WOOD-STAVE PENSTOCKS

Wood-stave penstocks are now in very general use in all parts of the country, particularly for moderate heads. Wood-stave construction, like concrete, is best adapted for the portions of a penstock line where, due to the minimum thickness requirement, steel pipe is not economical, or, say, up to about 150-ft. head. For heads above about 150 ft., substantially the same amount of steel will be required (assuming like values of tensile strength), whether the steel is used in plate form or as bands, modified somewhat, however, by the fact that the bands are or can be 100 per cent efficient, while the plates are limited by joint efficiency to 70 or 80 per cent. The net result is an ordinary limitation in the use of wood-stave pipe to heads under about 150 ft.

**Design of Wood-stave Penstock.**—The design of a wood-stave penstock is consistent with the fundamental hoop-tension formula, modified to suit the special qualities and limitations of the wood staves.

Assuming \( S = \pi r^2 f \), where \( S \) is strength of (circular) band in pounds, \( r \) is radius of band in inches, and \( f \) is allowable tensile strength of band in pounds per square inch, and, if the wooden stave of thickness \( t \) in. can safely carry \( e \) lb. per square inch in bearing across the grain, then

\[
S = \pi r^2 f = (R + t)(e \cdot r \cdot 1)
\]

assuming the band to have an effective width in bearing = \( r \). This value of \( S \) must not be exceeded, or the bearing stress of band or stave will exceed the safe value of \( e \), the latter usually being taken at 650 lb. per square inch.

For spacing of bands:

Using the value of \( S \) from Eq. (9), or for any size of band with lesser value of \( S \), the distance between bands will be

\[
d = \frac{S}{pR + e't}
\]
where \( e' \) is the crushing strength of the staves along the grain, due to swelling of the wood after the bands are tightened, \( e' \) usually being about 100 lb. per square inch.

Using the maximum size of band will often result in a value of \( d \) too large for practical use. The latter should not exceed 8 to 10 in., or the pipe is likely to leak.

**Numerical example:**

8\(\frac{1}{2}\)-ft. wood-stave pipe, 2-in. staves, \( f = 15,000 \) lb. per square inch, head = 50 ft.

For maximum size of bands:

\[
\pi r^2 \times 15,000 = (51 + 2.5) 650r \\
\frac{r}{\pi \times 15,000} = 0.74 \text{ in.}
\]

\[. \cdot S = \pi \times 0.74^2 \times 15,000 = 25,800 \text{ lb.}\]

For spacing of bands:

\[
d = \frac{25,800}{50 \times 0.43 \times 51 + 100 \times 2.5} = \frac{25,800}{1100 + 250} = 19.2 \text{ in.}
\]

which is too great to use.

If \( d \) is taken at 10 in.,

\[
10 = \frac{S}{1090 + 250}; S = 13,400 = \pi r^2 \times 15,000 \\
r^2 = 0.284; r = 0.53 \text{ in.}
\]

or approximately 1-in. bands spaced 10 in. center to center.

It will usually be possible, on a penstock line, to adopt a given size of band and vary the spacing with the head.

The staves will vary somewhat in thickness with the size of line. Horton\(^1\) has derived an empirical formula for stave thickness as follows:

\[
T = 1 + \frac{h}{100} + \frac{d}{100},
\]

(11)

where

\( T \) = thickness of stave, inches.

\( h \) = head, feet.

\( d \) = pipe diameter, inches.

**Practical Details** (see Fig. 156).—Staves are usually of redwood or fir milled on the edges to true radial planes, fitted with tongue and groove, and milled on the outside and inside faces to the correct curvature for the pipe size. The staves are trimmed square at the ends to form the butt joints, which break joints at least 24 in. The ends of the staves have a saw kerf cut across the face for the insertion of the metal tongues. The width of the kerf is exactly the thickness of the tongue; the depth of

the kerf is slightly less than half the width of tongue; and the length of the
tongue is slightly in excess of the finished width of the stave, measur-
ing along the saw kerf, so that, in the finished pipe, a water-tight joint is
made between the butt ends of the two staves and the sides of the adja-
cent staves.

The tongues are made from band steel and are usually about \( \frac{3}{8} \) in., of a length depending on the width of stave.

