[4] surface. The condition that results is referred to as gravity flow[5] or unconfined flow. A well that drains the pervious stratum in this case is called a gravity well or a water-table well.

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[1]Based on the opening chapter of a dissertation presented by the author to the Faculty of Arts and Sciences of Harvard University in January, 1951, in partial fulfillment of the requirements for the degree of Doctor of Science.

[2]Associate Professor of Civil Engineering, Northwestern University, Evanston, Illinois.

[3]So-called in reference to the town of Artois, in France where some of the oldest drilled wells in Europe are still in operation.

[4]From the Greek phrear, a well. Since capillary water always exists, this term seems to be less misleading as a name for the locus of points of atmospheric pressure.

[5]Although the term, gravity flow, is widely used in American literature to mean unconfined flow, it should be noted that the implied distinction is not, strictly speaking, correct: Artesian flow is also affected by gravity.

After a steady state of flow toward a gravity well has been reached, with the water surface in the well maintained at a constant level by pumping, the line of contact between the phreatic surface and the well remains at an elevation above that of the water surface in the well. The circumferential surface of the well between these two elevations is referred to as the free discharge surface.

Historical

The recovery of underground water through wells was a familiar procedure in ancient China and Egypt. But virtually all the technical knowledge of the phenomena connected with seepage toward wells that is available today is the result of work done within the last hundred years. The history of this development is traced on the following pages from its beginning with the work of the French engineers, Darcy and Dupuit, to the beginning of the present decade.

The organization of material is generally chronological. However, it has seemed worth while to call attention to traditions as important as that of the United States geologists or as the one that has led from Thiem and Forchheimer to Casagrande. And in the case of the non-steady-state investigations of Weber, Theis, and Steinbrenner, the convenience of discussing them together was considered justification for interrupting a strictly chronological sequence. Thus, some concessions to continuity have been made in timing changes of scene.

On the whole, an understanding of the principles has grown out of the contributions of individuals, with backgrounds, interests, and talents peculiar to themselves; and because the contributions of these individuals are frequently as broad as the field itself, there would have been no advantage, from the standpoint of conciseness in a brief treatment of this kind, in a subdivision other than chronological.

FOUNDATIONS: 1856-1925

Seepage toward wells is one of a number of phenomena whose analytical basis is to be found in ground water theory; and it was the problem of securement of water from wells that originally prompted the development of ground water theory. Thus, the history of the analysis of seepage toward wells begins as the history of the development of ground water theory and technology.

The development began independently during the second half of the nineteenth century in at least three different areas, namely, France, Germany, and the United States. Before the turn of the century the initiative in Europe had been assumed by the Germans and Austrians, with adequate, if not extensive, knowledge of the important original contributions of the French. However, not much of this information got across the ocean, and more than a quarter of the present century had passed before anything like an adequate exchange of information had been established between the United States, represented until that time in this field chiefly by geologists, and Europe, still influenced predominantly by the groundwork of Thiem and Forchheimer.

H. Darcy

The first rational analysis was the work of Henri Darcy, a French hydraulic engineer who had been occupied during several years prior to 1850 with the development of a public water supply for the municipality of Dijon, in France.

His report on this project [15],[6] published in 1856, was a detailed account of all the local historical background, technical information, and legal and economic considerations that he considered pertinent. In addition to the main text, several related matters were covered in a series of appendixes, one of which contained a discussion of the technique of purifying water by means of filtration through sand. It was in this appendix, in connection with his description of some tests he had made himself, that Darcy proposed the relationship which has formed the basis of all studies of flow through porous media. His tests were conducted with apparatus arranged as indicated in Fig. 1, with the flow directed vertically downward through the sand. The results, according to Darcy, indicated that the rate of flow through the sand filed could be determined from the equation

$$Q = \frac{kA}{L} \quad (H + L) \tag{1}$$

where[7] Q = the volume of water discharged in a standard length of time,

k = a coefficient depending upon the properties of the sand,

H = height of water above the top of the sand filter,

and L = length of filter in the direction of flow.

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[6]Numbers in square brackets refer to the Bibliography that appears at the end (Appendix B).

[7]Symbols throughout have been changed wherever desirable in the interest of consistency. A list of symbols used in this paper appears at the end (Appendix A).

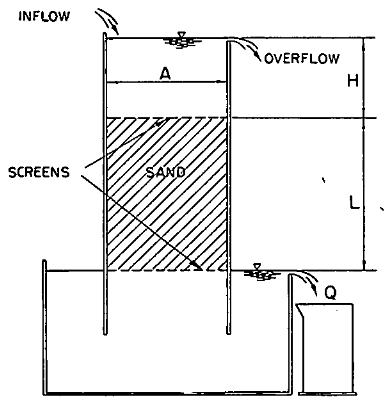

FIG. 1: DARCY'S FILTRATION APPARATUS

Equation (1) has been referred to in most European literature since its publication as Darcy's law. The name has gained in use in this country during the past fifty years until it may now be considered general.

In his discussion of the above equation, Darcy pointed out that the rate at which the water moved during a test could be determined simply by dividing the discharge in a unit of time by the cross-sectional area of the filtering tubes, which happened to be the cross-sectional area of the test specimen as well. But he carried the matter no farther, and did not define any special velocities nor introduce porosity into his computations.

The report on the public fountains of Dijon contains other evidence of Darcy's investigations of wells, largely with a view toward increasing yield. Except in the case of the filtration tests, he did not concern himself with the properties of the water-bearing medium. Thus, in analyzing the rate of discharge from an artesian well, he assumed that the aquifer could be considered as a large conduit leading from a reservoir at a high level to one at a lower level. Wells thus constituted tubes through which water was drawn out of the main line under whatever pressure obtained at their points of entry.

Several time-honored theories to the effect that artesian water originated in the earth's core, that rainfall never penetrated more than a few feet underground, and that all precipitation simply ran off into the ocean, were rejected by Darcy, together with some of his contemporaries, who realized that even the deepest wells were supplied by rainfall. As a result of his rational point of view he was able to gain some understanding of seasonal variations in productivity of wells, and to provide a logical explanation of the movement of ground water from its origin as precipitation to the subsequent appearance of some of it as the discharge from an artesian well.

In the presentation of his fundamental equation Darcy left no doubt of its empirical origin. This was typical of all of Darcy's work: His important contributions were based entirely on careful observations in the field and in the laboratory and on the conclusions he drew from them.

J. Dupuit

Among Darcy's contemporaries was another French hydraulic engineer, Jules Dupuit, whose published work was largely concerned with flow in pipes and open channels. In 1863 Dupuit published a revision of an earlier work on open-channel flow [17], and added a chapter on seepage. The contents of that chapter have established it as a standard reference in the field of ground water flow.

Dupuit approached the analysis of seepage phenomena via an equation for pipe and channel flow which had been proposed early in the nineteenth century [16] by another French investigator, de Prony, and which had gained wide acceptance among hydraulic engineers at that time. The de Prony equation was of the form:

$$\iota = \frac{\chi}{\omega} (\alpha v + \beta v^2) \tag{2}$$

where ι = sine of the angle of inclination of channel bottom,

χ = area of cross-section of stream

ω = wetted perimeter

v = mean velocity at the section in question

and α,β = constants whose values depended upon the nature of the bounding surface.

Dupuit visualized a mass of sand as a collection of minute channels, in each of which the conditions of flow could be expressed by equation (2). On the assumption that all such channels were subject to identical conditions, he concluded that the gradient and the resulting velocity were the same for all pores in a vertical section, and that i and v in equation (2) could therefore be generalized to denote a gradient and a velocity representative of the entire vertical section. Furthermore, on the premise that ground water motion was by nature very slow, he chose to neglect the term involving the second power of the velocity. Equation (2) applied to seepage thus took the form:

$$i = \eta v \tag{3}$$

where η = a constant whose value depended upon the nature of the soil.

Dupuit noted that since his v was proportional to Darcy's Q, the quasi-theoretical equation (3) was identical in form to Darcy's empirical expression.

In order to extend his equation to the case of gravity flow through a pervious stratum overlying a horizontal impervious base, Dupuit resorted again to the open-channel analogy, noted that the surface gradient at any point was simply the sine of the angle of inclination of the surface to the horizontal, and that this ratio could be replaced by the tangent in cases of gentle slopes. He then re-expressed equation (3) as follows:

$$-\frac{dz}{dx} = \frac{\eta q}{nz} = \eta' \left(\frac{q}{z}\right) \tag{4}$$

where x and z = horizontal and vertical coordinates, respectively, of a point on the phreatic surface,[8]

q = volume discharged through a unit of area of porous medium in a unit of time,

n = porosity, that is, the ratio of volume occupied by voids to total volume of soil,

and $\eta = \dfrac{\eta}{n}$

Equations (3) and (4) constitute the basis for all of Dupuit's

[8]Dupuit did not concern himself with the implications, or even the existence of a capillary zone. His phreatic surface was simply the boundary between a saturated region of flow and a completely dry remainder.

subsequent analysis. The assumptions upon which they are based can be conveniently stated as follows:

(1) The gradient is the same at all points in a vertical section; and

(2) The gradient at the phreatic surface (or at the piezometric surface[9] in artesian flow) is equal to the slope of the surface at that point.

These two statements, expressed in various ways, are usually referred to as Dupuit's assumptions. Although they impose serious restrictions upon the application of equations (3) and (4), Dupuit consistently disregarded them throughout his analytical work. Having paid them what he considered due respect in simplifying his fundamental equation, he apparently felt no further obligation to be limited by them. This may be accountable, first, to the fact that Dupuit apparently regarded the first assumption not as a limitation at all, but rather as a logical consequence of the implications of de Prony's equation; and second, to the fact that, unlike Darcy, Dupuit did not avail himself of all possible opportunities to check his theoretical conclusions against experimental data and field observations.

Dupuit distinguished between ordinary and artesian wells. To derive an equation for flow into an ordinary, or gravity, well, he considered the case of a cylindrical island of pervious sand surrounded by water at a constant level and underlain by a horizontal impervious base (Fig. 2).

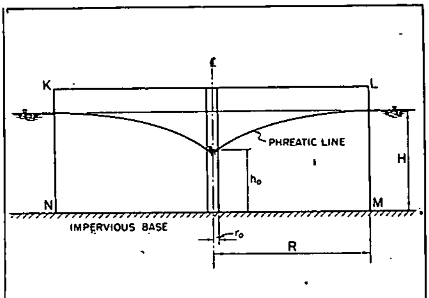

FIG. 2: VERTICAL SECTION THROUGH GRAVITY WELL
After Dupuit

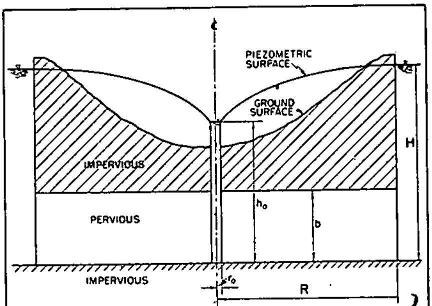

FIG. 3: VERTICAL SECTION THROUGH ARTESIAN WELL
After Dupuit

[9]The piezometric head at any point in a fluid stream is defined as the sum of pressure head and head due to elevation at that point. Thus, it is the elevation above datum to which the fluid would rise in a piezometer tube exposed to the fluid pressure at that point.

In an artesian aquifer whose thickness is small compared to the existing pressure heads, the piezometric head is approximately the same for all points in a vertical section. Under these circumstances, a piezometric surface can be defined as an imaginary surface whose elevation above the lower boundary of the aquifer at any point is equal to the piezometric head at a vertical section through that point.

Applying equation (4) to an arbitrary cylindrical surface surrounding a gravity well located at the center of the island and penetrating to the impervious base, and integrating from the well circumference to the entrance face (the vertical bank of the island), Dupuit derived the following equation for rate of flow.

$$Q = \pi k \left(\frac{H^2 - h_o^2}{\ln \frac{R}{r_o}} \right) \tag{5}$$

Q = volume discharge per unit of time
k = coefficient of permeability
H = depth of water in surrounding reservoir
h_o = depth of water in well
R = radius of island
r_o = radius of well.

Dupuit derived equation (5) on the basis of the assumptions expressed above. He did not indicate that he considered these assumptions any less valid near the well than at a distance from it. And he did not suspect the existence of a free discharge surface, since he assumed the point (r_o, h_o) to be on the phreatic surface.

However, regardless of the accuracy of his reasoning, he concluded from consideration of equation (5) that the location of the drawdown curve was independent of k and Q, and that it was determined solely by the combination of the dimensions H, h_o, R, and r_o.

In addition, he concluded that rate of discharge was not greatly affected by variation in well radius in cases of large drainage areas, that the shape of the well cross-section was an insignificant factor in influencing the discharge rate, and that the yield of a well located anywhere within a given cylindrical drainage basin would be the same.

Some mention should be made of the significance of Dupuit's cylindrical island in the application of equation (5) to a practical case. Given such an island, there is of course no problem involved in the evaluation of the radial distance, R. Some question does arise, however, in case the pervious stratum may be considered of unlimited extent. It is evident that the introduction of infinity as the value of R in equation (5) would destroy the usefulness of the equation. Dupuit was not explicit on this point; and it was left for Adolph Thiem to suggest a reasonable value for R, based on his observations that beyond a certain distance from the well the drawdown of the phreatic surface from the original ground water table became negligible, and that constant replenishment of the supply of ground water by rainfall tended to equalize the amount drained by the well, thereby keeping R approximately constant.

Dupuit's treatment of the case of a recharge well[10] consisted of reversing the signs of the head terms in equation (5) to get

$$Q = \pi k \left(\frac{h_o^2 - H^2}{\ln \frac{R}{r_o}} \right) \tag{6}$$

On the subject of artesian wells Dupuit returned to equation (4), which he recognized in this case as the equation of piezometric surface, and derived the following equation (see Fig. 3):

$$Q = 2\pi kb \left(\frac{H - h_o}{\ln \frac{R}{r_o}} \right) \tag{7}$$

where b = thickness of horizontal pervious stratum confined between two horizontal impervious strata,
H = elevation of original piezometric surface,
h_o = elevation of discharge point of well,

and the other quantities are the same as before.

It is interesting to note that whereas in the case of a gravity well Dupuit had been careful to specify full penetration of the pervious stratum, in the case of an artesian well he not only failed to make any such specification but illustrated his analysis with figures showing partially penetrating wells. Apparently he did not consider the factor important in the case of artesian wells.

Dupuit's work on ground water movement can be effectively appraised by comparing it to that of Darcy. Whereas Darcy had presented an admittedly empirical relationship whose accuracy had passed the test of laboratory investigation, Dupuit's contributions consisted essentially of theoretical analysis; and his conclusions were based upon the adaptation to ground water flow of current theory in a related field

[10]A recharge well may be defined as one from which water is seeping into the surrounding porous medium.

more familiar to him. However, in spite of the limitations to which his analysis is subject, and in spite of his failure to lay proper emphasis upon those limitations, the discharge formulas which he derived for gravity and artesian wells have proved to be of satisfactory accuracy for limited purposes.

Thus, the artesian well formula, equation (7), can be relied upon provided that the well penetrates the full thickness of the pervious stratum and that pressure heads are large in comparison to that thickness. In such a case the flow pattern consists for practical purposes of horizontal streamlines and vertical equipotential lines. Consequently, Dupuit's assumptions are valid all the way to the well circumference.

On the other hand, the gravity well formula, equation (5), is not a valid expression for the phreatic line, nor is it a theoretically exact expression for the distribution of piezometric head along the impervious base. However, the equation is generally used to compute Q or k, since experience has shown that the discrepancy between theory and observation in either of these cases is small. It is perhaps worth noting that the error can be expected to result in a value of Q that is too small. This follows from the fact that the law of continuity must be fulfilled, while the computed flow pattern is an approximation. Thus, since the principle of minimum energy requires maximum flow for a particular set of boundary conditions, any artificially induced deviation will result in less than the actual rate of discharge.

A. Thiem

Exchange of information between nations, even when unimpaired by politics, was not as simple in Darcy's and Dupuit's time as it is now. Notice of the contributions of the two French engineers did not spread abroad rapidly, and as a result much of their fundamental work was duplicated in the course of independent developments of the same material shortly afterward in Germany and somewhat later in the United States.

The trail-blazer among German investigators in the field of ground water movement was Adolph Thiem, a civil engineer for the city of Dresden in 1870, when he published the first and most important of his many papers on various phases of the subject of wells. The 1870 paper [79] was an analytical study of flow toward artesian wells, gravity wells, and filter galleries; and it contained most of the important ideas contributed by its author to the development of consistent theory in those subjects.

Referring briefly to Darcy and Dupuit,[11] Thiem reviewed Darcy's experiments and went on to derive the same equations as Dupuit had for gravity and artesian wells. In the case of the gravity well he was as casual as Dupuit had been about assuming the same gradient throughout a vertical section and using the tangent rather than the sine of the phreatic surface slope angle as its value—it seems that to Thiem, as to Dupuit, these considerations were logical inferences rather than simplifying assumptions. In the case of the artesian well Thiem restricted himself, as Dupuit had not, to full penetration of the aquifer by the well. Thiem was the first to collect extensive field data in support of these equations, and published several papers containing his observations [77, 81, 86].

Thiem gave brief consideration to partially penetrating gravity wells, but here he oversimplified. Fig. 4 shows a partially penetrating gravity well. Thiem based his analysis on the implicit premise that the flow pattern would be virtually the same whether or not the region ABCD was occupied by soil. Thus he reasoned that the resistance offered by that amount of soil was not an appreciable addition to the total for the corresponding fully penetrating well, and concluded that the effect of partial penetration on yield would be inconsiderable.

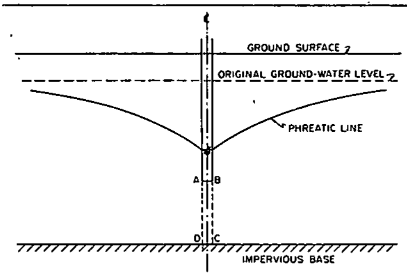

FIG. 4: VERTICAL SECTION THROUGH PARTIALLY PENETRATING GRAVITY WELL

After A. Thiem

Thiem (also in the 1870 paper) was the first to attempt any analysis of non-steady seepage phenomena; but his results were by his own admission of little value. However, he did inject a practical note into the theoretical considerations by pointing out that it was not necessary to complicate the problem by insisting upon a value of in-

[11]Apparently Dupuit's chapter on seepage was not known to Thiem, at least until after he had worked out most of the material himself, so that the duplicated work was performed independently by both men.

finity for R, the horizontal distance from well to point of zero drawdown, and therefore for the time required to reach the steady state. He observed that no serious inaccuracy was entailed in the substitution for R of the distance at which the drawdown became so small as to be negligible.

In the course of extensive field work, Thiem had made much use of the method of ground water velocity measurement which involved the injection of coloring matter at one point and its subsequent detection elsewhere by means of observation wells. A troublesome feature of this procedure was the fact that since the dyestuff tended to diffuse even in still water, its progress in a ground water stream was not dependent solely upon ground water velocity. Consequently an error of unknown magnitude was introduced. To eliminate this defect, Thiem introduced the use of salt instead of coloring matter into the process [84, 88]. He calibrated a salt solution of known concentration and time at various distances from the point of injection in still water. It was then possible to apply an accurate correction for diffusion to the value of salt content measured at a given time and at a specific observation well during a field test.

That the problem of the combined effect of natural ground water flow and flow toward a gravity well occupied much of Thiem's attention is indicated by the fact that he first treated the subject in his earliest paper and then returned to it years later [89]. Although some of the details of his solution were incorrect, the principle of flow in the direction of the steepest gradient had impressed itself upon him, and he realized that flow conditions should not be discontinuous anywhere within a fluid mass.

Drawing upon many years of experience in the field, Thiem published a long list of papers and books covering the securement of water from underground aquifers for numerous German cities. The importance of his work in the development of the theory of flow toward wells sprang largely from his extensive experience and the consequent emphasis which he placed on field observations and the necessity of reconciling analytical methods and ideas with them.

G. Oesten and O. Smreker

During the period of Adolph Thiem's greatest productivity, the only other investigators of any importance who were interested in flow toward wells were two other German engineers, Günther Oesten and Oscar Smreker. The two men have been grouped together because the chief contribution of each was the same: The publications of both men involved errors which were sufficiently fundamental to evoke discussions by Thiem of matters which he might not otherwise have considered worth mentioning. Both Oesten [48], and Smreker [63, 64, 65] discredited Darcy's law and the work of Dupuit and Thiem which stemmed from it; each, in his objections, was guilty of fallacious reasoning; and Thiem brought out important fundamental considerations in several discussions [78, 83, 85]. Oesten also took issue with Thiem on the matter of flow toward a partially penetrating well within a flowing ground water stream [49], and tried to convince him that there existed a lower boundary of the region feeding the well. Thiem's reply [83] contributed a little more to the available material on the as yet undeveloped concept of continuous equipotential and stream surfaces. Meanwhile, Smreker noticed that the water level inside a well and the phreatic surface elevation just outside were not the same [64]; but he underestimated the extent of the difference, attributed it to head loss through the perforations, and returned to the development of an extremely unwieldy equation of ground water flow, which he championed againt Darcy's law to the bitter end.

P. Forchheimer

The foundations laid by Darcy, Dupuit, and Adolph Thiem soon came to the attention in Austria of one of the most original, as well as prolific, contributors to the development of ground water technology. Philipp Forchheimer was a young hydraulic engineer in Graz in 1886 when he published his earliest paper on flow toward wells [25]. His career as a practicing engineer and later as a professor extended over nearly half a century, during which his many contributions to ground water technology were among the most important in that field. His early work (prior to about 1900) is of special significance in that it provides an excellent digest of the literature to date in addition to his accounts of his own research. References may be found in Forchheimer's early publications to contributions Thévenet [76], Fossa-Mancini [28], Fink [20], Pennink [48], Kröber [38], Lüger [40], and Prinz [51], among those who had treated the subject toward wells.[12]

The most important idea introduced by Forchheimer into the

[12] Of this group, the only one whose contributions warrant more than passing mention, in view of the extent to which they were all overshadowed by Forchheimer, was Fossa-Mancini. The germs of several of Forchheimer's many well-developed ideas can be found in Fossa-Mancini's publications.

development of the theory of ground water flow was the concept of the equipotential surface and its relation to streamlines. Until his appearance there had been no evidence of a clear understanding of the fact, for example, that equipotential surfaces were not vertical in cases of gravity flow. Consequently, where earlier investigators had simply been compiling a somewhat disjointed mass of field observations, and semi-empirical derivations, Forchheimer's flow-net principle[13] provided a logical foundation upon which to build the theory.

A treatise by Holzmüller [30] on the application of conformal mapping to heat flow problems suggested to Forchheimer a similar approach to the analysis of ground water flow phenomena. Accordingly, he began by applying Darcy's law and Dupuit's assumptions to the case of gravity flow in a pervious stratum underlain by a horizontal impervious base [25], and arrived at Laplace's equation in the following form as an expression for the phreatic surface:

$$\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} = 0 \qquad (8)$$

where z = elevation of the phreatic surface above the horizontal impervious base,

and x, y = coordinates of the projection of the point in question on a horizontal plane.

He observed that the practical validity of equation (8) was most secure in cases of great depth of ground water stream; and went on to show that in regions where the depth was small enough so that its changes from point to point were appreciable in comparison, equation (8) should be modified to read:

$$\frac{\partial^2 (z^2)}{\partial x^2} - \frac{\partial^2 (z^2)}{\partial y^2} = 0 \qquad (9)$$

Thus it was Forchheimer who first pointed out the fundamental ap-

[13]The analytical method of which the flow-net is a particular example was not new when Forchheimer arrived on the scene. Nor was Forchheimer's earliest published flow-net—which was contained in the first edition of his book on hydraulics [23] in 1914—the first to appear in print, since by that time L. F. Richardson had developed the procedure independently in England and had published flow-nets several years earlier [52]. But it is clear from the paper which Forchheimer published in 1886 that the idea had already begun forming in his mind, so that it seems reasonable to regard the application of the device to ground water phenomena as one of his contributions.

plicability of Laplace's equation to the analysis of ground water flow phenomena.[14] He accepted Dupuit's and Thiem's analysis of flow toward a single gravity well; but he was the first to offer a clear statement and a perceptive appraisal of their assumptions [22].

At this point he introduced the theory of functions of a complex variable and undertook the analysis of gravity flow toward a group of wells (Fig. 5). In its original form, the equation he derived may be expressed as follows:

$$z^2 - h^2_o = \frac{Q}{\pi k}\left(\frac{1}{N} \quad \ln R_1R_2 \ldots R_N \quad - \ln r_o\right) \qquad (10)$$

where N = number of wells
Q = total rate of discharge during a steady state of flow,
z = elevation of a point (e.g., P in Fig. 5) on the phreatic surface during steady-state flow,
$R_1, R_2, \ldots R_N$ = distances from the point in question to the respective wells,
h_o = depth of water in an imaginary equivalent single well from which the same rate of discharge could be drawn as from the group of wells,
and r_o = radius of the equivalent single well.

In deriving equation (10) Forchheimer assumed that the yield of each well was the same, and imposed no restriction on the equivalent single well other than an implicit requirement of a roughly central location. In this form the equation lent itself to use in predicting the drawdown required of individual wells of a proposed group on the basis of the performance of a single test well. Forchheimer later [23] adapted the same equation to use in the analysis of an existing group of wells by introducing the relationship

$$r_o = \sqrt[N]{r_{o1}\ r_{o2}\ \ldots\ r_{oN}} \qquad (11)$$

as a definition of the radius of a hypothetical equivalent single well, and reexpressing the equation in the form:

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[14]Slichter, unaware of Forchheimer's work, later arrived at the same point in the United States [60].

$$z^2 - h^2 = \frac{Q}{N\pi k}\left(\ln\frac{R_1}{r_1} + \ln\frac{R_2}{r_2} + \ldots + \ln\frac{R_N}{r_N} \right) \qquad (12)$$

where r_1, r_2 ... r_N = radii of respective wells (see Fig. 5). Thus, he had retained the simplifying assumption of equal yield from all wells; but the equivalent single well had become essentially an analytical device, and h_o^2 a constant characteristic of the given system.[15]

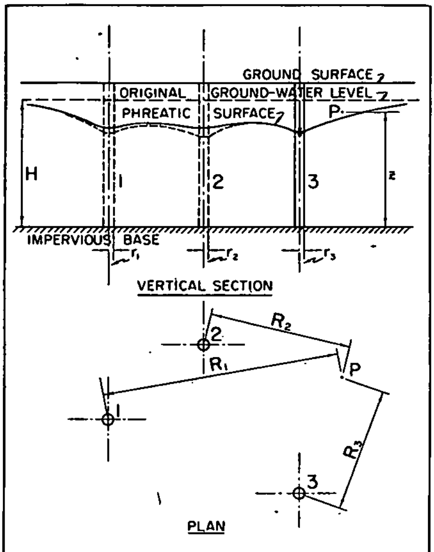

FIG. 5 : GROUP OF GRAVITY WELLS

After Forchheimer

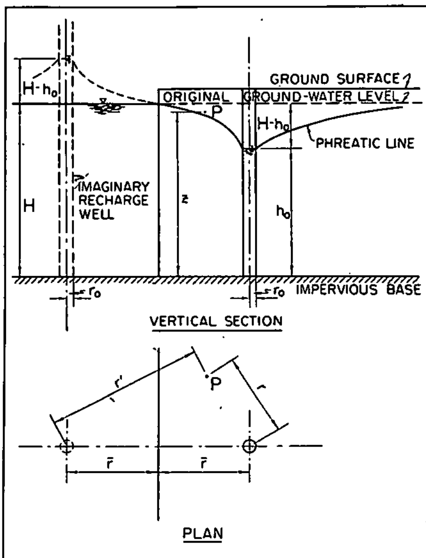

FIG. 6: SINGLE GRAVITY WELL NEAR OPEN WATER

After Forchheimer

Equation (12) was expressed in several other ways, one of which eliminated the equivalent single well and related rate of discharge to the phreatic surface elevations in two observation wells:

$$z_a^2 - z_b^2 = \frac{Q}{N\pi k} \sum_{i=1}^{i=N} \ln \frac{R_{a_i}}{R_{b_i}} \qquad (13)$$

where the subscripts, a and b, refer to the observation wells, and the symbols are otherwise the same as in equation (12).

[15]The simplest form of the multiple well equation, whose derivation had received rather casual treatment from Forchheimer in his anxiety to get on with the applications, has been presented most clearly by Dachler [13] and will be discussed in the section devoted to him.

Forchheimer was the first to apply an analytical device now known as the method of images to ground water theory [22]. Fig. 6 illustrates the case of a permeable stratum whose edge forms the vertical bank of a river of indefinite length perpendicular to the plane of projection. A gravity well is located near the river's edge, the whole is underlain by a horizontal impervious base, and the ground water table is assumed to be a horizontal surface at the same elevation as the river surface. To determine the flow toward the given well, the river is replaced by a continuation of the pervious stratum; and an imaginary recharge well, feeding as much water into the pervious stratum as the given well removes, is located as the mirror image of the given well with respect to the river bank. Application of this multiple-well relationship (Equation 13) to the group consisting of the real and imaginary wells gave the following result:

$$H^2 - z^2 = \frac{Q}{\pi k} \ln \frac{r'}{r} \tag{14}$$

where Q = rate of discharge from the given well
H = elevation of river surface
and z, r, r' = coordinates of a point, P, on the phreatic surface (see Fig. 6).

It should be noted that equation (14) is independent of the distance, R, to the point of negligible drawdown; and that all water which flows into the well comes from the river.

Introducing to the same problem the additional feature of a natural ground water flow toward the river, Forchheimer extended the image analysis to the determination of a limiting distance from well to river bank, beyond which a well so located would receive no water from the river. He found the distance to be

$$\bar{r} = \frac{Q}{\pi q} \tag{15}$$

where $\bar{r}$ = critical distance from well to river
and $\bar{q}$ = rate of flow of natural ground water stream per unit of horizontal width transverse to the direction of flow.

Assuming that the natural ground water flow is directed toward the river, equation (15) implies that if a well is located at a distance greater than $\bar{r}$ from the river, all water discharging into the well will be contributed by the ground water stream; and that if a well is located nearer than $\bar{r}'$ to the river, some of the water draining into the well will come from the river.

