HYDRAULIC DESIGN OF DETENTION TANKS

By R. Stevens Kleinschmidt,* *Member*

Introduction

The use of large tanks or basins for improving the quality of water goes back at least to Roman times. Frontinus[1] reports that in the first century of the Christian era a basin was provided for the removal of suspended matter from the water of New Anio Aqueduct. In the more recent past, settling basins were often provided for control of turbidity well before the advent of modern water treatment. In present day water and sewage treatment plants such tanks are still of major importance. Their use is to provide time for suspended solids to settle, and for this reason they come under the general heading of detention tanks. However, as shown by Hazen,[2] the operation of a settling basin is primarily controlled by the surface area and flow rate and may be quite independent of depth. It is, therefore, not primarily a function of the detention time of the basin, so these will be excluded from the definition of detention tanks.

On the other hand, there are in use today tanks provided for the sole purpose of allowing time for some process other than sedimentation to take place. The name "detention tank" will be reserved for these. Chlorine contact tanks are a good example. In these, time is provided for the chlorine to kill any organisms present in the water. Another use is in the disposal of radioactive wastes with a short half-life. Here, basins are used to provide time for decay.

Another use of continuous flow tanks is for the dilution of slugs of objectionable material in order to keep their concentration below a maximum permissible level. Such a tank might well be placed in the sewer from a laboratory in order to prevent concentrated chemical solutions from entering the receiving system. These will be called integrating tanks and their ideal performance will be seen to be quite different from that of detention tanks.

The field of sedimentation tank design has been well covered in the

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[1] Frontinus, "The Stratagems and the Aqueducts of Rome," Tr. Charles E. Bennett, p. 357, Putnam, 1925.

[2] Allen Hazen, "On Sedimentation," Trans. Am. Soc. Civil Engrs., 53, 63 (1904).

past[3] but a literature search disclosed an almost complete lack of information on the design of detention tanks. The present work attempts to alleviate to some degree this vacuum. The practical importance of the work can be seen by the fact that today there are large and expensive detention tanks in use in the atomic energy industry which are giving removals which might be expected of tanks of one-half the size, working near optimum efficiency.

The fundamental engineering problem is "How can the most satisfactory detention tank be built for the least money?" To answer this one must first consider to what use the tank is to be put. Next, one must determine what optimum operation would be, and follow with a look at those factors which will prevent this optimum performance from being realized. Then means must be found to minimize these detrimental factors, and finally, one must determine from the over-all picture just what will constitute the most economical design to fulfill the requirements. This is a complex problem since it involves the cost of materials, labor, excavation and available space. Moreover, the shapes of tanks that provide the greatest volume per unit cost are generally unsuitable for good detention tanks. However, if the effect of shape, velocity, baffles and inlet and outlet arrangements on performance can be evaluated and the practical limits established over which these factors may be varied, then the designer will be in a better position to design the most economical tank for a given set of conditions. As a secondary objective an attempt will be made to develop a theory for operating small scale models so that where cut and try is needed it can be done at small expense before construction of a prototype is begun.

Because of the common occurrence of exponential decay of substances to be removed from water it will be worth while to investigate tanks used to provide time for such a process to take place. Optimum performance would be realized if each particle remained in the tank for exactly one theoretical detention time. Such a situation can be visualized as follows. If a slug of dye were introduced into the inlet of such an ideal tank, the dye would spread instantly into a thin plane at right angles to the flow and this plane would move down the tank remaining undistorted until it reached the outlet where it would draw together and leave the tank as a unit. That this would give minimum concentration in the effluent will be proved following the discussion of a most powerful research tool—the flow-through curve.

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[3] G. M. Fair and J. C. Geyer, Water Supply and Waste Water Disposal," Ch. 22, Wiley 1954.

THE FLOW-THROUGH CURVE

In the investigation of detention tanks, the so-called "flow-through curve" (Figure 2-1, Curve A) is a most useful analytical tool. Ideally, such a curve indicates the statistical distribution of the flow-times of individual water molecules in passage through the tank. Actual flow-through curves can only approximate such a distribution since the tracer molecules or ions do not necessarily follow pathlines that are identical with those of water molecules or particles of waste. Moreover, limitations are imposed by imperfections in the sensitivity and precision of the tracer detection apparatus. However, these non-ideal conditions may ordinarily be controlled so that the error is negligible. A flow-through curve obtained with a good tracer and measuring apparatus provides useful information relating to the detention characteristics of a tank. With a knowledge of the statistical distribution of flow-times of individual particles, it is possible to calculate the reduction in activity of any radioactive isotope of specified half-life in passage through the basin. To do this the decay curve for the isotope (Curve B, Figure 2-1) can be drawn starting with a concentration of one at time zero. Then each ordinate of the flow-through curve (Curve A, Figure

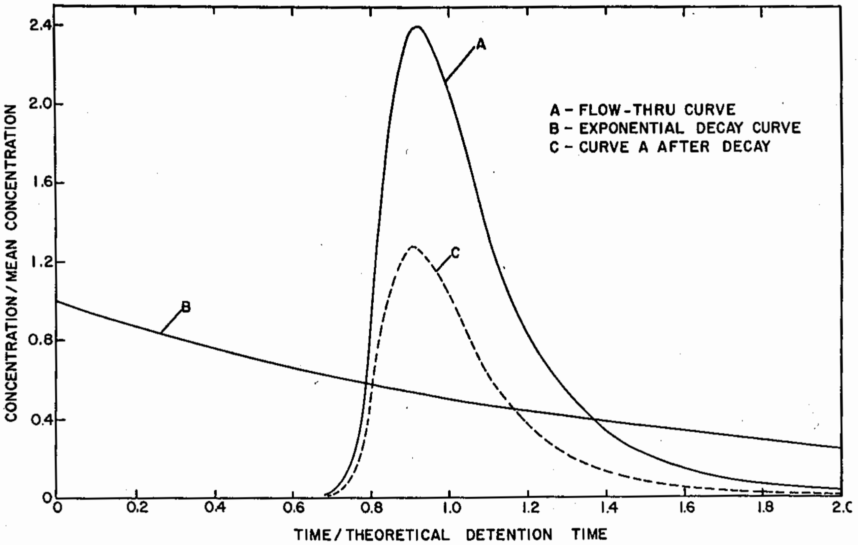

FIGURE 2-1.—TYPICAL FLOW-THRU CURVE WITH AND WITHOUT DECAY.

2-1) is multiplied by the corresponding ordinate of the decay curve giving the flow-through curve with decay (Curve C, Figure 2-1). The area under this curve represents the ratio of effluent to influent concentrations.

METHOD OF OBTAINING FLOW-THROUGH CURVES

To get a flow-through curve, a "slug" of tracer is abruptly introduced into the flow at the inlet and the concentration of tracer at the outlet measured at regular intervals. The results are plotted in dimensionless form. The observed concentration c, is divided by a mean concentration $\bar{c}$, which is defined as the amount of tracer in the slug, W, divided by the volume, V, of the tank, so that the ordinate of the flow-through curve is $\frac{cV}{W}$ or $c/\bar{c}$. Time is made dimensionless by dividing the time, t, by the theoretical mean detention time, T, which is defined as the volume of the tank divided by the discharge rate, Q. In this way the curve is made independent of detention time and size of slug and the comparison of different designs is facilitated.

FUNDAMENTAL PROPERTIES OF FLOW-THROUGH CURVES

All flow-through curves have two fundamental properties: first, the area, A, under the curve is equal to unity; and second, the center of gravity of the curve falls at $t/T = 1$. In general, both of these statements entail a small error. For example, consider a section of channel with highly turbulent flow. Some molecules of tracer will pass back and forth across the end of the section a number of times before being carried on down stream, thus, increasing the probability of their being detected. This would give an area of more than one for the flow-through curve. In tanks of the usual type which have a weir or other control producing high velocities in the downstream direction just outside the tank, it is evident that such an error is negligible.

That the area under the flow-through curve equals unity follows from the following relation:

$$A = \int_0^\infty \frac{c}{\bar{c}} \frac{1}{T} \, dt = \frac{1}{\bar{c}T} \int_0^\infty c dt = \frac{Q}{\bar{c}V} \int_0^\infty c dt = \frac{W}{\bar{c}V} = \frac{\bar{c}}{\bar{c}} = 1 \tag{2-1}$$

To show that the centroid falls at $t/T = 1$ is more difficult. By definition the centroid is:

$$T_c = \frac{1}{T} \frac{\int_0^\infty ctdt}{\int_0^\infty cdt} \tag{2-2}$$

From the definition of a perfect tracer the portion of the flow which gets through the tank in time, t, is:

$$dQ = Q \frac{dW}{W} = Q \frac{cQ}{W} dt = \frac{Q^2}{W} cdt \tag{2-3}$$

rearranging:

$$cdt = \frac{W}{Q^2} dQ$$

Substituting in equation (2-2)

$$T_c = \frac{1}{T} \frac{\int_0^\infty \frac{W}{Q^2} tdQ}{\int_0^\infty \frac{W}{Q^2} dQ} = \frac{1}{T} \frac{\int_0^\infty tdQ}{\int_0^\infty dQ} = \frac{1}{TQ} \int_0^\infty tdQ \tag{2-4}$$

$dQ = v\, dA$ and $v = \frac{L}{t}$ so that $dQ = \frac{L}{t}$ dA making

$$T_c = \frac{1}{TQ} \int_0^\infty t \frac{L}{t} dA = \frac{L}{TQ} \int_0^\infty dA = \frac{LA}{TQ} = \frac{V}{TQ} = \frac{T}{T} = 1 \tag{2-5}$$

Observed curves often deviate from these properties. The measured area of an observed curve is equal to the fraction of the tracer accounted for in the effluent of the tank. Any removal of tracer within the tank by adsorption, or fading in the case of dyes, or decay in the case of short-lived radioisotopes, will cause the area to be less than one. Another cause is a long tail on the curve of a low concentration below the threshold of sensitivity of the detecting instrument. This long tail also usually accounts for any discrepancy between the centroid of the curve and the theoretical detention time. Where no loss of tracer occurs within the tank, if the recovery is low and the centroid is somewhat to the left of 1, the missing tail can often be reconstructed as follows: Some simple curve, such as an hyperbola, is fitted to the existing portion of the tail. When the curve is so chosen that the area between the initial curve and infinity approximately accounts for all of the missing tracer, it is usually found that the centroid of the flow-through curve with extrapolated tail falls very close to $t/T = 1$.

INTERPRETATION OF FLOW-THROUGH CURVES

As previously mentioned, from the flow-through curve one can compute the reduction in concentration of a radioactive isotope present in the flow, but while this is important as a measure of how well the tank is performing, the flow-through curve provides much more information. From the shape of the curve it is possible to diagnose the ills of a poorly performing tank. Let us refer to Figure 2-2. Curve A is a very good flow-through curve. The first trace efficiency (defined as the time of arrival of the first trace of tracer at the outlet divided by the theoretical detention time) is high, the peak is high and sharp and located very close to $t/T = 1$. Curve B presents a very different picture. The first trace efficiency is low, and the peak is very low and rounded. This indicates excessive short-circuiting of flow due to violent turbulent mixing, Curve C illustrates an even more excessive form of short-cir-

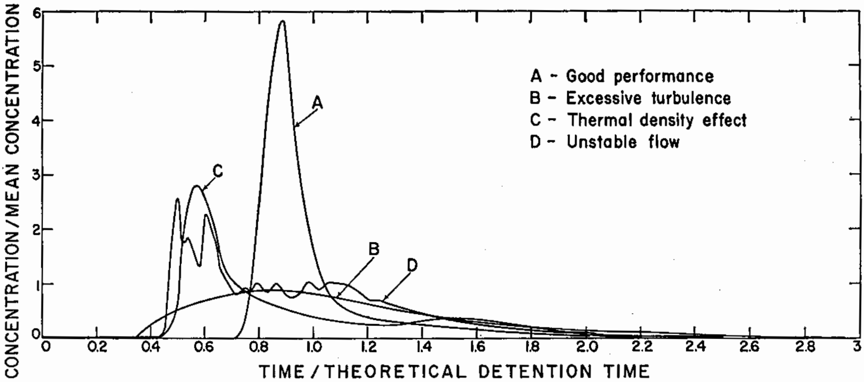

FIGURE 2-2.—FLOW-THRU CURVES FOR VARIOUS MODES OF TANK PERFORMANCE.

cuiting caused by extensive stagnant areas in the tank. The low first trace efficiency combined with the steep rise and relatively high peak are characteristic of this condition, as is also the thick long tail. This tail is caused by tracer being trapped in the dead areas and slowly released to the active flow over a long period of time. Such curves as C usually have rather poor tracer recovery and it appears that the centroid must be some distance to the left of 1, but if all the tracer in the long tail is accounted for, the centroid is usually found to coincide with 1 to a remarkable degree. Curve D is the result of a highly unstable flow condition where the tracer slug is not spread out in a single cloud as it travels through the tank, but is broken up into different sections which arrive more or less individually at the outlet causing the very rough curve. The performance of such a tank would be very erratic and highly undesirable.

