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SIPHON PENSTOCK INSTALLATIONS AT HYDROELECTRIC PROJECTS: A SURVEY OF DESIGN, CONSTRUCTION AND OPERATING EXPERIENCE

David Burgoine,[1] Peter Rodrigue,[2] and Julia Crittenden Tarbell[3]

There can be advantages to using siphon penstocks at small hydro projects, particularly those constructed at existing dams. One problem, however, is a lack of documentation of siphon penstock installations. The design considerations, construction and operating aspects of siphon penstock installations are described here.

INTRODUCTION

The conveyance of water with a siphon is not a new technology. Archaeological studies indicate the use of siphons in Egypt around 1500 B.C. Lead pipe siphons were constructed by the Greeks and Romans to convey drinking water. Siphons up to 20 ft in diameter are installed on modern-day water supply and irrigation projects.

Some early hydro plants have siphon-type intakes. However, much of the hydroelectric development in the 1930s to 1960s involved relatively large units

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[1]Project Manager, Acres International Corporation, Amherst, NY
[2]Head, Mechanical Engineering Department, Acres International Corporation, Amherst, NY
[3]Mechanical Engineer, Acres International Corporation, Amherst, NY

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constructed at new dams. In general, siphon intakes or siphon penstocks were not suitable for such installations. Over the past ten years with renewed activity in the development of small hydroelectric projects, there is increased interest in siphon-type penstocks, particularly at projects where a dam already exists.

There are several advantages for selecting siphon penstocks for hydroelectric projects constructed at existing dams, including:

- Minimal impact on an existing dam because penstocks usually pass over the dam;

- Elimination of a shutoff device upstream of the turbines since flow can be stopped and waterpassages dewatered by breaking the siphon; and

- Ability to construct the facility without an upstream cofferdam.

A review of design, construction and operating considerations for siphon penstocks, based on experience at 11 operating facilities are summarized below.

PROJECT DATA

The data for the 11 siphon penstock installations are summarized in Table 1. Plant capacities range from 70 to 8570 kW. Except for the Traicao project in Brazil which went into operation in 1944, all of the projects were constructed in the United States at existing dams within the past five years.

REASONS FOR SELECTING SIPHON PENSTOCKS

On six of the projects, siphon penstocks were evaluated as overall less costly than conventional intake and penstock designs. The reduction in project capital cost for the siphon penstock schemes ranged from about 12 percent to 20 percent.

At Schaads Reservoir, utilizing an existing outlet works pipe was estimated to be slightly less expensive than a siphon penstock, but represented a greater possibility of cost overrun due to unknown conditions. Conventional penstocks could not be installed at the Second Broad River plant because of a concern for dam safety; therefore, a siphon design was adopted. A siphon penstock was chosen for Pine Grove

Dam for a similar reason. At Tierckenkill Falls, the siphon concept was selected for research and evaluation purposes.

SIPHON PENSTOCK DESIGN

Siphon Lift

The siphon lift (headwater level to top of siphon crown) is dependent upon the site characteristics and plant layout. The maximum lift for the various plants is given in Table 1 and ranges from 3.8 ft to 25.5 ft.

At Lac Courte Oreilles, the maximum siphon lift (25.5 ft) exceeds the normal recommended value of 20 to 25 ft. However, the maximum lift occurs only at unusually low headwater levels, and it was assumed that the 9 ft diameter penstock could operate under these extreme conditions with the siphon crown only half full.

Siphon Priming System

At all projects, except Schaads Reservoir, a permanent vacuum system is provided for priming the siphon prior to plant operation. At Schaads Reservoir, normal headwater is at the crown of the siphon, and the penstock may be filled by gravity. Provision is made for priming the system with a portable vacuum pump when the headwater level is low.

Vacuum systems range from rather simple designs with a single vacuum pump connected directly through piping to the crown of the siphon, to more complex systems incorporating multiple pumps and vacuum tanks. Figures 1 and 2 show schematics of siphon priming systems. The vacuum system is controlled by water level switches or vacuum pressure switches. The pumps are isolated from the penstock either by an electrically-operated valve or a float-operated priming valve. Both liquid ring seal and positive displacement-type vacuum pumps are used, the liquid ring seal type being most common. Vacuum pump capacities range from 1.5 hp (Tierckenkill Falls) to 75 hp (Traicao).

At two projects (Lac Courte Oreilles and Pine Grove Dam) provision has been made to fill the penstock downstream of the siphon crown with water prior to completion of siphon priming with the vacuum system. At Lac Courte Oreilles, this is accomplished with separate pumps. A priming siphon, which is also primed by the vacuum system, is used to fill the penstock at Pine Grove Dam.

Siphon priming times for the various projects range from 3 minutes to 390 minutes. Plants with a positive shutoff device at the turbine (i.e., wicket gates or an isolating valve) have longer priming times, because the siphon can remain primed during a normal unit shut down. Units without a shutoff device (i.e., fixed discharge or semi-Kaplan units without valves) require breaking the siphon on each shutdown and priming for each startup. These plants have shorter priming times (3 to 25 minutes).

The vacuum system also removes air accumulation at the siphon crown during plant operation. At some plants, it has been noted that the flowing water in the penstock is sufficient to prevent excessive air accumulation.