The problem of flow toward a single gravity well within a natural ground water stream was solved by Forchheimer under two different conditions. In one case [25] he assumed that the natural ground water stream flowed through a permeable stratum overlying an inclined impervious base, and that the undisturbed water table could be represented by a plane inclined surface. Introducing the Dupuit-Thiem assumptions, he mapped the surface streamlines in plan (Fig. 7), and arrived at the following expression for the curve that bounded the region feeding the well:

$$-\frac{y}{x} = \tan\left(\frac{2\pi k h_o a}{Q}\,y\right) \tag{16}$$

where a = inclination of the natural ground water surface in the absence of the well.

He observed that the discharge could be expressed by the Dupuit-

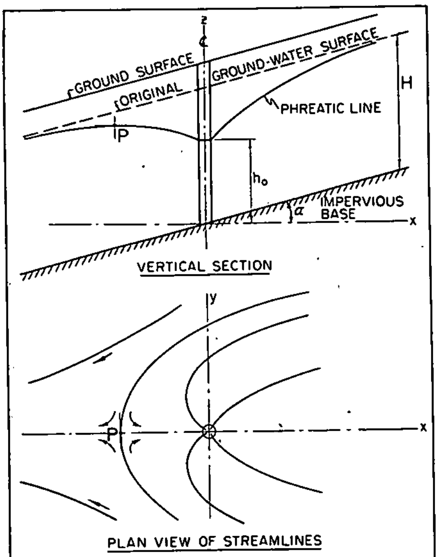

FIG. 7: GRAVITY WELL IN GROUND-WATER STREAM: CASE I After Forchheimer

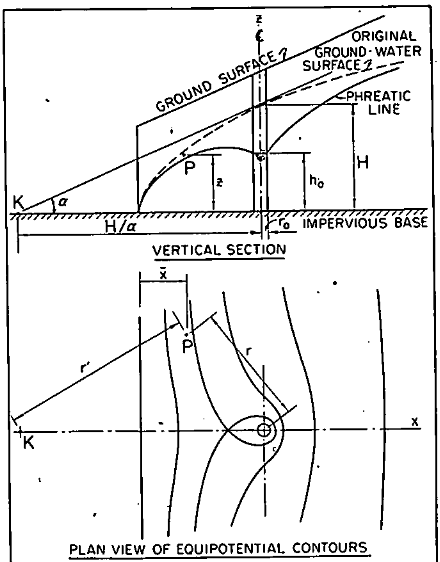

FIG. 8: GRAVITY WELL IN GROUND-WATER STREAM: CASE II After Forchheimer

Thiem equation if H and h were measured from the inclined impervious base. In the second case [22] he assumed flow through a pervious stratum overlying a horizontal impervious base, and adapted the method of images to the analysis of the problem by imagining the river bank moved to the point of intersection of the natural ground water surface parabola with the impervious base (Fig. 8). Application of equation (14) then gave the following expression for the phreatic surface during operation of the well:

$$z^2 = \left(\frac{2\bar{q}}{k} \right) \bar{x} - \frac{Q}{\pi k} \ln \frac{r'}{r} \tag{17}$$

where $\bar{x}$ = distance to river bank from point in question.

And the drawdown at the well could be determined from the equation:

$$H^2 - h^2_o = \frac{Q}{\pi k} \ln \frac{H}{\alpha r_o} \tag{18}$$

where H = original elevation of phreatic surface at location of well,
and α = inclination of original ground water surface at location of well.

In all of the analyses outlined so far, Forchheimer had assumed the wells to penetrate to the underlying impervious base. He also considered the case of partially penetrating gravity wells [22]. In this case the analysis was semi-empirical, since his equations were based on a series of tests using apparatus which was essentially an improvement of that used originally by Thévenet [76] and Fossa-Mancini [28]. The resulting equations were rather unwieldy, and, because of the nature and size of the testing apparatus, could not be considered of unrestricted validity.

Several different cases of flow through plane and hemispherical bottoms of wells having water-tight walls were also analyzed by Forchheimer [24]; and some idealized well-group arrangements provided exercises in purely mathematical analysis [26, 27]. He kept abreast of development in field procedures and occasionally published brief digests of current practice [21].

Forchheimer's important contributions to the theory of ground water flow, as to other branches of hydraulics, were the result of an extraordinary facility in the handling of analytical tools. He made more fruitful use of the complex variable, conformal mapping, potential theory, the method of images, and the like, than any other investigator in the field of ground water flow up to his time; and the foundation which he laid provided a helpful guide for those who followed him.

G. Thiem

The analytical contributions of Adolph Thiem and Forchheimer were ably complemented early in the present century by an abundance of field data amassed by Günther Thiem,[16] in the course of hydrological investigations conducted over a period of years. In the process of analyzing his data and reporting his results, he made several contributions in the way of adaptation of current theory to practice.

In his most important publication [90], which appeared in 1906, he presented his own method of making field measurements of velocities and permeabilities by means of groups of observation wells and test wells. His procedure can be described briefly with reference to Fig. 9. Driving three wells at the vertices of an arbitrary triangular area which was usually roughly equilateral, he located an equipotential contour G-G by interpolation. A line drawn through one of the wells perpendicular to the equipotential contour then determined the direction of flow. By pumping from the well thus selected and observing the level in the other two, he could obtain sufficient data to determine the permeability of the soil and the rate of natural ground water flow.

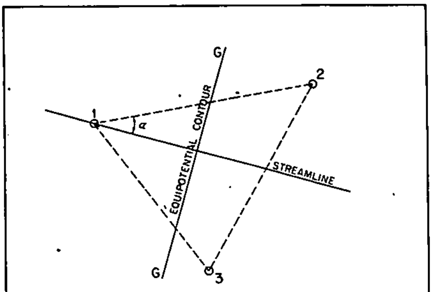

FIG. 9: GROUND WATER VELOCITY MEASUREMENT

After G Thiem

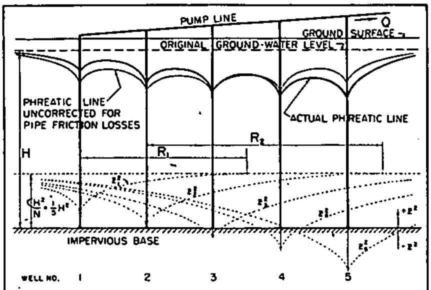

FIG. 10: VERTICAL SECTION THROUGH A ROW OF WELLS

After Dachler

He based his analytical work on the assumption of small slopes of the phreatic surface. Thus, he observed that the permeability of a soil stratum could be determined in situ without knowing the gradient

[16]Son of Adolph Thiem.

of the natural ground water stream, because drawdown values induced by the operation of a well would be nearly identical whether measured from a horizontal or an inclined phreatic surface. He also pointed out that the thickness of an artesian aquifer and the depth of an unconfined ground water stream were non-essential items in the determination of natural ground water flow, because each could be eliminated by securing data from two observation wells. Finally, he noted that if the Dupuit-Thiem equation were applied to two arbitrary points corresponding to the locations of observation wells, and if the term involving the difference of the squares of the depths were factored, the equation could be written:

$$z_1 + z_2 = \frac{Q}{\pi k} \cdot \frac{\ln \frac{r_1}{r_2}}{(z_1 - z_2)} \tag{19}$$

Then, assuming small drawdown, the left-hand side of this equation could be approximated by 2H, and the equation would become

$$H = \frac{Q}{2\pi k} \cdot \frac{\ln \frac{r_1}{r_2}}{(z_1 - z_2)} \tag{20}$$

It followed from equation (20) that if k were known and Q, r_1, and r_2 measured during operation of a test well, measurement of the difference in drawdowns for the two observation wells would permit the calculation of the depth of impervious base.

The simplifications in analysis proposed by Günther Thiem were probably not original, since both Adolph Thiem and O. Lüger had mentioned the same ideas briefly in their own work. But Günther Thiem's work contained the first orderly presentation of the material. However, the chief value of his work lay in the copious field data and descriptions of field procedures contained in it.

J. Boussinesq

Several Austrian engineers who followed in the Forchheimer tradition, notably Schaffernak, A. and L. Casagrande, and Dachler, were to contribute significantly to many phases of ground water technology in the years following the first World War. However, during the second decade of this century some of the emphasis shifted from wells to some two-dimensional problems that had begun to attract attention, such as seepage through dams and under weirs and sheet-pile walls. The temporary preoccupation of Forchheimer's disciples with these new matters provides an opportunity to check on progress in France and the United States.

In spite of the fact that the original impetus to the investigation of seepage toward wells had been provided by two very capable French engineers, relatively little of major practical importance in this specialized field has appeared in French literature since the time of Darcy and Dupuit. Following those two, except for the almost inconsequential tests by Thévenet [76], and the more important work of Fossa-Mancini [28], whose ideas had been extended and developed by Forchheimer, the only other name of importance in French literature in the field of ground water motion during the latter half of the nineteenth century was J. Boussinesq.

Boussinesq's work was chiefly in applied mathematics and elasticity. The subjects he treated ranged widely over the field of engineering, and his contributions were many and important. Flow toward wells was not one of the subjects to which he ever applied direct attention; but he did publish important work of a mathematical nature on fluid flow in pipes and conduits, in which flow through porous media was briefly touched upon [6, 8]; and he also paid some attention directly to seepage phenomena [7, 9].

On the strength of these general treatments of ground water flow, published at a time when ground water theory and well theory were virtually synonymous, Boussinesq's name is included here. However, his analysis was all of a strictly theoretical nature and his results as a rule were not easy to apply. Consequently, his conclusions have not found wide use in practice.

C. S. Slichter et al

The earliest important investigations of ground water phenomena in the United States were made by a number of geologists during the last quarter of the nineteenth century. The outstanding pioneer among these men was C. S. Slichter, whose publications provided the first authoritative source of field data and theoretical analysis to appear in this country on the motion of underground water.

The three most important papers that Slichter published on ground water motion appeared in 1899 [60], 1902 [59] and 1905 [61]. At this time Slichter appears not to have been familiar at first hand with some of the publications of his European predecessors. He knew of Darcy's report on the public fountains of Dijon, and could give a detailed description of Adolph Thiem's method of measuring ground water velocities in situ. But his acquaintance with the rest of Thiem's papers and all of Dupuit's was limited largely to their titles; and he had apparently never heard of Forchheimer. Consequently, in much of this theoretical work he unknowingly duplicated material already published in Europe.

In his first treatment of ground water phenomena [60], Slichter derived the following equation for flow of water through a vertical column of soil:

$$Q = 1.0094 \frac{(\Delta p)(d^2)(A)}{\mu h K} \tag{21}$$

where
Q = rate of flow, in cubic centimeters per second,
p = difference in "pressure"[17] at the ends of the column, in centimeters of water,
d = mean diameter of soil grain, in centimeters,
A = cross-sectional area of column, in square centimeters,
h = height of column, in centimeters,
μ = coefficient of viscosity of water, in gram-seconds per square centimeter,
and K = a constant whose value depended upon the porosity and the geometric characteristics of the porous medium.

Slichter recognized the fact that his equation was identical in form to Darcy's. However, whereas Darcy had been content to lump together the effects of several factors in the single constant, k, Slichter had attempted to break the constant down into its component parts. In order to do this, he had simplified the analysis by considering a mass of equal spheres, and had modified Poiseuille's law in an attempt to take account of the resulting shape of pore cross-section. Consequently, Slichter's equation was an improvement over Darcy's in that

[17]"Pressure" was the word he used. Slichter's publications were not clear about the distinction between pressure and piezometric head. He almost always spoke of "pressure," but clearly meant what is conventionally called piezometric head. On the other hand, equipressural lines appeared correctly identified in some of his drawings although he used the term interchangeably with "equipotential lines."

it provided specific information about the composition of Darcy's constant, k; but in a quantitative sense, equation (21) was of doubtful validity when applied to a natural granular material.

Unaware of any of Forchheimer's work, Slichter demonstrated that Laplace's equation was fundamental to ground water motion. Here again he introduced pressure as the potential function.

Slichter's theoretical work on wells was restricted to the artesian type, for which his expression for discharge was identical to the Dupuit-Thiem equation. He also considered briefly the problem of flow toward a well with a semi-spherical bottom just protruding into an artesian aquifer. In this case he had been preceded by Forchheimer [24].

The applicability of Lapalace's equation, potential theory, and conformal representation to ground water analysis had been impressed upon Slichter by the same publication of Holzmüller [30] that had given Forchheimer many of his ideas. Slichter applied these concepts to several cases of flow in a horizontal plane, to the combination of natural ground water flow with flow into an artesian well, and to the problem of interference among artesian wells. He mapped the appropriate flow pattern for each problem, and in the cases involving artesian wells he also determined the relative quantities flowing into the different wells. Since he was concerned in all these analyses with flow in a horizontal plane or in a relatively thin aquifer, his solutions contained no inaccuracies as a result of his failure to distinguish between pressure and piezometric head. Here again he had been preceded by Forchheimer [26, 27], who in these cases had carried the analysis well beyond the point which Slichter reached.

In other papers [59, 61] Slichter described his own method of measuring ground water velocities in the field by the use of electrodes in observation wells and the injection of an electrolyte into the ground water. Rate of seepage was correlated with variation in concentration of electrolyte as indicated by the reading of an ammeter in a circuit connecting the electrodes.

Slichter's importance should not be underestimated because of his having been preceded in Europe in much of his fundamental theoretical analysis. Incomplete as his acquaintance with Dupuit, Thiem, and Forchheimer was, he seems nonetheless to have been unusually well informed, under the circumstances, on activity abroad. And in the general absence of all but the most meager information on progress elsewhere, Slichter's work was as important to the development of ground water technology in this country as his counterparts' had been in France and Germany. Furthermore, quite apart from his significant theoretical work, Slichter contributed a great quantity of field data and observations whose value was the greater for having had the benefit of appraisal by such a perceptive examiner.

The United States Geological Survey has been a consistently fertile source of analytical and experimental information on ground water theory, almost always accompanied by an abundant supply of field data and observations. It would be difficult, as well as misleading, to attempt to segregate a distinct part of all this material and label it the section on seepage toward wells. However, the early development of that branch of the subject can be outlined with reasonable accuracy by listing a few significant contributions.

One of the earliest treatments of artesian wells was a paper published in 1885 by T. C. Chamberlin [12]. The discussion was entirely of a qualitative nature, and contained none of the voluminous numerical data and analysis which were to feature Slichter's papers; but it was nonetheless a careful study of its kind. At the turn of the century F. H. King published a lengthy report [35] containing, among other things, some experimental data which is still among the best available on drainage phenomena in sands. Later, M. L. Fuller and O. E. Meinzer discussed well problems [29], and W. H. Norton touched on wells in a treatment of artesian phenomena [47]. Both of these papers were done more in the discursive style of Chamberlin and did not contain a great quantity of numerical data; but each contributed new considerations to the available technology on wells. Meanwhile, Isaiah Bowman had become interested in well-drilling methods and surveyed the field in a paper published in 1914 [10]. The contribution of Meinzer listed above was but one of many from one of this country's most outstanding hydrologists. His contributions extended over more than three decades; and in 1923 he outlined the development of field work and theoretical analysis in ground water hydrology up to that time in the first of several compendiums he was to write on the subject [42].

Correlation and Consolidation: 1925-1940

The transition in the field of ground water theory in general and analysis of seepage toward wells in particular from a group of continuous but independent investigations to a reasonably well-coordinated whole has not been a sudden one, and is not wholly satisfactory even now. But the exchange of information across the ocean began to increase following the first World War, and within the next few years a period of more serious examination of the work of others on a trans-atlantic scale had begun. The year 1925 marks approximately the beginning of this period of more extensive interchange of information. It also has some significance as the birth date of modern soil mechanics, which has greatly influenced subsequent developments in ground water analysis.

At about this time, the attention of the Forchheimer disciples who were last seen undertaking some investigations of seepage through dams began to return occasionally to the subject of wells; and a considerable amount of new material, not only by that specific group but by others clearly influenced by them, followed in the next ten or fifteen years. A great part of this work originated, appropriately enough, on Forchheimer's home grounds, using that term in a reasonably broad geographical sense; and the first important contributors continued to be Germans and Austrians. However, during this phase of the development of the analysis of flow toward wells other influences began to enter, particularly with the arrival of Karl Terzaghi and Arthur Casagrande in this country and the fresh points of view introduced by Muskat and others from one direction and Theis, Hubbert, Jacob and others from another, so that a tradition of clear national or geographic significance could finally no longer be distinguished.

R. Dachler

Among the first of the group under consideration to appear in print on the subject of wells was Robert Dachler. Dachler's publications are of consistently superior quality in clearness, simplicity, and accuracy; and his ground water text [14] is one of the most understandable published treatments of the subject.[18]

Dachler's chief interests in his published work were two-dimensional flow phenomena, including applications of potential theory and flow nets. However, one of his earliest papers [13] was a brief elabo-

[18]It should be noted that some of Dachler's most important published work was based on ideas which originated with Forchheimer and Schaffernak. However, at least in the opinion of this reviewer, Dachler surpassed the masters in lucidity of presentation.

ration of Forchheimer's analysis of flow toward a row of wells. Beginning with a convenient form of the Dupuit-Thiem equation,

$$z^2 = h^2_o + \frac{Q}{\pi k} \ln \frac{r}{r_o} \tag{22}$$

where r, z = coordinates of a point on the phreatic surface,

and r_o, h_o = coordinates of the water surface in the well at its circumference,

and introducing a point (R, H) of negligible drawdown for the random point above, he eliminated r_o and h_o to get

$$z^2 = H^2 - \frac{Q}{\pi k} \ln \frac{R}{r} \tag{23}$$

Applying this result to the case of a row of gravity wells (Fig. 10), Dachler followed Forchheimer's procedure of summing a series of equations (23) to get a simple form of Forchheimer's equation (12):

$$z^2 = H^2 - \sum_{i=1}^{i=N} \frac{Q_i}{\pi k} \ln \frac{R_i}{r_i} \tag{24}$$

where z = elevation of phreatic surface above the impervious base at an arbitrary point during the operation of all wells,

H = original depth of ground water stream,

r_i = distances from the i-th well, to the arbitrary point,

R_i = distance from the i-th well, to the point at which drawdown due to that well become negligible,

and Q_i = contribution of the i-th well to the total rate of discharge of the N wells.

To explain the presence of the same H in equations (23) as in their sum, equation (24), Forchheimer had simply noted that it was a matter of fitting the same boundary conditions to a number of different functions, z^2, each of which satisfied Laplace's equation. Dachler added, with perhaps a little more compassion for those whose intuition was more physical than mathematical, that the fundamental assumption involved was to the effect that the contribution of each well to the total drawdown was the same as if the well had been acting alone. Thus, Forchheimer had actually been implicitly summing drawdowns, H-z, while retaining the depth, z, as the explicit variable. Consequently, to suit the mathematics to the assumption of superposition of drawdowns, it became necessary to adjust the depth of ground water stream for each well to an appropriate imaginary value.

By referring to a point on the original water table and another in the region of relatively small phreatic-surface slopes, equation (24) avoided consideration of the troublesome point at the well circumference, where the Dupuit-Thiem assumptions could not be justified.

As indicated in Fig. 10, Dachler compared the actual drawdown curve with the curve which would have been obtained if losses in wells and main pumping line had been neglected. And to illustrate the details of the analytical device, he showed the individual contributions to the summation of equation (24) by drawing a z^2-curve referred to the H^2/N-datum for each well.

J. Kozeny, R. Ehrenberger, et al.

The many important contributions of Forchheimer and his closest associates during the first quarter of this century were probably largely responsible for the appearance of a considerable number of other investigators in this field at the end of that period. Among the contemporaries of Schaffernak and Dachler, one of the most prolific writers was another Austrian hydraulic engineer, Joseph Kozeny.

Kozeny frequently carried the development of a theoretical concept considerably beyond the limit of practical value, and sometimes beyond the limit of accuracy. However, he carried out a large amount of original research, and some of the results were of use provided their limitations were understood. On the other hand, in several cases, his theories have been accepted and applied by investigators[19] who have failed to take due note of these limitations; and the results have been of questionable accuracy. The characteristic which seems to be shared by all of the latter group is an inclination toward complex mathematical analysis.

Kozeny's theory of ground water motion [37] led him to an analysis of flow toward wells [36] in which he was among the first to

[19]See below, pp. 39-40.

offer any theoretical reasoning to account for the presence of a free discharge surface. However, his fundamental theory, based on a minimum energy concept and originally applied to plane flow problems, led to incorrect results in the case of a gravity well because he disregarded the boundary conditions. Specifically, he applied the Dupuit-Thiem equation to a point which lay in a vertical cylindrical section at the well circumference, where the Dupuit-Thiem assumptions are not valid; and he assumed that a phreatic surface must intersect a vertical discharge face at an angle of 45°, neglecting capillary effects.

His analysis of non-steady flow into a fully penetrating gravity well, and of steady flow into a partially penetrating gravity well was inaccurate as a result of the same disregard of the limitations of the Dupuit-Thiem assumptions. However, even this part of his work contributed to the development of the theory of flow toward wells because it stimulated others, and was thereby instrumental in maintaining the progress of research on this subject.[20]

The most important experimental appraisal of Kozeny's theoretical conclusions was a series of sand-model tests conducted by R. Ehrenberger [19]. Ehrenberger's model was in the form of a sector of a right cylinder with the simulated well at the vertex and the outer cylindrical surface representing a vertical equipotential entrance face.

Fig. 11 is a sketch of a radial section of the sand model, in which

H = depth of water at entrance face above horizontal impervious base,

z_0 = depth of water at well circumference,

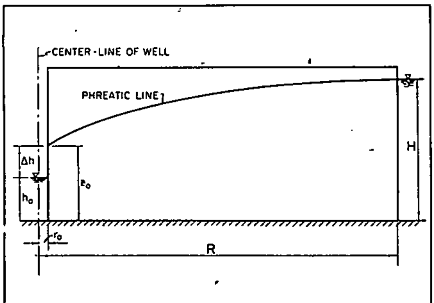

FIG. 11: EHRENBERGER'S MODEL: TYPICAL RADIAL SECTION

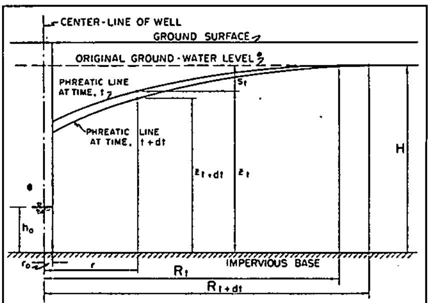

FIG. 12: DEVELOPMENT OF FLOW TOWARD A GRAVITY WELL: WEBER'S SOLUTION

[20]For further comments on Kozeny's work, and a more detailed discussion of some of his results, see Muskat [44], pp. 365-367.

h_o = depth of water in well,
Δh = vertical dimension of free discharge surface
r_o = well radius
R = radial distance to the entrance face from well center-line.

Ehrenberger found that his test results could be satisfactorily expressed by the following approximate equation:

$$\frac{z_o}{H} = \frac{1}{2}\left[1 + \left(\frac{h_o}{H}\right)^2\right] \tag{25}$$

This equation agreed with Kozeny's theoretical conclusion that the maximum drawdown could never be greater than one-half H.

Thus,

$$z_{o_{min.}} = \frac{1}{2} H \tag{26}$$

which occurs

when $h_o = 0$

Ehrenberger accepted the Dupuit-Thiem assumptions at the well circumference just as Kozeny had. In addition, it seems likely that the correspondence between the general shape of his observed phreatic surface and of Kozeny's theoretical one was interpreted as verification of each, whereas actually the failure of the observed phreatic surface to curve tangent to the discharge face was at least partly the result of capillary effects. Ehrenberger also joined Kozeny in the erroneous conclusion that ground water velocity increased with depth below the phreatic surface irrespective of the level of the water surface in the well.

Following Ehrenberger have been a few others, notably Jaeger [34] and Vibert [93[, who accepted Kozeny's conclusions without sufficient investigation of an experimental or a theoretical nature. As a consequence, their results were not of much value.

J. Schultze, W. Sichardt and W. Kyrieleis

Complementing the analytical work within this same period and area of influence, several publications appeared which were of value because of the quantity of field data contained in them. Among these were J. Schultze's general treatment of the theory and practice of lowering ground water levels [54], which appeared in 1924; and two texts by W. Sichardt, one on the recovery of water by means of wells [58], and one in collaboration with W. Kyrieleis, on lowering of ground water tables in connection with foundation construction [39]. The latter two books were published in 1928 and 1930, respectively. The theoretical material contained in these volumes was either incorrect or of no great value. Sichardt, for example, attempted to predict the extent of the free discharge surface of a gravity well by means of an empirical formula containing the square root of the coefficient of permeability. However, the field observations and data were of interest to the theoretical and experimental investigators as well as to practicing engineers. In spite of the fact that his theoretical conclusions were incorrect, Sichardt was among the first to realize that the free discharge surface was accountable to something more than a simple head loss through the well shaft; and his field data was the more valuable for that reason.

H. Weber, C. V. Theis, et al., and W. Steinbrenner

A very important phase of the theory of flow toward wells upon which Forchheimer and his associates were relatively silent was the non-steady state. Once again, the first important published treatment came from Germany; but two more independent contributions appeared within a decade, one of them from a geologist in the United States who treated the problem from a completely different viewpoint from that of the other two. The accident of timing in the appearance of the three contributions eliminates confusion in grouping them together for discussion, and in fact permits the presentation of a virtually complete account of the present status of non-steady-state analysis, since very little of a general analytical nature has been added to the original contributions of these three men.

The first investigator to produce anything of important practical value on the non-steady state of flow toward a well was Hermann Weber, whose publication in 1928 [94] is still one of the most complete treatments of the subject.

As illustrated in Fig. 12, Weber considered the case of a gravity well penetrating the full depth of a pervious stratum overlying a horizontal impervious base. He assumed no natural ground water flow, so that the original water table could be represented as a horizontal plane at elevation H above the impervious base.

Assuming pumping to have begun at time $t = 0$, and holding the water level in the well constant at elevation h_o, Weber visualized the phreatic surface at any subsequent instant as taking the form indicated in Fig. 12. He defined the radius of influence, R,[21] as the radial distance from the well to the boundary of the region in which a lowering of the original water level existed at the instant in question. This was simply an adaptation to the transient case of an idea originally expressed by Adolph Thiem [79]. Theoretically, the radial distance to the point of zero drawdown was infinite from the outset. However, Thiem and others had long since established the fact that in any actual case the drawdown became negligible within a few hundred feet of the well. Consequently, Weber's use of a relatively large but finite value of radius of influence had the advantage of practical validity in addition to the fact that it was a convenient analytical device.

Weber based his analysis on the Dupuit-Thiem assumptions, although he was aware of the existence of a free discharge surface, and pointed out, as many others had not, the inaccuracy of the Dupuit-Thiem analysis in the vicinity of the well. According to Weber's conception, discharge during the period of transient flow conditions resulted entirely from the drainage of the cone of depression bounded by the drawn down portion of the phreatic surface and the plane of the original water table. It therefore followed that flow through the vertical cylindrical surface at distance R at any instant was zero, rate of discharge into the well was that computed from the Dupuit-Thiem equation using the appropriate value of R, and flow through any intermediate vertical section could be expressed by an equation of the form:

$$Q_r = Q\left[1 - \left(\frac{r}{R}\right)^{a}\right] \tag{27}$$

where Q_r = rate of flow through the arbitrary section at time, t,

Q = rate of discharge from the well assuming steady flow under the conditions existing at time t,

R = radius of influence at that instant,

r = distance from well center-line to an arbitrary vertical section $(0 \leqslant r \leqslant R)$,

[21] Weber, and possibly others before him, called this distance "die Reichweite." The term "radius of influence" is widely used in English for the same distance.

and α = an exponent whose value depended upon the shape and manner of variation of the drawdown curve at successive intervals of time.

Substituting for Q_r its value according to the Dupuit-Thiem assumptions and integrating, Weber obtained

$$Q = \frac{\pi k(H^2 - z^2)}{\ln \frac{R}{r} - \frac{1}{\alpha}\left(\frac{R^\alpha - r^\alpha}{R^\alpha}\right)} \tag{28}$$

where r, z = coordinates of a point on the drawdown curve,

R, H = coordinates of point of tangency of drawdown curve to original ground water table,

Q = rate of discharge from well at the instant in question.

He then solved equation (28) for z, expanded the result as an infinite series, neglected higher-order terms, and obtained:

$$z = H\left\{1 - \frac{Q}{2\pi k H^2}\left[\ln \frac{R}{r} - \frac{1}{\alpha}\left(\frac{R^\alpha - r^\alpha}{R^\alpha}\right)\right]\right\} \tag{29}$$

To determine R as a function of time, he derived an expression for the volume of the cone of depression at an arbitrary instant, and set it equal to the integral of Qdt up to that instant. To solve the resulting equation it was necessary to make some assumption about the variation of Q with time. Assuming Q constant, he obtained:

$$R = C\sqrt{\frac{Hkt}{n'}} \tag{30}$$

where t = time

and n' = effective porosity, that is, the ratio of volume of voids actually drained of water to the total volume of the cone of depression.

Consideration of the manner in which the drawdown curve progressed led Weber to the conclusion that a value of 1 was appropriate for during the early stages, and a value of 2 later. Thus, for

$$1 \leqslant \alpha \leqslant 2$$

it followed that

$$3.46 \geqslant C \geqslant 2.82$$

indicating an average value of 3 for the constant C, so that

$$R = 3\sqrt{\frac{Hkt}{n'}} \tag{31}$$

He concluded from equation (31) that the value of radius of influence was independent of the rate of discharge, provided the latter remained constant, and provided values of drawdown were not large.

Weber went on to investigate the effect on his results of a number of less simple hypotheses: He concluded, for example, that the influence of Q upon R would not be great even under the assumption of a variation of Q with time according to an equation of the form:

$$Q = Q_o + \frac{K_1}{t + K_2} - \frac{K_1}{K_2} \tag{32}$$

where K_1, K_2, and Q_o are constants. The case of a recharge well yielded the same expression for R as an ordinary well. An investigation of the rate at which the value of R progressed showed that the initially high velocity of the point (R, H) dropped almost immediately to a low value and then approached zero asymptotically. Application of the same analysis to various well groups gave expressions for radius of influence as a function of time in problems involving wells arranged in a circle, a rectangle, and in several rows. The case of an artesian well was also treated, with account being taken of the volume change accompanying the drawing off of water from an aquifer under pressure. Finally, some consideration was given to the practical limit of increase of R as a result of natural process of replenishment.