PROOF OF STATEMENT OF OPTIMUM PERFORMANCE OF DETENTION TANKS

It was stated above that for optimum performance each particle of tracer should remain in the tank for exactly one detention time, or in other words, the flow-through curve should be a sharp spike occurring at $t/T = 1$. A proof of this is now in order. Stated mathematically:

$$C_o \geqslant C_i\, e^{-KT} \tag{2-6}$$

where

C_o is the steady state concentration in the effluent
C_i is the steady state concentration in the influent
K is the decay constant for the isotope in question
T is the theoretical detention time of the tank, volume/discharge.

From the fundamental properties, the center of gravity of the flow-through curve (Figure 2-3, Curve A) falls at $t = T$, thus from Equations 2-2 and 2-5

$$\int_0^\infty ctdt = T\int_0^\infty cdt \tag{2-7}$$

where c is the concentration given by the flow-through curve at time, t.

Also $$W = Q\int_0^\infty cdt \quad \text{or} \int_0^\infty cdt = \frac{W}{Q} \tag{2-8}$$

where W is the weight of tracer used in getting the flow-through curve.

Introducing c′ as the concentration with decay at time t gives

$$C_o = C_i \frac{\int_0^\infty c'dt}{\int_0^\infty cdt} = C_i \frac{Q}{W}\int_0^\infty c'dt \qquad (2\text{-}9)$$

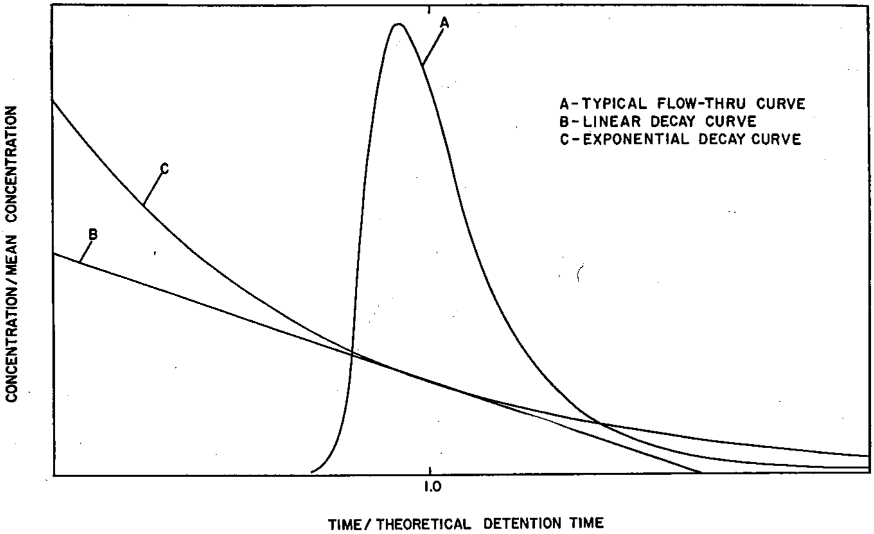

FIGURE 2-3.—TYPICAL FLOW-THRU CURVE WITH LINEAR AND EXPONENTIAL DECAY CURVES.

Now consider a linear decay function (Figure 2-3, Curve B) such that

$$c' = c\left(1 - \frac{t}{T'}\right) \qquad (2\text{-}10)$$

where T′ is the time at which c′ = 0
Substituting in equation (2-9)

$$C_o = C_i \frac{Q}{W}\int_0^\infty c\left(1 - \frac{t}{T'}\right) dt$$

which can be written

$$C_o = C_i \frac{Q}{W}\left(\int_0^{T'} c\left(1 - \frac{t}{T'}\right) dt + \int_{T'}^\infty c\left(1 - \frac{t}{T'}\right) dt\right) \qquad (2\text{-}11)$$

The second part of the integral is seen to be negative and since negative values of concentration have no physical meaning

$$C_o = C_i \frac{Q}{W} \int_0^{T'} c \left(1 - \frac{t}{T'}\right) dt$$

One can also write

$$C_o \geqslant C_i \frac{Q}{W} \int_0^{\infty} c \left(1 - \frac{t}{T'}\right) dt \qquad (2\text{-}12)$$

where for the moment it is understood that the right hand side of the inequality is merely a mathematical expression.

Rewriting equation (2-12) in a different form

$$C_o \geqslant C_i \frac{Q}{W} \left(\int_0^{\infty} cdt - \frac{1}{T'} \int_0^{\infty} ctdt \right) \qquad (2\text{-}12')$$

but from equation (2-7)

$$\int_0^{\infty} ctdt = T \int_0^{\infty} cdt \qquad (2\text{-}7)$$

thus

$$C_o \geqslant C_i \frac{Q}{W} \left(\int_0^{\infty} cdt - \frac{T}{T'} \int_0^{\infty} cdt \right)$$

or

$$C_o \geqslant C_i \frac{Q}{W} \left(1 - \frac{T}{T'}\right) \int_0^{\infty} cdt \qquad (2\text{-}13)$$

and substituting from equation (2-8)

$$C_o \geqslant C_i \frac{Q}{W} \left(1 - \frac{T}{T'}\right) \frac{W}{Q} = C_i \left(1 - \frac{T}{T'}\right) \qquad (2\text{-}14)$$

Thus it is seen that for a linear decay if each particle takes just one detention time to pass through the tank, we will get optimum reduction of concentration. In this trivial case it is interesting to note that if on the flow-through curve $c = 0$ before $T = T'$ then

$$\int_0^\infty c\left(1 - \frac{t}{T'}\right) dt = \int_0^{T'} c\left(1 - \frac{t}{T'}\right) dt$$

and

$$C_o = \left(1 - \frac{T}{T'}\right) C_i \qquad (2\text{-}14')$$

In this special case, then, the shape of the flow-through curve makes no difference.

Now consider an exponential decay function (Figure 2-3, Curve C)

$$c' = ce^{-Kt} \qquad (2\text{-}15)$$

Draw a straight line (Curve B, Figure 2-3) tangent to the decay curve at $t = T$. The equation of this line is:

$$c'' = ce^{-KT}\,(1 + KT - Kt) \qquad (2\text{-}16)$$

Since the point in question has been proved for such a linear decay as equation (2-16), one needs only to show that $c' > c''$ for all $T > O$).

To prove $$e^{-Kt} \geqslant e^{-KT}\,(1 + KT - Kt) \qquad (2\text{-}17)$$

let $$t = T + t_1 \qquad (2\text{-}18)$$

then $$e^{-KT}\,e^{-Kt_1} \geqslant e^{-KT}\,(1 + KT - KT - Kt_1)$$

Cancelling and rearranging

$$1 - Kt_1 \leqslant e^{-Kt_1} \qquad (2\text{-}19)$$

if $t_1 = 0$ then the equality holds

since $1 - 0 = e^0 = 1$ and $c' = c''$

if $t_1 < 0$, it must be shown that

$$1 + Kt_1 < e^{-Kt_1} \qquad (2\text{-}19')$$

Expanding e^{-Kt_1}, we get

$$1 + Kt_1 < 1 + Kt_1 + \frac{(Kt_1)^2}{2!} + \frac{(Kt_1)^3}{3!} + \ldots\ldots$$

so that $$c' > c''$$

If $$t_1 > 0$$

then $$1 - Kt_1 < e^{-Kt_1} \qquad (2\text{-}19'')$$

from this expression it can be seen that for $Kt_1 < 1$ the inequality holds since the left side will be negative and the right side always positive. By expanding it in a series:

$$1 - Kt_1 < 1 - Kt_1 + \frac{(-Kt_1)^2}{2} + \frac{(-Kt_1)^3}{3} + \ldots\ldots$$

One sees that for $Kt_1 < 1$ the terms decrease so that each positive one is greater than the next negative one. Thus, the inequality holds and we have proved that

$$C_o \geqslant C_i\, e^{-KT}$$

RELATION OF DECAY CHARACTERISTICS TO TANK REMOVAL EFFICIENCY

In practical tanks the flow-through curve will always have more or less dispersion so that C_o will always be greater than $C_i\, e^{-KT}$, but the important question is how much. It is evident that this will depend on the shape of the flow-through curve and on the half-life of the substance. Figure 2-4 is useful in illustrating this point. Curve A is from a tank showing good performance with little dispersion, while Curve B is from a poorer tank. Both curves have areas of very close to one and their centers of gravity fall near one on the time axis. Curve C is an exponential decay curve with a half-life of one theoretical detention time, while Curve D is similar with a half-life of one tenth of a theoretical detention time. Both these decay curves have been adjusted to give a concentration of one at $t = T$, so that in a tank of optimum performance, they would each give a concentration of one in the effluent. The actual concentrations are represented by the areas under Curves AC, AD, BC, BD, and are given in the table on Figure 2-4. It is thus seen that in the removal of relatively short half-lived substances, it is important to have a tank with good flow-through characteristics. To do this, the tank must have good distribution of the flow at the inlet, uniform velocity distribution across the flow, and a good outlet. Our first major objective will be to determine how best to get these characteristics, but first a look at the experimental equipment.

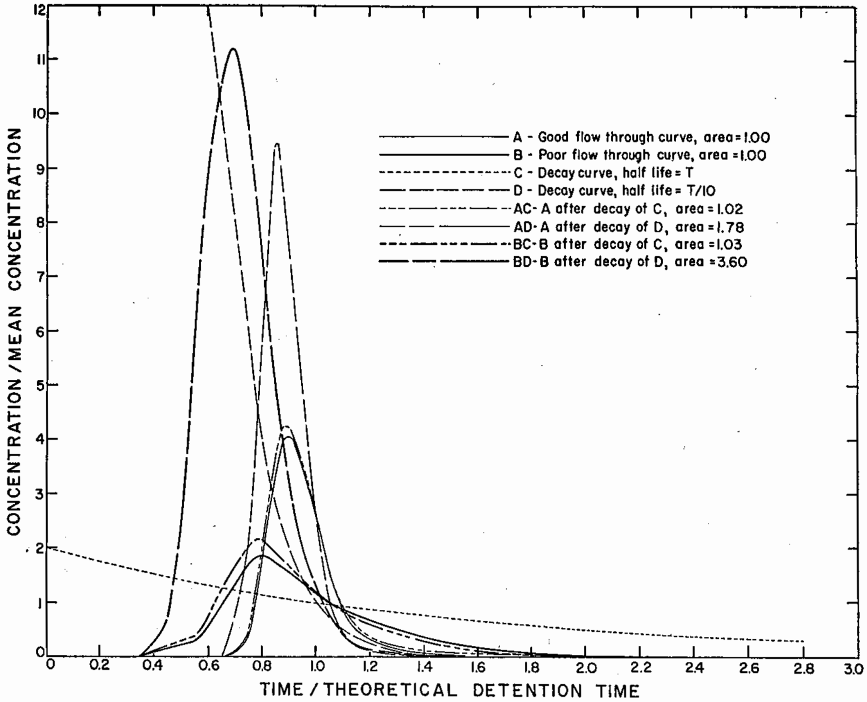

FIGURE 2-4.—COMPARISON OF PERFORMANCE OF TWO TANKS IN REMOVING SUBSTANCES WITH DIFFERENT HALF-LIVES.

EQUIPMENT

Considerable time and effort were spent on developing sensitive, precise, and reliable techniques for obtaining flow-through curves. The most important decision in this respect is the choice of a tracer. The ideal tracer should have the following properties: 1) It must not affect the flow pattern by inducing density currents; 2) it must be stable in solution and not adsorb appreciably on solid boundaries; 3) its concentration must be readily and precisely measurable with high sensitivity. It is also desirable that it be safe and easy to handle.

Radiotracers were first considered. They are excellent with respect to the first condition as the total weight of tracer need be very small. Condition (2) could be met satisfactorily by proper choice of isotope, one with a long half-life relative to the theoretical detention time, and by the addition of carrier isotopes to reduce adsorption. Condition (3) however, brought up some difficulties. Sampling of the effluent with subsequent evaporation and counting would give more than sufficient sensitivity but to get reliable and accurate results would require slow and painstaking work. For properly measuring directly in the effluent as it flowed from the tank much larger quantities of tracer would be required for each run and suitable equipment such as a special scintillation counter with rate meter was not readily available. Also, radio-tracers are expensive and safety precautions in their use are a nuisance.