The bands, usually \( \frac{3}{8} \) to 1 in. in diameter, consist of steel rods, circular
in cross section, with a head at one end and a thread at the other end, the
two ends being united by a malleable iron shoe (Allen type), the rod being
tightened with a nut and washer. For pipes of larger diameters the rods

---

Fig. 156.—Details of wood-stave pipe construction. (Redwood Manufacturers Company.)

are in two sections, one section being double headed and the other section
being double threaded. In this case two malleable iron shoes are required
for a complete band. In pipe of 10 ft. diameter or over, three rods and
three shoes would form a complete band. The threads on the rod are
cold rolled on upset ends, and the dimensions of the head and thread are
such that the thread and head ends are as strong as the body of the rod.
The bands have a tensile strength of 55,000 to 65,000 lb. per square inch
and are furnished according to standard steel specifications. The Allen-
type shoe is so shaped that it fits closely upon the outside of the pipe and
the cinching of the rod produces a straight pull, the entire bands, when
in place, lying in a plane perpendicular to the direction of the pipe. The
shoe is so designed as to develop the full tensile strength of the band.
If shoe and band were tested to destruction, the band would break first,
which enables the factor of safety to be accurately determined by the
tensile strength of the band.
In erection (see Fig. 157) the staves are assembled in the trench and put together to form a circle of the diameter of the pipe, and the bands put around the outside and tightened to hold the staves together. End joints in staves are broken by a lap of at least 2 ft. and the pipe put together continuously in the trench, the metal tongues being inserted as previously described.

![Erection of wood-stave pipe line. (Courtesy of Redwood Manufacturers Company.)](image)

Fairly sharp curves can be obtained by bending the staves, the approximate limit in sharpness of curve being as follows:

<table>
<thead>
<tr>
<th>Diameter of Pipe, Feet</th>
<th>Shortest Radius, Feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>125–150</td>
</tr>
<tr>
<td>5</td>
<td>150–175</td>
</tr>
<tr>
<td>6</td>
<td>200–225</td>
</tr>
<tr>
<td>7</td>
<td>275–300</td>
</tr>
<tr>
<td>8</td>
<td>305–400</td>
</tr>
<tr>
<td>9</td>
<td>450–500</td>
</tr>
<tr>
<td>10</td>
<td>600</td>
</tr>
<tr>
<td>11</td>
<td>650</td>
</tr>
<tr>
<td>12</td>
<td>700</td>
</tr>
</tbody>
</table>
After the pipe is completed and before the water is turned in, the bands are gone over and tightened uniformly so as to place an even tension on them. When the pipe is filled with water, the staves swell sufficiently to bed the bands slightly into the wood and make longitudinal joints water-tight.

Fig. 158.—Methods of connecting steel and wood-stave pipes.

Sharp bends in wood-stave penstocks are usually made by the use of short steel-pipe sections curved to the requisite amount. The connection between wood-stave and steel pipe may be made by either of the two methods shown in Fig. 158, one of these using a caulked joint of lead and oakum, as commonly employed for cast-iron pipe, and in the other a packed joint with gland ring.

Fig. 159.—Sixteen-foot wood-stave penstock at Copco Plant 2 of California-Oregon Power Company. (Courtesy of Federal Pipe and Tank Company.)

Cradles, usually of concrete, are spaced 8 to 12 ft. apart on centers. In the case of the Searsbury plant of the New England Power Company, built in 1921, reinforced-concrete precast cradles were used, set on concrete sills.
In some cases wood-stave penstocks have been covered with earth. In wet ground the staves will last many years, but the bands will usually deteriorate rapidly. On the whole, practice favors exposed pipe on cradles.

![Wooden cradle for small sizes of wood-stave pipe lines.](image)

A wood-stave pipe line of largest diameter yet built, 16 ft., is in use on the Cepco Plant 2 of the California-Oregon Company in northern California. It is of 3000 sec.-ft. capacity, 1318 ft. long, connecting two concrete-lined tunnels, and carries a maximum head of 60 ft. The staves are 4 in. thick by 5\(\frac{3}{4}\) in. wide, with \(\frac{7}{8}\)-in. steel bands spaced from 3.62 to 3.71 in. Concrete footings on an earth foundation, built of reinforced T-beams 48 by 14 in. wide at the top, 3 ft. wide at the base, and 21.5 ft. long, carry structural steel cradles, weighing 1940 lb. each, bolted down by six \(\frac{3}{4}\) in. bolts grouted in place. The cradles are 8 ft. on centers on curves, 10 ft. on tangents, and extend to a height a little above the center-line level of the pipe (see Fig. 159). A steel T-bar

![Wooden cradle for 13.5 wood-stave penstock—Condit plant. (Courtesy of Stone and Webster Engineering Corporation.)](image)

passing over the top of the pipe, with ends bolted to the top of each cradle, takes the place of a band at the cradle section. The details of bands, cradles, and footings in Fig. 159 should be studied.