In the course of his analysis Weber pointed out the fallacies in Schultze's [54] argument and also showed that equation (28) reduced to the Dupuit-Thiem expression when $\alpha = \infty$. The basis of superiority of Weber's equation over that of Dupuit and Thiem, as indicated by Weber in his paper, was of course the fact that its validity was not restricted to cases of flow in the steady state. Furthermore, Weber's drawdown curve fitted the boundary conditions better than the Dupuit-Thiem expression, and his results were in somewhat better agreement with field data. One question which Weber left unanswered—in fact, he seems to have decided in favor of discretion against valor and left it unasked as well—was the evaluation of the effective porosity, n′. His definition of the term shows that he recognized the difficulty; but it was not, strictly speaking, a part of his problem; and as a matter of fact, the evaluation of n′ leads to considerations of capillary phenomena, drainage, and transient flow which extend beyond the limits of the subject of flow toward wells.

The geologist mentioned at the beginning of this section was Charles V. Theis of the United States Geological Survey, who published three papers on non-steady flow toward wells [73, 74, 75] during the years 1935 to 1940. Theis' approach was by way of an analogous heat-flow problem, for whose solution he was indebted to C. I. Lubin. The heat-flow problem involved the variation of temperature with time at a point in an infinite plane as a result of the introduction of a line source of strength Q in a position perpendicular to the infinite plane.

The equation which Theis derived from this analogy can be applied to seepage toward a gravity well in the following form:

$$H - z = \frac{Q}{4\pi kH} \int_{u = \frac{n'r^2}{4kHt}}^{u=\infty} \frac{\epsilon^{-u}}{u}\, du \tag{33}$$

where Q, H, z, k, r, n′, and t have the same meanings as in Weber's work, and the definite integral is carried over unchanged from the heat-flow analogy, with the variable of integration reexpressed in terms appropriate to the ground water problem.

Appraising the practical validity of equation (33), Theis pointed out that it was a theoretically rigorous solution of the problem of seepage toward a gravity well, subject to the following assumptions: (1) a homogeneous porous medium of infinite areal extent; (2) a fully penetrating well of infinitesimal diameter; (3) constant coefficient of transmissibility (see below); and (4) zero time-lag between fall in water-table and corresponding increment of discharge.

Investigation of the influence of these factors showed that the only one which could cause serious errors was variation in the coefficent of transmissibility. Theis defined this quantity as the rate of flow through the porous stratum per unit of horizontal distance transverse to flow. It appears in equation (33) as the product, kH, which is of course constant for a given case. However, the coefficient of transmissibility varies both with time and location during non-steady seepage, so that the product kH introduces an error of increasing magnitude as time and drawdown increase. It follows that the validity of the equation for gravity wells is restricted to cases involving small drawdowns.[22]

However, the Theis equation has the advantage of adaptability to discontinuous variations in rate of discharge. For example, the process of recovery following sudden stoppage of pumping can be analyzed by the introduction into the Theis equation of a second integral, opposite in sign to the original one, and measuring time from the instant at which pumping stopped. Thus:

$$H - z = \frac{Q}{4\pi kH}\left\{\int_{u=\frac{n'r^2}{4kHt}}^{u=\infty}\frac{\epsilon^{-u}}{u}\,du - \int_{u=\frac{n'r^2}{4kHt_s}}^{u=\infty}\frac{\epsilon^{-u}}{u}\,du\right\} \qquad (34)$$

where t_s = time measured from the instant at which pumping stopped. Likewise, other variations in rate of discharge could be treated by this method.

The effective porosity, n', in equation (33) appeared in Theis' work as a factor called the specific yield, defined as the volume of water drained from a unit volume of saturated water-bearing material under gravity drainage. Thus, in the case of a gravity well the specific yield can be identified with the effective porosity as used here. However, in the case of an artesian well, the significance of this factor becomes somewhat less simple because it properly depends upon the elastic properties of the aquifer, the compressibility of the water, and the rate of leakage from the confining strata. Considerable attention has since been given to this matter by Jacob (q.v.).

A considerable quantity of field data substantiating the validity

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[22] An interesting comparison of Theis' and Weber's analyses is given by A. Casagrande (q.v.).

of the Theis equation was collected and published during the same period by another American geologist, L. K. Wenzel [95, 96, 97]. Wenzel conducted numerous field tests in which he not only checked Theis' equation but also investigated Adolph Thiem's method of measuring ground water velocities and conducted numerous measurements of permeability of natural soils in situ.

The same problem of non-steady seepage toward a fully-penetrating gravity well was analyzed in 1937 by Steinbrenner [70].[23] Steinbrenner concluded that the value of radius of influence, R, could be expressed as

$$R = 1.5\sqrt{\frac{Hkt}{n'}} \tag{35}$$

and that the drawdown curve at any instant could be expressed by the equation:

$$H - z = \frac{Q}{2\pi kH} \ln \frac{R}{r} \tag{36}$$

Comparison of Steinbrenner's equations (35) and (36) with Weber's equations (31) and (29), respectively, indicates that the results obtained by the two men are essentially identical in form, but that the values of their empirical constants are different. Thus Weber's constant, C = 3, compares with Steinbrenner's value of 1.5; and if the value of the exponent, a, in Weber's equation (29) is taken as infinite, Steinbrenner's equation (36) follows immediately.

In conclusion, it should be reemphasized that one of the most serious shortcomings of all of the foregoing theoretical treatments of transient flow phenomena is the assumption of instantaneous change from complete saturation to the final value of effective porosity in the wake of the receding drawdown curve. F. H. King [35] and others have shown this to be an exceedingly complex process, even when not further complicated by recharge from rainfall.

A. F. Samsioe

From a different area and a different background, in about the middle of this period, came several important contributions from a Swedish engineer in a paper published in 1931 [53]. A. F. Samsioe approached the analysis of seepage toward an artesian well by way of

[23] A digest of Steinbrenner's work may be found in Terzaghi's text on theoretical soil mechanics [72].

potential theory. Proceeding from the fundamental case of three-dimensional radial flow toward a point sink in an infinite porous mass, he idealized an artesian well as a line of point sinks, and adapted the results to various cases of practical significance by adjusting the theoretical expression to the appropriate boundary conditions. In his simplest practical case, he considered an artesian well of radius, r_o, penetrating a distance, a, into a semi-infinite porous mass overlain by an impervious stratum, as shown in Fig. 13 (assuming $b = \infty$), and derived the following equation for the steady state:

$$s = \frac{Q}{4\pi ka} \ln \left[\frac{-a - z + \sqrt{r^2 + (a - z)^2}}{a - z + \sqrt{r^2 + (a + z)^2}} \right] \qquad (37)$$

where s = drawdown of piezometric head at an arbitrary point

and a = penetration of well below impervious stratum

and r, z = radial and vertical coordinates, respectively, of the point in question.

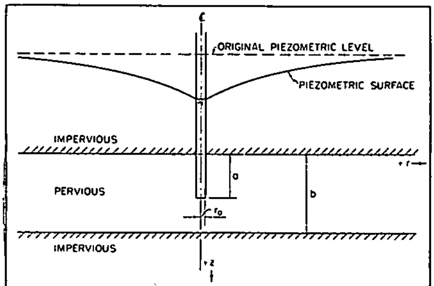

FIG. 13: PARTIALLY PENETRATING ARTESIAN WELL

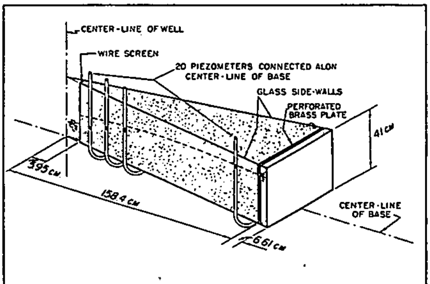

FIG. 14: SKETCH OF MUSKAT'S MODEL

Part of the problem of adjusting to the boundary conditions arose from the absence of the radius, r_o, in equation (37). This was an obvious result of the analytical device being used; but it just as obviously destroyed the accuracy of the solution at any point not far enough from the well for the value of r_o to be negligible in comparison.

In extending his analysis to the more restricted case of a pervious stratum of finite depth, Samsioe made use of the method of images, the earliest application of which to ground water motion had been by Forchheimer in connection with potential-theory solutions of other well problems [22].

A statement of the principle of the flow net as applied to axially symmetrical three-dimensional flow[24] was also included in this paper, as well as the earliest published presentation of the principle of the transformed section for two-dimensional flow in homogeneous anisotropic soils having maximum and minimum permeability in perpendicular directions.

Although Samsioe's results are satisfactorily accurate, his equations are not easy to use—a feature which they share with the solutions to the same problems subsequently developed by Muskat and his associates. However, Samsioe did demonstrate, by numerical solutions of several representative cases of partially penetrating wells, the relatively insignificant reduction in rate of discharge resulting from a large reduction in depth of penetration in a stratum of finite thickness.

A. Casagrande

The transition in the development of ground water theory in engineering from the predominant background and point of view of Thiem and Forchheimer to the wide variety of approaches and applications of the present can perhaps be observed most clearly in the work of Arthur Casagrande, whose contributions have covered many different phases of the field of soil mechanics and foundation engineering. However, many of his ideas in ground water theory have reached practicing engineers only through a course in seepage which he has presented at Harvard University since 1934. This course and several similar ones which it has inspired elsewhere constitute a detailed coverage of the aspects of this specialized subject which are of significance in civil engineering.

The flow net, although its conception as a method of seepage analysis is properly attributed to Forchheimer in Germany and to Richardson in England, was not widely applied even in those countries until Casagrande had developed it into the versatile analytical tool which it has now become. Casagrande's contribution in this case consisted essentially of suiting to the requirements of engineering practice an idea which had never actually been exploited by its originators very far beyond the demonstration of its theoretical validity. And although the flow net is restricted in its usefulness largely to two-dimensional flow problems, some of the details of Casagrande's presentation are of

[24]The radial flow net later developed by Taylor.

more general significance. With an understanding of the behavior of a phreatic surface at a discharge face, for example, Kozeny would have avoided some of the mistakes in his analysis of gravity flow and flow toward gravity wells.

Casagrande's presentation of Weber's work includes several simplifications: It was noted that in deriving equation (29) Weber had simplified his solution by use of infinite series. However, beginning with equation (28), Casagrande accomplishes the same end by noting that for drawdowns of not more than a tenth of the original depth of ground water stream, the following approximation is acceptable:

$$H^2 - z^2 = (H + z)\,(H - z) \approx 2H\,(H - z) \tag{38}$$

Equation (29) of Weber then follows immediately. Casagrande's simplification is of course subject to the same restriction as Weber's, but the nature of Casagrande's approximation is clearer. The same relationship may be used to simplify the Dupuit-Thiem equation, which can be written:

$$s = \frac{Q}{2\pi kH} \ln \frac{R}{r} \tag{39}$$

where $s = (H - z) = \text{drawdown}$

In appraising the Weber and Theis equations, Casagrande finds it useful to introduce a time factor, T, defined as follows:

$$T = \frac{n'r^2}{4kHt} \tag{40}$$

Reexpressing Weber's equation (29) in terms of s and T, and neglecting small quantities on the basis of the assumption that

$T < < 1$

he then evaluates s for values of $\alpha = 1$ and 2, and arrives at the following as an average:

$$s = \frac{Q}{4\pi kH} \left[\ln \frac{1}{T} - 0.6 \right] \tag{41}$$

Equation (41) may then be compared with Theis' equation. After evaluating the definite integral by series expansion and neglecting terms containing the first and higher powers of the argument u (= T), the Theis equation reads:

$$S = \frac{Q}{4\pi kH} \left[\ln \frac{1}{T} - 0.577 \right] \tag{42}$$

Again, it should be noted that the basis for neglecting terms is the same in both Weber's and Theis' analysis—a fact which this comparison points up very clearly.

M. Muskat et al.

During the early 1930's a series of investigations ranging over a broad field of subject matter was being carried on in the laboratories of one of the large oil companies by Morris Muskat and a number of associates, including R. D. Wyckoff, H. G. Botset, D. W. Reed, and M. W. Meres. These investigations, intended primarily as a foundation for a treatise on the problems involved in flow of oil and oil-gas mixtures through rocks and sands, culminated in 1937 in the publication of a book of encyclopedic proportions treating all phases of flow of homogeneous fluids through porous media [44]. At intervals during the preparation of this work publications by Muskat and/or one or more of his associates appeared, in which certain of the pertinent problems were treated somewhat more in detail than was to be the case upon their inclusion in the book. Several of these shorter papers, as well as a considerable portion of the book, were concerned with flow toward wells.

Muskat's point of view was consistently that of a theoretical and experimental physicist more than of an engineer, so that his appraisal of an analytical method or of an experimental procedure tended occasionally to be less concerned with the practical needs of the moment than with the more detached considerations of theoretical consistency.[25] However, the quantity of experimental data obtained, the range of subject matter treated, and the completeness of the survey of the work of predecessors and contemporaries, both of a theoretical and of an experimental nature, and involving water alone as well as multi-phase systems, made the accomplishments of this group of great value to those who followed.

Muskat approached the problem of partially penetrating artesian wells by way of electrical model investigations, in which an electrode in the form of a rod representing a well was embedded in the center of a large disk representing the porous medium [46]. The analysis of

[25] A statement of the civil engineer's point of view in connection with Muskat's treatment of problems in ground water flow may be found in a review of his book published by A. Casagrande in 1939 [11].

the flow conditions was accomplished with the help of potential theory, using the method of images. The problem was the same one that Samsioe had treated: A partially penetrating artesian well in a pervious stratum of finite thickness bounded by impervious strata on the top and bottom (Fig. 13).

Muskat encountered the same difficulties in satisfying boundary conditions as Samsioe had, and overcame them in a similar way. A plot of equipotential lines in a radial vertical section indicated that deviations from the pattern corresponding to full penetration of the well were restricted to a region within a distance from the well of one or two thicknesses of the pervious stratum for any penetration of half its thickness or more. This was in agreement with Samsioe's conclusion that penetration of more than fifty per cent was for practical purposes the same as full penetration. The analysis finally led Muskat, as it had Samsioe, to an equation whose solution involved trial-and-error adjustments of elementary discharge rates. His proposed approximate formula, however, was considerably more forbidding than Samsioe's had been:

$$Q \doteq \frac{2\pi kb(\Delta p/\mu)}{\frac{1}{2\left(\frac{a}{b}\right)}\left[2\ln\frac{4b}{r_o} - \ln\frac{\Gamma(0.875\,a/b)\,\Gamma(0.125\,a/b)}{\Gamma(1-0.875\,a/b)\Gamma(1-0.125\,a/b)} - \ln\frac{4b}{R}\right]} \tag{43}$$

where Q = rate of discharge
k = coefficient of permeability
b = thickness of pervious stratum
Δp = pressure drop (assumed large in comparison to h)
μ = viscosity of liquid
r_o = well radius
R = radial distance to outer boundary
a = well penetration
and Γ = gamma function

Muskat went on to adapt the same analysis to a stratified or anisotropic earth [45]. In the case of stratification, assuming essentially the condition of maximum permeability in the horizontal direction and minimum in the vertical, he solved the problem using the analytical equivalent of the transformed section.

Wyckoff, Botset, and Muskat conducted a series of sand-model investigations of flow toward a gravity well [98]. Fig. 14 illustrates the model, which represented a 15-degree sector of the region surrounding a well. Their results indicated that the Dupuit-Thiem equation gave accurate values of discharge rate when used in the form

$$Q = \frac{\pi k \, (H^2 - h_o^2)}{\ln \frac{R}{r_o}} \tag{44}$$

where h_o, r_o = coordinates of a point at the water level in the well at its rim.

However, since the equation was based on assumptions which were not valid under certain conditions, and since it could not be used to determine the shape of the phreatic surface, the authors rejected the Dupuit-Thiem approach entirely, and Muskat later derived the same equation by an approximate method which he found preferable [44]. The substitute derivation led to a more accurate location of the drawdown surface, although the equation was not simple.[26]

The model tests also indicated that the variation of piezometric head along the base satisfied the equation:

$$\frac{h_b^2 - h_o^2}{\ln \frac{r}{r_o}} = \frac{H^2 - h_o^2}{\ln \frac{R}{r_o}} \tag{45}$$

where h_b = fluid head at distance r from well centerline, measured along model base.

To account for the effect of a capillary layer above the phreatic surface, Muskat and his colleagues proposed the following equation for rate of discharge:

$$Qg + c = \frac{\pi k \, (H - h_o) \, (H + h_o + h_o)}{\ln \frac{R}{r_o}} \tag{46}$$

where $Qg + c$ = total rate of discharge, including that from the capillary layer

and h_c = thickness of capillary layer.

[26] Muskat seems to have given more serious thought to the question posed by the limited validity of the Dupuit-Thiem equation than anyone before or since. His conclusion: Its accuracy, when it *is* valid, is a lucky accident.

It should be noted in connection with these tests that the sector had a vertical dimension of only about 16 inches, as compared to a radius of about five feet from well center to entrance face. Proportions such as these would make it very difficult to secure any accurate measurements of the sharp curvature of the drawdown surface in the immediate vicinity of the well. In Muskat's model the location of the drawdown curve was accomplished by observation of dye-stream paths.

Muskat also treated multiple-artesian-well systems at considerable length. Cases involving finite numbers of regularly arranged wells and various infinite arrays were included.

Recent Developments: 1940-1950

During the final ten years to be covered in this summary the advances have become more widely scattered in their origins and applications, and the contributions of particular individuals have tended for the most part to affect more limited areas within the general field of seepage toward wells than had the work of Forchheimer, Slichter, Casagrande, Muskat, and others. A review of this final period has therefore been divided into separate sketches of predominantly analytical, experimental, and observational progress. It will be noted that the contributions made during this time are generally of the nature of development of details which, although none the less important for that reason, follow in the directions indicated in the fundamental research and analysis of the preceding period.

Analytical Investigations

For nearly twenty years in England, R. V. Southwell and a group of colleagues have been developing and applying an analytical procedure called the relaxation method, which has been applied effectively to the analysis of flow toward wells. The method, as presented by Southwell in numerous publications [66, 67, 68], is one of successive approximations, which is distinguished from other variations of the same idea only in the mechanics of its application. The method has been applied by its originators to a wide range of types of problem in engineering and theoretical physics.

Of particular interest in the present discussion is the application of the relaxation method to problems governed by what Southwell calls [1] the quasi-plane-harmonic equation:

$$\frac{\partial}{\partial x}\left[\chi\left(\frac{\partial\phi}{\partial y}\right)\right]+\frac{\partial}{\partial y}\left[\chi\left(\frac{\partial\phi}{\partial x}\right)\right]+Z=0 \qquad (47)$$

where χ and Z are functions of x and y. Laplace's equation, applied to axially-symmetrical three-dimensional flow, may be expressed in cylindrical coordinates and reduced to the form,

$$\frac{\partial}{\partial r}\left[r\left(\frac{\partial\phi}{\partial r}\right)\right]+\frac{\partial}{\partial z}\left[r\left(\frac{\partial\phi}{\partial z}\right)\right]=0 \qquad (48)$$

where r, z = radial and vertical coordinates, respectively,

and ϕ = piezometric head $= \dfrac{p}{\gamma w} + z$.

It follows from a comparison of equations (47) and (48) that the problem of flow toward a gravity well falls into the category typified by the quasi-plane-harmonic equation.

Among Southwell's collaborators, F. S. Shaw has concentrated upon application of the relaxation method to problems in seepage through porous media [55, 56, 57]. In the Southwell-Shaw approach to the well problem the presence of an unknown boundary—namely, the phreatic surface—is a troublesome feature. In the relaxation analysis of this type of problem a first approximation of the solution is outlined on the basis of an initial estimate of the unknown boundary. Local inconsistencies are then corrected to a satisfactory degree of accuracy and the resulting solution checked against the physical requirements for the whole. The initial estimate is revised, and the process repeated until a satisfactory degree of accuracy and consistency from all standpoints is reached. Thus, the strategy of the relaxation method is similar to that of other numerical procedures. Unfortunately, a discrepancy disclosed by the check against physical requirements does not carry with it an indication of the magnitude or direction of the error.

However, a modification of the Southwell-Shaw treatment of gravity flow problems has been developed by S. T. Yang in an analysis of steady-state seepage toward a gravity well [99]. Yang's modification reduces the time and labor entailed in the trial-and-error location of the unknown boundary by making it possible to assess the accuracy of an original estimate during the numerical process of elimination of local discrepancies and to make appropriate revisions while still air-borne.

D. W. Taylor suggests the adaptation of the method of the flow net to the same problem [71]. He notes that in a radial section the curvilinear quadrilaterals would no longer be square, but would have sides whose ratio of width (transverse to flow) to length (direction of flow) would vary inversely as the radius. The introduction of this feature partially defeats the objective of the flow net, which is to provide accuracy without analytical complications. But the method has been used with satisfactory results for single-well problems.

Among the most recent contributions to the list of applications of theory to practice are two publications by R. A. Barron, which are concerned chiefly with mathematical analyses of the flow phenomena involved in the use of wells to drain a fine-grained soil subjected to consolidation [3, 4]. The wells are of the artesian type, and are assumed to penetrate the full thickness of the pervious stratum.

Recent Experimental Investigations

During the past ten years a series of sand-model tests have been conducted by A. Vibert [92, 93] in France. However, the value of his experimental results cannot be judged, since his publications do not specify the size of his model nor any of the technique of the testing. The analytical material with which Vibert accompanied the reports of his model-test results was based on Kozeny's maximum-discharge theory. And his attempt to derive a rigorous equation for rate of discharge from a gravity well was based on simplifying assumptions no less restrictive than those of Dupuit and Thiem.

An extensive experimental investigation was conducted at the University of Illinois by H. E. Babbitt and D. H. Caldwell [2]. A sand model and an electrical model provided the experimental data. The adaptation of the electrical model to a three-dimensional flow problem had not been accomplished before these tests. A pressed carbon wedge having uniformly increasing thickness was used to simulate a thin sector of the region surrounding a well. In other respects the technique of the electrical model tests was similar to that used by earlier investigators of two-dimensional problems.

The sand model was similar to other such models in that it was made to represent a 15-degree sector of the region around a well, and had a vertical dimension of about 16 inches. However, the Babbitt and Caldwell model was of considerably larger radius than the others —about 100 inches. It should be noted that this particular feature would not in itself increase the accuracy of the results, since it amounts simply to extending the region in which the Dupuit-Thiem equation is valid, without magnifying the effect at the well circumference.

The results obtained by Babbitt and Caldwell substantiated the Dupuit-Thiem equation for rate of discharge from a gravity well; but as an expression for the phreatic surface the authors proposed the following:

$$Q = \frac{\pi k H (H - z)}{2.3 C_x \log_{10} \left(\frac{R}{\frac{1}{10} H} \right)} \tag{49}$$

where C_x = drawdown, expressed as a fraction of H, at a point (r, z) under conditions of maximum flow toward a well of radius H/10,

and other symbols have the meaning they have had before. Equation (49) was derived on the basis of the proportionality of Q to the drawdown at the point in question.

The effects on the rate of discharge from a gravity well of a sloping water table, of a non-circular area of influence, of location of the well at a site other than the center of the area of influence, and of partial penetration of the pervious stratum were also investigated with the help of sand models. Finally, a sand-model study of interference among wells in regular groups numbering up to five was made.

Results of the various tests indicated generally satisfactory agreement with theoretical expressions. The Dupuit-Thiem equation was judged accurate for computation of rate of discharge from a well drawing from a sloping water table in the case where the water table was parallel to an inclined impervious base. The variation in rate of discharge corresponding to an eccentricity in well location of over fifty per cent of the radius to the entrance face was found to be less than five per cent. The authors plotted a set of curves from which to select the ratio of rates of discharge of partially and fully penetrating wells for various combinations of values of other factors. Muskat's theoretically developed equations expressing the effect of interference among individual wells in well groups were checked to the satisfaction of the authors by the use of a thirteen-foot square sand bed about thirteen inches deep.

V. E. Hansen (101) performed an interesting and somewhat different type of experimental investigation of steady flow toward gravity and artesian wells in 1949. Prandtl, half a century ago, noted that small transverse displacements of a flexible membrane under uniform tension in all directions in the plane of the membrane could be expressed by Laplace's equation in two independent space variables. This suggested the study of the behavior of such a membrane as a suitable analogy to a flow problem; but the idea has not been widely exploited. Hansen, however, built an apparatus that permitted him to apply appropriate boundary conditions to a thin membrane and measure its transverse displacements as an analogous mechanical representation of the variations of piezometric head in some problems of steady flow toward single and multiple wells.[27] Hansen was primarily interested in multiple well problems, and has continued the work that began with the membrane-analogy tests. His more recent publications have appeared subsequent to the end of the period covered in this summary.

At about the same time that Hansen was completing his original investigation, H. P. Hall (100) was conducting a combined analytical and experimental investigation of steady flow toward a single gravity well. Hall's objectives were to determine as accurately as possible the phreatic surface in the immediate vicinity of a well, where Dupuit's assumptions are no longer valid, and to make an experimental check of the adaptation of Southwell's relaxation technique that had just been worked out by Yang (99). In the course of the investigation, Hall found it necessary to take account of capillary effects in the relaxation analyses of the various test cases and was able to establish a satisfactory check of observed flow conditions, including some significant distortions near the well. The experimental work was done in a sand-model representing a 15-degree sector of the region surrounding a well. To minimize capillary effects, the model was made unusually large, with a height of five feet, a radial length of over six feet, and a diameter of simulated well of about eight inches. With the

[27]The analogy, as applied to an axially-symmetrical three-dimensional flow pattern, can be improved from a theoretical standpoint by varying the thickness of the membrane in inverse proportion to the distance from the axis of symmetry. This refinement, with its obvious mechanical difficulties, was not a feature of Hansen's apparatus.

assistance of dye injections and a large number of piezometers in one of the lucite side-walls of the model, sufficient observations were made to determine detailed flow patterns for several different sets of boundary conditions. The results obtained were in general agreement with those of Muskat, Hansen, and Babbitt and Caldwell on points common to all of these investigations. Hall concluded by proposing a pair of empirical equations for locating the upper limit of the free discharge surface and the phreatic line near the well.

Recent Field Investigations

Applications of some of the more complex analytical material to certain specific problems in practice have been the subject of some important publications during this period: P. T. Bennett has published material on the design of relief wells [5]; F. B. Slichter has reported on the performance of relief wells [62]; and T. A. Middlebrooks and W. H. Jervis [43] have treated the subject of relief wells for dams and levees at some length. Meanwhile, C. E. Jacob has been one of the most frequent contributors to the continually increasing supply of new material from the United States Geological Survey.

Bennett discusses some of the theoretical considerations involved in the design of relief wells, and illustrates with field data and references to a specific case. As a basis for his theoretical work, Bennett refers to Jervis' development of some material originally derived by Muskat. The Jervis-Muskat relationships also formed the basis for the theoretical parts of the paper by Middlebrooks and Jervis (see below).

Slichter presents a brief report on the performance of some relief wells at Fort Peck.

Middlebrooks and Jervis have combined considerable theoretical and experimental work with the securement of their field data. Their problem is the control of underseepage beneath dams and levees in cases where the existence of a relatively pervious stratum introduces the danger of piping and formation of boils. The analytical approach is an adaptation of Muskat's analysis of artesian flow toward a row of wells from a line source parallel to it. Complications are introduced by the facts that both the line of wells and the line source are of finite length, and the wells are not fully penetrating.

Jacob's interests extend over the entire field of ground water technology, but several of his contributions have been directed rather specifically at seepage toward wells, usually of the artesian type. In 1940, in a treatment of the subject of artesian flow [32], he derived the fundamental differential equation for radial flow in an elastic artesian aquifer directly from hydrodynamic considerations, and showed that Theis' expression was a solution of that equation. Jacob's fundamental equation was of the form:

$$\frac{\partial^2 z}{\partial r^2} + \frac{1}{r}\left(\frac{\partial z}{\partial r}\right) = \frac{S}{kb}\left(\frac{\partial z}{\partial t}\right) \tag{50}$$

where r, x = coordinates of a point on the piezometric surface,
k = coefficient of permeability,
b = thickness of aquifer,
t = time,
and S = storage coefficient

The storage coefficient, S, was a dimensionless ratio defined as the volume of water released from storage in a column of aquifer of unit cross-sectional area under a unit reduction of piezometric head. Jacob demonstrated the dependence of S on the elastic properties of the porous medium and seeping fluid, and showed that it was the correct quantity to express Theis' specific yield in the case of an artesian well. In gravity flow the storage coefficient is equivalent to the effective porosity. Thus Jacob established Theis' relationship without the use of the heat-flow analogy.

Building on this foundation, Jacob later considered the complication of leakage into an artesian aquifer from above and its effect on the drawdown during discharge from the aquifer through a well [33]. As shown in Fig. 15, he considered the case of a horizontal artesian aquifer of thickness b and coefficient of permeability k resting on an impervious base and overlain by a semi-pervious confining stratum of thickness b′ and coefficient of permeability k′. Overlying the confining stratum was a pervious sand with an initially horizontal ground water surface. The system was imagined to be discharging through a well designed to draw from the artesian aquifer only. The analysis led to the expression

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\left(\frac{\partial s}{\partial r}\right) = \frac{S}{kb}\left[\left(\frac{\partial s}{\partial t}\right) + \left(\frac{k'}{b'S}\right) s\right] \tag{51}$$

as the fundamental differential equation for radial flow of water in

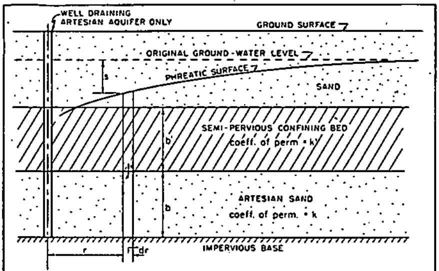

FIG. 15: RADIAL FLOW IN A LEAKY ARTESIAN AQUIFER
After Jacob

a leaky elastic artesian aquifer. The symbols all appear in Fig. 15 except S = storage coefficient and t = time. Comparison with equation (5) shows that the two equations are the same if leakage is not appreciable ($k' \approx 0$).