While for large scale field tests radio-tracers are certainly the most satisfactory, with small scale models where flow times are short and the quantities of water are small, methylene blue dye has been found to be more convenient and sufficiently sensitive as a tracer. A photo-electric colorimeter was arranged to operate with a continuous portion of flow from the tank effluent through its sample cell. The range of the instrument with a sample cell 15 cm long was 0 to 1.0 mg/liter with a sensitivity near zero of 0.002 mg/liter/division. It is thus seen that condition (3) for a good tracer was well met. With respect to condition (1), values for $\bar{c}$ in the order of 0.20 mg/liter have been found satisfactory so that even where peak concentrations as high as $c/\bar{c} = 5$ have occurred, the dye amounts to only one part per million, a quantity which should not affect the flow pattern. As to condition (2) considerable work was done to evaluate the stability of methylene blue in Cambridge tap water. Careful tests showed that over a range of pH from 6 to 9 no appreciable change in color occurred nor was there any fading in periods of several days. Some adsorption occurred on glass after long contact, but adsorption of surfaces in the 8″ × 8″ flume was found to be negligible in the times involved. Considerable difficulty was encountered in this respect with the 1:32 scale model but although the flow through curves obtained were in error they still served to compare performance of the model under different conditions. One source of error stemmed from changes in the turbidity of the water supply but it was found that with reasonable care this could be kept down to less than one-half of a division of drift during any one run.

THE CONTINUOUS FLOW COLORIMETER

To get accurate flow-through curves with minimum effort the continuous flow colorimeter was devised. The apparatus set up for use with the flume is shown in Figure 3-1. Here the various components are

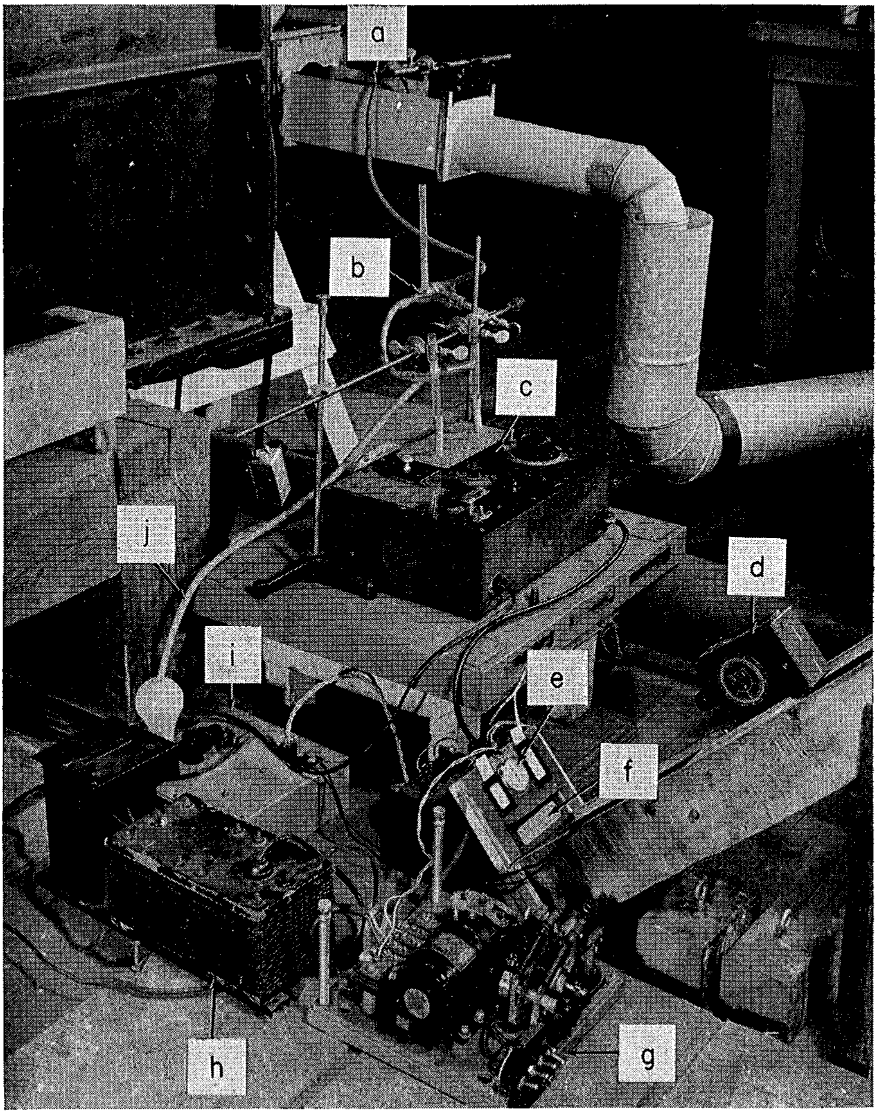

FIGURE 3-1.—CONTINUOUS FLOW COLORIMETER AS SET UP FOR USE WITH FLUME. (SEE TEXT FOR IDENTIFICATION OF PARTS)

labeled with letters for easy reference in the text. Figure 3-2 shows the schematic diagram of the camera operating circuit.

The basic instrument was a Lumitron colorimeter model 402-E to which no alterations were made except replacement of the sample cell compartment cover with one having two holes for the inlet and outlet tubes. The sample cell was a standard Lumitron cell with cemented ends 15 cm long having a filling neck at each end to which the inlet and outlet tubes (a and j) were attached. In the sample inlet tube (a) there was a bubble trap (b) to prevent air bubbles from entering the cell. The dye concentration in the cell was indicated by the deflection of the galvanometer (f) which was recorded along with a time reading from the stop watch (e) by the 16mm movie camera (d). The camera was solenoid operated to take single frames at time intervals determined by the time switch (g) which could be set to operate at time intervals of one, four, ten, twenty, and sixty seconds. The constant voltage transformer (h) was used to stabilize the operation of the colorimeter. A power supply (i) was provided to activate the camera solenoid.

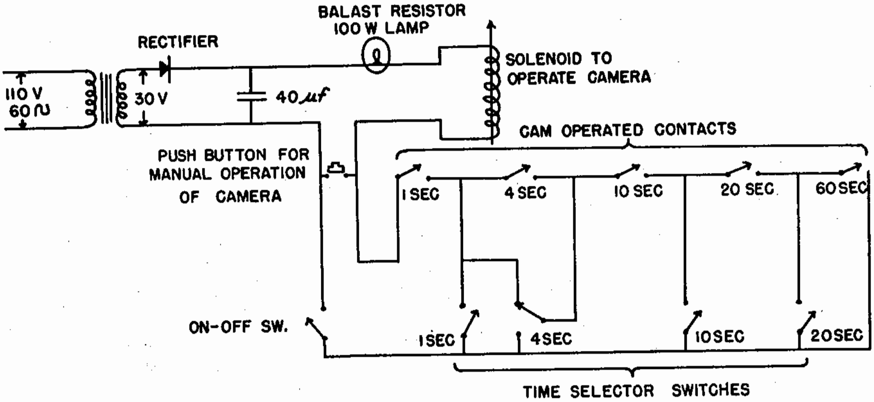

FIGURE 3-2.—SCHEMATIC DIAGRAM OF TIME SWITCH TO OPERATE CAMERA ON CONTINUOUS FLOW COLORIMETER.

The operation of the apparatus was as follows: before making a run the water was started flowing through the colorimeter cell, and the colorimeter which had been warmed up for at least one-half hour was balanced to give zero deflection on the galvanometer. Then the light beam through the sample cell was cut off and the light intensity adjusted to give full scale galvanometer deflection. After these adjustments had been checked back and forth several times and found to be accurate, the run was started. To do this the time switch was set on the sixty second interval and turned on. At the instant the first picture was taken the dye was introduced at the inlet of the tank and the stop watch started. As the run progressed the time switch was reset as necessary to provide sufficient points to give a good curve.

At the completion of a run the exposed film was removed from the camera and developed after which each frame was read and recorded and the galvanometer readings converted to concentration values by means of a calibration curve.

The Lucite Flume

The Lucite flume shown in Figure 3-3 and schematically in Figure 3-4 was a most useful research tool. The 8 inch by 8 inch transparent

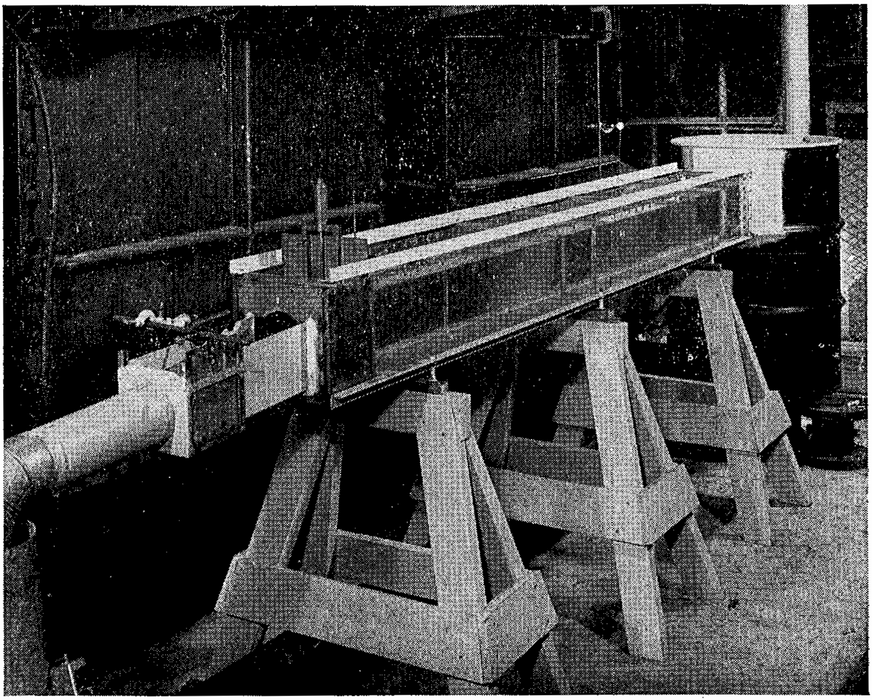

Figure 3-3.—8″ × 8″ × 8′ Lucite Flume.

section was constructed of ½ inch thick Lucite and could be used as a closed conduit by the addition of a Lucite cover. The flume was strengthened by 1 inch angle irons at the corners and was held together with brass screws which passed through the angle irons and plastic sides and were threaded into brass inserts in the bottom. The cover was mounted in a similar way by brass inserts in the upper edges of the sides. When one was operating with the flume open several ½ inch x ½ inch brass cross pieces took the place of the cover in bracing the sides.

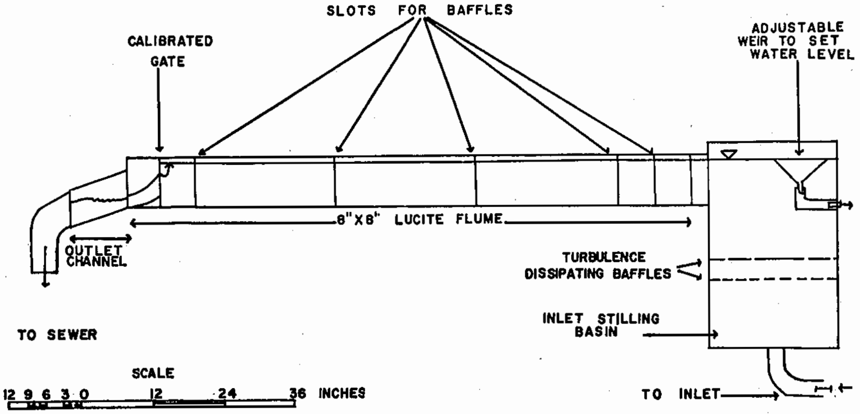

FIGURE 3-4.—SCHEMATIC DIAGRAM OF FLUME.

Two slots were provided at the inlet and two at the outlet, spaced six inches and twelve inches from the ends, to support inlet and outlet baffles and controls. Other slots dividing the remaining length into three two foot sections were provided. The entire transparent section and outlet was mounted on leveling screws on three substantial supports.

The inlet tank, which was connected to the flume with a flexible rubber joint, consisted of a 55 gallon open-end drum. The water entered at the bottom from a large storage tank through a four inch galvanized sheetmetal pipe with the joints soldered, in which there was a valve to adjust the flow. In flowing upward through the drum the water passed through two perforated baffles to dissipate turbulence. The first had small holes giving relatively high head loss and the second had large holes placed out of line with the holes below. In the top of the drum was a spillway weir consisting of a glass funnel used to hold the water level constant.

The outlet was designed to permit gravimetric measurements of discharge. As shown in Figure 3-3 the water would flow straight through the outlet channel to the sewer. For discharge measurements a tank on a platform scales was placed under the side gate and five or ten pounds weight in excess of the weight of the tank added to the scale beam. A gate was closed across the outlet (gate not shown) and the side gate opened. When sufficient water had flowed into the tank to balance the scales a stop watch was started and a convenient weight added to the beam. When the scale balanced again the watch was stopped and from the weight and time the discharge was computed.

For most work an easier means of getting discharge measurements was provided by a control gate which was placed in the last slot of the flume. It was adjusted by a micrometer screw and had a fixed hook gauge attached to the frame. A calibration curve obtained by gravimetric measurements gave discharges from micrometer readings, with the water level behind the gate at the point of the hook, to plus or minus 2 percent. By proper adjustment of the in-flow valve and the height of the weir spillway at the inlet, the level at the gate could be maintained within several thousandths of an inch of the hook point.