Wooden cradles are also in very general use for wood-stave penstocks. In Fig. 160 the arrangement for smaller sizes of pipe is shown, and in Fig. 161 the wooden cradles are shown as used for the 13.5-ft. wood-stave penstock line of the White Salmon (Condit) plant, near Portland, Ore., serving two 9000-hp. wheel units under a head of 160 ft. at 360 r.p.m. There are 1120 cradles in a total length of penstock of 5100 ft.

ACCESSORIES—PENSTOCK LINES

Air Vent.—An air vent of ample size should always be installed just below the gates at the upper end of the penstock, to permit air to enter when the head gates are shut and water drawn out of the penstock.

The maximum air requirement, with head gates closed and wheel gates wide open, would evidently be the same number of cubic feet of air per second as the discharge; but, as the penstock water level lowered, the head on the wheels would lessen and the wheel discharge would diminish, varying as the square root of the head on the wheel. Furthermore, in draining the penstock the wheels would, with a careful operator, be at only part gate. It is safer, however, to provide the air vent for possible full discharge.

Thus, with an 8-ft. penstock and discharge of 300 sec.-ft., as for the Searsburg plant (Table 69, page 360), 300 cu. ft. of air per second may have to enter the air vent for a time. A 3-ft. vent pipe is provided at the head gate house of this plant which would give a possible air velocity through the vent pipe of about 43 ft. per second to provide air enough to keep the pipe filled with air as the water was drawn off. While this air requirement is unlikely with a careful operator, it is evident that the air vent should be ample, as in this case. It is also essential that the gate house be so arranged that air can enter freely at all times.

In one case, at a plant in Connecticut some years ago, the water in the vent pipe became frozen over, resulting in collapse of the penstock line, when the head gates were shut and water drawn out. It is, therefore, also essential that the air vent be protected from frost so as surely to function at all times. A simple means of effecting this is by the use of a small electric heater floating on the water in the top of the vent pipe.

Surge Tank.—Usually a surge tank is required in the penstock line, located as near as practicable to the power house for purposes of speed and pressure regulation. The principles involved and arrangement of the surge tank are discussed in Chap. X.

Air Valves.—An air valve to permit air to enter the pipe may be required at the lower end of a flat grade where the penstock line begins
to pitch suddenly to the power house. In case of sudden load acceptance by the wheels, the water may be drawn out of the lower, steep portion of the penstock faster than it can flow in the flatter part, thus tending to cause a collapsing pressure on the pipe at the change in grade. The requirements for and arrangement of air valves are also discussed in Chap. X.

**RELATIVE CAPACITY OF DIFFERENT PENSTOCKS**

The various kinds of penstocks described—steel, concrete, and wood stave—differ considerably in their carrying capacity, due to difference in frictional effect.

Based on Table 63, King's "Hydraulic Handbook," values of $n$ in the Manning formula are as follows:

<table>
<thead>
<tr>
<th>Kind of pipe</th>
<th>$n$</th>
<th>Inverse ratio to $n$ for wood pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean cast iron</td>
<td>0.012</td>
<td>0.92</td>
</tr>
<tr>
<td>Clean riveted steel</td>
<td>0.015</td>
<td>0.74</td>
</tr>
<tr>
<td>Lock-bar steel</td>
<td>0.011</td>
<td>1.00</td>
</tr>
<tr>
<td>Clean wood</td>
<td>0.011</td>
<td>1.00</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.013</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Keeping in mind that, for a given hydraulic radius, capacity varies practically inversely as $n$, the relative hydraulic advantage of wood-stave, lock-bar, and concrete over riveted-steel pipe is obvious from the above table.