Jacob applied equation (51) to the analysis of three cases of practical import, including steady flow from an infinite aquifer, for which he used the solution obtained earlier by Steggewentz and Van Nes [69], and the non-steady-state condition. The analyses were of sufficient complexity to require the use of Bessel functions in the solutions; but both Jacob and his discusser, D. Kirkham, translated their equations into some useful curves from which similar problems can be solved without difficulty.

Jacob also devised a method of predicting the drawdown in an artesian well necessary for a desired rate of discharge [31]. Noting that the rate of discharge, Q, is related to the drawdown, s, in the following way:

$$s = K_m Q + K_w Q^2 \tag{52}$$

where $K_m Q$ = component of total drawdown accountable to losses through the porous medium

$K_w Q^2$ = component of total drawdown due to losses through the screen and in the casing;

he expressed the specific capacity, or rate of discharge per unit drawdown, as follows:

$$\frac{Q}{s} = \frac{1}{K_m + K_w Q} \tag{53}$$

In order to determine the variation of specific capacity with rate of discharge, he then outlined a procedure for measuring the values of

K_m and K_w by means of a multiple-step drawdown test on an existing well and a graphical evaluation of the pertinent soil properties.

Conclusion

The process of flow toward a well is not generally susceptible of simple analytical treatment even when the porous medium is assumed to be homogeneous and isotropic. Gravity flow is further complicated by the existence of a capillary fringe and the absence in nature of a well defined line of demarcation between saturated and dry soil. Theoretical analysis can therefore be no more than a guide at best; and such factors as non-homogeneity, anisotropy, and capillary phenomena introduce complications which make formal theoretical analysis practically hopeless. The Dupuit-Thiem equations, used cautiously and with full understanding of their limitations, have proved adequate for use in the determination of rate of discharge; and have been successfully applied to the measurement of coefficient of permeability in a region where the slope of the free surface is relatively small. This accounts for a large percentage of the problems of practical importance.

Among the fundamental problems of practical significance that remained to be carefully investigated at the conclusion of the period covered in this summary were two of particularly broad scope, namely (1) the non-steady state in cases involving large drawdown and (2) the development in detail of the analysis of flow toward multiple wells.

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The responsibility for errors of fact or judgment that remain in the paper rests with the author.

APPENDIX A. LIST OF SYMBOLS

The following list is a compilation of all symbols used in this paper. The dimensions of each quantity are indicated in square brackets in terms of force (represented by the letter F), length (by L), and time (by T). If the quantity is dimensionsless, the figure 1 is indicated in the square brackets; and in certain cases of constants which appear in dimensionally inhomogeneous empirical equations, no indications of dimensions are given.

A = cross-sectional area of a pervious mass, taken transverse to the direction of seepage [L^2]

a = depth of penetration of a partially penetrating artesian well into an artesian aquifer [L].

b, b' = vertical dimension of a horizontal stratum [L].

C = a constant = $f(\alpha)$ in Weber's equations [1].

C_x = an empirical constant, introduced by Babbitt and Caldwell, expressing drawdown as a fraction of the entrance water level, H, at an arbitrary point on the phreatic surface under conditions of maximum rate of seepage toward a gravity well of radius $\frac{1}{10}$ H [1].

d = (average) diameter of a soil grain [L].

H = height of the surface of a body of water above an arbitrary datum [L].

h = height of a column of water [L].

h_b = fluid head, measured at a point on the impervious base at a distance, r, from the center-line of a fully penetrating gravity well [L].

h_c = height of capillary rise [L].

h_o = depth of water in a well [L].

i = gradient = hydraulic gradient = loss of piezometric head per unit distance in the direction of seepage [1].

K = an empirical constant introduced by C. S. Slichter, determined by the porosity and geometric character of a porous medium.

K_m, K_w = empirical constants, introduced by Jacob, in connection with drawdown of the piezometric surface at an artesian well.

K_1, K_2 = empirical constants suggested by Weber in an equation for varying rate of discharge during transient flow toward a gravity well.

k, k' = coefficient of permeability [LT^{-1}].

L = length of a soil mass, measured in the direction of seepage [L].

N = number of wells in a group of wells [1].

n = porosity = ratio of volume of voids to total volume [1].

n' = effective porosity = ratio of voids occupied by seeping water to total volume [1].

p = pressure [FL^{-2}].

Q = rate of discharge [L^3T^{-1}]:

Q_{g+c} = total rate of discharge from a gravity well, including that from the capillary layer $[L^3T^{-1}]$.

Q_i = rate of discharge from the i-th well of a group of wells $[L^3T^{-1}]$.

Q_o = empirical constant in Weber's equation for varying rate of discharge during transient flow toward a gravity well $[L^3T^{-1}]$.

Q_r = rate of seepage through a cylindrical surface of radius r surrounding a gravity well at time t during transient flow $[L^3T^{-1}]$.

q = rate of seepage per unit of area transverse to the direction of seepage $[LT^{-1}]$.

$\bar{q}$ = rate of seepage of a ground water stream per unit width of cross-sectional area transverse to the direction of flow $[L^2T^{-1}]$.

R = radial distance from a well center-line to the point of zero or negligible drawdown; radius of influence [L].

R_{a_i}, R_{b_i} = radial distances from observation wells, a and b, to the i-th well of a group [L].

R_i = (1) distance from an arbitrary point to the i-th well of a group [L]; (2) radius of influence of the i-th well of a group [L].

r = radial distance from a well center-line, measured in a horizontal direction [L].

r_i = same as R_i (1) [L].

r_o = radius of a well [L].

r_{oi} = radius of the i-th well of a group [L].

$\bar{r}$ = shortest radial distance from a well to a straight-line sink or source (river bank, lake shore, etc.) [L].

r' = radial distance to a point of reference from the image of a given well [L].

s = drawdown of a phreatic or piezometric surface, measured vertically from its original elevation [L].

S = coefficient of storage [1].

T = (1) time factor $= \dfrac{n'r^2}{4kHt}$ [1]; (2) temperature, °C [1].

t = time [T].

t_s = time, measured from stoppage of pumping in Theis equation [T].

u = variable of integration in Theis' equation [1].

v = discharge velocity = rate of discharge divided by total cross-sectional area of porous mass $[LT^{-1}]$.

x = displacement in a horizontal direction [L].

$\bar{x}$ = horizontal distance from a line sink or source (river bank, lake shore, etc.) to an arbitrary point in a ground water stream [L].

y = displacement in a horizontal direction, at right angles to x [L].

Z = f(x,y) = variable coefficient in Southwell's quasi-plane-potential equation [various].
z = height of phreatic (or piezometric) surface above the level of the bottom of a fully-penetrating well [L].
z_a, z_b = height of water surface in observation wells, a and b, above the level of the bottom of a fully penetrating well [L].
z_i = height of water surface in i-th observation well, measured from the level of the bottom of a fully penetrating well [L].
z_0 = height, above the base of a fully penetrating well, of the point of contact between the phreatic (or piezometric) surface and the well circumference [L].
α = (1) constant in de Prony's pipe- and channel-flow equation; (2) exponent in Weber's equations [1]; (3) angle of inclination of the phreatic surface of a natural ground water stream, expressed as a slope referred to the horizontal [1].
β = constant in de Prony's pipe- and channel-flow equation.
Γ = gamma function [1].
γ_w = unit weight of water [FL^{-3}].
Δ = finite increment.
ϵ = base of Napierian (natural) logarithms.
η = constant, depending upon the nature of the soil, appearing in an early Dupuit equation [$L^{-1}T$].
$\eta' = \dfrac{\eta}{\text{porosity}}$ [$L^{-1}T$].
μ = coefficient of viscosity [$FL^{-2}T$].
Σ = summation.
ϕ = (1) potential [various]; (2) piezometric head of water = $(\dfrac{p}{\gamma_w} + z)$ [L].
χ = (1) cross-sectional area of stream in de Prony's pipe- and channel-flow equation [L^2]; (2) f(x,y) = variable coefficient in Southwell's quasi-plane-potential equation [various].
ω = wetted perimeter in de Prony's pipe- and channel-flow equation [L].
ln( ) = natural logarithm of ( )
$\approx$ = is approximately equal to
$>$ = is greater than
$<$ = is less than

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SYMPOSIUM ON AIR POLLUTION

THE STATUS OF KNOWLEDGE OF AIR POLLUTION TODAY

By Charles R. Williams,* Ph.D.

(Presented at a meeting of the Sanitary Section, BSCE, held on March 3, 1954.)

There is a vast literature in the field of air pollution culminating in the report of the United States Technical Conference on Air Pollution (1). At this conference there were 97 papers in sections on agriculture, equipment, health, instrumentation, legislation and meteorology. A glance at the table of contents is sufficient to indicate the magnitude of the job of attempting to summarize the present status of knowledge of air pollution. One obvious fact is that there is an almost unlimited number of facets and that the over-all picture is extremely confused.

One of the most serious problems in the field is directly related to the variety of sciences which are necessary to deal with all aspects. Reports and papers appear in a large number of technical and semi-technical journals, some relatively obscure. In addition, there are many monographs from various symposia and reports of municipal and state agencies.

It was recommended by the meteorology panel at the Technical Conference on Air Pollution (1—p. 12), "That the organization be undertaken of existing and current literature on all phases of atmospheric pollution so that everyone may be aware of the work of those in other phases. Publication might be in toto or in abstract form." This is an extremely valuable suggestion, but one involving tremendous amounts of library research. The meteorologists have themselves taken an important first step in the publication of Meteorological Abstracts by the American Meteorological Society covering Atmospheric Pollution, Aerobiology and Carbon Dioxide in the Atmosphere.

The purpose of this report is to summarize what has been done to date so that we may better plan for the future. The control of pollution by engineering means and measurement are also extensive

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fields. These will be discussed in subsequent papers. This must go on without awaiting the results of long-time studies on the nature and effects of contaminants. It should be emphasized here that industry is not alone as a source of air contamination. It is becoming increasingly evident that the public, as a result of its very numbers is a frequent primary factor in city air pollution. Exhausts from automobiles, burning rubbish, smoke from home heating units and many other individual activities make each person a contributor as well as a victim.

The effects of air pollution are generally classified as those of economic loss, injury to health and nuisance effects. This is usually an over-simplification since, particularly in large cities, all three may result. While excess dust on the back porch, dirt on clothes hung out to dry and offensive odors are all definitely nuisances, they may also be injurious either to property or health.

We are faced with two quite different basic problems regardless of whether the effect is economic, injurious to health or merely a nuisance. One of these is the single unusual incident such as those at Meuse Valley, Belgium and Donora, Pennsylvania. These occurrences were spectacular and widely publicized because of the loss of life involved. Single incidents without apparent human injury occur quite often, usually with property damage such as discoloration of paint on houses, ruin of finishes on automobiles, damage to machinery and destruction of fabrics. They generally are the result of process failure, careless release of large quantities of corrosive effluents, atmospheric peculiarities or combinations of these. They may be obvious both as to primary cause and solution.

The more difficult case is the continuing exposure resulting from routine release of contaminants, often in relatively small amounts. These may come from industry, municipal dumps, private homes, motor vehicles, and railroads. They go on day after day, usually for years. Any physical damage such as corrosion of metals, discoloration of paint or erosion of stone is difficult to evaluate precisely because some of these processes take place naturally and the effect of pollution is merely to accelerate the normal action.

Economic Loss

A wide variety of effects of pollution may cause economic loss to individuals and to the general population. This includes such things as damage to livestock and vegetation; corrosion of metals and structural materials, damage to clothing and other fabrics; damage to automobile finishes. These may all occur either as a result of single, short-time incidents or over a long period of time. One important segment is damage to livestock and vegetation. There has been considerably more study of these effects than any others for many obvious reasons. For example, there is an extensive literature throughout the world on the effects of fluorides on animals and vegetation. The bibliography numbers several hundred references. In fact, this is one air pollution problem which is fairly well understood. While there are many unanswered questions as to the amounts of fluoride required to produce damage in various species of plants and animals and in some cases there is a discouraging similarity between chemical effects and disease there is little doubt as to the mode of entry and physiological effect. There is an interesting controversy as to the roles of fluoride dust and HF gas, but this is related to the part of the country in which the damage occurs. The kind of vegetation, type of soil and weather are all factors. It is fairly obvious from studying the arguments on both sides of the dispute that both dust and gas can produce fluorosis. If one happens to be working in Tennessee, dust appears to be most significant, while in the Pacific Northwest HF gas appears to be the important case. This case emphasizes the extreme complexity of the whole problem and the necessity for a broad viewpoint.

For many years the smelting industry has been dealing with sulfur dioxide as an ever-present problem in their operations. Trail, B. C. and Ducktown, Tennessee, are monuments to the destructive effects of sulfur dioxide on vegetation. As a result of such occurrences, SO_2 and related compounds have been studied intensively from every aspect.

Economic loss from the operations of a single plant usually result in effective pressure to force control measures. In the case of general urban pollution, however, usually no individual can be singled out, since there is rarely an outstanding single cause. Control in this case can be brought about only by cooperative efforts of industry and the public.

Injury to Health

The question of the role of air pollution on the health of a community is so involved that the job of answering it seems almost insurmountable. Even from the standpoint of a relatively severe short-time exposure the answers do not come easily. This is borne out by the fact that the intensive study of the so-called Donora (3) incident failed to reveal conclusive answers to all of the questions which were raised. This can be attributed in a large measure to the fact that investigations of such occurrences take place after they are over and not while they are going on. The general conclusion of the Donora study was that no single polluting agent was present in sufficient quantity to account for the effects on the population but that apparently some combination of contaminants occurred which was responsible. Bearing in mind the difficulties in studying these effects of a severe short-time occurrence it is possible to visualize the problem of evaluating the more nebulous effects of long-time exposure to much smaller amounts of contamination. In the latter case, one has much more opportunity to study the contamination itself and in this phase of the work considerable progress is being made. A comparison of the Second Technical and Administrative Report on Air Pollution Control in Los Angeles County (2) with the one issued a year previously (4) shows the advances which have been made in analytical methods and in an evaluation of the contaminants which are present. At the beginning of this work much emphasis was placed on sulfur dioxide which is usually given the number one position as an air contaminant in large urban areas. This is partially the result of its known irritating effect, partially its ease of determination and partially its abundance. After a substantial reduction of SO_2 in the Los Angeles area failed to provide any appreciable relief, emphasis was shifted to a study of other possible irritants. This led to a discovery of the fact that certain hydrocarbons including gasoline vapors could be oxidized in air to form compounds capable of producing all the known effects, including eye irritation, found in Los Angeles smog.

A much more difficult challenge is that of studying the possible effects of atmospheric contaminants on the general health of persons exposed. This introduces an epidemiological problem of staggering proportions. To date no comprehensive conclusive studies have ever been made on any population group for the purpose of evaluating the chronic effects of exposure to air pollution. The so-called Detroit-Windsor international program includes an approach to this problem. A study of the proposed plan for this group gives an idea of the variables which must be taken into consideration in such a study. Such factors as density of population, economic status, race, education, must all be evaluated. This will, of course, ultimately produce information as to the health of various groups, but it is not clear yet just how any relationship will be established between air contamination and the incidence of any particular kinds of diseases.

There have been some attempts in the past to approach this problem of chronic disease, but these have all been extremely limited. The incomplete data always create the impression that air pollution is responsible for increases in the incidence of certain diseases, but the methods of approach leave room for considerable doubt as to the validity of the conclusions.

For example, in studies made in Cincinnati, Pittsburgh, Chicago, Detroit, Nashville and Atlanta (5, 6) attempts were made to relate certain pulmonary diseases to air pollution. The cities were divided into areas according to differences in sootfall, which was the only measure of pollution, and the death rates for pneumonia, pulmonary tuberculosis and respiratory tract cancer were compared. In the cases of Atlanta and Nashville there were no data on pollution and areas were divided on the basis of "clean," "intermediate" and "dirty." The conclusion was drawn that all differences in death rates from the diseases selected were attributable to air pollution. All other factors were ignored.

A second type of approach as typified by a recent spot survey of a city in Maryland involves interviewing individuals in high and low dustfall areas determined by the "dubious method of dust pots placed throughout the city" (7—p. 2). It was stated in this study that the Socioeconomic status of the individuals in the two groups was nearly identical—on the basis of mechanical refrigeration, presence of a telephone, having a regular family physician, median monthly rent and median number of rooms per person. The one difference between the groups was that in the low dustfall area, 75% of the homes were owned by the occupants while in the high dustfall area 40% of the homes were so owned.

The medical data were obtained by Public Health nurses who filled out questionnaires to obtain information as to economic status and general health with particular relation to the lungs, heart and upper gastro-intestinal system. The general conclusion reached was that the frequency of the common cold was significantly greater in the high dustfall area than in the low dustfall area.

While studies of this type are a step in the right direction, they lose considerable value in the absence of data as to the nature of the contamination. The reason for such a paucity of information on the composition of the polluted air is largely financial. The cost of operating the Los Angeles County Air Pollution Control District for 1950-51 was nearly a half million dollars of which about $345,000 was for salaries and wages (2). This, of course, represents the cost of a program involving not only research but inspections and enforcement, issuance of permits involving engineering review, and public relations. Nevertheless with this vast expenditure there is no evidence in the reports of this organization that any attempt has been made to correlate the intensive evaluation of the composition of the smog with possible chronic disease in the population.

An answer to the question of the relation between air pollution and chronic disease must be found because of the many indications that a polluted atmosphere is not conducive to the best of health. The greatest need today is for some type of coordination of the many widespread activities which are now going on. There are many outstanding investigations being conducted in specific related fields, but there is no evidence of any fully coordinated study of the health of communities having an air pollution problem.

In his summary of the deliberations of the health panel at the United States Technical Conference on Air Pollution, Dr. J. G. Townsend, U.S. Public Health Service, emphasized the following points (1—p. 31):

"1. The pollution of the atmosphere with allergenic material of natural, artificial, and industrial origin is associated with a frequent, and apparently increasing, occurrence of acute and chronic disease, involving especially the respiratory tract and the skin.

"2. Certain acute manifestations, caused primarily by respiratory or occular irritation, have been observed in association with industrial operations and accidents and unusual weather conditions in localized areas.

"3. The effects of the more common atmospheric pollutants upon the general health of the population of our urban and industrial centers have not been demonstrated in the form of authenticated chronic disease processes.

"4. The complexity of the problem is such that further evidence must be sought before the hazard to public health can be appraised adequately.

"RECOMMENDATIONS

"In order to determine the effects of exposure to air pollutants, singly and in various combination, the investigative approaches should include the following:

"1. Carefully controlled animal experimentation.

"2. Study of the effects on human volunteers of controlled and specific atmospheric conditions within safe limits.

"3. Comprehensive clinical investigations of exposed persons, correlated with all the essential studies of their atmospheric exposure.

"4. Carefully planned and executed epidemiological studies on the effects of air pollution upon general population groups, in correlation with comprehensive determination of the composition of the community atmospheres.

"5. All of these investigations should use and be correlated with findings in other related fields.

"6. Without awaiting the results of long-term investigations, all possible aid and encouragement be given to measures for the appraisal, prevention, and alleviation of currently existing human health hazards from air pollution."

There has been no evidence in the literature since this statement to indicate that any substantial progress has been made in evaluating air pollution as a causitive agent in chronic disease.

It is obvious that a determination of the role of atmospheric pollution in affecting the general health of a population is going to require a tremendous amount of painstaking and costly research over a long period of time.

LEGISLATION

The legislative approach to solution of air pollution problems is complicated by the fact that contamination does not stay within local, state or even international boundaries. The international dispute at Trail, B. C. (8) and the Detroit-Windsor study (9) illustrate this point. It has been repeatedly stressed that control of pollution is a local problem which should be handled by local ordinances and state laws. There is considerable feeling against any Federal activity in the fields of legislation and enforcement.

In 1948 (reprinted 1949) The American Municipal Association published a report (10) summarizing municipal practices related to smoke abatement as of that date. It includes summaries of smoke abatement ordinances of 46 cities in the United States having populations over 100,000 plus proposed codes for two others.

All of these codes or ordinances prohibit dense smoke, some include residences in the prohibition. In general, the rules governing other contaminants are extremely broad, prohibiting, for example "such quantities of soot, cinders, noxious acids, fumes or gases in such place or manner as to cause injury, detriment or nuisance to any person or to the public or to endanger the comfort, health or safety of any such person or to the public, or in such manner as to cause injury or damage to business or property." (10—p. 9). If such an ordinance were enforced there would be no air pollution problem and probably very little industry. Even a person burning leaves in his backyard on a fall afternoon would be in violation. The reason for such a broad approach is, of course, the result of lack of reliable data for establishing quantitative evaluation of contamination and its effects.

Beyond the municipal level, there is increasing activity in state legislatures. More and more bills are being proposed, but always the formulation of a practical control law is blocked by lack of information both as to measurement and the actual hazard involved.

Unfortunately laws are going to be necessary. We can only hope that the urgency of the problem will not result in bad legislation.

Conclusion

From a review of published material, it is possible to draw several conclusions which should be used to guide our future thinking.

1. The problem is so complex and involves so many different branches of science that it is difficult for any individual to grasp the whole picture. A coordinating agency to act as a clearing house and to evaluate results should be set up to attempt to bring some order out of the present confusion.
2. The literature in this field is so scattered that it is virtually impossible to keep abreast of all developments.

   A medium for providing an abstract service as suggested at the Technical Conference on air pollution is the only immediate answer. Every effort should be made by those working in the field to reduce the number of journals used for publications.

3. Considerable progress has been and is being made in a few aspects. Among these are methods of analysis, with the result that when applied intensively more valid information about the nature of the contaminants is being obtained. This has already brought about an appreciation of the kinds of reactions which can take place in the atmosphere producing secondary offending materials.
4. The most significant advances have been made in the so-called agricultural phase. The action of many chemicals on both vegetation and livestock is being actively investigated.
5. Control of effluents from industrial plants involves the application of standard techniques and new methods are being developed. Progress in control would be accelerated if more valid standards for permissible levels of contamination could be developed. The great unexplored area in this phase of the problem is control of the many sources which are the responsibility of individual members of the public.
6. Each problem is unique. Variations in meteorology, geography, industry and populations make it difficult to project known results from one area to another.
7. The solution of the problem of the chronic effects of air pollution on exposed populations is nowhere in sight. Even the proper techniques are lacking. The main problems are those of coordination and financing.

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MEASUREMENT OF ATMOSPHERIC POLLUTION

BY RICHARD DENNIS*

(Presented at a meeting of the Sanitary Section, BSCE, held on March 3, 1954.)

INTRODUCTION

IN THE previous paper (1) the author has indicated that the air pollution problem is so complex and involves so many different branches of science that it is difficult for any one person or group to see the picture in true perspective. The measurement of air pollution, which may be defined broadly as the determination of composition and concentration of atmospheric contaminants, represents the initial phase of any air pollution survey. Even though we confine ourselves to problems of measurement, it is still necessary to draw upon several scientific specialties, i.e., sampling instrumentation, analytical methods, meteorology, sampling statistics, etc. It is also apparent that information regarding the source and nature of typical contaminants must be acquired before starting a sampling program.

We encounter the usual state of disagreement among investigators not only as to the merits of certain analytical and sampling methods but also as to the identity and source of certain atmospheric pollutants. For example, smog surveys in the Los Angeles area have presented conflicting opinion as to the source of irritating organic vapors in the atmosphere, although recent data indicate ultraviolet irradiation of hydrocarbons as the apparent source. Recognition that certain trace contaminants are highly toxic has presented serious instrumentation problems (such as beryllium or the entire new family of radioactive gases and particulates). In addition, the downward revision of maximum allowable concentrations based upon long term medical studies has required an increase in sensitivity for several analytical methods (applied to daily industrial exposures).

In spite of problems and failings in present techniques, we find better agreement in methods for measuring atmospheric pollution than we do in the evaluation and interpretation of these data from the legal, medical and economic viewpoints. We can usually establish the sources of pollution, describe the primary components in at least a qualitative

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sense and estimate the degree of exposure to persons or materials in the contaminated area. How these data relate to the overall solution of the air pollution problem in any community depends upon local ordinances pertaining to stack emissions, local meteorological conditions, zoning regulations and the physiological hazard associated with the contaminants. As pointed out by Williams (1), damage to building structures through corrosion or staining is readily detectable. Aside from catastrophes of the Donora category, however, the long-range harmful effects on human beings of many atmospheric pollutants remain to be established.

It is the purpose of this paper to outline the main factors to be considered in preparing to survey a contaminated area and to describe methods of air analysis which have a broad application. The techniques to be presented tell us only what and how much contaminant exists. Evaluation of collected data is not within the scope of this paper.

Sources of Air Pollution

Although it has been stated previously that measurement of atmospheric pollution constitutes the first step toward solving the overall problem, one cannot over-emphasize the value of a preliminary survey to determine the source and probable nature of contaminants dispersed in the area under study. If we are dealing with a very localized situation where complaints originate from a limited area, it is not difficult to track down the offenders. Establishing a particular stack or group of stacks as the source of dispersed contaminants simplifies our measurements since stack sampling may in part substitute for area sampling. The comparative merits and relationship between both testing methods will be discussed later. In a few cases, enlightenment of the factory owners may result in immediate corrective measures which eliminate the need for extensive pollution studies.

Unfortunately, the serious air pollution problems facing us today involve relatively large areas, for the most part highly industrialized, where the sources of contamination are not readily identifiable. Although industry must carry a large share of the responsibility through their discharge of process wastes, it should be pointed out that several non-industrial sources may contribute to air pollution. Heating plants in private homes and public buildings, backyard incinerators and fumes from automotive traffic may in some instances play a large part in air pollution.

Effects of Meteorological Conditions

Local topography and meteorology must be given an important place in an air pollution survey since they often determine where and how often we must collect air samples to insure representative data. In a community where weather conditions are fairly stable, selection of sampling sites is nowhere near as complicated as when spasmodic diurnal variations occur in both wind direction and velocity. Air contamination may also be favorably or adversely affected by topography or meteorology. Strong winds may dissipate the fumes from a high stack to the point where through dilution they no longer constitute a problem. The same quantity of stack effluent released in a region where inversion conditions are prevalent (such as the Los Angeles area) may lead to difficulties. A particularly annoying problem, of course, is where the effluent from one locality is removed by favorable wind conditions and carried downwind to another community which has no jurisdiction over the offender (2).

Composition of Atmospheric Pollutants

Preliminary surveys will furnish an excellent guidepost from which to direct a sampling program. In the Greater Detroit-Windsor Air Pollution Study (3) the first step was to request industry's cooperation in supplying detailed information on: 1) location of power plant and type and quantity of fuel burned, and 2) process information including type and quantity of raw materials, nature of stack effluent, height of stack and methods adopted to reduce amount of stack effluents. It should again be emphasized that such information is only groundwork. Responses to questionnaires indicated an almost complete absence of data on nature and concentration of stack effluents. Fortunately, with an understanding of a plant's operation, one can often predict the chemical and physical nature of the stack effluents. Estimation of their concentrations and degree of dispersion, however, will depend largely upon stack and area sampling.

Physical Nature of Air Pollutants

We find an extreme variation in the composition of atmospheric contaminants (Fig. 1). They have been classified according to Silverman (4) as follows:

A. Gases and vapors

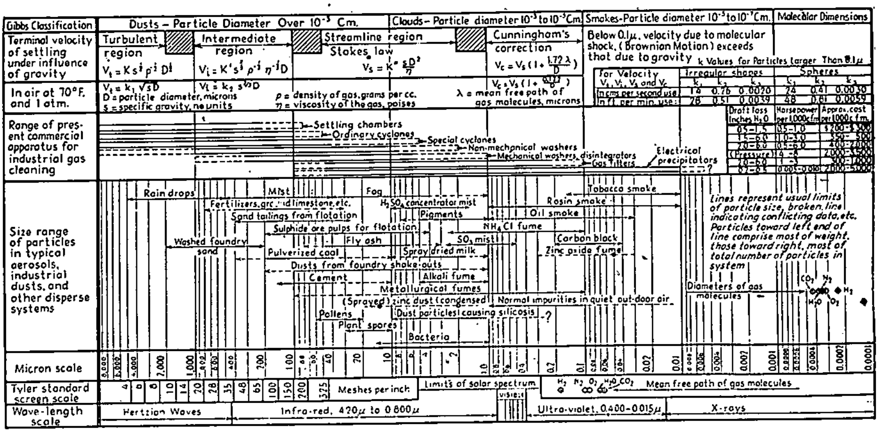

FIG. 1.—PROPERTIES OF TYPICAL AEROSOLS FROM INDUSTRIAL AND OTHER SOURCES (4).

B. Particulate matter
  1. Dusts
  2. Fumes
  3. Smokes
  4. Mists

From a practical standpoint, gases and vapors may be considered to exist in the same physical state, although vapors are actually the evaporation products of substances which are liquids at normal temperatures.

Particulate materials are usually distinguished from one another by 1) method of generation, and 2) particle diameter. Dusts are generated by crushing, grinding or blasting processes and may vary in size range from the visible to microscopic. In air sampling, one seldom finds particles greater than 50 microns in diameter since they are too large to remain in suspension for any length of time.

Fumes may be formed from solid materials by combustion, sublimation or condensation processes. Condensation of zinc vapor to form fluffy zinc oxide is a typical fume-forming operation. Discrete particle sizes are considerably less than one micron although rapid flocculation usually produces larger diameters.

Smokes are considered as the products of combustion of organic materials such as coal, oil, resin, etc., and are usually less than 0.5 micron.

Mists may be produced by atomization of liquids, condensation of vapors or by gaseous entrainment of liquids. Typical mist particles may range from 0.1 to 25 microns in diameter.

Chemical Nature of Air Pollutants

It is not the object of this paper to present a complete listing of all the chemical substances responsible for air pollution. We can safely say, however, that most industries discharge effluents that trademark their operations. Fumes from ferrous or non-ferrous foundry cupolas will represent the metals processed. Non-ferrous smelting operations produce large volumes of SO_2 and SO_3 and may release arsine, stibine, fluorides and other trace contaminants to the atmosphere. Petroleum refining results in the emanation of several offensive sulfur compounds including H_2S, thiopenes, mercaptans and SO_2 from the combustion of these materials.

Industrial and home heating plants may discharge large quantities of fly ash depending upon the type of fuel, method of combustion and the degree of smoke control exercised. Its principal components are unburned carbon and mineral dusts, the latter often containing traces of several elements. SO_2 and CO invariably accompany the fly ash emission.