The flume with associated equipment proved to be indispensable in research on density effects, since it was possible to see not only the horizontal, but also the vertical distribution of flow. Figure 3-5 which shows the progress of a dye-colored density current along the bottom of the flume illustrates this point.

OTHER EXPERIMENTAL TANKS

A rectangular wooden tank 12′ × 20′ × 16″ deep was used for a number of tests. It is shown in Figure 3-6. With pumping equipment to supply about 0.5 cubic feet per second, a wide range of theoretical detention times could be obtained ranging upward from 10 minutes.

Two models were also built of existing detention tanks. Figure 3-7 shows the model of a circular tank scaled 1:100 built of galvanized sheet iron and Figure 3-8 shows a wooden model of a rectangular tank scaled 1:32.

The general arrangement of the equipment in the laboratory is shown in Figure 3-9. Water was supplied to the storage tank from the building supply. It had a capacity of some six hundred cubic feet and was used primarily for obtaining hot water. After the tank was filled steam could be run into the water through a perforated pipe to heat it

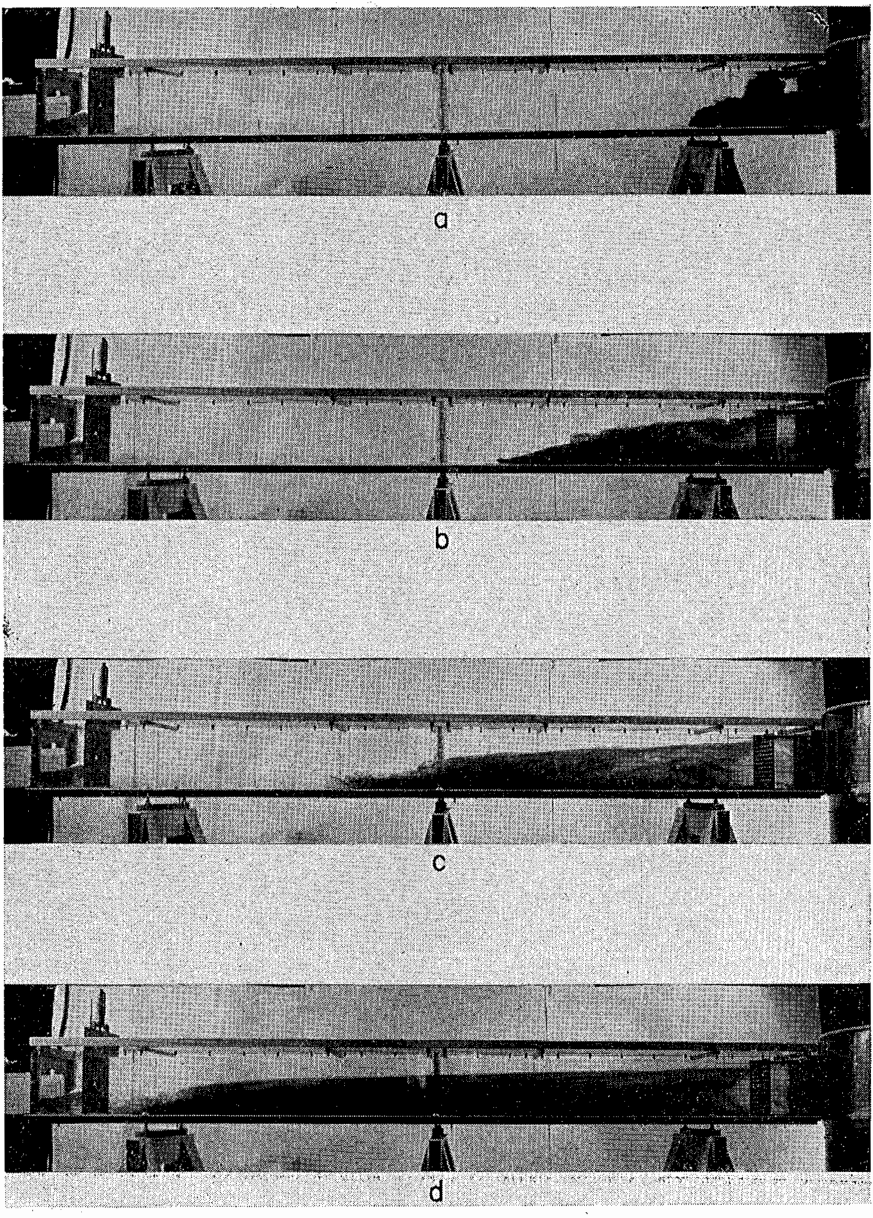

FIGURE 3-5.—THE PROGRESS OF A THERMAL DENSITY CURRENT ALONG THE BOTTOM OF THE FLUME.

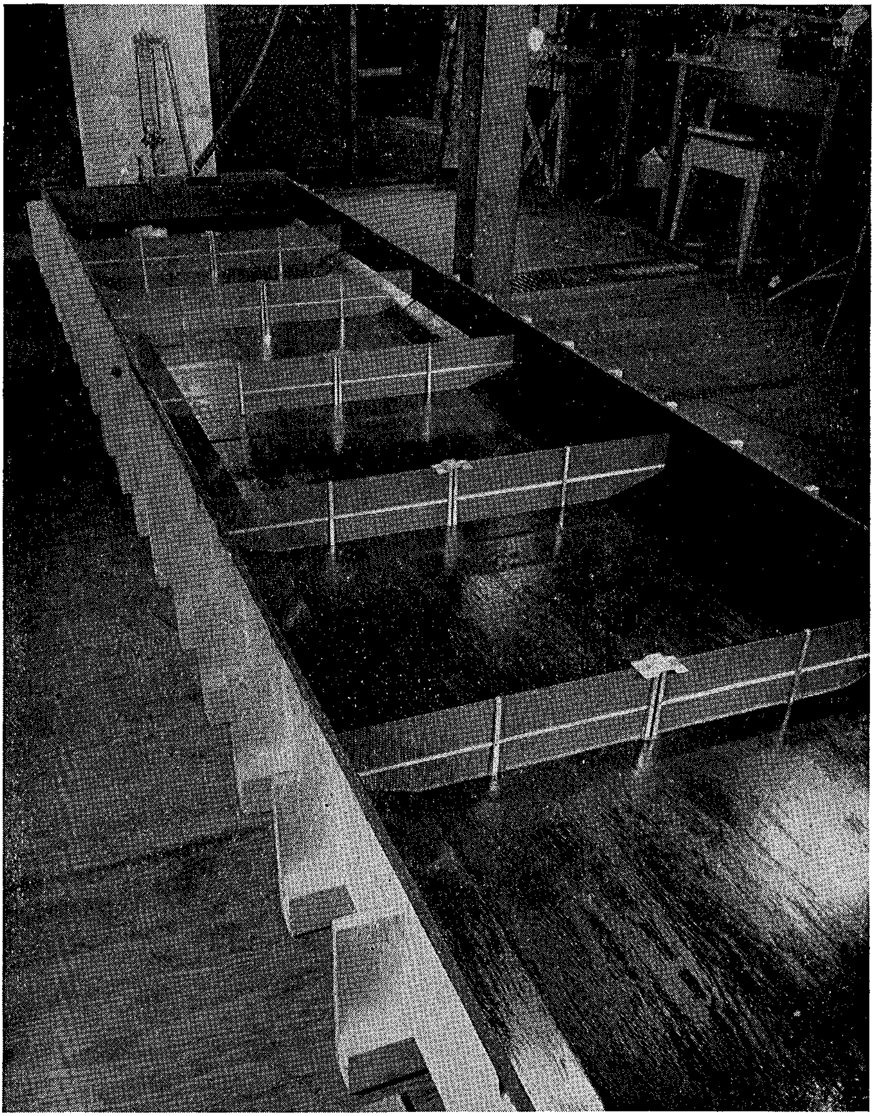

FIGURE 3-8.—SCALE MODEL 1:32 RECTANGULAR COOLING WATER DETENTION TANK.

to any desired temperature. Sufficient water could be stored and heated at one time to complete at least one test on any of the experimental models except the large rectangular wooden tank. When running the latter, the storage tank was used as a constant head tank with a steady flow from the building supply.

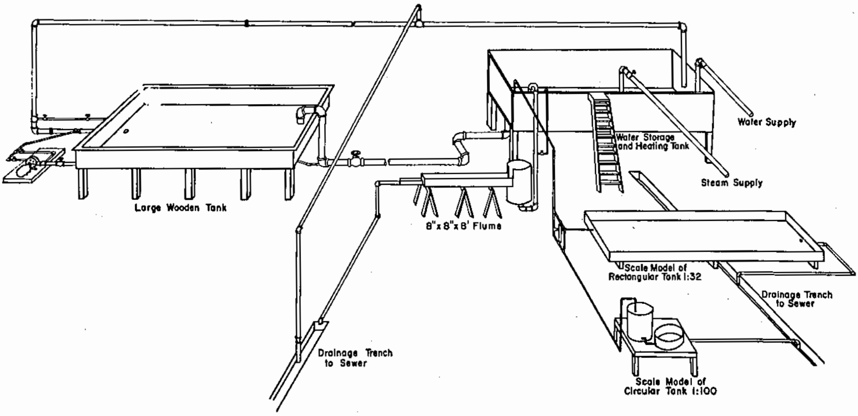

FIGURE 3-9.—ARRANGEMENT OF EQUIPMENT FOR DETENTION TANK STUDIES.

THE DIFFERENTIAL THERMOMETER

In studying thermal density problems a sensitive differential thermometer was used. This consisted of two copper-constantan thermocouples connected through a resistance box to a multiple reflection Rubicon galvanometer. The galvanometer had a sensitivity of 0.0015 microamperes per millimeter and the entire circuit resistance was about 500 ohms with the resistance box at zero giving a maximum voltage sensitivity of 0.75 microvolts per millimeter. With copper-constantan couples this gave a temperature sensitivity of approximately 0.03 degrees F. per millimeter at temperatures around 100 degrees F. By introducing additional resistance with the decade box the sensitivity could be reduced to give any desired range.

The time and effort spent in building this equipment was considerable, and even more was required to get it all operating properly, but it is felt that the results as shown in the following sections more than justify the expenditures.

INLET ZONE DESIGN

The inlet to a detention tank serves two purposes. First, it distributes the flow horizontally and vertically so that velocities will be uniform across the cross section of the tank. Secondly, it dissipates any excessive energy in the incoming flow. The problem of design is thus similar to that encountered in sedimentation tanks; however, in detention tank inlets the transportation of suspended solids and the destruction of fragile flocs does not have to be considered, but the vertical distribution of the flow is more important.

Another problem in inlet design is the equal distribution of flow between tanks operating in parallel or the distribution between multiple inlets to one tank. This has been well treated by others[4] so that the present discussion will be restricted to proper handling of the flow after it leaves the influent conduits and enters the inlet zone within the tank.

To study inlets, the 8″ × 8″ Lucite flume was used. The transparent walls made it possible to observe the vertical, as well as the horizontal distribution of the flow, and the small size of the flume made it possible to use small easily built inlets for the different tests. The flume also provided an ideal flow condition with which to compare the various test inlets. Without baffles at the inlet, water entered from the relatively large inlet tank with practically no turbulence and with almost perfect distribution.

Flow through curves for this ideal inlet are shown in Figure 4-1 along with those for a one inch horizontal slot and for the slot followed by a perforated baffle with 36% open area. The slot illustrates how a poor inlet can spoil the performance of a tank; the slot with baffle shows how relatively simple measures can often provide important improvements in inlet performance.

INLET DESIGNS

A number of inlets are shown schematically in Figure 4-2. (A) is the simplest and poorest inlet. The jet from the inlet pipe can be expected to travel down the tank for about five times the width or depth of the tank, whichever is greater, before the velocity distribution becomes more or less uniform over the cross section. If the velocity of the jet is low enough so that the flow is laminar, an unlikely, but possible situa-

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[4] G. M. Fair and J. C. Geyer, Elements of Water Supply and Waste—Water Disposal, Wiley, New York, pp. 325-326 (1958).