The different types of steel pipe also show considerable variation in friction losses. A summary of tests by the Pacific Gas and Electric Company\(^1\) gives the following values of $n$ in the Kutter formula:

<table>
<thead>
<tr>
<th>Kind of steel pipe</th>
<th>$n$</th>
<th>Inverse ratio to $n = 0.015$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lap-welded, bump joints</td>
<td>0.013</td>
<td>1.15</td>
</tr>
<tr>
<td>Thin pipe, lap joints</td>
<td>0.014</td>
<td>1.07</td>
</tr>
<tr>
<td>Moderately thick pipe, butt joints</td>
<td>0.016</td>
<td>0.94</td>
</tr>
<tr>
<td>Heavy pipe, triple-riveted butt joints</td>
<td>0.018</td>
<td>0.83</td>
</tr>
</tbody>
</table>

As will be noted, in general, joints of high-strength efficiency are lower in hydraulic efficiency, with the exception of lock-bar steel pipe, which

is high in both. The bump joint is apparently most efficient hydraulically for riveted-steel pipe.

PENSTOCK CONSTRUCTION COSTS

Riveted-steel Pipe.—Based upon a 200 per cent cost-index factor (see Table 122, Chap. XII), the steel for straight pipe will cost from 4 to 4½ cts. per pound. In estimating weight of pipe based upon the pipe thickness, about 10 per cent should be added to allow for lap of plates, butt plates, rivets, etc. The cost of pipe erected, but not including cost of unloading and hauling to site, will be from 5½ to 8 cts. per pound, depending chiefly upon the difficulties of erection. Unloading and hauling will cost generally from 1½ to 2 cts. per pound, so that the total cost of pipe erected is likely to be from 7 to 10 cts. per pound. Additional items of cost will be:

1. Excavation and grading, costing from $1 per cubic yard upwards, depending on conditions.
2. Cradles, which may be of steel and included at about the same price per pound as the pipe or of reinforced concrete, with suitable unit costs.
3. Footings, usually of concrete.

Wood-stave Pipe.—The requirements for bands and staves, and estimated cost of redwood pipe erected, including a freight allowance of 90 cts. per 100 lb. (or, practically, the freight from coast to coast), but not

<table>
<thead>
<tr>
<th>Diameter, feet</th>
<th>Head, feet</th>
<th>Band diameter, inches</th>
<th>Band spacing on centers, inches</th>
<th>Finished stave thickness, inches</th>
<th>Estimated cost, dollars per running foot erected</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>30 ½</td>
<td>9.47</td>
<td>1½</td>
<td>5.30</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ½</td>
<td>5.04</td>
<td>1½</td>
<td>5.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150 ½</td>
<td>1.60</td>
<td>2</td>
<td>9.78</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>30 ⅛</td>
<td>9.08</td>
<td>2½</td>
<td>12.77</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ⅛</td>
<td>5.08</td>
<td>2½</td>
<td>14.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150 ⅛</td>
<td>1.29</td>
<td>2½</td>
<td>23.00</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>30 ⅛</td>
<td>10.00</td>
<td>3½</td>
<td>21.68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ⅛</td>
<td>6.38</td>
<td>3½</td>
<td>23.58</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80 ⅛</td>
<td>3.09</td>
<td>3½</td>
<td>27.44</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>30 ⅛</td>
<td>8.05</td>
<td>3½</td>
<td>29.88</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ⅛</td>
<td>5.10</td>
<td>3½</td>
<td>32.12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80 ⅛</td>
<td>3.02</td>
<td>3½</td>
<td>36.10</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>30 ⅛</td>
<td>7.08</td>
<td>3½</td>
<td>33.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 ⅛</td>
<td>4.25</td>
<td>3½</td>
<td>38.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80 ⅛</td>
<td>2.65</td>
<td>3½</td>
<td>46.50</td>
<td></td>
</tr>
</tbody>
</table>

Note: Maximum band spacing = 10 in.
including cost of grading, cradles, footings, or unloading and hauling pipe, are given in Table 71\textsuperscript{1} for a considerable range in size of pipe and head. These costs are as of 1926 or, approximately for a 200 per cent cost-index number.

Redwood cradles similar to those shown in Fig. 160, page 381, spaced 12 ft. on centers on tangents, cost about 85 cts. per linear foot for 4-ft. pipe and $1.25 per linear foot for 6-ft. pipe. Above 6 ft. in diameter, concrete cradles are usually cheaper.

\textsuperscript{1} Furnished by Allen V. Garratt, eastern states representative of Redwood Manufacturers Company.