Atmospheric dust concentrations on a weight basis may be roughly catalogued as follows:

Rural and suburban districts	— 0.4 to 0.8 mg./cu.m.
Metropolitan districts	— 0.9 to 1.8 mg./cu.m.
Industrial districts	— 1.8 to 3.5 mg./cu.m.

Fly ash is in large part responsible for the variations in concentrations noted above although industrial process wastes may be the major factor in some communities.

Air Pollution Measurement—Basic Principle

Two approaches are necessary to establish the amount of air pollution. The first step involves identifying the source and determining the type and quantity of material dispersed in the atmosphere. Stack sampling represents a direct means of obtaining this information. One can immediately locate the origin of the air pollutant and collect a sufficiently large sample for accurate analysis. The number of separate samples required to furnish representative data will depend upon the constancy of a plant's operations. Ordinarily, local meteorology does not influence these tests.

The second step is to determine by area sampling the degree of dispersion and area contamination caused by the pollutant. Two distinct disadvantages accompany this sampling technique: 1) The substances that we are searching for are now present in very dilute concentrations and thus require either long period measurements or extremely precise analytical methods; 2) The number of separate samples necessary to portray true average concentrations in a given area are related not only to the rate of generation at the source but in considerable part to topography and local weather conditions.

It should be recognized, however, that area sampling is the only means through which we can establish with any certainty the dispersion pattern of any pollutant. Conversely, stack sampling is the only reliable index for estimating total volume of material discharged to the atmosphere.

All samples must be collected in such a manner that they represent true concentrations and, in the case of solid materials, true size distributions. This factor is very important in stack measurements, where failure to sample isokinetically (i.e., sampling velocity equal to duct or stack velocity) may lead to serious error for particle diameters greater than 5 microns. Although it is advisable that collection efficiencies of sampling devices approach 100%, there are some applications where less efficient collectors are useful in classifying particulates according to size fraction. Recent studies (5) have shown that small cyclone type collectors will remove from the entering aerosol, a dust size fraction, comparable to that retained in the upper respiratory tract.

Stack Sampling Measurements

(1) *Location of Sampling Point*

Stack samples should be collected at a point where the gas flow pattern and contaminant distribution are uniform. The desired uniformity usually exists some 15 to 20 pipe diameters downstream from mechanical disturbances, i.e., elbows, tees, or breechings etc. Thus, in many instances, the most desirable sampling point (for example a 50 foot elevation on a 100 foot stack) is not readily accessible. However, practical compromise can be made without sacrificing accuracy, by (1) determining the velocity distribution in a stack breeching or other convenient location, and (2) withdrawing samples from several points in the test cross-section. Such sampling traverses must be made iso-kinetically to obtain the correct particulate loadings although they are not necessary where gaseous materials alone are sought.

(2) *Sampling Devices*

The simplest stack sampling apparatus consists of a metal or glass probe inserted in the duct and connected to a suitable filtration or separating device. Flowmeters and pumps are ordinarily located downstream of the collection media to prevent clogging by particulates or condensed vapors.

Gases that are readily absorbed may be collected in impinger or gas washing bottles. Packed columns wetted with absorbing agents, silica gel, activated charcoal or alumina are frequently employed to capture gases and vapors not easily collected in simple absorbers. It frequently is necessary to prefilter a gas stream containing both solid and gaseous materials to prevent the particulates from plugging the gas absorbing media. It may also be required that heating elements surround the sampling probe when testing high temperature gas streams so that condensation in the probe may be avoided. Complete condensation of water vapor, accomplished by placing absorbing bottles in a cooling bath, has been used successfully in testing effluents from steam drying operations (6). This step permits accurate metering of the sampling rate since air alone passes through the flowmeter.

A probe designed for sampling solid materials should have a streamlined entry and sufficiently large diameter (½ inch) to avoid plugging. Isokinetic sampling is best accomplished by 1) employing interchangeable probe nozzles having different diameters, and 2) by varying the sampling rate. To avoid the problem of dust deposition within the probe, the collecting media should be located in the sampling head whenever possible. Sampling equipment described above is illustrated in Figure 2 (7). Several specially designed probes, Figure 3 (8), eliminate the need for knowing duct or stack velocity in order to sample iso-kinetically. In these devices flow rates are adjusted to maintain the same static pressure within the probe as in the duct. Recent tests (9) on two types of "null-point" or static balance probes showed that sampling rates could be in error by as much as 30%. Since it is necessary to determine velocity profiles in any stack evalua-

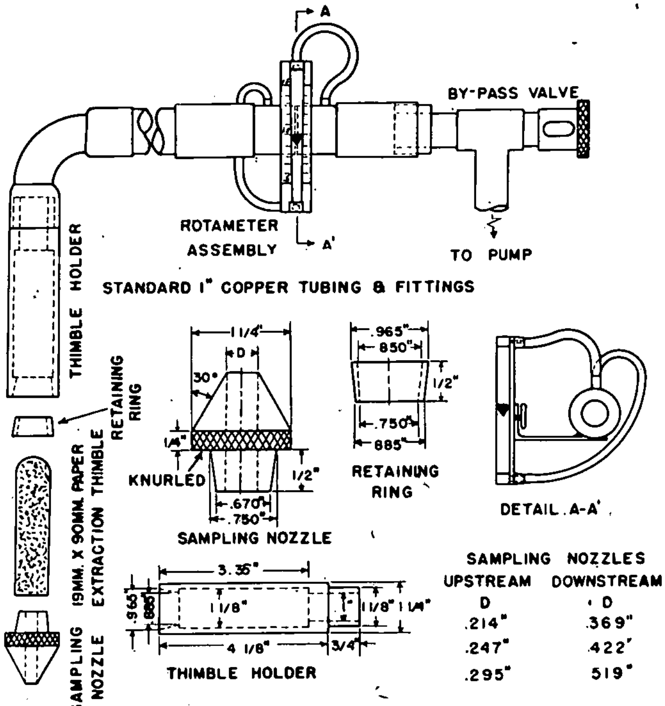

FIG. 2.—SAMPLER AND ATTACHMENTS FOR SAMPLING STACK EFFLUENTS.

tion problem, the use of elaborate sampling probes does not appear particularly advantageous.

Paper thimbles (10) offer an effective means of filtering solids down to 0.2 micron and in conjunction with the probes described above form a compact testing device. However, since charring may occur at temperatures greater than 150°C, glass fiber thimbles (11) should be substituted for high temperature studies. Excessive moisture usually precludes the use of such dry filter media and it is necessary to employ scrubbing devices or electrostatic precipitators for dust or mist removal. Cyclone type collection is satisfactory for coarse materials (down to 1 micron in diameter) where the total weight of discharged effluent is of primary concern. In any sampling apparatus where lengthy probes are required, material deposited in sampling lines must be taken into account.

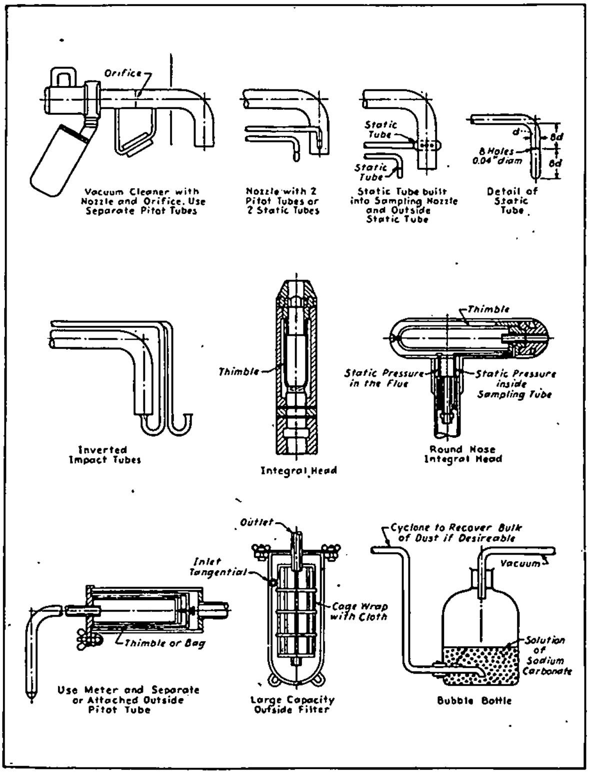

FIG. 3.—METHODS FOR AUTOMATIC SAMPLING AND COLLECTION OF STACK EFFLUENTS (ASME POWER TEST CODE (8)).

All sampling techniques described so far are satisfactory for supplying data on weight concentrations. They are not always appropriate for determining particle size distributions since redispersion of dry dusts for microscopy does not necessarily represent the original state of an aerosol (aggregates or discrete particles) and collection by impingement devices may cause disintegration of aggregates. For purposes of microscopic sizing, sample collection by thermal or electrostatic precipitation of dust upon glass slides may provide direct means for obtaining sizing data when aerosol concentrations are not too high. Membrane filters (12) are suitable for sampling low aerosol concentrations (<2 mg./cu.m.) since they may be prepared for direct microscopic observation by placing a few drops of immersion oil on the filter surface. (Oil of the proper refractive index makes the filter transparent). The above technique permits inspection of the dust particles as they exist in the gas stream; i.e., agglomerates or discrete particles.

Area Sampling

(1) *Instrumentation*

Area sampling, in contrast to stack sampling involves very dilute concentrations of pollutant and thus requires much larger sample volumes to obtain sufficient material for analysis. Sedimentation or settling pans are commonly used to furnish an approximate measure of coarse particulate fall-out. They may aid in locating the origin of gross pollution since large particles will not be carried appreciable distances from their source. However, the composition of settled material is not necessarily the same as the fraction remaining air-borne and only indicates average fall-out rate.

Visual or photometric techniques such as filter stain measurements are useful in establishing the staining characteristics of atmospheric dust. Although such data may not relate directly to the total amount of contaminant present, they do indicate the apparent nuisance value of air-borne particulates and correlate closely with neighborhood complaints.

Collecting apparatus and analytical methods for area sampling operate on the same principles as those used for stack sampling. High volume samples (13) (60-70 cfm) containing pleated filters enable collection of weighable quantities of dust in as little time as one hour. Several devices are available for determining dust count data such as the Bausch and Lomb Counter (14) and the Konimeter (15). These instruments operate on the impingement principle wherein a metered volume of test air is made to impinge at high velocity upon a glass collecting plate. A low power microscope, an integral part of these samplers, permits immediate observation of the dust deposited on the slide. Membrane filters and the Cascade Impactor (16) (Figure 4) are particularly useful for particle size studies when dealing with atmospheric dust concentrations.

(2) *Meteorological Considerations*

The most difficult problem in area sampling is to keep sampling time and locations within reasonable bounds and yet produce results which have statistical significance. For example, let us assume that a

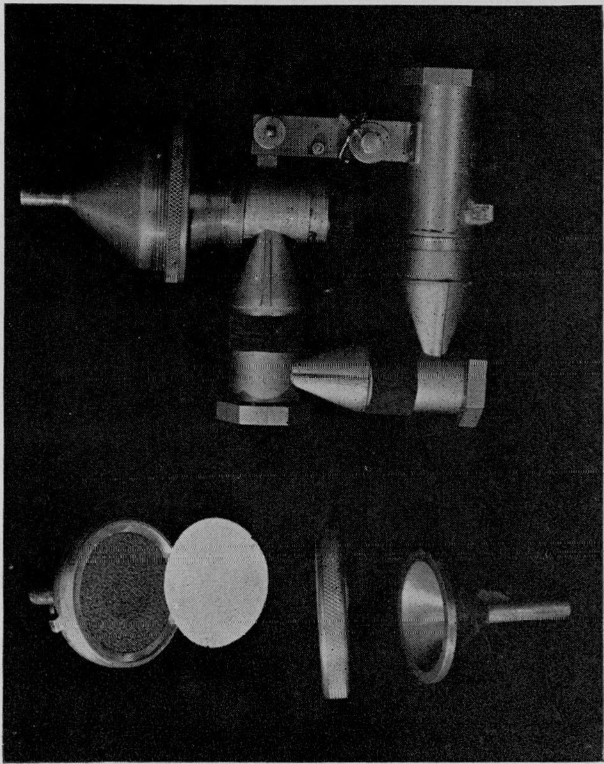

FIG. 4.—CASCADE IMPACTOR WITH MEMBRANE FILTER HOLDER AS FIFTH STAGE (UPPER). EXPLODED VIEW OF MEMBRANE FILTER HOLDER (LOWER)

stack is discharging some toxic contaminant which is not readily detectable, but which may possibly be present in sufficiently high concentration to be physiologically harmful. The potential hazard to the community cannot be based entirely upon the total volume of stack effluent since the contaminant concentration will be subject to tremendous dilution before reaching ground level. Church (17) has indicated the following dilution factors downwind of a 200 foot stack:

Distance from Stack Feet	Dilution Factor
450	2,000
900	4,000
1,700	10,000

Stack gases may be considered to disperse in the form of a cone whose overall shape is governed by the stability or instability of the air, wind velocity, turbulence or geographical obstructions. Investigations have shown that time-average ground level concentrations vary directly as the emission rate of the material, inversely with the wind speed and inversely as the distance from the stack raised to the power of 1.5 to 2.0. They also depend upon stack height and diffusion coefficients for vertical and horizontal motion, as defined by air turbulence.

Maximum ground level concentrations may occur anywhere from 10 to 20 stack heights from the source. Gosline (18) has reported that, due to eddies and turbulence measureable gas concentrations at various sampling points in line with the smoke plume exist on the average for only 25% of the sampling time. Maximum concentrations recorded during the fumigation period may be approximately 10 times greater than time-average concentrations. In estimating the actual weighted average concentrations, the above factors must be correlated with the per cent time that the wind disperses the pollutant over a given location. Typical tests reported by Gosline (18) show that weighted average concentrations at a test site were approximately 2.5% of maximum values.

The sampling techniques presented represent the more common methods for estimating atmospheric pollution. References included in this report offer detailed information on the subject. To summarize, the overall measurement program should consist of 1) a detailed survey of the contaminated area, and 2) an integrated stack and area sampling study.

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MODERN METHODS FOR THE CONTROL OF AIR POLLUTION

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(Presented at a meeting of the Sanitary Section, BSCE, held on March 3, 1954.)

Introduction

In this third paper of the Air Pollution Symposium I plan to describe methods and procedures for the prevention of air pollution from effluent airborne contaminants. My colleagues have already discussed the processes which cause air pollution and methods of measuring the degree of pollution. The most difficult problem from a technical and a practical viewpoint, I believe, is the control of the pollutants since it is largely an economic problem and the devices necessary in most cases do not result in an economic return to the manufacturer and in several situations require further handling and disposal as solids or liquids.

We may divide air contaminants from the control standpoint into two basic forms of matter, gaseous contaminants and particulates. Particulate matter may be further classified into solid or liquid forms. The solids we again divide into arbitrary groups depending upon their state or formation and method of production into classifications such as dust, fumes and smokes. Liquid particles are considered only as mists although less informed people attempt to bring the word "fume" into the liquid mist category and also talk about fogs such as acid fogs. However, in current practice it is recognized that the simplest classifications of particulate matter are those which have already been mentioned.

In this paper I am going to discuss the methods of removing contaminants from air which are based upon their physical state. Thus, the first section we will consider is the handling of gases and vapors which are in the form of dilute concentrations in air. The second portion will discuss problems of handling particulate matter whether liquid or solid.

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Control of Gases and Vapors

From the standpoint of control, gases and vapors are usually considered simultaneously. The thermodynamic distinction between these two, as you will recall, is not significant. The air pollution engineer is apt to consider vapors as those materials emanating from substances that are liquid at ordinary temperatures. However, once they are in the form of vapor they behave as gases and the important factors in control are their physical properties and chemical reactions.

The basic methods used for control of gases can be classified as follows:

1. Dispersion by tall stacks
2. Absorption or chemical scrubbing
3. Adsorption
4. Combustion (catalytic or total)

As has already been indicated, the major problem with gases and vapors is one of whether the diluted contaminant in air creates an offensive odor or more seriously a concentration at ground level which is damaging to man, vegetation or property.

Dispersion by stacks

From the standpoint of economics, atmospheric dispersal by means of a tall stack or dilution from a stack is the cheapest and simplest method of control. Unfortunately, it is a method which is highly dependent upon meteorological and topographical conditions. It is common practice among certain large industries employing such methods of control to use the services of meteorologists.

The dynamics of gas dispersal from stacks has been a subject of extensive study in recent years and it can be shown that when gases are dispersed into air under proper meteorological conditions they will reach certain dilutions when at ground level based upon aerodynamic parameters. (For example, see Sutton (1), Thomas, et al (2), and Church (3). These parameters unfortunately usually only apply to regions which are not complicated by the presence of building structures and other impediments to a normal air flow pattern. Consequently, it may be stated that in many instances the meteorological dispersion by stacks for gaseous contaminants can only be universally satisfactory in situations where environmental conditions are ideal.

In many instances the stack will provide a satisfactory method, especially if the quantity of material to be discharged is not too great and if the general terrain and topography are ideal for its application. One should not be misled, however, especially in crowded metropolitan districts about the efficacy of the stack for dispersion. Basically, the stack was primarily intended as a method of producing draft for boilers or combustion processes and as a device for controlling contaminants it has only a secondary role in most applications. Therefore, most modern studies of applying stacks to certain situations have been based on scale model studies in wind tunnels whereby the actual patterns, as influenced by air conditions and surrounding buildings can be studied in detail. It should be pointed out here that basically when particulates are of very small size, less than 5 microns, they too will behave like gases and can be said to obey all stack dispersal laws developed for gases. This has been shown mathematically by Baron, Gerhard and Johnstone (4).

The "rule of thumb" in regard to use of stacks for dispersal may be stated as, *at all times it is desirable to disperse the gas at as high a temperature as possible because of the more rapid diffusion and the additional effective height that the thermal gradient provides, an arbitrary rule is that each degree Fahrenheit of smoke temperature above environment is equivalent to 2.5 feet in stack height.* Consequently, it is desirable to discharge gaseous effluents at as high a temperature as possible. Ground level concentrations are usually highest at a point 10 stack heights downstream but this is only a rough rule and the location of maximum depends upon several factors.

There are many situations that are favorable to stack dispersal. For example, under certain weather conditions when the wind is blowing inland non-ferrous smelting plants located along the west coast are equipped to make sulfuric acid from the stack gases and they discharge their sulfur dioxide to the atmosphere when the wind is blowing out to sea. Because of economic changes in recent years it has proved more advantageous to recover the gases because of the present high price of sulfur.

As another item, it may be pointed out that the dispersal of gases by stacks has proved to be the source of an international incident, namely, when the gases from the Trail Smelter in British Columbia passed over the border into the United States and caused crop damage to areas on our side of the border. The undesirable effect of stack dispersal, of course, may be seen in certain smelting areas where the benefit of the stack has been largely to produce defoliation and denuding of the countryside surrounding the stack for several miles. Damage to vegetation by sulfur gases is called "fumigation" and is highly destructive.

Modern design of stacks is still practiced in industry as witnessed by the recent construction of a 696 foot stack at El Paso, Texas. This one was very important from the Civil Aeronautics Authority's standpoint since it was potentially a hazard to civilian aviation. The use of such an extremely high stack makes it almost impossible to produce ground level concentrations which are injurious to vegetation or man since the dilution factor is tremendous (several thousand fold).

There is only one other point to be made with regard to high stacks for dispersion of contaminants and that is that when dealing with coarse particulates, those over 50 microns, the fallout from the stack can usually be predicted based on the gravity and wind movement factors. Particles larger than 10 microns will also have a significant settling component and will thus appear in the immediate vicinity of the stack. Distance of travel for such particles has been determined by methods such as described by Croft (5).

Absorption or Chemical Scrubbing

The method of choice for the removal of gases or vapors by chemical engineers has been the use of the so-called scrubbing tower or chemical scrubber. These devices consist of towers filled with packings or extended surfaces to provide ample area for absorption and reaction and have been usually applied in the chemical industry for the recovery of process gases. However, the design of such equipment for removal to the extent necessary to prevent air pollution problems is often uneconomical and there has been unfortunately, a tendency in practice to apply scrubbing equipment for control of contaminants when the absorption coefficients are unknown or indeterminate. The result is that the scrubbing liquid and the absorbing surfaces consequently are unable to remove enough of the material in question to prevent an air contamination problem. Many of the problems which occur in air pollution today are not satisfactorily handled by chemical scrubbing equipment because of the difficulty of absorbing very dilute concentrations of gases. A good example of this is the attempt to recover odors or contaminants from fish meal processing or rendering plants. Here the attempt to use water scrubbers or scrubbers dosed with chlorinated water has, in general, not been completely satisfactory because the scrubber cannot absorb all of the contaminants at the high velocities and short contact time employed and cannot remove any large proportion of the non-condensable gases. The result is that only a partial oxidation can result from the chlorine or chlorine dioxide in aqueous solution which has been used as a scrubbing liquor and the gaseous effluent still contains a high percentage of odorants.

In the case of easily soluble gases or highly reactive gases, chemical scrubbing with alkali or acid will give effective results. However, in the case of non-reactive or slowly reactive gases, it is not usually completely satisfactory. The velocities necessary to obtain effective removal result in large size equipment and high initial costs. We have worked to a considerable extent in the past few years with improving scrubbers by using extended surfaces of fine fibrous materials. The wet cell washer such as we have investigated and shown in Figure 1 is a device which utilizes a continuous flow of water or absorbent over a fiber glass bed. This was originally proposed for humidification of air streams and then adopted for air cleaning of particulates. Our tests (6) indicate that it does not do an effective job with particulates but does provide a tremendous surface area for gas absorption and shows very effective results as indicated in Table 1. Where the gas is apt to contain fine droplets or acid mists the plain scrubbing surface from plates or irregular packings is not enough and

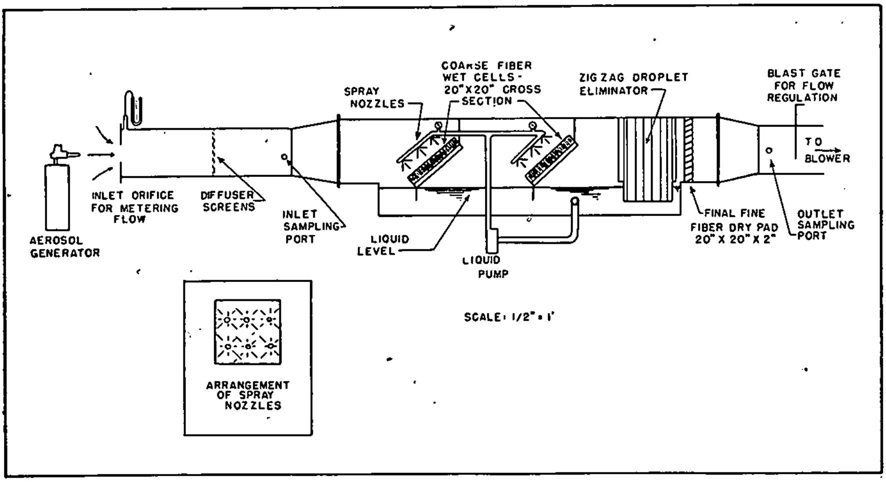

FIG. 1.—WET CELL WASHER EMPLOYING FIBROUS MATERIALS AS SCRUBBING SURFACE.

TABLE I

Wet Cell Washer Efficiency with Aerosols Containing Inorganic Acids and Ammonia

	Concentration, Mg./Cu. Meter	No. Observations	Cumulative Weight Efficiency* % Stage 1	Stage 2	Stage 3
HNO_3	5-30	4	76	90	97
HCl	12-70	4	61	89	99+
Concd. H_2SO_4	23-33	4	—	99	99.9+
NH_3	5-25	4	57	76	91
HF	50-200	4	94	97	99.5

*Air washer consisted of one countercurrent and one concurrent 8-inch partially oriented 255-micron fiber wet cell (stage 1), one 20 x 27 x 2 inch dry pad of 10-micron glass fibers packed to 0.46 lb./cu. ft. (stage 2), and an additional concurrent wet cell and dry pad in series (stage 3). Wet cells were wetted with 0.2 gal. of water/min. per cell; flow rate, 600 cu. ft./min.; overall resistance of washer ranged from 2.46 to 2.77 inches water gage at start of each group of tests.

one must depend on filtration mechanisms for separation. The one other application we have made recently with this type of device, has been the scrubbing of small concentrations of hydrofluoric acid. It can be recognized, of course, that the use of glass fibers is ruled out but by substituting Saran or Dynel (chemically resistant synthetic fibers) a comparable extent of surface is obtained and we (7) have been able to recover up to 99.9% of hydrofluoric acid gas. Hydrofluoric acid mist or fluoride particulate removal is comparable to those for other particulates with the wet cell washer which we have reported elsewhere (6).

It can, in general, be stated with reasonable assurance that chemical absorption does not work well enough for pollution control problems if the gases are noncondensable or slowly reactive. The time required for reaction and the surface available makes the size of equipment too uneconomic to attempt to get enough recovery.

Adsorption

Adsorption methods have been widely applied in industry where the gaseous material is in the form of a condensable vapor. Adsorbents such as activated charcoal, silica gel and activated alumina are the principle forms used. The recovery of solvents from synthetic coating processes, enameling operations and other similar cases by the adsorption method has proved to pay for itself in a short time. In fact, the adsorption principle is economically sound and should be applied in all cases where there is a significant solvent loss in gallons per day which, if recovered, would result in a dollars and cents return.

Adsorbents are usually stripped by steam or high temperatures and can be used over and over again. One installation in Reading, Massachusetts, that I know of has been in operation for 15 years without any serious difficulty and has successfully recovered aromatic, aliphatic and chlorinated solvents which are reused. When the concentration of the contaminant is very low in the effluent gas stream, so that the adsorbent recovery system is not worthwhile, from an economic standpoint, then the control needed depends upon the evaluation as to whether the contaminant is in such concentration that it produces odor problems based on effluent concentrations below one part per million. If this is the case then odor absorbing charcoal canisters may be applied with success and can yield effective control. The cost of the odor absorbing charcoal is prohibitive, however, if the canisters have to be replaced more often than once every six months. Activated charcoal may take up nearly 30 to 50% of its own weight in solvent before the rate of loss begins to be a problem. The application of absorbents for air pollution control breaks down if concentrations are above one PPM and if solvent losses are not worth recovering.

Combustion

Combustion methods are usually applied where the methods described above are not suitable because of inefficient removal or the kind of economics mentioned. In many situations combustion methods also have to be weighed on a basis of economics. The combustion techniques that have been used successfully in practice either pass the gas under existing boilers or heat exchangers or through a specially constructed incinerator which is fired by a separate heat source. They may also utilize, as in the past few years, a catalytic combustion agent to lower quantities of heat necessary. One type, the catalytic combustion unit, consists of noble metals plated on Berl saddles or a similar absorbing surface and in another type it consists of ribbons of platinum and other noble metals arranged in the form of a filter. The advantage of the catalyst is that it lowers the temperature necessary for combustion to take place. However, the gas must be at 500°F or higher in order for the catalysis to become effective. If the contaminant contains any sulfur gas or an agent which will poison the catalyst then the catalytic combustion method is usually ruled out because of poisoning of the catalyst and a high cost of replacement.

Direct combustion is usually an expensive proposition unless a large volume of gas is being heated for other purposes. In my recent experience with fish meal plants on the New England coast it appeared that the boiler plants were large enough to handle a considerable volume of gases. For practical purposes we consider that a gallon of oil per hour with 100% excess air will provide approximately 50 cubic feet of air per minute for combustion treatment. This air can be taken from the ventilating or process control system and when such gases are passed through the fire box at a temperature of 1100°F or higher, total destruction of the contaminant, whether solid or gaseous, results. In some instances an auxiliary incinerator can be used to preheat gases for dryers and other purposes so that the actual economic loss from combustion is not severe. I know of at least two installations where the addition of combustion in order to control the process waste gases has not involved additional cost of fuel and yet the previous costs to management in terms of nuisance complaints and other difficulties before arriving at this solution were very high.

Catalytic combustion can be applied to such processes as enameling ovens, paint stripping, paint dipping operations, whereas complete combustion is needed for fish meal production, rendering and certain special chemicals. By reducing the volume of gas to be handled to a minimum by proper enclosure of the equipment it is usually possible to bring the volume of gas to be burned to a small value. From the combustion standpoint, the higher the concentration of the contaminant the more efficient the combustion and the more effective the burning will be since some exothermic reaction takes place.

Control of Particulate Contaminants

The problem of controlling particulates in air or gases is one which requires a consideration of more factors than the handling of gases and vapors. In the latter case it was indicated that the important factors are the physical properties of the gas and vapor. In the case of contaminants again the physical properties of the contaminant are important and these are much more varied because, as has been indicated by the previous papers, the nature of particulates that occur as air contaminants are quite broad.

From the standpoint of the type of equipment to be employed, we should bear in mind that in many cases the problems which result may involve mixtures of gases and particulates. Such cases will be discussed in connection with the handling of particulates. The basic factors that must be considered in the removal of particulates may be described by the five *ess* factors. These are, particle size, size distribution, shape, specific gravity and surface characteristics, of the aerosol particles. These are the essential factors in considering the type of equipment to be employed in removing the suspended material from the process effluent. The concentration of the particulate to be removed is usually 1000 times that or more of the normal dust in the atmosphere, hence the simple equipment used for warm air or air conditioning work is not adequate. Another major problem in the discussion of any control equipment for particulates as well as for gases is the efficiency of collection. In the case of particulates, however, the collection efficiency based on weight or volume which is used for gases is easier to obtain in high values than other expressions of efficiency. For practical purposes we consider that the efficiency of a process effluent collector can be rated on a basis of either weight removal, surface area removal (that is, discoloration of a specific surface such as the discoloration of a piece of white filter paper, produced by fly ash or carbon smoke) or by a particle count basis (each particle thus given an equal weighting). The efficiency to be referred to will depend entirely upon the nature of the contaminant and the problem it produces. In the case of coarser materials particles above 5 microns in size, the weight basis is ordinarily implied and used. If discoloration is a problem such as soiling of painted surfaces of houses or general areas then a surface measurement or discoloration basis is desirable. If the material is highly reactive or toxic, the particle count or number basis is the one to be applied. This should not be confused with radioactive materials where a count is also taken but the value is usually based upon the weight of the material. By count in the ordinary sense we mean the actual enumeration of the number of particles.