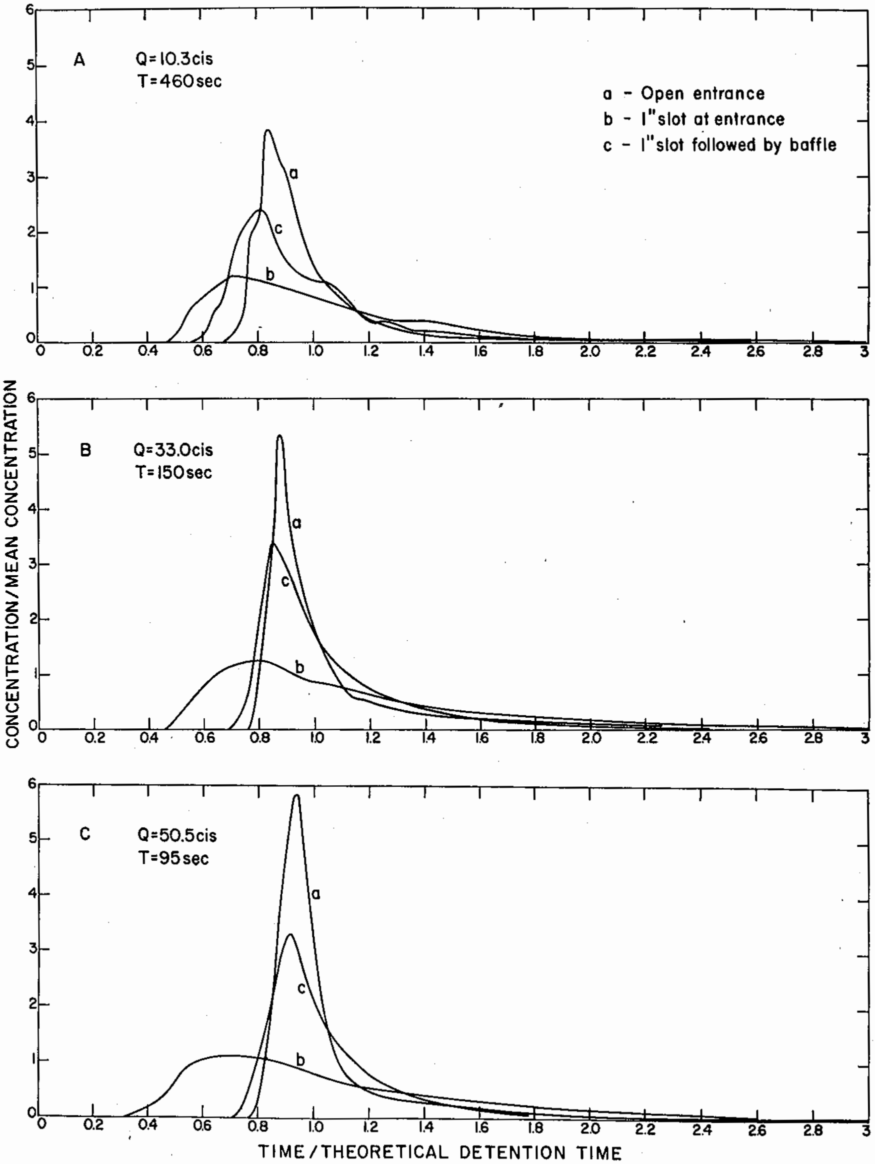

FIGURE 4-1.—EFFECT OF INLET DESIGN ON TANK PERFORMANCE.

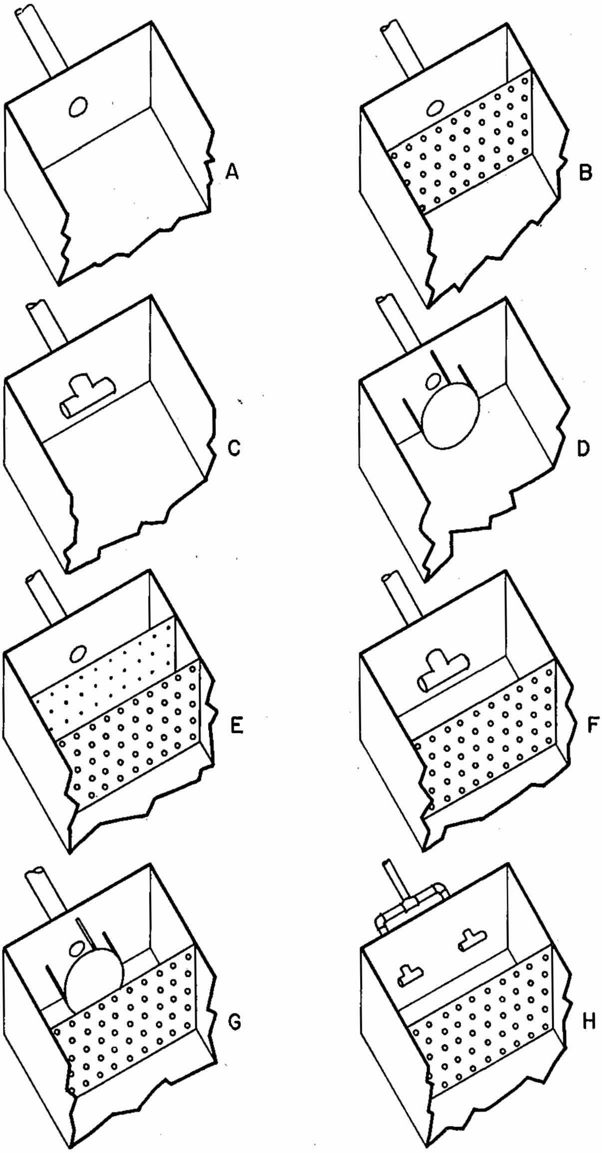

Figure 4-2.—Detention Tank Inlets.

tion, the jet will persist for a much longer distance causing even worse short circuiting. It is evident that a baffle (B) or a tee (C) or a disc (D) will break up the jet and improve the distribution of the flow. Any of these three followed by a perforated baffle, (E), (F), and (G), should give even better performance. It is logical to consider more than one inlet (H) where the tank is wider than it is deep.

The inlet using two perforated baffles is attractive as it can be designed from theoretical considerations. The first baffle should have a head loss sufficiently high to insure equal flow through each hole. Under the worst conditions, this was found to be approximately equal to the velocity head in the influent pipe, but since the velocity of a submerged jet is rapidly reduced as it moves away from its origin, the maximum velocity head which could be caused by the incoming jet on a few holes is seldom realized and a much smaller head loss will ordinarily suffice. The spacing between the two baffles should be sufficient to allow the jets from the holes in the first to expand and cover the entire cross section of the tank. Rouse[5] indicates that the expansion ratio of a jet is about one to five. From this, it is seen that the spacing between baffles should be about five times the distance between holes in the first. Experimental work confirmed this. The second baffle works in the same manner as the first but instead of having above it a velocity distribution ranging from several feet per second to zero as the first has, the second baffle should have a velocity distribution of less than two to one in the flow approaching it. Because of this, a very small head loss is required to get almost perfect distribution of the flow downstream.

TESTS ON INLETS

The flow pattern in inlets using tees or small baffle plates to dissipate the influent jet is not amenable to theoretical treatment: however, the performance of these devices can be studied readily in the laboratory. For tests on these, as well as the two-bafflle inlets, the flume was arranged as shown in Figure 4-3, which also shows the different influent pipe endings and baffles which were tested. Baffle Number 3 was not used as it had too high a head loss at the desired flow rate. The desired inlet was placed at section A-A and baffles, if used, were placed at sections B-B and/or C-C. A small quantity of fluorescein dye was injected with a medicine dropper just upstream from sec-

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[5] H. Rouse, "Fundamental Principles of Flow" Engineering Hydraulics, Wiley, New York, pp. 95-99 (1950).

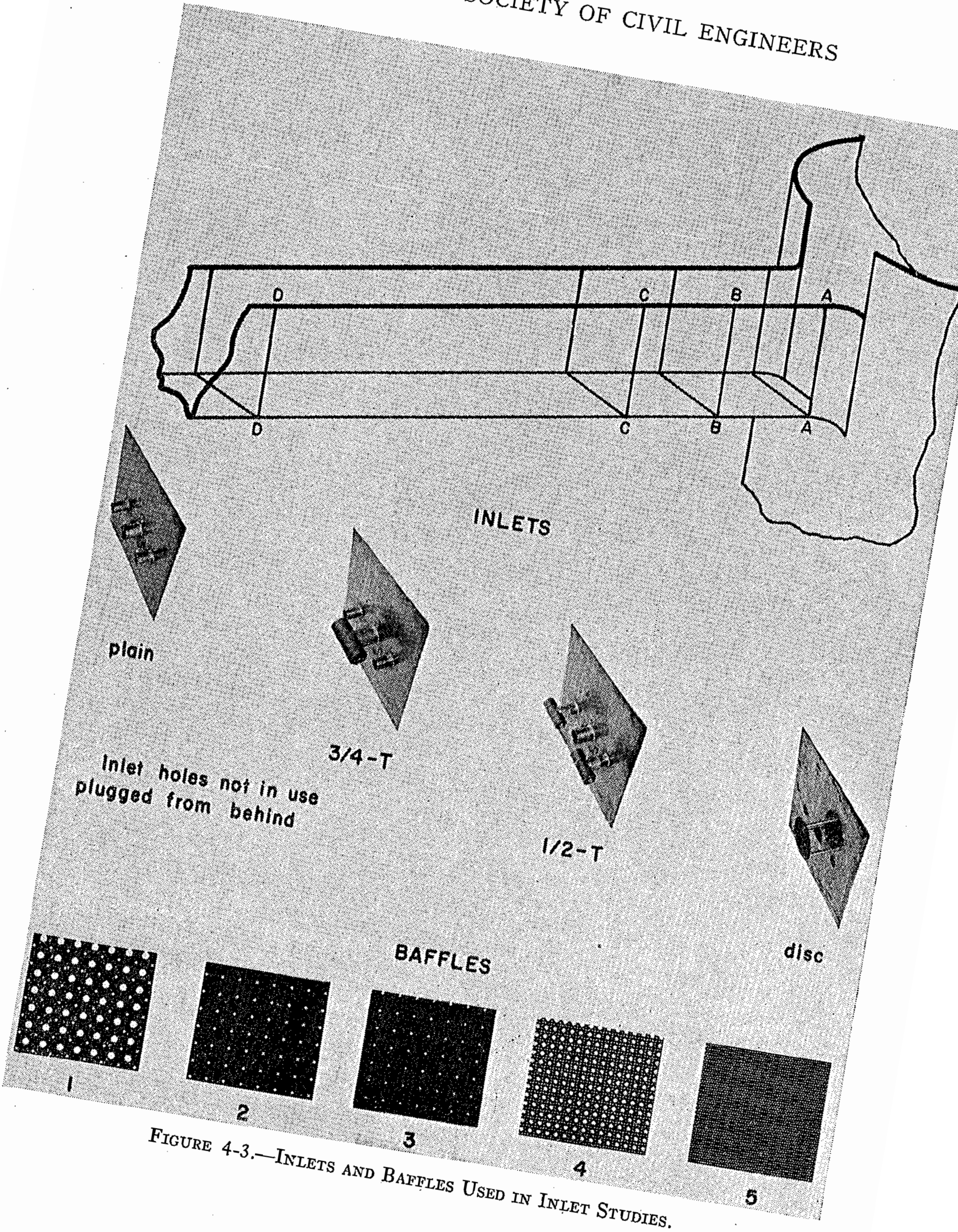

FIGURE 4-3.—INLETS AND BAFFLES USED IN INLET STUDIES.

tion A-A and the first trace time was measured from the time the first trace of dye passed section C-C until it passed section D-D. This transit time divided by the theoretical detention time for the volume between sections C-C and D-D gave the first trace efficiency. It was felt that this method of measuring first trace efficiency was better for the purpose at hand than the more usual one involving the entire volume and measuring first trace time from the introduction of the tracer, because it compared inlet designs on the basis of their ability to permit the volume outside the inlet zone to perform efficiently without masking the results with the necessarily low first trace efficiency of the inlet zone.

Table 4-1 shows the different arrangements tested along with the first trace efficiency for each. It also shows the head loss of the inlet and the loss across the different baffles. These head losses were measured with point gauges mounted on micrometer heads which could be read consistently to 0.0005 inches. Besides the obvious comparison of first trace efficiencies of the different arrangements, there are some other points which can be discovered from Table 4-1. Consider tests Number 4 and 5. Baffle 2 had a row of holes right at the bottom but the highest row through which water flowed was about a half inch below the surface. This caused an excessive velocity along the bottom which was easily observed. In test Number 5, the bottom row of holes was plugged as indicated and with the elimination of the bottom current, the significant improvement in performance was noted. This illustrates the importance of designing baffles to be symmetrical with respect to the flow. This is particularly noticeable where a baffle with relatively few holes is used.

