in the pipe are shown at different instants during the propagation of the pressure waves back and forth along the pipe, sections under supernormal, normal and subnormal pressure being indicated by black, gray and white shading respectively. To the right of the diagonal lines, crossing these sections, the pressure is always normal. To the left it is supernormal, in the second, third and fourth section from the top, and subnormal in the sixth, seventh and eighth.

Arrows drawn with full line show the direction of the water flow from reservoir to pipe or vice versâ, and arrows drawn with broken lines show the direction of propagation and of the pressure wave.

Thus, in the uppermost space we have a *broken* arrow pointing to the *right*, and a *full* arrow pointing to the *left*, indicating that, during the period between the two moments represented by the first and second figures, respectively, the *pressure wave* is traversing the pipe *from the gate toward the origin*, while *water* is flowing in the opposite direction, *viz., from the large main into the pipe.*

It will be noticed that we always find *normal* pressure between the head of the wave and the *origin*, and *abnormal* pressure between the head of the wave and the *gate*; in other words, that disturbances of pressure come always from the gate and the restoration of normal pressure comes always from the origin. Hence, the pressure at any point remains normal so long as the head of the pressure wave (moving in either direction) is between such point and the gate; and the nearer the point is to the origin, the longer will be its periods of normal and the shorter its periods of supernormal and subnormal pressure, and vice versâ.

It is in dealing with long water mains that one generally encounters the problem of maximum water hammer. In hydro-electric work we nearly always find the condition for ordinary water hammer, that is the time of gate closure on the water turbines, is greater than the critical time. This does away with excessive pressure rises in penstock which in a very long pipe line might easily be greater than the static pressure.

Ordinary Water Hammer.—A brief outline of the phenomena of ordinary water hammer, or pressure rise, as it is generally accepted, in the light of experiments that have been made up to the present time, will doubtless help to make clearer the difference in meaning between the two terms for water hammer that are used on the charts.

Allow the gate at the lower end of the penstock to be closed a small amount, the velocity is changed and a pressure wave is at once propagated along the pipe towards the forebay, resulting in a rise in pressure at the gate. If the gate movement is now discontinued this pressure wave will remain constant until the wave has travelled to the forebay and back to the gate in a time equal to $\frac{2L}{a}$. The pressure at the gate then falls to normal, then to subnormal. The subnormal pressure would be equal to the supernormal if friction, atmospheric pressure, etc., did not interfere. The above cycle is repeated until the wave is entirely dissipated by friction, etc.

Now, on the other hand, if the gate closure is continued it will be found that for each increment of gate closure, we have a new wave propagated with a corresponding rise in pressure. These pressure waves will continue to mount up as the gate closes until they are interfered with by the reflected waves.

As by far the greater number of pressure rise problems fall under this heading, Chart No. 2 for ordinary water hammer will probably be found more useful to the hydro-electric engineer than the preceding Chart No. 1.

In order to show the application and the method of reading the charts, several typical problems will now be worked out.

Nomenclature.

a = velocity of vibration along the pipe, in feet per sec.
D = inside diameter of pipe, in inches.
d = thickness of pipe walls, in inches.
E = modulus of pipe material in tension, in lbs. per square foot.
g = acceleration of gravity, taken as 32.2.
h = excess head in feet, due to water hammer.
H = normal static head, in feet.
K = modulus of elasticity of water in compression taken as 42,400,000 lbs. per square foot.
L = length of pipe, in feet.
$N = \left(\frac{LV}{gTH}\right)^2$.
T = time of closing of gate, in seconds.
V = velocity of water in pipe, in feet per second.
T_0 = critical time, $\frac{2L}{a}$

Formulæ.

"Maximum water hammer, ($T < \frac{2L}{a}$)"

$$h = \frac{aV}{g}$$

$$a = \frac{4660}{\sqrt{1 + \frac{K}{E}\frac{D}{d}}}$$

"Ordinary water hammer ($T > \frac{2L}{a}$) — "

Allievi's formulæ:

$${}^*h = \frac{NH}{2} \pm H\sqrt{\frac{N^2}{4} + N}$$

$$N = \left(\frac{LV}{gTH}\right)^2$$

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*Use + sign for gate closure, and — sign for gate opening.

Problem 1—Chart No. 1.—Find the maximum water hammer that can occur in a steel pipe line, 10,000 feet long, 36 inches in diameter, made of ½-inch plate, carrying water at a velocity of 3 feet per second.

In order to have the condition for maximum water hammer the time of gate closure must be less than $\frac{2L}{a}$, the critical time. Let us first find the critical time by obtaining the value for a, from Chart No. 1, and then the maximum water hammer from the same chart. This problem is worked out on the chart by means of dotted lines which indicate the method of reading; but in order to make it as clear as possible, it will be followed through verbally.

Given: L = 10,000 feet.
D = 36 inches.
d = ½ inch.
E = 4,000,000,000 pds. per square foot.
g = 32.2.
V = 3 feet per second.
Material = steel plate.