Based upon their performance factors and perhaps their order of frequency of application in industry we may list the control equipment and their operating principles as follows:

A. Inertial separators or cyclones (settling and centrifugal force).
B. Scrubber (impaction, centrifugal force, settling, absorption)

C. Filters (impaction, diffusion, charge, settling, sieving)
D. Electrostatic precipitators (electrostatic charge)

An extended discussion of the various types may be found in the recent "Handbook on Air Cleaning" (8). Here I can only describe briefly their general application in industry.

Inertial Separators

These devices are perhaps the most widely applied in industry because they are, as might be suspected, the least expensive. They depend entirely upon applying centrifugal force or inertial separation by a change in direction. They produce separation by the fact that the particles lose their forward motion and are dropped out of the entraining gas stream. In a recent article we have described several important types now in use (9). In principle, they range from the simplest form, a settling chamber, which is a large duct section or housing in which the velocity is reduced to a point where the particle gravitational component is greatest and thus separates the particle. From a practical standpoint the gravitational chamber is usually only applicable for particles greater than 100 microns. When it is necessary to separate smaller particles some centrifugal or inertial component greater than gravity is necessary and involves the use of baffles or vanes to give the air a curved path. The radius of curvature is an important factor in producing the amount of centrifugal force. Large cyclones for the collection of wood shavings and sawdust such as you are familiar with and have seen on roofs of woodworking plants are not very effective for particles less than 10 microns. In order to separate these and smaller particles it is necessary to use smaller radius cyclones such as have been installed in the power plants for the collection of fly ash. Because of increased wear with small diameter and higher tangential velocity these smaller type units are usually made of heavy cast metal (¼ inch or heavier walls). This particular design which utilizes a bell-mouth shaped entry and a vertical body of 2 to 3 inches is capable of separating particles as small as 1 or 2 microns but the particle separation for particles over 8 microns is usually 100%. The separation curve is based on the size of particles. It must be recognized, of course, that in a given air stream the 10 micron particles will weigh 1000 times that of the 1 micron particles and consequently these devices give fairly high weight efficiencies, over 90% for most applications on power plants and similar installations.

Inertial separators have definite limitations and cannot be applied to metal fumes and particulates resulting from combustion processes without some additional agglomerating force or aggregation of particles. They will remove a percentage of any type of particulates but are not considered effective in the submicron size range.

Scrubbers

Scrubbers or inertial collectors which are provided with fluid addition range in types from simple cyclones in which spray nozzles are placed or which have wetted walls to intricately baffled patterns of equipment. The scrubbing device may be a simple chamber or one in which a rotating element or wheel is included. Figure 2 shows a typical scrubber using inertial forces and baffles in which a mechanical rotor

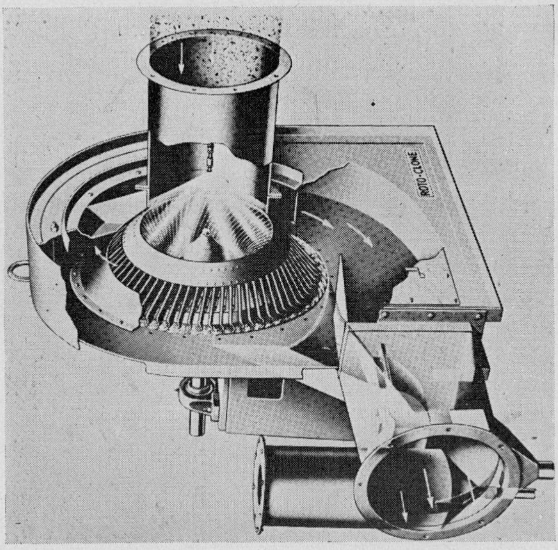

FIG. 2.—TYPE W ROTOCLONE WITH MECHANICAL ROTOR (AMERICAN AIR FILTER CO.).

is incorporated to provide intimate contacting. These devices show performance comparable to inertial collection in a dry state but the addition of water or a scrubbing liquid increases separation and provides retention of the particulates. Their performance depends upon the type of sprays and number of passes made before discharge.

From the standpoint of maximum separation it has been determined in our laboratory that in a centrifugal separator the optimum particle size of the spray droplets ranges between 50 to 100 microns, since this size droplet will impact the particles and carry them to the wall where they may be removed. A recent development along this line is the Venturi scrubber. This device includes a narrow throat through which the dust laden gas is passed and where air injected water stream is atomized. The spray created contacts the aerosol and the impacted dust particles are separated in the centrifugal separator.

All wet collectors are subject to the same considerations, namely; that the separating forces that must be applied are the same as those in dry collectors. Once the dust particle has been impacted by the water droplet, some method must be utilized to separate the entrained droplet and particle. This may either be centrifugal or a filtration force such as will be described later and was indicated in the packed tower or the wet cell washer.

Wet scrubbers have the added advantage that they can handle both the solids or particulates and gases. They are also well adapted to mists although their efficiency is dependent on particle size as with solid particulates. The efficiency of the device for gases depends upon the type of spray nozzle used and the area of the extended surfaces employed in the collector. Engineers not familiar with air pollution control in general have the idea that by the addition of water alone the problems of air pollution may be easily solved. This perhaps stems from the fact that the beneficial effects of rain on clearing the atmosphere have been observed so many times. However, the actual measurements indicates that rain washing does not remove appreciable numbers of particles smaller than 1 micron and its action is primarily confined to larger particles.

Filters

With the exception of the wet filters which have been discussed previously in the form of a wet fibrous packing, filters are used primarily for the collection of dry solids. Wetted filters are usually employed for gases and liquid particulates.

Filters employed in the cleaning of process gases differ markedly from the type of filter with which most engineers and laymen are familiar, namely, the warm air furnace or air conditioning systems impingement filter. Those filters utilized in industrial air pollution control are intended for small particulates since the devices already discussed above are able to handle larger sizes. However, when dealing with metallurgical fumes and fine dusts resulting from crushing and grinding operations where the mean particle size is one or two microns it is necessary to remove the material by a filter. The most widely applied filters in industry today are the so-called bag type units which consist of cotton or wool fabrics (synthetic fibers are also used for higher temperatures). These are made in the form of socks drawn over frames or tubes suspended so that the dust laden air is passed through the inverted tubes or over the covered frames. The filter is taken off the airstream and the bags or frames are shaken permitting the collected material to drop into a hopper. In recent years methods have been developed to improve the cleaning and to utilize more effective fabrics such as felts. The most recent development along these lines is the so-called Hersey Reverse-Jet filter which consists of a wool-felt bag arrangement in vertical tubes with a traversing ring cleaning mechanism blowing air under high pressure through a narrow annular jet and cleaning a section of the bag continuously. The ring is operated by a pressure switch. The advantage of this system over the ordinary shaking bag, however, is that a reasonably constant resistance system may be maintained. In the customary bag house the filter resistance increases with the time of operation and the unit is withdrawn from the gas stream and the gases are switched to another unit during which time the original onstream bags are shaken. A woven fabric bridges over the openings and most of the effective filtration is provided by the layer of deposited aerosol. Because of the resistance involved rates are limited to one to three feet per minute in most instances. In the case of the reverse-jet unit, however, because of more effective cleaning, wool-felt is an effective filter since it presents fibers in depth and higher filtration velocities can be obtained. Felt can be cleaned by reverse-jetting which results in a milking of the fabric as indicated in Figure 3. The advantages of the reverse-jet, in addition to continuous operation with fairly constant resistance, is the fact that filtration rates may be as high as 15 feet a minute resulting in a much smaller sized unit for a given installation. It can be pointed out that in the case of large smelters, baghouses may often be as large as the smelter building but in such cases it is also important to note that the baghouses are actually collecting the metallic fume which will be sold later as a product.

The results of our field studies (10) measuring the performance

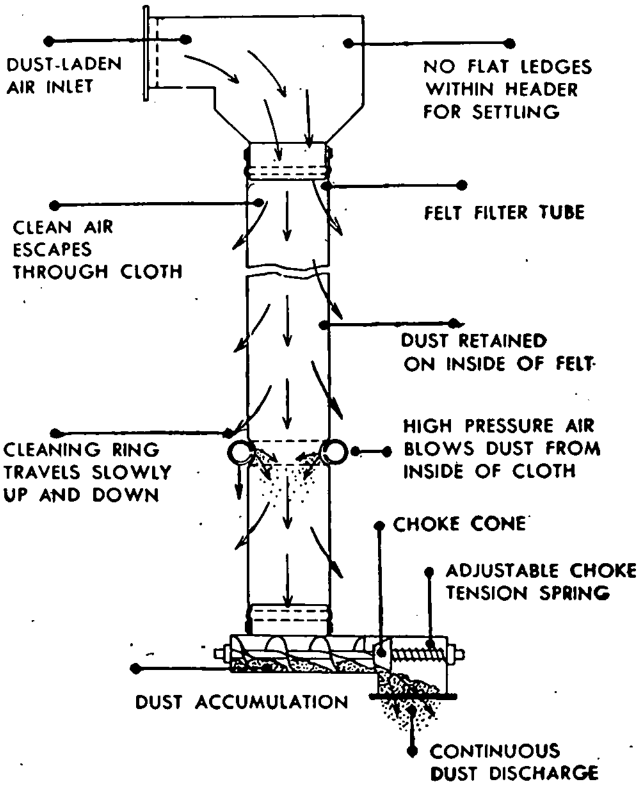

FIG. 3.—REVERSE JET FILTER UNIT.

of both reverse-jet and shaking bag type units (Figure 4) indicates that in most cases with the types of aerosols encountered which range from tapioca dust to synthetic abrasives with sizes of 50 microns down to less than 1, efficiencies well over 99% and sometimes as high as 99.9% can be obtained with either type of unit.

One of the chief limitations of the filter unit is the fact that it cannot operate at temperatures much above 200°F with wool bags or 275°F with synthetic bag materials such as Orlon. The problem of high temperature filtration is one which is undergoing considerable research in our laboratory and we hope to develop equipment which will be able to withstand temperatures up to 1000°F. Many of the problems in control today lie in the temperature range just mentioned. The use of glass fabrics has been tried but has not been completely

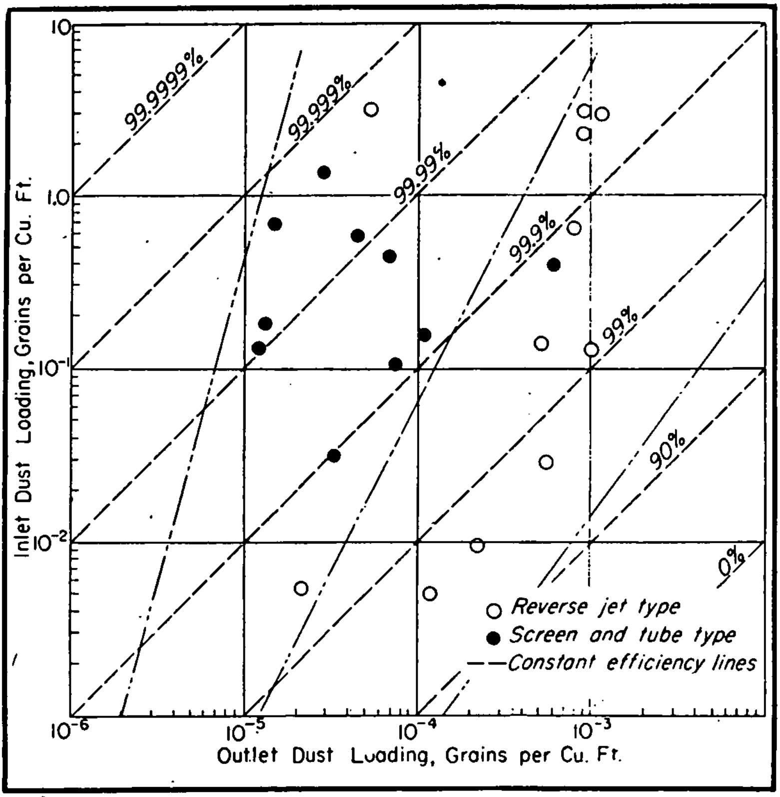

FIG. 4.—PERFORMANCE OF CLOTH BAG, SCREEN AND REVERSE-JET FILTERS FROM FIELD TESTS.

successful because of their inability to stand much flexing or abrasion. There are any number of metallurgical industries as well as power plants which must use wet collectors to bring the temperature of the gas down to where it can be handled by ordinary equipment. If filtration equipment were available for the higher temperatures we feel certain that it would be applied quite widely.

Electrostatic Precipitators

The last piece of equipment that will be discussed in this paper is that of the electrostatic precipitator. The type of precipitator under consideration is that used for high loadings such as power plants and metallurgical industries or the device known as the Cottrell Precipitator. This should not be confused with the Precipitron or two-stage device used for cleaning outdoor air loadings which are approximately one thousandth or less of the industrial stack effluent. The electrostatic precipitator depends upon the charging of the aerosol and subsequently separating it on a charged surface whose charge is opposite to that of the charged aerosol. The chief advantage for application in industry is the fact that it offers practically no resistance to air flow. However, to obtain efficient collection the device must use voltages far in excess of 20,000 volts. In some installations values as high as 80,000 volts have been employed. There are a number of power plants and other operations which utilize the electrostatic precipitator and obtain weight removal of submicron particles on the order of 90 to 95%.

The chief drawback to this type of equipment in practice today is the high capital cost. Separation varies with the type of contaminant handled since the deposited contaminant on the surface of the collector plates accumulates an electrical resistance and lowers the voltage at the collecting surface. Devices in practice utilize continuous shaking and rapping of plates or else liquid washing of the plates in order to obviate this handicap. They are also handicapped by the fact that at certain temperatures the voltage which may be applied is limited by the dielectric capacity of the gas and consequently, most installations must use some type of pretreatment or cooling before passing the gases through the precipitator. They are, however, able to handle gases as high as 300 to 400°F. In this field in particular there have not been any new startling developments but there are a number of new manufacturers of equipment in this country utilizing devices developed abroad. In the last two years, two foreign makes, one from Switzerland and one from Sweden have been produced in this country by American licensees. There are some special instances in certain power plants where the electrostatic precipitator is used as an agglomerator before the cyclone or the inertial separator. There are at least three power plant installations in this country that I know of where the precipitator is placed before a multiclone or small cyclone bank unit and these show a very high overall removal because of the agglomerating effect of the electrostatic field.

General Discussion

In this paper I have attempted to present some of the most important of devices used for cleaning process effluent gases. Table 2

CHARACTERISTICS OF COMMERCIAL AIR CLEANERS

Type of Collector	Separating Forces	Capacity CFM x 10^3	Air Velocity FPM	Pressure Loss, Inches Water Gage	Optimum Dust Loadings, gr./cu.ft.	Approximate Particle Size Efficiency-% by Weight: Less than 1 Micron	1-5 Microns	5-10 Microns	Usual Service Life, Yrs.	Installed Cost Per CFM of Rated Capacity, $	Resistance to Heat, Corrosion, etc.	Miscellaneous Notes
						A. DRY MECHANICAL COLLECTORS						
Settling Chambers	Gravitational	0.5-10.0	25-75	0.2-0.5	10+	<10	<10	<10 (60-80% with particles >50μ)	10-20	0.05	Corrosion and heat resistant materials available.	Very bulky for handling large volumes of gas.
Baffle Chambers	Inertial	0.5-10.0	1000-1500	0.5-1.0	10+	<10	<10	10-40 (60-80% with particles >25μ)	10-20	0.05	•	Re-entrainment of dust at velocities great enough to produce large inertial forces.
Large Diam. Cyclones	Centrifugal	1 - 10	(entry velocity) 2000-4000	0.5-2.5	1+	<10	<10	40-75	10-20	0.10-0.25	Corrosion and heat resistant materials available. Rubber lining for abrasive dusts.	Internal vanes, baffles and spacers or dust skimming devices do not appear to materially improve collection efficiency.
Small Diam. Cyclones	Centrifugal	0.03-0.1 per unit (Collectors contain 4 - 500 units)	(entry velocity) 2000-4000	2.0-4.5	0.5-10	<10	10-40	75-95	5-20	0.25-0.50	Corrosion and heat resistant materials available, subject to abrasion.	Uniform distribution of air and dust to each unit difficult in large banks of collectors. Tendency to plug at very high dust loadings.
Mechanical-Centrifugal Collectors.	Centrifugal	0.5-10	(entry velocity) 2500-4000	—	1-10	<10	10-20	60-80	5-20	0.20-0.35	•	Fan and dust collector in single unit. Compact. Not recommended for materials that cake and stick on blades thereby putting rotor out of balance.
						B. WET COLLECTORS						
Spray Washer	Impaction	0.5-100	200-500	0.1-0.2	<1	<10	10-20	20-40	10-20	0.10-0.20	Corrosion resistant materials available.	May be used for humidification and to cool hot gases.
Wetted Baffle Towers	Inertial Impaction	0.5-5	200-500	0.20-0.75	0.1-2	<10	10-20	20-40	5-20	0.20-0.40	Corrosion resistant materials available. Hot gases cooled in apparatus	Baffle towers in which air is blown through water cascades are somewhat more eff. for small particles, but pressure drop is much higher than indicated.
Wetted Packed Towers	Inertial Impaction	0.5-5	200-500	1-10	<1	<10	20-60	60-90	5-20	0.40-0.60	•	Efficiency depends on size of packing. Not recommended for solid particulates due to rapid plugging of packing.
Wetted Cyclones	Impaction Centrifugal	0.5-5	(entry velocity) 2000-3500	1-5	1-10	<10-20	10-40	50-80	5-20	0.25-0.40	•	Good for hygroscopic materials. Efficiency dependent on location and design of spray nozzles.
Scrubber or Disintegrator	Diffusion Impaction Centrifugal	0.1-1.0	—	10 HP/1000 CFM	<1	80-90	99+	99+	5-20	1.0-2.0	•	Very high power requirements.
						C. FABRIC FILTERS						
Bag and Screen Cloth Filters (Intermittent Cleaning)	Diffusion Inertial Electrostatic Sieving	0.06-200	2-5 (velocity through filter medium)	0.2-0.5 (clean) 2-4.0 (loaded)	0.1-10	90-99	95-99+	95-99+	1-10	0.20-1.00	Corrosion and heat resistance varies with fabrics.	For constant head, volume and efficiency vary over operating cycle (4-24 Hrs) falling and rising, respectively. Must be shut down for cleaning. Moisture and oily, sticky dusts plug filter. Synthetic fabrics now available for temperatures to 275°F.
Bag Type Cloth Filters (Constant Pressure Loss)	•	0.6-5	5-35 (velocity through filter medium)	2-8	0.1-30	90-99	95-99+	95-99+	1-5	0.5-1.0	•	Air volume and efficiency constant because of continuous automatic cleaning. Unit does not have to be shut down for cleaning. Moisture and oily, sticky dusts plug filter cloth.
						D. HIGH EFFICIENCY FILTERS (LOW DUST LOADINGS)						
Cellulose-Asbestos Filters (CWS-6)	Diffusion Inertial Electrostatic Sieving	.03-1 per unit. (One to several hundred units comprise collector)	5 through medium	1.0 (clean)	$<10^{-5}$	99+	99+	99+	<1-2	0.30-0.60	Not resistant to heat or corrosive materials.	Low dust-holding capacity. Usually preceded by pre-filter. Air or gases must be well below dewpoint.
Deep Bed Fibrous Filters	•	0.04-0.06 per unit. (One to several hundred units per collector)	2-50	0.1-0.5	$<10^{-4}$	10-70	30-90	50-99	0.5-1.0	0.05-0.10	Corrosion and heat resistant materials available.	Efficiency and pressure loss increase with decrease in fiber size and increased packing density. Used in depths of 1-8 inches. Some may be cleaned when loaded, others are discarded. Good dust holding capacity.
All-Glass Papers	•	.05-1 per unit. Several may be used.	5 through medium	1.0	$<10^{-5}$	99+	99+	99+	<1-2	0.60-0.80	Resists temperatures to >1000°F and acid gases except HF.	Low dust-holding capacity. Usually preceded by pre-filter. Air or gases must be well below dewpoint.
						E. ELECTROSTATIC PRECIPITATION						
Single Stage Electrostatic Precipitator	Electrostatic	0.1-200	200-500	0.25-0.75	<1	80-99+	80-99+	80-90	5-20	0.50-2.0	Corrosion and heat resistant materials available.	Suitable for high loading pressures and wet gases. Operate at 10,000-60,000 volts. Produces ozone and nitrogen oxides. Usually DC from mechanical rectifier. For coarse aerosols precede with mechanical collector.
Two Stage Electrostatic Precipitator	•	0.1-100	200-400	0.25-0.50	<1	80-95	80-95	80-95	5-20	0.25-0.50	Corrosion resistant materials available. Hot gases may buckle plates.	10,000-13,000 volts ionizing sections; 6000 volts collection section. Produces ozone and nitrogen oxides. Primarily for light dust loads.

TABLE II

from a recent article (11) summarizes the basic features of all types now in use. There are a number of new developments which are applied to special cases, some of which are necessary because of high toxicity of the gas or the special nature of the contaminant. It is worthwhile to point out that some of the high efficiency filters shown in Table 2 which have been applied to processes in Atomic Energy plants do not handle the types of contaminants or loadings that ordinary industrial processes create. It should be borne in mind that the loading entering the equipment for which the process devices described above are usually used, range from 1 to 40 grains per cubic foot of air. The high efficiency filter used in Atomic Energy control of active particulates provides air which is considerably cleaner than that of country air and represents loadings only a trace of usual process effluents. Thus, the life of the high efficiency equipment can be several months to a year. If loadings of an industrial nature are supplied to one of these filters the life would be a matter of minutes since a 1000 cfm unit holds approximately 2 pounds of material before its resistance is doubled (from 1 to 2 inches of water).

The efficiency of the cellulose-asbestos or the all-glass filters which have been developed recently, of course, is phenomenal (penetration less than 0.02%). However, it is not too much greater than that of the bag or reverse-jet filter which has been described above. In our laboratory we have simulated the cellulose-asbestos filter by feeding powdered asbestos into bag filters under suction and obtain results comparable to the highest efficiencies. Those of you who are sanitary engineers may be interested in knowing that some bag filters have been used for cleaning air for aeration in sanitary disposal and treatment plants. These devices which are essentially cleaning outdoor air loadings use asbestos fed into the entering air stream in order to build up a high efficiency asbestos layer on the surface of the cloth.

Summary

This paper summarizes the type of equipment used for handling gases and particulate matter in air pollution control problems. The use of stacks, absorption, adsorption and combustion devices for gases and fine particulates is explained in detail. Equipment such as inertial collectors, scrubbers, filters and electrostatic precipitators used for handling particulate loadings from chemical and other processes are discussed at length.

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PROBLEMS WHICH NEW YORK CITY FACES IN EXPANDING ITS WATER SUPPLY SOURCES

BY KARL R. KENNISON*, Member

(Presented at a meeting of the Boston Society of Civil Engineers, held on May 19, 1954.)

A WATER supply is generally taken for granted so long as the water comes whenever the faucet is turned on. The general public needs to be reminded often as to just what its sources of supply are and how much engineering planning and even "blood, sweat and tears" have been spent in obtaining them. New Yorkers may well be proud of their water supply. Not only is it in a class by itself as to size but its quality is unexcelled among large municipal supplies. However, the great size and growing needs of the City have, for many years past, created what practically amounts to a continuous emergency.

As you Boston Engineers well know, it takes about 15 years to authorize, design and construct a new major water supply development. To most cities an additional source yielding as much as 200 million gallons daily would give quite a boost. However, New York's needs grow so rapidly that unless any increment to its supply exceeds that figure, it practically would be consumed before it could be made available. For you to think in terms of New York's supply, you have to multiply the Boston Metropolitan District figures by about six.

New York City's water supply sources will, upon completion of the Delaware River works authorized to date, safely yield an estimated 1460 mgd. Ground waters from wells in Long Island can supplement the supply at present to a very limited and decreasing extent but cannot be counted on in the future and hence are not included in the future safe yield. The consumption of the City, including a small supply required by outside communities, averaged in 1953 1139 mgd; and to play safe, the addition of an average annual increase of 20 mgd has to be anticipated. A daily high of over 1600 mgd was consumed in the summer months of last year.

There are many points of similarity between the Boston and New York supplies. In both cases, the principal developments as we now regard them were commenced at the beginning of the present

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century. Boston was a few years ahead, and in fact set a precedent for the Metropolitan District idea, which has since spread widely, by its legislation in 1898. Both recognized the necessity for a thorough comprehensive survey looking far into the future and both weighed the possibility of obtaining a non-gravity supply from ample near-by sources requiring filtration against a program of going continually further afield for gravity supplies from relatively clean upland sources. Both chose the upland supply.

Boston developed its supply in stages, setting up engineering organizations as they were needed in intervals. New York, however, on account of its great size realized at the start that the problem of finding more supplies would be a continuous one, and set up a permanent organization, the Board of Water Supply. One difference is that the Boston Metropolitan District Commission is a department of the Commonwealth while the New York Board of Water Supply, although an independent agency, is of the nature of a municipal department. One point of similarity, particularly so far as the recent Boston situation is concerned, is that your Metropolitan District Water Supply Commission and its successor, the Construction Division of the Metropolitan District Commission, are engaged only in the construction of the works, that is, making the capital expenditures, and when the works are completed they are turned over for operation and maintenance to the Water Division of the Metropolitan District Commission. Similarly, in New York the Board of Water Supply constructs the works and they are turned over to, and operated by, another municipal department, the Department of Water Supply, Gas and Electricity. Incidentally, the Board of Water Supply has been under civil service from the start, different in that respect from the Boston organization.

Following is a brief description of the various New York sources:

The Croton Supply, which has a present safe yield of 330 mgd was already in use when the Board of Water Supply was organized in 1905. Its Boston counterpart is the old Cochituate and Sudbury System. The principal structures in the Croton System are the two Croton Aqueducts, the old and the new, and the new Croton Dam mostly of stone masonry with gravity section, 174 feet high, and 297 feet above its foundation. Its spillway is at elevation 200, permanent flashboards 202. In this Croton system 12 reservoirs and 6 controlled lakes impound with flashboards, 103 billion gallons, from 375 sq. mi.

drainage area of the Croton River in Westchester and Putnam Counties.

The Catskill Supply has its Boston counterpart, chronologically, in the Wachusett system. It has a safe yield of 555 mgd., 340 from the Ashokan Reservoir, first made available in 1915, and 215 from the extension to Schoharie Reservoir in 1924. The Ashokan Dam is 4650 feet long including 1000 feet of cyclopean masonry, with gravity section, 210 feet high above the bed of Esopus Creek and 252 feet above the foundation, impounding with flashboards 130.5 billion gallons of available storage at elevation 591 west basin, 588 east basin, from 257 sq. mi. of drainage area at Olive Bridge in the Catskill Mountains west of Kingston.

Water was first obtained from Schoharie Reservoir in 1924. Its Gilboa Dam is composed of two parts, an overflow cyclopean masonry spillway 1324 feet long, 155 feet high above the bed of Schoharie Creek, 187 feet above the foundation, and an earth section with concrete core wall about 1000 feet long, impounding 19.6 billion gallons of available storage at elevation 1130 from 314 sq. mi. of drainage area at Gilboa. The water is diverted into Esopus Creek, a tributary of the Ashokan Reservoir, via the Shandaken Tunnel of horseshoe section 11′–6″ x 10′–3″ 18.1 miles long, with a capacity of 650 mgd under full head.

The Catskill Aqueduct is about 92 miles long from Ashokan Reservoir to the Hill View Distributing Reservoir in Yonkers, elevation 295. It is for the most part a cut-and-cover conduit at grade, 17′ x 17′–6″, horseshoe section, with a number of steel pipe siphons, and grade and pressure tunnels. A notable deep-rock tunnel siphon 14′ diameter, 1114 below sea level, crosses under the Hudson River above West Point. The aqueduct has a capacity in excess of 600 mgd. Like its Boston counterpart, the Wachusett Aqueduct, it is a gradeline feeder and subject to all the operational difficulties inherent in that type of aqueduct.

Kensico Reservoir was constructed primarily as an equalizing basin on the Catskill Aqueduct but has a drainage area which provides an additional safe yield of 10 mgd. It also provides storage of water near the City as a safety factor against a breakdown of the Catskill Aqueduct. It is therefore maintained as full as the draft to the City and other factors permit. The Kensico Dam is of cyclopean masonry, with gravity section, 168 feet high above the bed of the Bronx River and 307 feet above the foundations, impounding with permanent flashboards, 30.6 billion gallons of available storage at elevation 357 from 22 sq. mi. of the Bronx River and Byram River drainage areas just north of White Plains.

Incidentally, in developing these rivers, the City diverted the flow from about 9 sq. mi. tributary to the Byram River. Although the expected riparian damages were paid, Connecticut did not make an issue of the interstate diversion to the point of taking the matter to the United States Supreme Court. It is interesting to note that this was similar to Boston's early experience when it built the Wachusett Reservoir involving a diversion from the Nashua River, tributary to the Merrimack River, in which case New Hampshire made no important issue of that as an interstate diversion.

The water is distributed from Hill View Reservoir via two deep-rock tunnels which form a 38-mile loop, City Tunnel No. 1 with diameter decreasing from 15 feet to 11 feet dipping to 704 feet below sea level under the Boroughs of the Bronx and Manhattan to Brooklyn, put into service in 1917, and City Tunnel No. 2 with diameter decreasing from 17 feet to 15 feet dipping to 553 feet below sea level under the Bronx, Queens and Brooklyn, put into service in 1936. From Brooklyn, two submarine pipes, 36″ and 42″ flexible-joint cast-iron, cross the Narrows to the Silver Lake Terminal Reservoir on Staten Island, elevation 228, supplying the Borough of Richmond. This supply can be advantageously supplemented locally in the Borough by wells which add 5 mgd of safe yield.

The Delaware Supply has a Boston counterpart in the Quabbin supply. The entire Delaware supply is diverted into Rondout Reservoir, which impounds 48.7 billion gallons of available storage at elevation 840 from 95 sq. mi. drainage area in the Catskills at Lackawack, and which has a safe yield from its own watershed of 120 mgd. The Merriman Dam, which forms this reservoir, is a rolled-fill earth embankment 2400 feet long and 195 feet high above the bed of Rondout Creek and its concrete core wall, the deep portion of which was constructed with rectangular sectioned caissons, extends to a depth of 180 feet below the bed.