Another point to consider is the effect of a given volume before or after the final baffle. With two exceptions, when similar tests were run with a baffle at B-B or at C-C, the efficiency was higher with the baffle at C-C. The added volume before the baffle allowed more room for excessive velocities to dissipate, thereby, reducing the difference in the effective head on each hole in the baffle. In one case where the baffle at B-B gave a higher efficiency, the baffle involved had big holes with only 20% open area, giving a coarse grained turbulence with a relatively long persistence. Here the stilling volume after the baffle was more important than a better velocity distribution upstream. In the other case, the two half inch T inlets gave such a good distribution of flow that the volume between B-B and C-C was more valuable for

TABLE 4–1

First Trace Efficiency for Various Inlet and Baffle Combinations
For Identification of Inlets and Baffles See Figure 4–3. All Tests Run at a Flow of 9.75 Cubic Inches Per Second

Inlet*	¾–0	¾–T	½–0	½–T	¾ D 1	¾ D ½	¾ D ¼
head loss	0.78″	0.86″	0.81″	0.85″	0.83″	0.85″	0.95″
Baffle	1	2	4	5	2′**		
head loss	0.005″	0.058″	0.002″	0.003″	0.085″		

Number	Inlet	First Baffle	Second Baffle	First Trace Eff.
1	¾–0	0	0	7.8%
2	¾–0	2	0	30.2%
3	¾–0	2	4	48.9%
4	¾–0	2	5	53.2%
5	¾–0	2′	5	58.9%
6	¾–0	4	4	41.1%
7	¾–T	0	0	49.5%
8	¾–T	4	0	65.1%
9	¾–T	0	4	69.5%
10	¾–T	5	0	56.6%
11	¾–T	0	5	64.4%
12	¾–T	1	0	48.2%
13	¾–T	0	1	54.7%
14	½–0	0	0	11.5%
15	½–0	2	4	58.1%
16	½–T	0	0	38.3%
17	½–T	0	4	63.9%
18	½–T	4	0	66.7%
19	½–T	5	0	69.2%
20	½–T	1	0	72.1%
21	¾ D 1	0	0	30.4%
22	¾ D 1	4	0	51.0%
23	¾ D 1	0	4	61.3%
24	¾ D ½	0	0	32.5%
25	¾ D ½	4	0	47.8%
26	¾ D ½	0	4	63.4%
27	¾ D ¼	0	0	36.8%
28	¾ D ¼	4	0	44.7%
29	¾ D ¼	0	4	54.4%

* ¾–0 is plain inlet using center hole.
½–0 is plain inlet using two outer holes.
¾–D 1 (½, ¼) is inlet with disc spaced 1 (½, ¼) pipe diameters from pipe end.

** 2′ is number 2 baffle with bottom row of holes plugged.

dissipating the relatively small turbulence generated by the baffle than for dissipating the inlet energy before the baffle.

The inlet with baffle plate mounted in front of the pipe gave poor results. Of the three spacings tried, the one where the plate was located downstream from the pipe, a distance equal to one-half the pipe diameter, gave the best performance. It is possible that even better performance could have been obtained with some other plate size; however the flow in the inlet zone was unstable and the efficiency was quite sensitive to flow rate. The arrangement as a whole was less satisfactory then the T inlet.

Conclusions from Inlet Tests

The following conclusions can be drawn from the research on inlets and observations on inlets of prototype and model tanks:

1. Perfect symmetry about the longitudinal axis of the tank in a horizontal plane is almost a necessity.
2. A zone should be provided for energy dissipation and distribution. Within this zone the flow should be highly turbulent, but with transverse components of velocity kept to a minimum.
3. The flow pattern in this inlet zone should be stable under all expected conditions.

The two-baffle inlet, the tee and baffle inlet, and the baffle-disc and baffle inlet can all be made to give satisfactory performance, but of the three, the tee and baffle seems to best fill the requirements for a good inlet. The number of tees to give best performance cannot be specified at present. It seems probable that one tee for each unit of width equal to the depth should prove to be good design. The baffle should have thirty to forty percent open area with relatively small holes of one thirty-second to one sixty-fourth of the smaller dimension of the baffle. Placing it downstream from the inlet, a distance equal to the depth of the tank, should provide satisfactory results. Finally, it is recommended that a model of the proposed inlet zone be built from which the number of inlets, the design of the baffle, and the spacing of the baffle from the inlet can be easily and quickly determined.

Detention Zone Design

The detention zone in a tank should be designed in such a way that tendencies toward hydraulic short circuiting are damped out rather than amplified. The tank should be such that the uniform velocities produced across the cross section by the inlet are maintained throughout the tank. Toward this end the velocities should be kept high. It is well known that laminar flow tends toward a parabolic distribution of velocity ranging from zero at the boundaries, to a maximum at the center, whereas turbulent flow tends to produce a much more uniform velocity distribution. Also, if the flow is turbulent there is less chance for density currents or layers to form. On the other hand it is possible that excessive turbulence would contribute to short circuiting by speeding a part of the flow through the tank at a velocity considerably above the mean. This is indeed true in the case of large scale turbulence generated by initial imperfect transverse distribution of the flow, or in bends or corners, or transverse perforated baffles. However, the turbulence generated by flow through a straight unobstructed channel is relatively fine grained and the resulting degree of short circuiting is more than compensated by the advantages gained with improved velocity distribution and the elimination of density layers.

UPPER LIMIT OF VELOCITY

The question immediately arises: Is there an upper limit to the velocity above which logitudinal dispersion becomes a serious problem? Work by Taylor[6] is illuminating on this. He has treated the case of longitudinal dispersion in pipes with turbulent flow. Using the standard deviation σ of the flow-through curve as a measure of dispersion:

$$\sigma = \frac{\sqrt{2KT}}{v} \qquad (5\text{-}1)$$

where T is the theoretical detention time,
v is the mean displacement velocity,
K is the effective longitudinal diffusion coefficient,

Taylor showed that for turbulent flow:

$$K = 1.785 \, d \, v \sqrt{f} \qquad (5\text{-}2)$$

where d is the diameter of the pipe, and f is the Darcy-Weisbach friction coefficient.

Now consider two pipe reaches having the same volume. One is

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[6] Sir Geoffrey Taylor, "The Dispersion of Matter in Turbulent Flow Through a Pipe," Proceedings of the Royal Society, Section A, CCXXII, December 1953.

long and small in diameter while the other is short in length and large in diameter. At the same flow rate, Q, they will both have the same theoretical detention time, T. Using subscript 1 to denote the small diameter pipe and subscript 2 to denote the large we can write:

$$\frac{K_1}{K_2} = \frac{d_1 v_1}{d_2 v_2} \tag{5-3}$$

assuming f to be constant. Also

$$Q = \frac{\pi}{4} d_1^2 v_1 = \frac{\pi}{4} d_2^2 v_2 \tag{5-4}$$

so that

$$\frac{v_1}{v_2} = \frac{d_2^2}{d_1^2} \tag{5-5}$$

making

$$\frac{K_1}{K_2} = \frac{d_2}{d_1} \tag{5-6}$$

The ratio of the two dispersions is

$$\frac{\sigma_1}{\sigma_2} = \frac{\sqrt{2K_1Tv_2}}{v_1\sqrt{2K_2T}} = \sqrt{\frac{K_1}{K_2}\frac{v_2}{v_1}} = \sqrt{\frac{d_2}{d_1}\frac{d_1^2}{d_2^2}} = \left(\frac{d_1}{d_2}\right)^{3/2} \tag{5-7}$$

It is thus seen that the small long pipe will give less dispersion of the flow-through curve than the short large one. If we consider that f is not a constant but in fact is a function of the Reynolds number, we can show that this also works in the direction of decreasing the dispersion in the smaller pipe. For moderate values of Reynolds number and smooth surfaces the Blasius formulation is

$$f = \frac{0.316}{R^{1/4}} \tag{5-8}$$

and

$$R = \frac{vd}{\nu} \tag{5-9}$$

It is evident that where Q is a constant the small pipe will have a higher Reynolds number since the velocity is inversely proportional to the square of the diameter. Thus the small pipe will have a smaller value of f giving a smaller value of K and a smaller value of σ. It is logical to assume that these results will hold true at least qualitatively for open channels used as detention tanks particularly where these are long and narrow. There appears to be, then, no upper limit on velocity as far as short-circuiting performance is concerned.

Lower Limit of Velocity

From a practical point of view where a tank must be fitted into a given space the question might well arise: How low a velocity can be used without having trouble with density layers and generally unstable conditions? This is more difficult to answer.

Theoretical analysis of the behavior of thermal density layers in a tank under steady state flow is beyond the scope of the present investigation. It involves heat transfer due to conduction through the walls, through the air-water interface, and by evaporation. Stability of the interface between layers of very slightly different density is important. In the case of open tanks wind action can be important. From a practical view all that is required is some parameter which can be used to determine whether a tank will be free of thermal density problems. Investigation showed that the Reynolds number is not suitable. A very large detention tank, the full scale prototype of the model shown in Figure 3-8, when operating at a Reynolds number of about two million, showed very serious short circuiting due to thermal density effects, while the 8″ × 8″ flume operating at a Reynolds number of about four thousand showed excellent performance. Flow-through curves for these two tests are shown in Figure 5-1A.

There are two conditions that can cause trouble. The first is a steady state stratification of flow due to heat transfer taking place within the tank. In the case of hot water entering, a large practically dead pool of water lying in the bottom of the tank can form. The pool is constantly being drained by entrainment at the interface with the flowing water above, by mixing at the inlet, which causes reverse flow along the bottom of the tank, and sometimes by withdrawal at the outlet. The pool is replenished by cool water formed at the surface by evaporation which flows by convection slowly down the walls. The second condition is transient, caused by a change in the temperature of the incoming water. This will cause a thermal density current to flow down as shown in Figure 3-5 causing a pool to form at the top or bot-

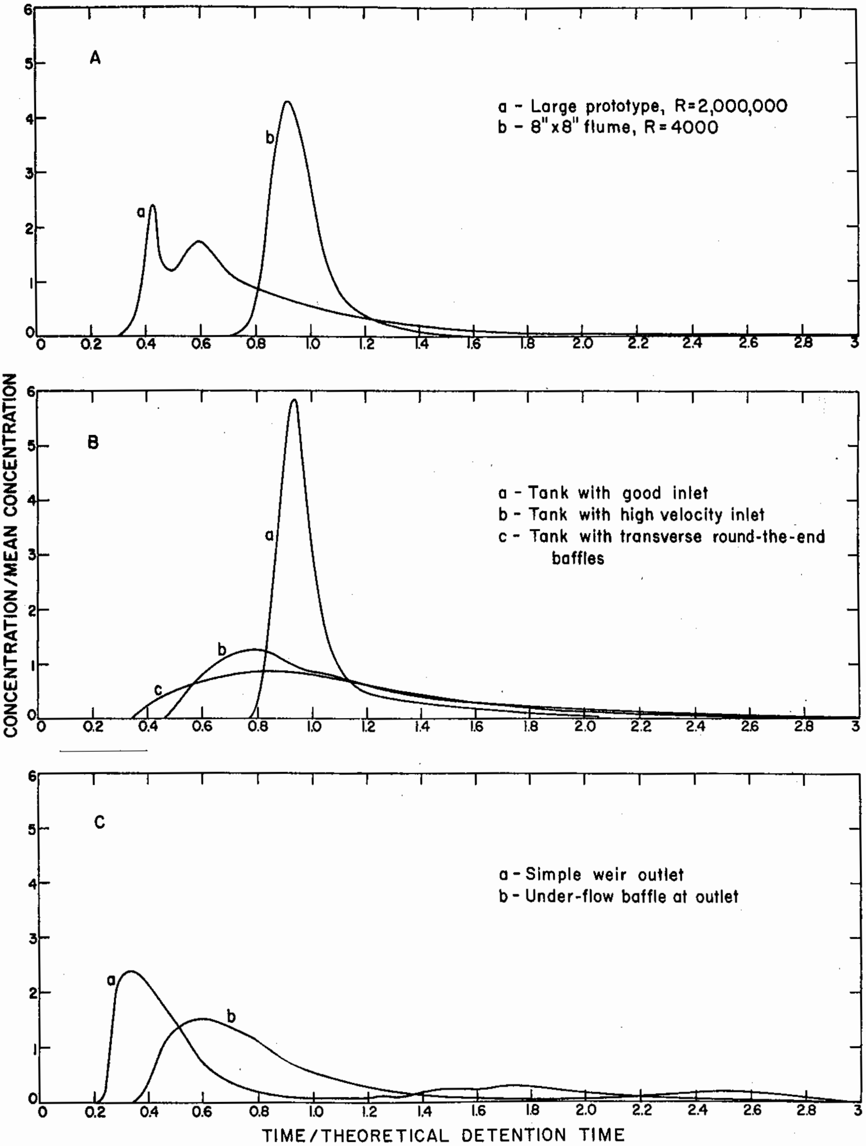

FIGURE 5-1.—FLOW-THRU CURVES ILLUSTRATING POINTS DISCUSSED IN TEXT.

tom depending on whether the incoming water is cooler or warmer than previously. Since this condition is truly transient, the pool will not be replenished so that the forces tending to drain it will in time remove it completely.

A CRITERION FOR DETENTION ZONE DESIGN; THE MEAN VELOCITY GRADIENT

For the steady state condition it is evident that there is a minimum amount of mixing that must be provided to prevent stratification in the tank. Camp[7] has shown how the performance of flocculators in water and sewage treatment plants can be evaluated in terms of the temporal mean velocity gradient within the flow. Since flocculators are primarily mixing devices this appeared to the author to be a promising parameter for detention tanks. From Camp's formulation, in open channels

$$G = \sqrt{\frac{f}{\nu}\frac{v^3}{8r}} \qquad (5\text{-}10)$$

where G is the mean velocity gradient
f is the Darcy-Weisbach friction factor
v is the mean velocity ft per sec
ν is the kinematic viscosity ft^2 per sec
r is the hydraulic radius of the cross section ft

Again using the Blasius formulation

$$f = \frac{0.316}{R^{1/4}} \qquad (5\text{-}8)$$

where the Reynolds number is $R = \frac{4vr}{\nu}$ (5-9′)

Substituting for R gives

$$f = \frac{0.224\,\nu^{1/4}}{v^{1/4}\,r^{1/4}} \qquad (5\text{-}11)$$

and putting this into Equation (5-10) gives

$$G = 0.167\,\frac{v^{1.375}}{\nu^{0.375}\,r^{0.625}} \qquad (5\text{-}12)$$

Equation 5-12 was derived for smooth circular tubes. However, no appreciable error is involved in extending its use to open channels.

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[7] T. R. Camp and P. C. Stein, "Velocity Gradients and Internal Work in Fluid Motion" Journal Boston Society of Civil Engineers, 30, pp. 219-237, October 1943.

Also it is strictly applicable only to flow where the Reynolds number is in the range of from a few thousand to one hundred thousand. This is the range in which most laboratory detention tank models will operate. In prototype tanks the Reynolds number may be above this range. Under these conditions the Blassius formulation for f gives values that are somewhat too low but the error is not large. Consideration of equation 5-10 will show that low values of f give low values of G so that the error introduced by using equation 5-12 for full size tanks is on the safe side. Values of G were computed for many tests run on all the tanks at many different temperatures and flow rates. These were plotted against first trace efficiency as shown in Figure 5-2. Tests in which short circuiting due to poor inlet conditions or other causes of excessive turbulence was marked, were not included since the present study was concerned only with short circuiting in the detention zone due to thermal density effects. From the plot it is evident that for flow with a value of $G = 0.3$ per second or more the first trace efficiency was consistently high.

METHOD OF OBTAINING REQUIRED MEAN VELOCITY GRADIENT

Maintaining a value of G above 0.3 per second will assure freedom from density problems, but it is important to note that the velocity gradient must be produced by friction loss in open channel flow if it is not to produce undesirable side effects. In flocculators the high values of G which are used (between 10 and 75 ft/sec/foot) are often produced by stirring mechanisms, by short round the end or over and under baffles, or by introducing the flow at high velocity. In detention tanks such means should never be employed to get the required value of G because of the serious turbulent short-circuiting which they produce (see Figure 5-1B). Relatively fine mesh perforated baffles which produce a fine grain turbulence do assist in reducing thermal density stratification, but their influence is effective for only a short distance down stream because of the rapid dissipation of their turbulence. This can be seen in the first view of Figure 3-5. Note how the cool water colored by dye used as a tracer flowed through the entire baffle in a uniform manner but almost immediately after getting through, it dropped to the bottom to form the density current. Tests run on the 1:32 scale model illustrate further the effectiveness of such baffles. The model was run at the same flow rate and same temperature with the baffles in place as shown in Figure 3-8, with no baffles except the one at the inlet, and with

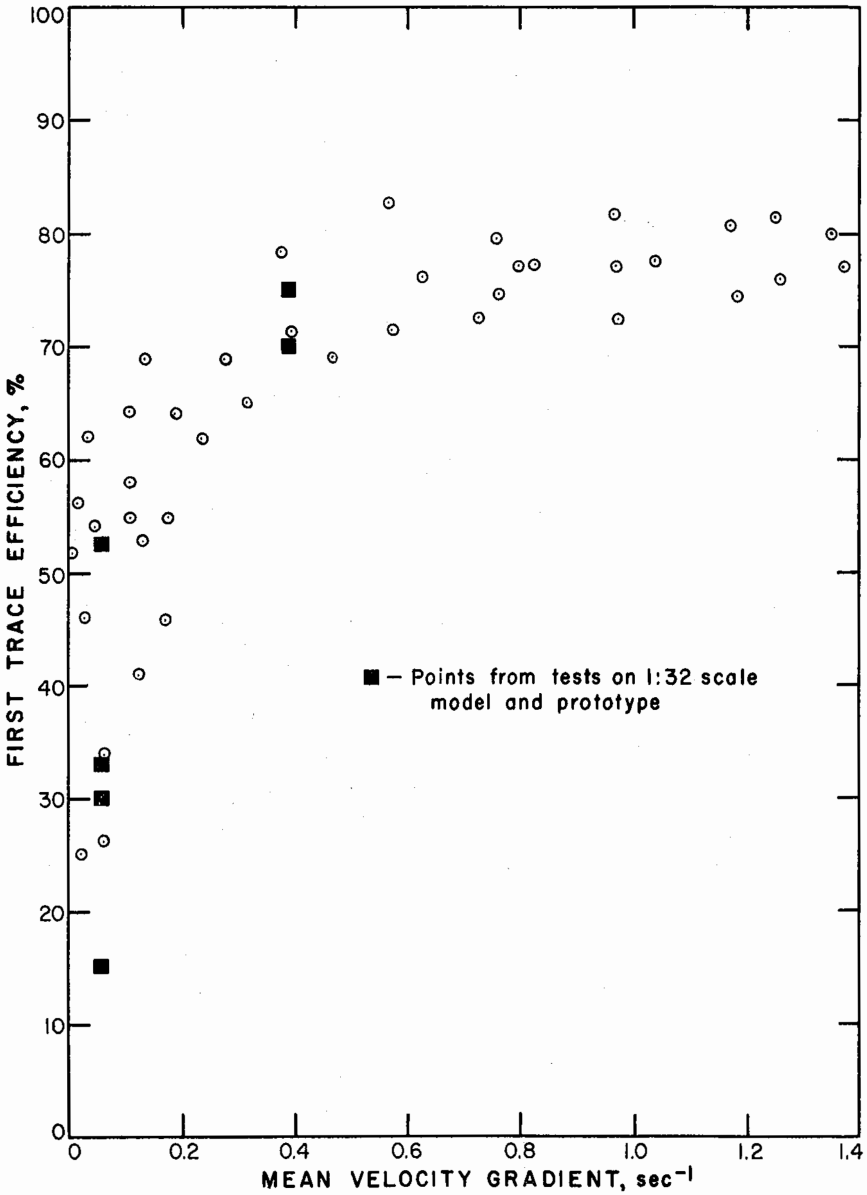

FIGURE 5-2.—FIRST TRACE EFFICIENCY VS. MEAN VELOCITY GRADIENT.

two long baffles dividing the tank into three channels in series as shown in Figure 5-3. In the first two runs, G, as computed from Equation (5-12), was 0.068 per second while in the last run, G was 0.386. Figure 5-4 shows that while the transverse baffles did some good the effectively long narrow tank with a value of G above the critical was far superior.

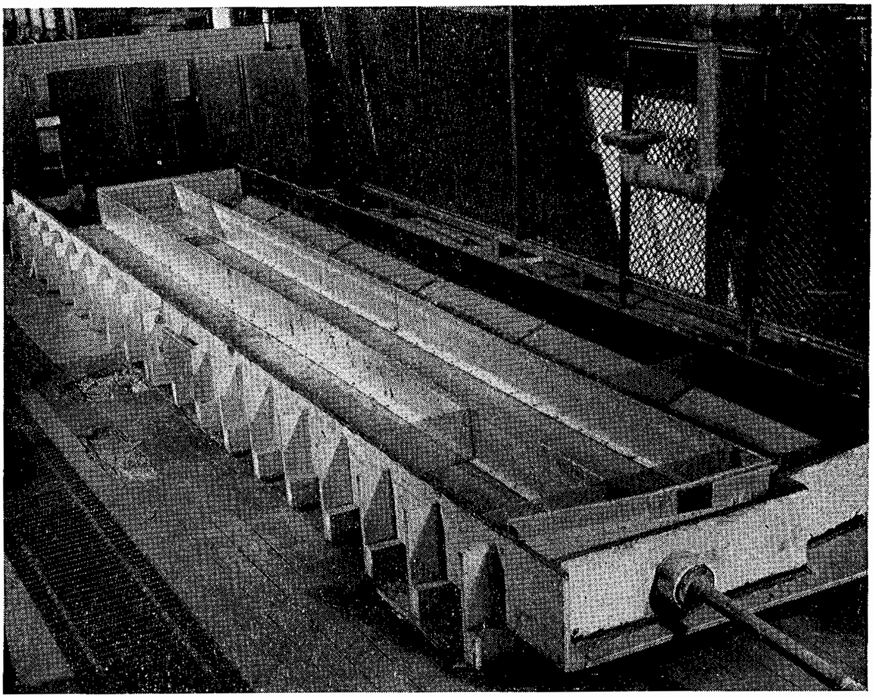

FIGURE 5-3.—1:32 SCALE MODEL MODIFIED BY INSERTING LONGITUDINAL BAFFLES.

The curves presented in Figure 5-4 do not meet the requirements of good flow-through curves. The areas under them are low, in the order of 65 percent, and for some, the center of gravity obviously falls to the right of t/T = 1. Adsorption of dye on the surfaces in the tank probably accounted for these conditions. This would obviously reduce the area of the curve and if dye were adsorbed during times of high concentration and some of it were released again as the concentration diminished this would shift the center of gravity of the observed curve to the right. More evidence of such adsorption is furnished in the case of Figure 5-4C by the high first trace efficiency combined with the rela-

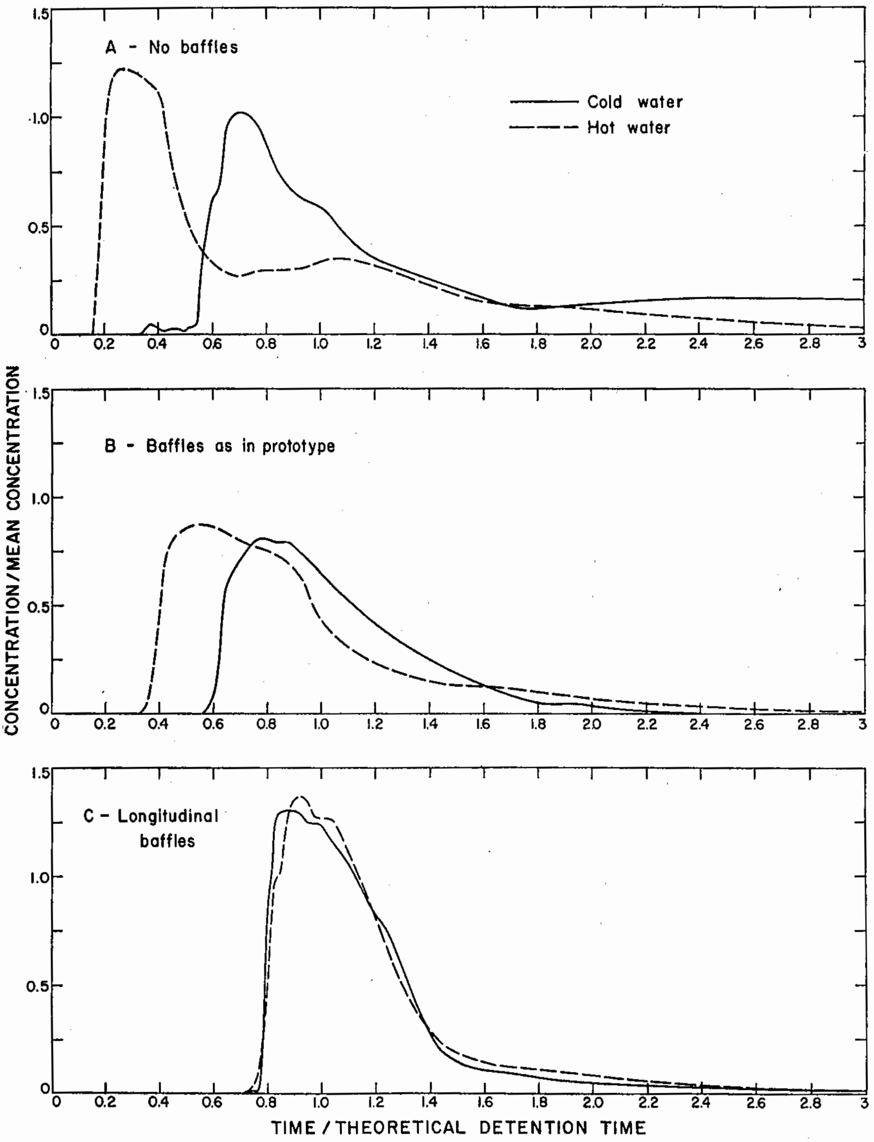

FIGURE 5-4.—FLOW-THRU CURVES FROM TESTS ON 1:32 SCALE MODEL.

tively low broad peak and not too rapid drop. The first trace time in these tests should be about the same as that expected with an ideal tracer since the first trace of dye travels through the tank with the flow of maximum velocity which would tend to stay away from the boundaries. However, with a first trace efficiency of about 80 percent one would expect a high sharp peak on the flow-through curve. Evidently the peak was adsorbed and then released again giving the distorted curve.