Incidentally, it is interesting to note the development of this type of caisson core wall. About 1930, the author and his colleague, Stanley M. Dore, inspected the first attempt to sink such a core wall through deep overburden to ledge at the Wyman Dam in Bingham, Maine; and we then used this method for Quabbin Dike and Winsor Dam at

Quabbin Reservoir. N. LeRoy Hammond, who was our Division Engineer in charge of that construction was transferred shortly thereafter to the New York City Board of Water Supply in charge of similar construction work at the Merriman Dam, where such a caisson wall was first used on the New York work.

The Delaware Aqueduct, first made available in 1944, is a deep-rock tunnel for its entire length from Merriman Dam to Hill View Distributing Reservoir, 85 miles, over six times as long as the Simplon Tunnel under the Alps, and over three times as long as Boston's Quabbin Aqueduct. Its maximum depth below the surface is about 25000 feet. Its deepest construction shaft was sunk 1551 feet, which is greater than the height of the Empire State Building and over 2-1/3 times as deep as the deepest shaft on Quabbin Aqueduct. It passes under the Hudson River at 600 feet below sea level. It is connected by uptake and downtake shafts not only to Kensico Reservoir but also to another equalizing basin, the West Branch Reservoir, elevation 503, where 43 sq. mi. of the Croton watershed can be intercepted at this high elevation, which is 303 ft. higher than the Croton Reservoir in which the runoff would otherwise be impounded.

The Delaware Aqueduct is 13′–6″ diameter for the first 44.2 miles to West Branch Reservoir, 15′ for the next 27.2 miles to Kensico Reservoir and 19′–6″ for the remaining 13.6 miles to Hill View Reservoir. The capacity of the Delaware Aqueduct across the Hudson River Valley to West Branch Reservoir is sufficient to accommodate in addition to the yield of the Rondout Reservoir drainage area, 800 mgd potential diversion from tributaries of the Delaware River. From West Branch Reservoir to Hill View Reservoir it has a higher capacity. The operation of the system is made flexible by the interconnections, at Kensico and Hill View Reservoirs, with the Catskill Supply. It also has connections from the lower Croton System at two pumping plants, and also as above noted at West Branch Reservoir without pumping.

The Neversink Reservoir, the first to be developed in the Delaware River watershed, has a safe yield of 115 mgd. The first interstate diversion from this reservoir was started January 1, 1954. Its Neversink Dam is a rolled-fill earth embankment 2820 feet long and 195 feet high above the bed of the Neversink River and its concrete-caisson core wall extends to a depth of 150 feet below the bed. It impounds 34.7 billion gallons of available storage at elevation 1440 from 93 sq. mi. drainage area at Neversink. The Neversink Tunnel is 10′ in diameter, 5.5 miles long to the upper end of Rondout Reservoir, where the discharge is through a 36,000 H.P. water turbine with 31,250 KVA generator.

The Pepacton Reservoir, the second to be developed in the Delaware River watershed, will have a safe yield of 375 mgd. Its Downsville Dam is a rolled-fill earth embarkment 2450 feet long and 204 feet high above the bed of the East Branch of the Delaware River and its concrete core wall extends to a depth of 100 feet below the bed. It will impound 143.5 billion gallons of available storage at elevation 1280 from 372 sq. mi. of drainage area at Downsville. The East Delaware Tunnel is 11′–4″ diameter, 25 miles long to the upper end of Rondout Reservoir where the discharge will be through a 25,000 H.P. water turbine with 22,500 KVA generator. The works are nearing completion and it is expected that water from this source should be made available sometime in 1955; or, at the latest in 1956.

There is a difference in elevation of 600 ft. between Neversink Reservoir and Rondout Reservoir and 440 ft. between Pepacton Reservoir and Rondout Reservoir. It was necessary to provide for the dissipation of energy at the two tunnel outlets. To accomplish this in the case of the Neversink, a power plant was constructed, and is being operated, by the Central Hudson Gas and Electric Corporation under a 50-year agreement which will compensate the Power Company for certain diversion damages. In the case of the Pepacton Reservoir a power plant is being constructed, and will be operated, by the Rockland Light and Power Company under a similar compensating agreement.

The total safe yield of the Neversink and Pepacton Reservoirs is 490 mgd but restricted by the 1931 Decree of the United States Supreme Court which limits the interstate diversion from the Delaware to the equivalent of 440 mgd.

Figure 1 shows, in plan, the drainage areas and aqueducts of New York's three water supply systems: The Croton System, East of the Hudson River, with its many reservoirs and its two aqueducts. The Catskill System, with its two reservoirs and the Catskill Aqueduct crossing the Hudson River above West Point. The Delaware System, with its three reservoirs, and a fourth contemplated, and the Delaware Aqueduct crossing the Hudson above Newburgh. Figure 1 also shows a profile of the Delaware Aqueduct.

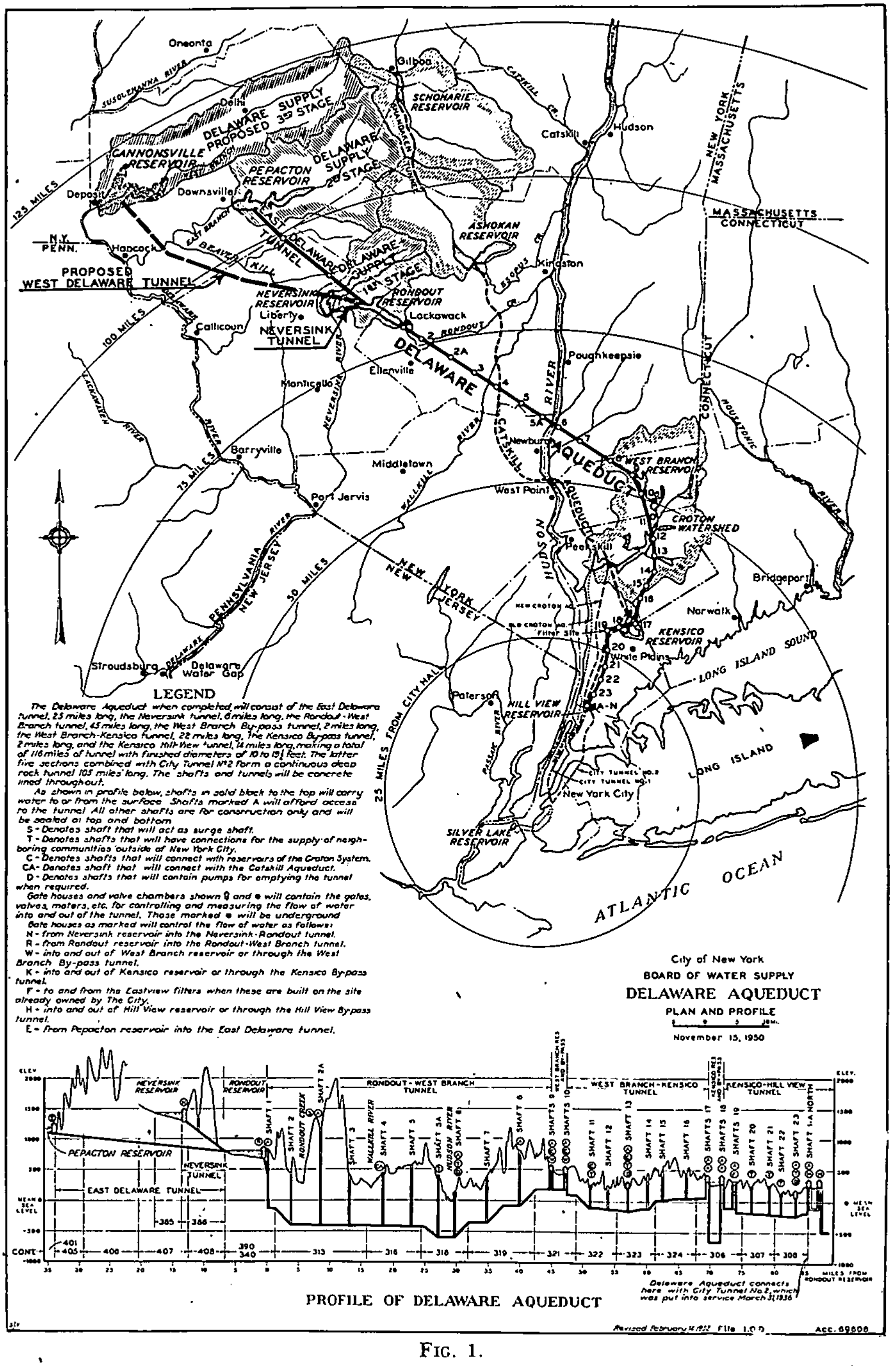
Oneonta
Gilboa
SCHOHARIE RESERVOIR
Delhi
DELAWARE SUPPLY PROPOSED 3RD STAGE
CANNONSVILLE RESERVOIR
PEPACTON RESERVOIR
DELAWARE SUPPLY 2ND STAGE
Catskill
Hudson
NEW YORK
MASSACHUSETTS
CONNECTICUT
Deposit
Downsville
EAST DELAWARE TUNNEL
DELAWARE SUPPLY 1ST STAGE
ASHOKAN RESERVOIR
N.Y.
PENN.
Hancock
BEAVER KILL
Kingston
PROPOSED WEST DELAWARE TUNNEL
NEVERSINK RESERVOIR
RONDOUT RESERVOIR
Liberty
Lackawack
Callicoon
NEVERSINK TUNNEL
DELAWARE
Poughkeepsie
Ellenville
Monticello
AQUEDUCT
Newburgh
WEST BRANCH RESERVOIR
Barryville
Middletown
West Point
Port Jervis
CROTON WATERSHED
Peekskill
HUDSON
NEW YORK
NEW JERSEY
PENNSYLVANIA
Bridgeport
Norwalk
KENSICO RESERVOIR
White Plains
LONG ISLAND SOUND
Stroudsburg
Delaware Water Gap
Paterson
HILL VIEW RESERVOIR
LONG ISLAND
New York City
SILVER LAKE RESERVOIR
ATLANTIC OCEAN
125 MILES
100 MILES
75 MILES
50 MILES
25 MILES FROM CITY HALL
LEGEND
The Delaware Aqueduct when completed, will consist of the East Delaware tunnel, 25 miles long, the Neversink tunnel, 6 miles long, the Rondout-West Branch tunnel, 45 miles long, the West Branch By-pass tunnel, 2 miles long, the West Branch-Kensico tunnel, 22 miles long, the Kensico By-pass tunnel, 2 miles long, and the Kensico Hill-View tunnel, 14 miles long, making a total of 116 miles of tunnel with finished diameters of 10 to 19½ feet. The latter five sections combined with City Tunnel Nº2 form a continuous deep rock tunnel 105 miles long. The shafts and tunnels will be concrete lined throughout.
As shown in profile below, shafts in solid black to the top will carry water to or from the surface. Shafts marked A will afford access to the tunnel. All other shafts are for construction only and will be sealed at top and bottom.
S - Denotes shaft that will act as surge shaft.
T - Denotes shafts that will have connections for the supply of neighboring communities outside of New York City.
C - Denotes shafts that will connect with reservoirs of the Croton System.
CA - Denotes shaft that will connect with the Catskill Aqueduct.
D - Denotes shafts that will contain pumps for emptying the tunnel when required.
Gate houses and valve chambers shown and will contain the gates, valves, meters, etc. for controlling and measuring the flow of water into and out of the tunnel. Those marked will be underground.
Gate houses as marked will control the flow of water as follows:
N - from Neversink reservoir into the Neversink-Rondout tunnel.
R - from Rondout reservoir into the Rondout-West Branch tunnel.
W - into and out of West Branch reservoir or through the West Branch By-pass tunnel.
K - into and out of Kensico reservoir or through the Kensico By-pass tunnel.
F - to and from the Eastview filters when these are built on the site already owned by The City.
H - into and out of Hill View reservoir or through the Hill View By-pass tunnel.
E - from Pepacton reservoir into the East Delaware tunnel.
City of New York
BOARD OF WATER SUPPLY
DELAWARE AQUEDUCT
PLAN AND PROFILE
November 15, 1950
NEVERSINK RESERVOIR
RONDOUT RESERVOIR
RONDOUT - WEST BRANCH TUNNEL
WEST BRANCH - KENSICO TUNNEL
KENSICO - HILL VIEW TUNNEL
PEPACTON RESERVOIR
NEVERSINK TUNNEL
EAST DELAWARE TUNNEL
PROFILE OF DELAWARE AQUEDUCT

FIG. 1.

Figure 2 shows the relation between these three systems in diagrammatic form, Figure 2A showing the actual average distribution of yield, aqueduct flow and consumption for the calendar year 1952, and Figure 2B showing the same for 1953.

The following tabulation summarizes the yield from New York City's water supply sources above described. Note that the years 1952 and 1953 were not critically dry years. Hence the actual yields available in those years were considerably more than the "safe yield"; and a relatively greater quantity was drawn from the more desirable sources.

Sources of New York City's Supply	Approximate Average Million Gallons Daily — Actually used by City and dependent outside communities in 1952 and 1953. 1952	1953	Safe Yield that can be depended on in a critical drought: at present	in the future
From the Old Croton Supply:	mgd	mgd	mgd	mgd
by gravity	160	186	175	175
by pumping	86	124	155	155
From Kensico Watershed	34	34	10	10
From Wells in Richmond	1	2	5	5
From Municipal Wells in Long Island	3	14	80	0
From Wells of Private Companies	40	41	40	0
From the Catskill Supply	601	570	555	555
From the Delaware Aqueduct Supply:				
Rondout Reservoir	196	168	115	120
Interstate Diversions				
Neversink Reservoir	only 440 mgd authorized to date		115	115
Pepacton Reservoir, nearing completion				375
Cannonsville Reservoir, proposed				310
	1121	1139	1250	1820

As a practical matter we should, under present conditions count on not over ¾, even much less, of the above yield from Wells in Long

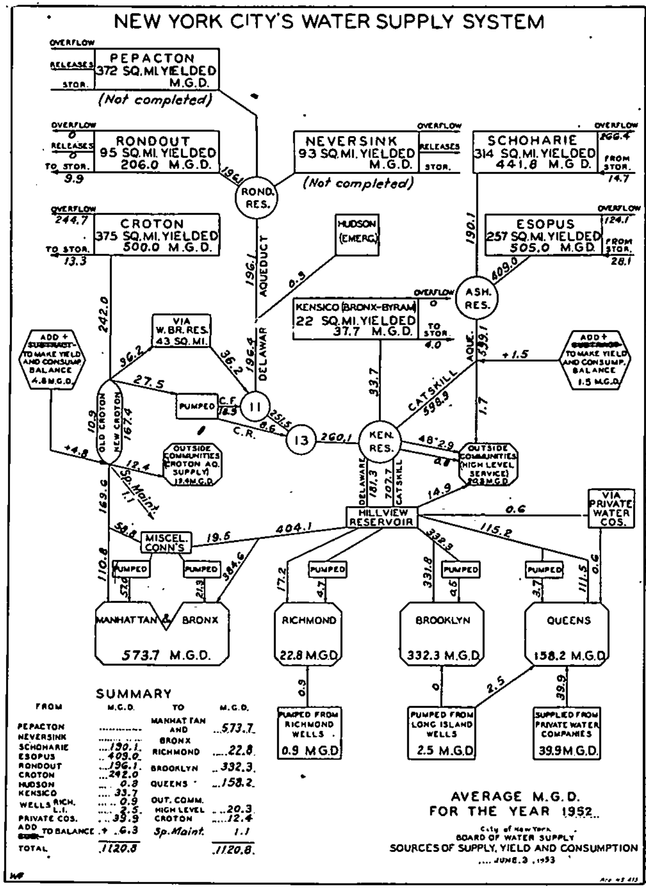
NEW YORK CITY'S WATER SUPPLY SYSTEM
PEPACTON 372 SQ. MI. YIELDED M.G.D.
(Not completed)
RONDOUT 95 SQ. MI. YIELDED 206.0 M.G.D.
NEVERSINK 93 SQ. MI. YIELDED M.G.D.
(Not completed)
SCHOHARIE 314 SQ. MI. YIELDED 441.8 M.G.D.
CROTON 375 SQ. MI. YIELDED 500.0 M.G.D.
ESOPUS 257 SQ. MI. YIELDED 505.0 M.G.D.
KENSICO (BRONX-BYRAM) 22 SQ. MI. YIELDED 37.7 M.G.D.
HILLVIEW RESERVOIR
MANHATTAN & BRONX 573.7 M.G.D.
RICHMOND 22.8 M.G.D.
BROOKLYN 332.3 M.G.D.
QUEENS 158.2 M.G.D.
SUMMARY
AVERAGE M.G.D. FOR THE YEAR 1952
SOURCES OF SUPPLY, YIELD AND CONSUMPTION

FIG. 2A.

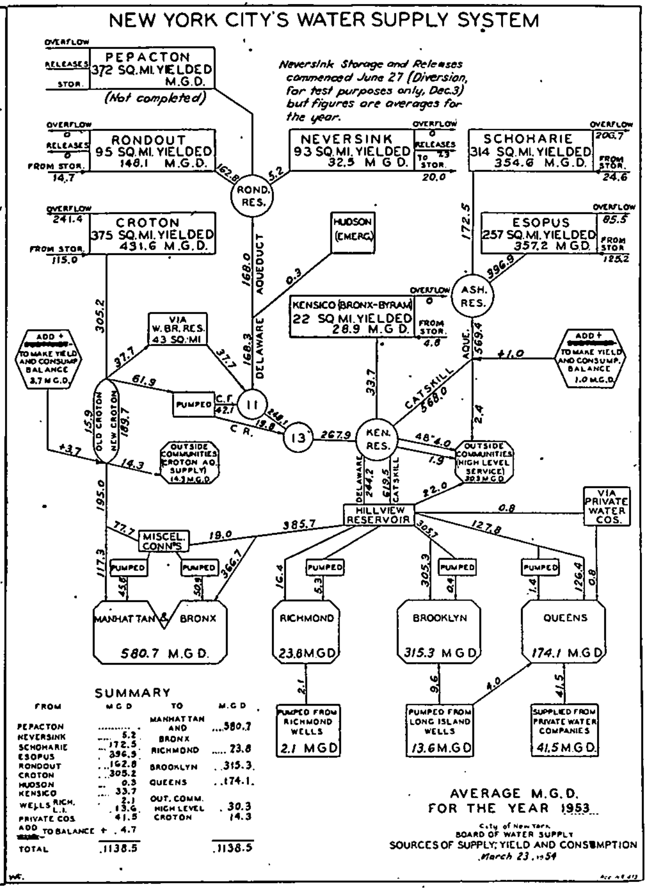
NEW YORK CITY'S WATER SUPPLY SYSTEM
PEPACTON 372 SQ. MI. YIELDED M.G.D.
(Not completed)
Neversink Storage and Releases commenced June 27 (Diversion, for test purposes only, Dec. 3) but figures are averages for the year.
RONDOUT 95 SQ. MI. YIELDED 148.1 M.G.D.
NEVERSINK 93 SQ. MI. YIELDED 32.5 M.G.D.
SCHOHARIE 314 SQ. MI. YIELDED 354.6 M.G.D.
CROTON 375 SQ. MI. YIELDED 431.6 M.G.D.
ESOPUS 257 SQ. MI. YIELDED 357.2 M.G.D.
KENSICO (BRONX-BYRAM) 22 SQ. MI. YIELDED 28.9 M.G.D.
HILLVIEW RESERVOIR
MANHATTAN & BRONX 580.7 M.G.D.
RICHMOND 23.8 M.G.D.
BROOKLYN 315.3 M.G.D.
QUEENS 174.1 M.G.D.
SUMMARY
AVERAGE M.G.D. FOR THE YEAR 1953
SOURCES OF SUPPLY, YIELD AND CONSUMPTION

FIG. 2B.

Island and those of Private Companies, in the column showing continuous safe yield at present. However, this is offset by the fact that some additional yield would be available in an emergency from the City's temporary pumping plant on the Hudson River, which has a few more years of life before its abandonment is required by the State Water Power and Control Commission.

This emergency pumping plant was described in a paper presented to the Society by George R. Rich, and published in the April, 1951, issue of the JOURNAL.

The average rate of consumption last year, 1953, was 1139 mgd with every expectation of reaching at least 1160 mgd in 1954. A glance at the above table shows that if it were not for the fact that the Board has nearly completed the Pepacton Reservoir, or second stage of the Delaware Supply, the City would have no adequate reserve but would be close to facing the same sort of a critical situation which it faced in 1949 and 1950, and only the fortunate occurrence of wet years could make certain that drastic measures which were then resorted to would not have to be repeated.

The search for new supplies is, of course, nothing new to the Board. It has been making such searches continuously since before water was first delivered from the completed Catskill System. The first comprehensive report of such a study was made thirty years ago. At that time a thorough examination of all possible sources within 200 miles of the City made it clear that tributaries of the Delaware River located on the westerly and southerly slopes and foothills of the Catskill Mountains adjacent to the Hudson River watershed were nearer to the City than any other source of equal capacity and, what is very important, sufficiently high for gravity delivery to the City. It was then shown that a supply from those sources would be of better quality, greater quantity and lower cost than other sources investigated.

There was one outstanding difficulty in the way of such a development, namely, the complications involved in the acquisition of interstate waters. This difficulty was overcome, or at least postponed, by a Decree of the United States Supreme Court of May 25, 1931. As a result, the Board immediately started the construction of its Delaware Aqueduct taking a broad look into the future. Now an aqueduct capacity has been provided as above described adequate to deliver from Rondout Reservoir in the Catskills to Hill View Distributing Reservoir in Yonkers at a rate high enough to ultimately accommodate the 800 mgd sought to be diverted from the Delaware watershed. The Decree of the Court in 1931 limited such diversion to 440 mgd but provided for a reopening of the case to permit consideration of a further request by any party to the case. New York has reopened it by petitioning for a modification of the decree to permit diversion of the entire 800 mgd, so that the interstate obstacle to the increased development may be removed.

It is particularly appropriate to compare New York and Boston developments with respect to their involvement in interstate diversions, because the first Delaware River Case and the Massachusetts-Connecticut Case were heard before the same session of the United States Supreme Court and paralleled each other in many respects. The conduct and outcome of these cases is a well-known matter of record, particularly to members of this Society, Past President Frank E. Winsor was Chief Engineer of the Metropolitan District Water Supply Commission at the time. The Court clearly established that the use of the water for public water supply purposes was a paramount one, and applied the doctrine of equitable apportionment. It also upheld the general policy that had been adopted by both New York and Boston, of looking to upland gravity sources, relatively free from pollution.

In delivering the opinion of the Court in New York's Case, May 4, 1931, Mr. Justice Holmes stated:

"A river is more than an amenity, it is a treasure. It offers a necessity of life that must be rationed among those who have power over it. New York has the physical power to cut off all the water within its jurisdiction. But clearly the exercise of such a power to the destruction of the interest of lower States could not be tolerated. And on the other hand equally little could New Jersey be permitted to require New York to give up its power altogether in order that the river might come down to it undiminished. Both States have real and substantial interests in the River that must be reconciled as best they may be. The different traditions and practices in different parts of the country may lead to varying results but the effort always is to secure an equitable apportionment without quibbling over formulas."

In the opinion in Boston's Connecticut Case, February 24, 1931, Mr. Justice Butler stated:

"Drinking and other domestic purposes are the highest uses of water. An ample supply of wholesome water is essential. Massachusetts, after elaborate research, decided to take the waters of the Ware and Swift rather than to rely on the sources in the eastern part of the Commonwealth where all are or are liable to become polluted. We need not advert to other considerations, disclosed by the evidence and findings, to show that the proposed use of the waters of the Ware and Swift should not be enjoined."

Figure 3, shows the actual and estimated growth of New York City and its water consumption and is one of the important exhibits in the current Court Case in which New York is setting forth its need of 360 mgd from the Delaware River in addition to the 440 mgd authorized by the Court's Decree of 1931.

Contrary to some widely circulated opinions, New York is not an extravagant user of water, considering its size. In fact, its daily per capita consumption of 136 in 1952 and 136 in 1953 is the smallest of the nine largest cities in the United States. Of the other eight, Chicago's, 229 gals per capita in 1952, was the largest, and the City of Boston's, 141, was next to New York's, the smallest. The past record of New York City's per capita consumption shows that the upward trend has been at the rate of about 0.7 g.p.c.d. per year and that the ups and downs are within a range of as much as 20 g.p.c.d., or plus or minus 10 g.p.c.d. In projecting this into the future it has been assumed that this trend will decrease after 1980 to the same general trend as indicated by the average of all the nine largest cities, namely, 0.5 g.p.c.d. per year.

The City's current petition to the Court to reopen the case was filed April 1, 1952, and was joined in by the State of New York. It was opposed by New Jersey in its answer filed June 2, and by Pennsylvania in its answer filed May 16, of that year. The City of Philadelphia moved to intervene but its Motion was denied April 6, 1953. Recently Delaware moved to intervene and its Motion was granted April 12, 1954, so that the City's petition was finally opposed by all three states.

Before the City could apply to the Court for an additional supply, it had to obtain approval by the New York City Board of Estimate and by the New York State Water Power and Control Commission, of its specific plan for a reservoir on the West Branch of the Delaware at Cannonsville.

At that time the pros and cons of the alternative plan of pumping and filtering Hudson River water were thoroughly aired at public

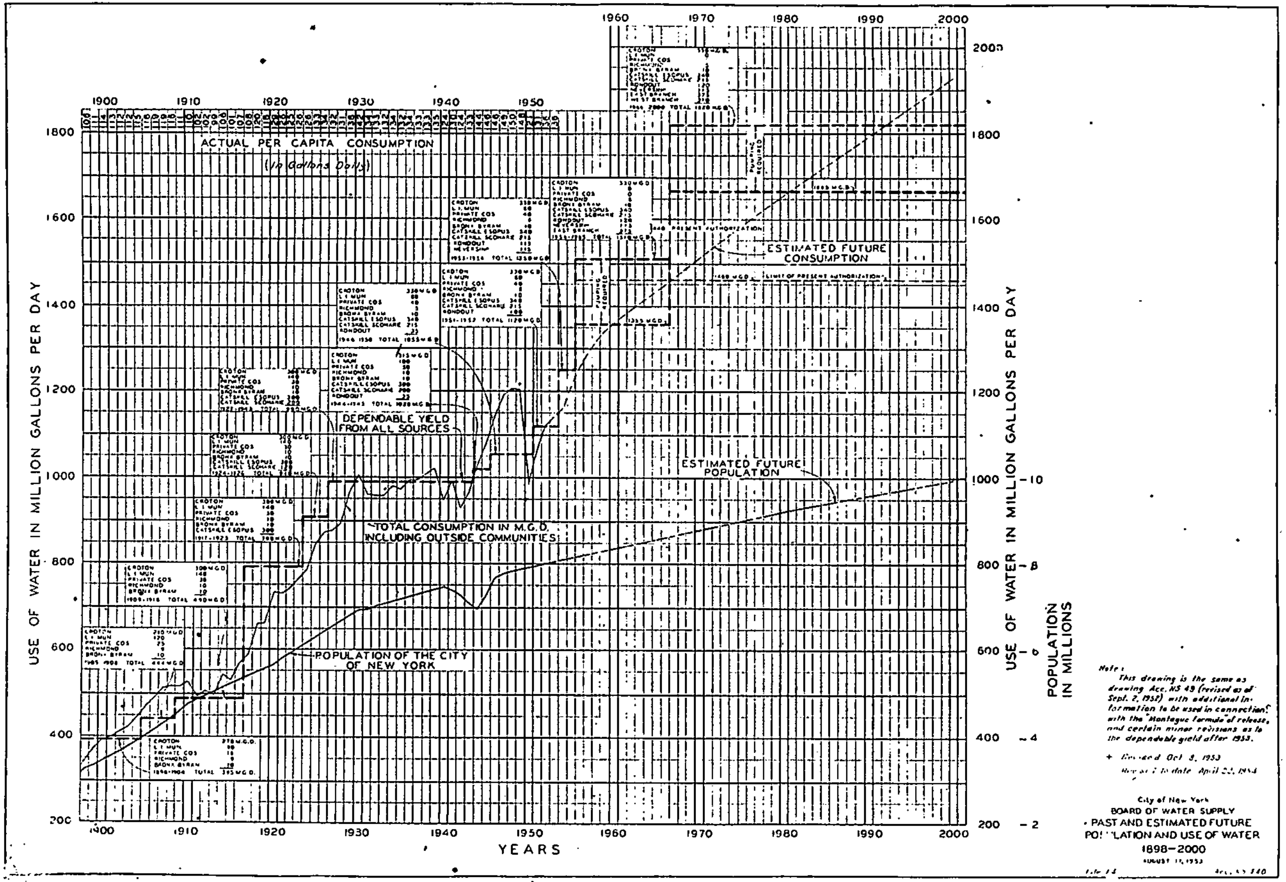
ACTUAL PER CAPITA CONSUMPTION
(In Gallons Daily)
DEPENDABLE YIELD FROM ALL SOURCES
TOTAL CONSUMPTION IN M.G.D. INCLUDING OUTSIDE COMMUNITIES
POPULATION OF THE CITY OF NEW YORK
ESTIMATED FUTURE CONSUMPTION
ESTIMATED FUTURE POPULATION
USE OF WATER IN MILLION GALLONS PER DAY
POPULATION IN MILLIONS
YEARS
City of New York
BOARD OF WATER SUPPLY
PAST AND ESTIMATED FUTURE
POPULATION AND USE OF WATER
1898–2000

FIG. 3.

Estimated Population and Consumption

	Population of New York City	Approx. Gals. per Capita per day		Con-sumption by New York City M.G.D.	Supplied to Outside communities M.G.D.	Total Con-sumption M.G.D.
		Average of ups and downs	Quan-tity that must be provided			
1953 (Actual)	8,050,000±	136		1094	45	1139
1960	8,366,000	147	157	1313	50	1363
1970	8,785,000	153	163	1432	80	1512
1980	9,210,000	159	169	1556	105	1661
1990	9,598,000	164	174	1670	125	1795
2000	9,955,000	169	179	1782	145	1927

hearings; and the stamp of approval given to the City's plan which included the construction of a reservoir at Cannonsville with a flow line at Elevation 1150 and a net available storage capacity of about 91.2 billion gallons. The Board's engineers had conservatively estimated that such a reservoir would be needed to obtain the necessary additional yield for the City and to make such compensation releases to the river as might be required.

In the original Decree of 1931 such compensation was obtained by requiring in effect a release from each reservoir of 0.66 cfs per square mile of its tributary area whenever the flow, either crossing the State line at Port Jervis, New York, or entering tidewater at Trenton, New Jersey, dropped below 0.5 cfs per square mile. In the City's current petition of April 1, 1952, compensation was to be accomplished by a release formula of the type which had been proposed several years earlier by the Interstate Commission on the Delaware River Basin, known as Incodel, or specifically: that the rate of release at each diversion point be 50 per cent of the mean annual runoff, as determined by observations covering the 13-year period 1928 to 1941, whenever the recorded rate of flow falls below that which is exceeded 90 per cent of the time; that the rate of release be 25 per cent of the mean annual runoff whenever the rate of flow is between that which is exceeded 90 per cent and that which is exceeded 76 per cent of the time; and that no release be required when the rate of flow is greater than that which exceeded 76 per cent of the time.

Incidentally, it is well to state briefly that, in spite of frequent reports to the contrary, the Incodel Project for the joint use of the Delaware River by the abutting States, is now out of the picture, for several reasons and principally because the necessary enactment of similar enabling legislation by the several states was never accomplished.

The conduct of the case has been unusual in many respects particularly in that all testimony was introduced in written form after careful editing, and copies, together with pertinent exhibits, were distributed to all parties. The Court appointed Kurt F. Pantzer, Esq. of Indianapolis, as Special Master on June 9, 1952, to take evidence and report his recommendations. Instead of the usual procedure which would have involved many formal hearings for presentation of testimony and cross-examination of witnesses, a comprehensive view of the watershed was first had, a number of informal conferences were held, some between counsel for all parties, some between both counsel and engineers and last, but by no means least, many between the engineering representatives of two or more of the parties.

As a result, the representatives of New York and New Jersey on February 17, 1953, agreed, without qualification, on a substitute formula for the making of compensating releases to the River which included a very practical solution to the problem. The City forthwith filed an amended petition on March 12, 1953, incorporating the new formula, to take effect upon the completion of the East Branch Reservoir now under construction.

From a practical standpoint, operation under this new formula will be greatly simplified due to the reduction of the number of control points to only one, namely, an existing U.S.G.S. gaging station located at Montague, New Jersey, about 8 miles below the State line and recording the effect of all the City's developments upon the flow in the river. Under this new Montague formula so-called, the City would, after completing the proposed reservoir at Cannonsville, maintain a minimum flow in the Delaware River at Montague substantially equal to 1750 cfs or approximately 0.503 csm.

Furthermore, this new formula sets up a working relation between the actual rate of consumption and the safe yield in a period of drought, to the end that as much of the overflow, or so-called waste, over reservoir spillways as New York can safely permit will be released during the dry months of the year when most needed in the lower river rather than held back to be wasted in the following spring months without any material benefit to the river.

This new Montague formula was discussed at length with New Jersey's and Pennsylvania's lawyers and engineers and all parties consented to a press release on June 22, 1953, setting forth that "it is now possible for all parties to make certain recommendations to the Special Master. These recommendations should materially shorten the hearings and expedite the ultimate determination of the Case. . . . In consideration of the increased capacity of the lower Basin resulting from the modified release formula thus offered by New York, New Jersey and Pennsylvania will not oppose the proposed diversions by New York. . . .

"In flood times, there is more than enough water in the Delaware for everyone. In seasons of abnormally low flow, the releases which New York has agreed to make will be a great boon to the Lower Delaware. In the opinion of the engineers for Pennsylvania and New Jersey the additional diversion by New York City under its enlarged plan of development will, if conditions do not change, have no adverse effect on the interests of Pennsylvania and New Jersey, but on the contrary will further such interests by increasing the quantity of water available to those States."

In releasing the above, Mayor Impellitteri stated, "These negotiations have resulted in what I believe is the very substantial accomplishment set forth in the joint press release. This reflects very definite clarifications of complicated engineering details and the narrowing of legal issues to be determined by the Special Master and the Supreme Court. . . . This formula does not involve any change in the City's original plans concerning the dam and reservoir near Cannonsville or any increase in its storage capacity. No additional cost to the City is involved. The formula provides a more effective use of the waters stored for release purposes by changing the timing of the releases. . . . The improved formula which accomplishes the above purposes will be put into effect by New York if it meets with the approval of the Special Master and the Supreme Court. . . ."

Although this apparently assured a report favorable to the granting of New York's petition, the consent of Pennsylvania was qualified principally on account of issues that were raised between New Jersey and Pennsylvania.

New Jersey wished to establish its right to continue certain diversions outside the watershed by its Delaware and Raritan Canal, and Pennsylvania wished to establish the fact that, when and if it desired to make a water supply diversion of its own, it would have the right to build a dam across the Delaware River between the two States. This latter right could be assured only if New Jersey passed certain legislation. Hence, Pennsylvania withheld all its testimony pending such action by New Jersey. The necessary legislation was finally passed on December 24, by Chapter 443 of the New Jersey Laws of 1953.

Since the case is still before the Court, its merits cannot well be discussed in further detail at this time. However, some idea of the ramifications of the case may be had from a brief outline of the testimony which we submitted.

On January 8, 1953, New York circulated: (1) testimony by our Board's President, Irving V. A. Huie, setting forth the factual history of the development of its proposed plan and the reasons why its request for additional interstate water is an urgent one, and filing, as a supporting exhibit, a study by one of our Senior Engineers, Eugene E. Farnan, of population growth and consumption needs; and (2) testimony and exhibits by our Deputy Chief Engineer in charge of Research, Henry Z. Pratt, Jr., explaining the details of all the basic data on river flows. Much time had been spent in preparing daily before-and-after hydrographs covering the entire period of U.S.G.S. records commencing in 1914. In a very real sense, New York's entire case rests on these hydrographs, and the accuracy of their portrayal has not been questioned. On January 21, New York circulated testimony and exhibits by one of our Division Engineers, Vincent G. Terenzio, explaining in great detail the results of studies over a long period of time to determine the seasonal variation of salinity in the tidal portions of the river and estuary and the effect of river flow, tides, etc., on the location of the so-called salt front. On February 3, New York circulated testimony and exhibits by the writer, confirming New York's urgent need, analyzing the physical characteristics and yields of the entire watershed with relation to New York's proposal, and pin-pointing the benefits accruing to the lower river and bay. The exhibits included a report by the Woods Hole Oceanographic Institution on the distribution of salinity in the estuary of the Delaware River.

As already stated, New York's amended petition incorporating the Montague Formula was then filed March 12, 1953. On June 2, New York circulated: (1) supplemental testimony by all four of the above witnesses, modifying their previous testimony to conform to this new formula, explaining the additional benefits to the lower river resulting from the substitution of this formula; and also (2) testimony by Consulting Engineer Frank A. Marston, a member of this Society, describing the results obtained in the sewage treatment plant for the City of Port Jervis which was required by the Decree of 1931 to be constructed as a precedent to any diversion by New York City.

New Jersey, on June 30, 1953, circulated testimony and exhibits by eleven witnesses, including a number of distinguished engineers, four of whom, Howard T. Critchlow, Thurlow C. Nelson, Sheppard T. Powell and Ezra B. Whitman, had testified in the earlier case in 1931. This testimony covered the matter of New Jersey's urgent water supply needs, industrial development, sewage pollution, water quality, salinity penetration, recreational features of the river, and the oyster industry in the bay.

On September 21, 1953, New York circulated: (1) testimony and an exhibit by Consulting Biological Engineer Joseph B. Glancy, discussing the oyster industry in Delaware Bay and the effect of New York's proposed diversion, and rebutting the testimony of New Jersey witnesses and (2) supplemental and rebuttal testimony and an exhibit by Mr. Terenzio, and (3) rebuttal testimony by Dr. Bostwick H. Ketchum, Marine Microbiologist at the Woods Hole Oceanographic Institution.

In the interest of clarifying the issues, a trial memorandum was prepared December 22, 1953, by the City and State of New York which presents a complete history of the case and a summary of New York's testimony to that date.

Following the passage by the New Jersey Legislature of the permissive legislation above referred to, Pennsylvania, on January 5, 1954, circulated testimony and exhibits by seven witnesses, including several distinguished engineers, two of whom, Charles E. Ryder and Abel Wolman, had testified in the earlier case. This testimony covered industrial development, particularly in the vicinity of Philadelphia, water quality, the future water supply needs and resources of all the parties, and the effect thereon of New York's proposal.

In lieu of any cross-examination, New York City, on February 11, circulated rebuttal testimony by Mr. Terenzio, Dr. Ketchum and the writer; New Jersey, on March 17, circulated rebuttal testimony by three of its witnesses, and Pennsylvania, on March 19, circulated rebuttal testimony by four of its witnesses. Delaware, on March 24, circulated testimony by six witnesses, covering its industrial development, water quality, salinity penetration, and miscellaneous affects of New York's proposal. Finally, Philadelphia, on April 7, circulated surrebuttal testimony by one of its witnesses. The final hearing for the record, before the Special Master, was held in Philadelphia, April 15, with no cross-examination of witnesses by any of the parties.

Following this a supplemental, and final, memorandum was filed April 17 by New York; and final briefs were filed by New Jersey on April 23, by Delaware on April 29 and by Pennsylvania on May 3.

The final briefs were summarized in a press release by the Board of Water Supply on May 10, 1954, setting forth that:

"Pennsylvania has now joined New Jersey and Delaware in conceding that New York City does not damage the lower Delaware River by taking 800 million gallons daily for its water supply. The Pennsylvania lawyers and engineers accompany this concession with the warning that the estimated growth of population and industry in the Delaware Valley may require a future readjustment of the amount of water diverted by New York City. This possibility has been studied with the greatest care by New York City Engineers, and they are completely satisfied that the principles of conservation and regulation which are being established in the present litigation eliminate any risk that the resources of the Delaware River may prove inadequate for the water supply of Pennsylvania and New Jersey as well as New York. . . . This principle of contributing to river regulation from storage reservoirs will prove of great benefit to all of the States which rely upon the Delaware as a source of potable water supply. Similar reservoirs can be constructed by Pennsylvania and New Jersey in their Delaware watersheds, and those reservoirs can add their contribution to river regulation. If the precedent established in this case of making contributions to river regulation is followed in the future, and we believe it will be, there are more than ample resources in the river for all conceivable use by New York, Pennsylvania, New Jersey and Delaware. New York City and New York State have taken the position throughout this litigation that the Delaware is a great natural resource belonging and available to New York as well as to the downstream States. This position conforms with the decisions of the Supreme Court of the United States. If each State proposing to use the Delaware River for municipal water supply makes comparable developments, with comparable releases for river regulation, there never will be need to raise any question of priority of right. The river, properly developed by all States, has ample resources for all."

The urgency of prompt action has led us to anticipate a favorable decree to the extent of laying the ground work for advertising and letting boring and other contracts without undue delay.

The site of our proposed Cannonsville Reservoir and certain appurtenant works extends for over 20 miles up the valley of the West Branch of the Delaware River and 7 or 8 miles up the valley of a tributary stream. The precise locations for a horizontal network are obtained as follows:

The United States Coast and Geodetic Survey has established triangulation stations on high points of land throughout this general area. In their original work they had to use 100-foot towers in order to obtain the necessary sights and these are of course not now available. They did, however, in their original work establish azimuths to distant points visible from surface set-ups which enable us to turn on to accurate base lines in the valley, one at the upper end of the main reservoir, another at the dam site at the downstream end, and another at the upper end of the tributary branch. We then triangulate in the wide bottom of the valley between these terminals by a series of rectangles extending the entire length of the main reservoir and up the tributary branch. In this way we establish the horizontal network with the desired degree of precision approaching that of the basic USCGS net.

The proposed tunnel which would divert the water from the Delaware watershed into our Rondout Reservoir is about 45 miles long. After first locating approximately the shaft sites, seven in number, by preliminary reconnaissance, we establish a horizontal network from adjacent USCGS triangulation stations in just the same way as above described in the case of the reservoir. The shaft sites average nearly 6 miles apart and we are able to do this separately for each shaft from nearby hilltop stations. In the adoption of a general coordinate system, the USCGS has divided the State into three areas spanning its entire longitude. We have adopted the appropriate, easterly, system and all our horizontal networks will be plotted on that system of coordinates.

As far as the vertical ties are concerned we run a precise level line between established USCGS bench marks, 15 miles apart in the main valley, and extend these elevations another 8 miles up the main valley and back and also 8 miles up the tributary branch and back. Also we run precise level lines in a similar manner, from other established USCGS bench marks, to the various shaft sites and back.

We had available to us contour maps in the reservoir site with a 10-foot contour interval, obtained from the United States Corps of Engineers who had made an earlier study in that location. Investigation convinced us that these do not give us sufficient detail. We planned for a map with a 5-foot contour interval in most of the area which has fairly steep slopes, and a 2-foot contour interval in the flatter areas where we are interested in more precise details. Accordingly, last November, after the leaves had fallen and before any important snowfall, we had the entire reservoir area photographed from the air. We can now proceed with a contract for the necessary contour maps by the photogrammetric method. From the precise level network previously described, we are running up the various highways to establish bench marks at or above the proposed flow line. From these we will now obtain without delay the elevation of checking points which the aerial contractor will spot for map control as needed from the photographs.

Thus we hope to be able to start the advertisement and letting of contracts promptly, in case we obtain a favorable Decree from the Court.

HAROLD KILBRITH BARROWS

1873-1954

Harold Kilbrith Barrows died March 15, 1954, having lived a full life of 80 years. He was born in Melrose, Mass. His father was Cyrus Moulton Barrows and his mother was Augusta (Kilbrith) Barrows. His father had a printing business in the market district of Boston. During his boyhood the family moved to Reading, from which he commuted to M.I.T.; where he graduated in the Class of 1895.

His was a fine record of important public service. Upon graduation he served for two years with the Newton (Mass.) City Engineering Department under W. D. Woods, City Engineer. Then for two years he was employed by the Boston Metropolitan Water Board working on design of Forbes Hill Reservoir, Wachusett Dam and Weston Aqueduct. The following two years he was Assistant and Associate Professor of Civil Engineering at the University of Vermont.

From 1904 to 1909 he served as district engineer, Water Resources Branch, U.S. Geological Survey for New England, and from 1906 to 1908 also for New York State. These services included river measurement, storage and power investigations. Here he learned the actions and antics of all of the New England rivers—which information served him to good purpose in his later assignments on flood control and water power development projects.

In 1907 he established an office as consulting engineer in Boston, which he maintained until 1949. During the period of 1910 to 1930, Charles B. Breed was associated with him under the firm name of Barrows & Breed. In his consulting practice he was frequently in court as an expert witness on water power.

His practice covered particularly water power, water supply and flood control. This involved services for several public utility corporations and membership on the Advisory Committee on Flood Control of Vermont. He was Regional Consultant of the National Resources Board from 1934-36. This Board produced two reports on water supply, water power, flood control, conservation by storage, navigation, recreation and water disposal, supplemented by basic reports on precipitation and runoffs; it was a very complete inventory of the water resources of this district.

Professor Barrows was Chairman of the Water Resources Committee, New England Planning Commission, composed of a member from each New England state. They took the lead in directing desirable legislation so that the New England states might work together in interstate river development. He presented a number of papers before the Boston Society of Civil Engineers and took a very prominent part in the preparation of the New England Flood Control reports of that society.

For thirty-one years he served M.I.T., first as Associate Professor and later as Professor of Hydraulic Engineering. He taught principally Water Power and Flood Control and retired in 1940 as Professor of Hydraulic Engineering, Emeritus. After that he served at M.I.T. as an honorary lecturer in water power engineering for three years.

He was a past president of the Boston Society of Civil Engineers and Director of the New England Water Works Association; an Honorary Member of the M.I.T. Chapter of Chi Epsilon and a member of American Society of Civil Engineers, American Society of Consulting Engineers, and a fellow of the American Academy of Arts and Sciences.

His book (1927) on Water Power Engineering has been accepted as authoritative and has been adopted as a text in many universities.

Professor Barrows married Mabel Jordan of Old Town, Maine, in 1907. They had one son, Kilbrith Jordan, who survives them.

The personal Barrows was gracious and kindly, a product of the time when engineers were just naturally ethical. He was of that kind.

OF GENERAL INTEREST

The Waterways Experiment Station

On June 18, 1954 the Waterways Experiment Station of the Army's Corps of Engineers will round out a quarter-century of research and experimental work that has saved the American tax-payer millions of dollars and has been an important part of the research and development program of the Defense Department.

More than 10,000 visitors are expected to inspect the Vicksburg and Jackson, Mississippi installations of the Experiment Station during Open House periods to be held on June 18, 19, and 20 in observance of the Engineer agency's Silver Anniversary, according to an announcement by Colonel Carroll H. Dunn, Director.

Among the visitors will be Major General Samuel D. Sturgis, Chief of Engineers, and some of the Nation's leading scientists and engineers. General Sturgis will introduce the principal speaker at a brief formal ceremony to be held as part of the Open House program at Vicksburg on June 18 at 8:00 P.M.

Born of the disastrous Mississippi

AERIAL VIEW OF THE VICKSBURG RESERVATION OF THE WATERWAYS EXPERIMENT STATION.

River flood of 1927, the Waterways Experiment Station has grown in 25 years from a small hydraulic laboratory devoted to studies connected with the flood control plan for the Lower Mississippi Valley into what General Sturgis recently called "the principal research and experimental facility of the Corps of Engineers in the fields of hydraulics, soils mechanics, and concrete engineering."

Hydraulics

The Station's Hydraulics Division has conducted hundreds of model studies covering almost every conceivable type of river, harbor and flood control problem in the past 25 years, including several for foreign Governments.

One example of the way the installation uses hydraulics studies to save the taxpayer money is the model of the entire Mississippi Basin, the largest hydraulic model in the world. This model, which sprawls over 200 acres, is located at the Experiment Station Suboffice near Jackson, Mississippi.

During the 1952 flood in the Missouri Valley, engineers from the Kansas City and Omaha Districts of the Corps telephoned rainfall and runoff data to the Experiment Station.

By working day and night to simulate flood conditions in the model, the Station was able to predict, with extraordinary accuracy and a week in advance, the time and occurrence of the flood crest along the endangered levee and which part of the valley (and towns therein) would be flooded and which parts would either remain dry or could be protected.

Having this advance information enabled field engineers to concentrate their flood-fighting at the critical points. The accuracy of the forecasts and the lead-time made possible by the model operation was, according to the Army Engineers' Missouri River Division, a major factor in preventing an additional $65,000,000 damage to the Omaha-Iowa City area.

Soils

Engineers of the Station's Soils Division have conducted field and laboratory tests of soils at the sites of many of the large earth dams and levees in the Mississippi Valley and have designed these flood control works.

They have also conducted foundation investigations for concrete dams and outlet structures in the Valley and have provided the slope design for the dam excavation. The Soils Division was added to the Experiment Station in 1932.

When the Corps of Engineers took over airfield construction early in the war, it found that there were no standards for design of flexible pavement (blacktop) runways. A flexible pavement laboratory was added to the Soils Division in 1943 to develop design criteria for these pavements. The results of the Vicksburg flexible pavement studies were used in constructing airfields throughout the world in World War II. Since that time this laboratory has been engaged in investigations of world-wide importance to our air-base construction program.

Concrete

The Corps of Engineers is probably the largest user of concrete in the United States. As the principal concrete research laboratory of the Corps, the Station's Concrete Division has the job of finding ways to make better concrete that will last longer, at less cost.

This requires a multitude of tests to learn how concrete will react under different conditions. Test specimens are subjected to continuous cycles of freezing-thawing and wetting-drying, actions by nature that cause most concrete cracking and failure.

One of the laboratory's research projects is an exhaustive study covering the use of 16 carefully selected materials which may be used advantageously to replace a portion of the

Portland cement in structures of mass concrete. Results obtained thus far have made possible a saving of some $4,000,000 in construction costs of projects recently completed.

Better Construction for Less Money

In discussing the Experiment Station recently, the Chief of Engineers said, "The studies conducted by the Waterways Experiment Station are contributing steadily to our knowledge of hydraulics, soils mechanics, and concrete engineering and are helping us tremendously in our efforts to provide better construction throughout the United States for less money."

"The work of this unique organization has saved the American taxpayer more than $100,000,000 and has been an important part of our flood control and national defense effort," General Sturgis added.

Classification of BSCE Members

The following breakdown of work classifications has been tabulated from the listing of Boston Society of Civil Engineers Members.

Architects	14
Bridge-Highway and Transportation	93
City & Town Engrs.	31
Construction Engrs.	126
Contractors	9
Contracts & Specifications	6
Draftsmen	17
Electrical	5
Hydraulics	106
Mechanical	16
Miscellaneous	9
Professors	64
Sanitary	134
Sales Engr.	15
Soils Engr.	10
Structural—Design	172
Surveying	86
Research	3

Registered Prof. Engineers	406
Registered Surveyors	86

(From Roster of Registered Professional Engineers and Land Surveyors Published in 1952)

PROCEEDINGS OF THE SOCIETY

MINUTES OF MEETING

Boston Society of Civil Engineers

April 13, 1954.—A Joint Meeting of the Boston Society of Civil Engineers with the Northeastern Section of the American Society of Civil Engineers, and the Transportation Section, BSCE, was held this evening at Northeastern University, 360 Huntington Avenue, Boston, Mass.

President John B. Wilbur, of the Northeastern Section, American Society of Civil Engineers, was presiding and called upon President Miles N. Clair of the Boston Society of Civil Engineers to conduct any BSCE business necessary.

President Clair called upon the Secretary to announce election of New Members and New Applicants for membership in the BSCE.

The Secretary also made an announcement of the Structural Section meeting to be held in the Society Rooms, 715 Tremont Temple, on Wednesday, April 14. Then President Clair turned the meeting back to President Wilbur.

President Wilbur called upon Herman G. Protze, Chairman of the Transportation Section to conduct the business of that section.

President Wilbur then introduced the speaker of the evening, Mr. John Kyle, Chief Engineer of the New York Port Authority, who spoke on "Traffic Unlimited".

Fifty-eight members and guests attended the dinner preceding the meeting and seventy-two members and guests attended the meeting.

The meeting adjourned at 8:40 P.M.

ROBERT W. MOIR, *Secretary*

MAY 19, 1954.—A Joint Meeting of the Boston Society of Civil Engineers with the Surveying & Mapping Section was held this evening at the American Academy of Arts & Sciences, 28 Newbury Street, Boston, Mass., and was called to order by President Miles N. Clair, at 7:00 P.M.

President Clair stated that the Minutes of the April 23, 1954 meeting would be published in a forthcoming issue of the JOURNAL and that the reading of the minutes therefore be waived unless there was objection.

The President announced the death of the following members:—

Vernald W. Fox, who was elected a member April 24, 1924 and who died May 9, 1954.

Dana M. Wood, who was elected a member February 19, 1908 and who died May 10, 1954.

President Clair called upon the Secretary to announce election of New Members and New Applicants for membership in the B.S.C.E.

The Secretary announced that the following had been elected to membership:—

Grade of Member.—Stuart M. Alexander*, Alan R. Chandler, John J. Dwyer, Charles G. Ellis, Alfred A. Grella, James R. Jones, Robert F. Kelsey, Joseph H. Lenney*, Jack Mulholland, James G. Noonan, Melvin R. Rubin*, Philip F. Sullivan, Joseph F. Willard*, Gordon R. Williams, William E. Wiley, Roy L. Wooldridge*.

Grade of Student.—Alexander Banach, Daniel J. Costello.

President Clair announced that this was a Joint Meeting with the Surveying and Mapping Section and called upon Wilbur C. Nylander, Chairman of that Section to conduct any necessary business at this time.

President Clair then introduced the speaker of the evening, Karl R. Kennison, Chief Engineer, Board of Water Supply, New York City, who gave a most interesting illustrated talk on "Problems Which New York City Faces in Expanding Its Water Supply Sources".

A discussion period followed after which the President announced that a collation would be served in the Lounge on the floor above.

Sixty-six members and guests attended the meeting.

The meeting adjourned at 8:45 P.M.

ROBERT W. MOIR, *Secretary*

*Transfer from Junior.

STRUCTURAL SECTION

APRIL 14, 1954.—A meeting of the Structural Section was held at the Society Rooms. Dr. Ruth D. Terzaghi, Chairman, opened the meeting at 7:30 P.M.

Dr. T. William Lambe, of the Civil Engineering Dept. of Massachusetts Institute of Technology, was the speaker. His subject was "The Improvement of Soil Properties with Dispersants". Dr. Lambe explained the use of chemical dispersants to stabilize soil and how these affect soil properties. Slides were used to illustrate the method of treating soils to reduce permeability and frost heaving. Several examples of its use in the construction of canal linings, reservoir floors and dam cores were discussed. Among them were projects at Jay, Maine, and Puerto Rico, wherein this method of soil treatment proved economical and satisfactory in sealing these structures.

The talk was well received by the 33 members in attendance.

It was announced that a joint meeting with the Hydraulics and Transportation Sections will be held May 4 at the American Academy of Arts & Sciences to hear Professor A. W. Skempton, D.Sc., of the University of London, speak on "Civil Engineering 1500-1900; an Historical Sketch".

A. L. DELANEY, *Clerk*

MAY 14, 1954.—A joint meeting of the Structural, Hydraulics and Transportation Sections was held at the American Academy of Arts & Sciences. Dr. Ruth D. Terzaghi, Chairman of the Structural Section, opened the meeting at 8:00 P.M.

Professor A. W. Skempton, D.Sc., of the University of London, was the speaker. His talk was on "Civil Engineering 1500-1900; an Historical Sketch".

One hundred thirty-five members were in attendance.

A. L. DELANEY, *Clerk*

TRANSPORTATION SECTION

FEBRUARY 24, 1954.—Following an informal dinner at the Century Restaurant, the meeting was called to order by Chairman H. P. Duffill at 7:30 P.M. The minutes of the previous meeting held on December 17, 1953 were read and approved. The report of the Nominating Committee was read by Albert A. Adelman and accepted. The Clerk was instructed to cast one ballot for the following officers:—

Chairman, Herman G. Protze
V.-Chairman,
Stanislaw J. V. Gawlinski
Clerk, Joseph F. Willard
Executive Committee,
Paul A. Dunkerly
Hugh P. Duffill
Marcello J. Guarino

The Chairman then introduced the speaker of the evening, Mr. John McCloskey, Project Engineer, Mass. Department of Public Works, who spoke on "Present Development of the Massachusetts Highway Program". The speaker described the various major highways now under construction or in the planning stage, including those being built under the various bond issues. He also described a program of spot improvements of existing highways which will modernize them at a minimum cost to the Commonwealth.

A discussion period followed the talk.

Sixty-four members and guests were in attendance.

JOSEPH F. WILLARD, *Clerk, pro-tem*

APRIL 13, 1954.—A Joint Meeting of the American Society of Civil Engineers, Northeastern Section, the Boston Society of Civil Engineers, and the Transportation Section of B.S.C.E., was held at Northeastern University. Following a catered dinner, the meeting was called to order by President John B. Wilbur, Northeastern Section, A.S.C.E., at 7:15 P.M.

A short business meeting was conducted by the Boston Society of Civil Engineers, after which the speaker of the evening, Mr. John Kyle, Chief Engineer of the New York Port Authority, was introduced. Mr. Kyle spoke on "Traffic Unlimited", giving a very interesting description of plans for traffic congestion relief in the New York City-New Jersey Area. A discussion period followed the talk.

Attendance—72.

JOSEPH F. WILLARD, *Clerk*

MAY 4, 1954.—A joint meeting of the Structural, Hydraulics, and Transportation Sections of the Boston Society of Civil Engineers was held at the American Academy of Arts and Sciences at 7:30 P.M.

Chairman Ruth Terzaghi of the

Structural Section presided, and introduced the speaker, Professor A. W. Skempton, of the University of London, whose subject was "Civil Engineering 1500-1900; an Historical Sketch".

Professor Skempton gave a very interesting, fully illustrated account of various important civil engineering works in Europe, America, and India. He described some of the early harbor developments in France, England, and Holland, showing the competition between the various countries in their attempts to become leaders in water transportation. He also showed various phases of development in bridge construction, including several well-known American bridges. This was followed by a description of the improvements in highways, brought about mainly due to an interest in obtaining faster mail service between different towns. The speaker concluded his talk by telling of irrigation projects in India, for the purpose of increasing food supply.

A short discussion period followed, and a collation was held after the meeting.

Attendance—135.

JOSEPH F. WILLARD, *Clerk*

ADDITIONS

Members

Alan R. Chandler, 293 Park Avenue, Arlington 74, Mass.
William E. Cawley, 48 Boundary Road, Malden, Mass.
Ara Demurjian, 18 Silk Street, Arlington, Mass.
Malcolm E. Dudley, 153 Rice Avenue, Rockland, Mass.
Alvin M. Fine, 37 Berkshire Avenue, Sharon, Mass.
Leon L. Furr, 42 Arlington Street, W. Medford, Mass.
Alfred A. Grella, 368 Summer Street, E. Boston, Mass.
Paul R. Johnson, 46 Hudson Street, Milton 87, Mass.
James R. Jones, 590 Weld Street, W. Roxbury, Mass.
Robert F. Kelsey, 103 Sylvan Road, Needham, Mass.
Donald J. McNamara, c/o Chas. T. Main, Inc., Malikan Baraja, Turkey
Saul Peraner, 12 Kilsyth Terr., Brighton, Mass.
Charles J. Reichenbacher, 51 Woodland Avenue, Melrose Hgds., Mass.
Raymond W. Sanborn, 112 Beach Street, Malden, Mass.
Anthony G. Sandonato, 70 Revere Street, Quincy, Mass.
Russell Trufant, North Carver, Mass.
John E. Zimarowski, 41 Waverly Street, Brockton, Mass.

Juniors

Francis M. Fullerton, 6 Rodman Street, Jamaica Plain, Mass.

Students

Alexander Banach, 79 Sycamore Street, Somerville, Mass.
Daniel J. Costello, 17 Henshaw Street, Brighton 35, Mass.

DEATHS

Vernald W. Fox, May 9, 1954
Dana M. Wood, May 10, 1954

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AND
ADVERTISEMENTS

The advertising pages of the JOURNAL aim to acquaint readers with Professional and Contracting Services and Sources of Various Supplies and Materials. You would find it of advantage to be represented here.

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