The transient condition caused by a change in water temperature was studied in the 8″ × 8″ flume. Numerous tests made by operating the flume with water of one temperature and then suddenly changing the temperature of the water showed that when G was above 0.3 per second the time required to remove all the water of the initial temperature was only two to three detention times under the most adverse temperature conditions while for lower values of G the stagnant layer remained almost indefinitely. This is as would be expected since for G values above 0.3 per second turbulence energy is present in sufficient quantity to cause mixing and subsequent removal of the stagnant layer.

TESTS ON VARIOUS TANKS

Tests on many different tank designs confirmed the importance of the mean velocity gradient in detention tank design. Tests on converging and diverging walls made in the large wooden tank showed that for G greater than 0.3 per second the performance of either was only slightly different from that of parallel walls, and was good, while for lower values of G the converging walls were superior to diverging walls but the performance in both was poor compared to that with G greater than 0.3 per second.

The 1:100 scale model of the circular detention tank illustrated in Figure 3-7 showed very poor results due to thermal density effects and non-uniform velocity distribution induced by the passage of flow around the ends of the baffles. The hydraulic design of this tank could have been improved by increasing the number of baffles so as to increase the displacement velocity, and by installing perforated baffles at the start of each straight channel to give a more uniform velocity distribution. These modifications, however, would increase the tank cost substantially.

DETENTION TANK OUTLETS

For tanks operating above the critical value of G no special outlets are required. The usual weir is satisfactory. On the other hand if a tank is operating with hot water below $G = 0.3$ per second a baffle wall with a slot at the bottom of the tank just before the outlet weir will help in drawing off cool water thereby reducing the size of the stagnant pool in the bottom of the tank. Figure 5-1C.

TANK PERFORMANCE AT LESS THAN DESIGN FLOWS

Performance of a detention tank at flows below that for which it was designed is of interest. It is evident that such reduced flow might well have a mean velocity gradient below the critical value. It is also true that the theoretical detention time for such flow would be longer than the design value. Results from many tests have shown that almost invariably with decreased flow rates the first trace time increases despite the fact that the first trace efficiency is reduced. The one exception which was noted occurred as follows: During a group of runs in the 8 inch by 8 inch flume at very low flows a certain run was made using baffle number 3 (see Figure 4-3) which had forty-nine one-quarter inch holes. The jets from the holes in the baffle traveled a few inches down stream and then broke up in turbulence. The next run was made with the same baffle at a slightly lower flow rate. This time the jets did not break up but remained as laminar flow and traveled with practically undiminished velocity well over half way down the flume, carrying the first trace of dye through in less time than in the previous run. This exception to the general rule is only of academic interest since no prototype baffle would be designed to operate at such a low velocity as is required for such laminar jets to exist.

MODEL SIMILITUDE

In operating models of detention tanks maintaining G the same in the model and prototype appears to be suitable for obtaining satisfactory similitude as far as the detention zone is concerned. Since

$$G = 0.167 \frac{V^{11/8}}{\nu^{3/8}\, r^{5/8}} \qquad (5\text{-}12)$$

we can write

$$\frac{V_r^{11/8}}{\nu_r^{3/8}\, r_r^{5/8}} = 1 \qquad (5\text{-}13)$$

where the subscript r denotes the ratio of the quantity between the model and prototype. If ν_r is assumed to be 1 as would be the case if the same water temperature were used in the model and prototype then

$$v_r = L_r^{5/11} \qquad (5\text{-}14)$$

It is of interest to compare this model operating criterion with the Froude criterion which would be normally used for operating inlet models. For free surface flow where viscous forces are not important

$$F = \frac{v}{\sqrt{gL}} \qquad (5\text{-}15)$$

gives

$$v_r = L_r^{1/2} \qquad (5\text{-}16)$$

as compared with $L_r^{5/11}$ when using G. Observations indicate that the flow patterns and velocity distributions in inlets are not sensitive to changes in flow expected in normal operation so that if the inlet is also designed and operated according to the velocity gradient criterion, satisfactory results will be obtained.

Figure 5-5 shows a comparison of flow-through curves obtained

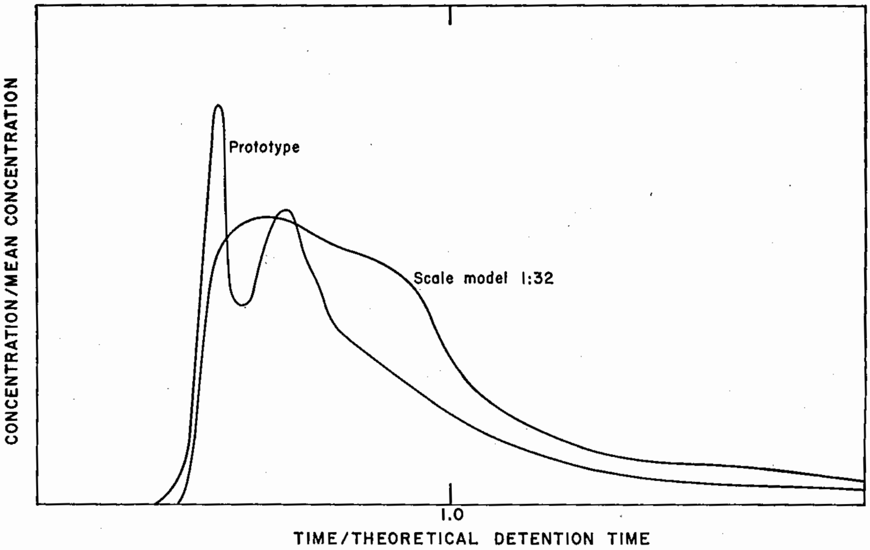

FIGURE 5-5.—FLOW-THRU CURVES FOR MODEL AND PROTOTYPE OPERATING AT SAME VALUE OF G.

from the 1:32 model and its prototype operating at the same value of G. Note the good fit as far as the time axis is concerned. The discrepancies in the concentration values are due to experimental difficulties. The prototype test was run under adverse conditions. For this reason the absolute values of concentration are in doubt. Also the baffles in the prototype were in bad condition and wind action was a factor, both of which could cause discrepancies between the model and prototype. Further tests run on other tanks and their models would be useful in proving the value of G as an operating criterion for such studies.

Integrating Tanks

Integrating tanks are used to reduce the concentration of slugs of toxic or otherwise undesirable substances introduced upstream from the tank. Their use is to provide dilution rather than detention. In a tank with perfect mixing a slug entering the tank will be instantly diluted with one tank volume of water. In terms of the flow-through curve at time zero $c/\bar{c}$ will be equal to one and as time progresses its value will drop exponentially to zero. Thomas and McKee[8] show that with two perfectly mixed tanks in series somewhat better dilution can be had. For such an arrangement $c/\bar{c}$ will have values somewhat less than 0.8. No special experiments were run on integrating tank design but it is evident from the results that some of those arrangements which gave very poor results as detention tanks would function well as integrating tanks. With the flume arranged with short round-the-end baffles the peak value of $c/\bar{c}$ was about 0.8. Apparently successful design of integrating tanks calls for good but not necessarily perfect mixing.

Conclusions

In previous sections the principles of detention tank design have been investigated. Now what remains is to indicate how these principles can be applied in practical situations. At this stage economics enters the picture, since the aim of every engineer is to provide a suitable structure at minimum cost.

Canals as Detention Basins

In the atomic energy industry it seems that in cases where installations are built at considerable distances from metropolitan areas,

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[8] H. A. Thomas, Jr. and J. E. McKee, "Longitudinal Mixing in Aeration Tanks," Sewage Works Journal, 16, 1 p. 48 (January 1944).

long narrow basins in the form of canals would prove economical. They should be designed so that at design flows as computed from Equation (5-12) the mean velocity gradient would be at least 0.3 and preferably 0.5 per second. The inlet to such a basin should be simple, such as the T-inlet with one transverse baffle. The possibility of omitting the baffle and adding slightly to the length of the basin would be worth considering. Such basins would be particularly attractive in areas where irrigation canals are common since equipment and technique for their excavation and lining would be readily available.

RECTANGULAR TANKS

In situations where space is limited it becomes necessary to "fold up" the long narrow tank to fit the available area. Under these circumstances the longest possible tank should be built and divided into channels with longitudinal baffle walls in such a way that G for the channels connected in series is at least 0.3 and preferably 0.5 per second. Such a tank must have a larger total volume for a given flow time than the long straight canal because the volume taken up by the return bends can not be considered as part of the detention zone. The T-inlet with baffle should be centered on the first channel. Some baffling at the return bends may be worth while to maintain a uniform velocity distribution.

CIRCULAR TANKS

Another design which shows promise is that of a circular tank with a spiral baffle giving a long spiral channel. A small scale model of such a tank was set up and visual observations indicated good performance. A spiral baffle has a number of inherent advantages. First, circular tanks and baffles are economical to build. Second, the flow can be introduced at the center so that in the case of radiation hazard from radioactive isotopes the most dangerous radiation zone would be farthest from the walls of the tank. Third, the secondary spiral flow induced by the continuous bend should help in keeping thermal density currents from forming. Fourth, there are no ineffective areas in the detention zone such as occur in a rectangular tank with return bends at the ends of longitudinal baffles. More experimentation would be worthwhile on such tanks to determine optimum width to depth ratios and to find what velocities should be used for best results. In the absence of further information, designs using the same values of G as recommended for straight channels would most probably give satisfactory results.

Circular tanks without baffles with the flow entering at the center and leaving over a peripheral weir such as are used for settling tanks should never be used as detention tanks. The low velocities and diverging pattern of flow both tend to cause instability and extreme short-circuiting.

MODEL STUDIES

In the design of long canal type basins without return bends a model study would appear to be unnecessary; a satisfactory design could be based on the theoretical principles embodied in Equation (5-12). A small scale model of the inlet zone would be helpful in determining an effective and economical design, but in all but the largest projects it might well prove cheaper to increase slightly the length of the canal as a factor of safety, and to dispense with the model tests. On the other hand if a tank with longitudinal baffles and return bends is contemplated, a model study is almost a necessity. Experimentation on a model will often show that marked improvements can be made in the return bend zones by the proper placing of small baffle walls or deflectors to reduce high velocities and increase the homogeneity of the turbulence. In many instances such inexpensive measures may permit the omission of more costly perforated transverse baffles with little or no sacrifice in performance. As for spiral tanks it is thought that when some experience has been gained in their design and operation good performance will be achieved without the necessity of making a model study. However, on the basis of present knowledge it would be unwise to proceed with the construction of a circular prototype tank without first undertaking a model study.

ECONOMIC IMPLICATIONS OF HYDRAULIC DESIGN OF DETENTION TANKS

Cost estimates on three tanks which give the same performance show that good hydraulic design is economically worthwhile. The 1:32 scale model modified by inserting longitudinal baffles (Figure 5-3) was used as the "standard" of performance. The flow-through curves (Figure 5-4) indicate that in order to get the same performance from the tank with transverse perforated baffles as shown in (Figure 3-8), the length would have to be increased. The exact amount of increase would depend on the decay characteristics of the substances to be removed by the tank. If the half-lives of these are very short it would be necessary almost to double the tank length so that the leading edge of the flow-through curve would come through in the same absolute time as in the standard. To be conservative it was assumed that a fifty percent increase in length would be sufficient. The following additional assumptions pertaining to construction were made: 1) External walls and bottom 12 inches thick; 2) Internal walls 8 inches thick; 3) Transverse perforated baffles made of standard 8 inch concrete blocks with holes, reinforced with concrete beams and buttresses were taken to have the same cost per unit area as 8-inch thick concrete longitudinal baffles; 4) Concrete cost, including reinforcing steel, $40.00 per cubic yard in place; 5) Excavation cost $0.50 per cubic yard; 6) Flow line level with ground surface. On this basis the standard tank would cost approximately $240,000 while the longer tank would be approximately $295,000. On the same basis the prototype tank as built in Figure 3-8 would cost only $200,000; however, its performance is well below that of the other two. The cost of a canal to give a performance equivalent to that of the standard tank was also calculated. The cross-section selected had a bottom width of 24 feet, a depth of 17 feet including 1 foot of freeboard and side slopes of one on one. The required length was 1870 feet. When operating at design flow the canal would have a mean velocity gradient of 0.47 per second, somewhat higher than that in the tank. This canal excavated to a depth of 16 feet below the natural ground level at a cost of $0.50 per cubic yard and lined with four inches of concrete at $40.00 per cubic yard, would cost about $90,000. The high cost for concrete was used in this case to cover the expense of providing unusally effective water stops at the expansion joints and superior concrete work throughout to insure a water-tight lining.

The design of detention tanks will always require the services of a competent hydraulic engineer. His judgment is necessary in selecting the best arrangement for any given situation. It is hoped that the results of this research will aid him in providing a suitable, efficient, and economical design.

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