A butterfly or ball valve is typically used to admit air into the penstock for breaking the siphon and, at most plants, the valve is designed for automatic operation. The ratio of valve to penstock diameter ranges from 0.033 to 0.188. Where the ratio is less than 0.038, there have been problems with an inability to break the siphon with full flow in the penstock.

Intake

The considerations for intake design (e.g., submergence, trashrack velocities, etc.) are the same for a siphon penstock facility as a conventional penstock and intake arrangement. In general, there is a greater incentive for a vertical or inclined intake with a siphon penstock than with a conventional penstock design. Seven of the 11 plants have vertical or inclined intakes. Typical arrangements for horizontal and vertical/inclined-type intakes are shown on Figures 3 and 4.

Most of the intakes have provision for manual cleaning of the trashracks. However, at some plants where access to the trashracks is difficult, there is no direct means for rack cleaning. Breaking the siphon and allowing reverse flow to clear the racks is a method sometimes used to cope with trash problems.

Penstock Design

The siphon penstocks were governed by the same basic considerations as for design of a conventional pressurized penstock system. Factors which are somewhat unique to siphon penstocks are the negative pressure at the siphon crown, the possibility of ice load on the penstock at the water line, and penstock uplift which occurs if air is trapped in the siphon crown by rising headwater level.

Some siphon penstocks were designed for one atmosphere of negative pressure. Safety factors against buckling at the various plants range from about 1.5 to 7. At Schaads Reservoir, a relief valve has been provided to ensure the negative pressure does not exceed 10 ft in the event that the reservoir is drawn down.

Penstock Material

Most penstocks are of welded steel construction, and many are fabricated with structural grade (ASTM A36) steel. Coal tar epoxy has been commonly used as a protective coating. Other materials which were used include prestressed concrete cylinder pipe and steel-lined reinforced concrete pipe with gasketed bell and spigot-type joints. The 1.4 ft penstock for Tierckenkill Falls is constructed of high density polyethelene pipe with fusion joints.

Penstock Support

Penstock support considerations are the same as for conventional penstock designs. Structural steel columns or saddles are common where the penstock is supported from a concrete dam. Where construction was done without an upstream cofferdam, special support was sometimes required upstream of the siphon crown. For a short section of penstock upstream of the siphon crown, the penstock is usually cantilevered from the top of the dam (Figure 4). On earthfill dams, gravel bedding and/or tremie concrete placed underwater has been used for penstock support.

Freeze Protection

In areas that experience cold temperatures, freeze protection is a consideration. The vacuum system is usually protected by a heated enclosure; critical piping and valves in an outside environment are heat traced. The flow of water prevents significant ice buildup in the penstock. When the unit is not operating, methods used to prevent penstock freezing include: breaking the siphon and draining the penstock; providing a small bypass line to continue water flow through the penstock; depressing the water level within the penstock with compressed air and allowing warm air to bubble out the intake; and inserting a bubbler probe in the dewatered penstock to prevent freezing at the water surface inside the penstock.

SIPHON PENSTOCK CONSTRUCTION METHODS

The construction methods for installation of a siphon penstock are similar to those used for a conventional penstock arrangement. Major items are shop fabricated into components whose size is usually dictated by shipping and access. Components may be site fabricated into large assemblies prior to installation.

Where project construction is accomplished without an upstream cofferdam, underwater construction is sometimes required, and unusual approaches may be necessary. Combination cofferdam/forms have been used to pour concrete caps at or slightly below water level to support the penstock. Barges and divers were employed for handling and installing large penstock sections upstream of the siphon crown. At some projects, tremie concrete supports were poured underwater for trashrack structures. Dredging was required to prepare the upstream slope of earthfill dams for penstock support.

OPERATION

As mentioned previously, there are two basic categories of siphon penstock operation:

- Plants which have positive shutoff at the turbine(s) and therefore do not require siphon priming for each startup or the siphon to be broken each time the unit is shut down. For these plants, the siphon priming operation is infrequent and usually initiated manually, separate from unit startup.

- Plants which have no shutoff device and require siphon priming for each unit start and breaking of the siphon on each shutdown. At these plants, the siphon priming is initiated automatically as part of the unit start sequence. Water starts flowing through the turbine as soon as the upstream water level rises to above the invert of the siphon crown.

Both concepts have been found to work very well.

SIPHON PENSTOCK PROBLEMS

The siphon penstock installations reviewed have operated quite satisfactorily. There have been no reported problems with the generating units which could be attributed to the siphon concept.

A common difficulty with some siphon designs was the tendency of the vacuum system to "overshoot" during siphon priming, causing water to be drawn into the vacuum system and vacuum pumps. Methods used to alleviate the problem include: providing a high siphon control column at the crown of the siphon; lowering level switches which control the vacuum system to below the top of the penstock (and allowing the water flow to remove the remaining air); designing the vacuum system to allow water to enter a drainable vacuum tank; providing a water separator; and providing a float-operated priming valve at the siphon crown to isolate the vacuum system.

Other problems which have been reported include:

- Insufficient vacuum breaker line size to break the siphon under flowing water conditions;

- Vortices caused by excessive trash buildup where there is is no provision for easy rack cleaning; and

- Freezing of the vacuum breaker valve.

CONCLUSIONS

Siphon penstocks are a proven concept and are particularly well suited for small hydroelectric installations at existing dams. The successful application of siphons at Traicao indicates that the concept may also be used for plants with relatively large flow capacities. A review of several installations has shown that siphon designs can operate effectively and efficiently with few operational problems.

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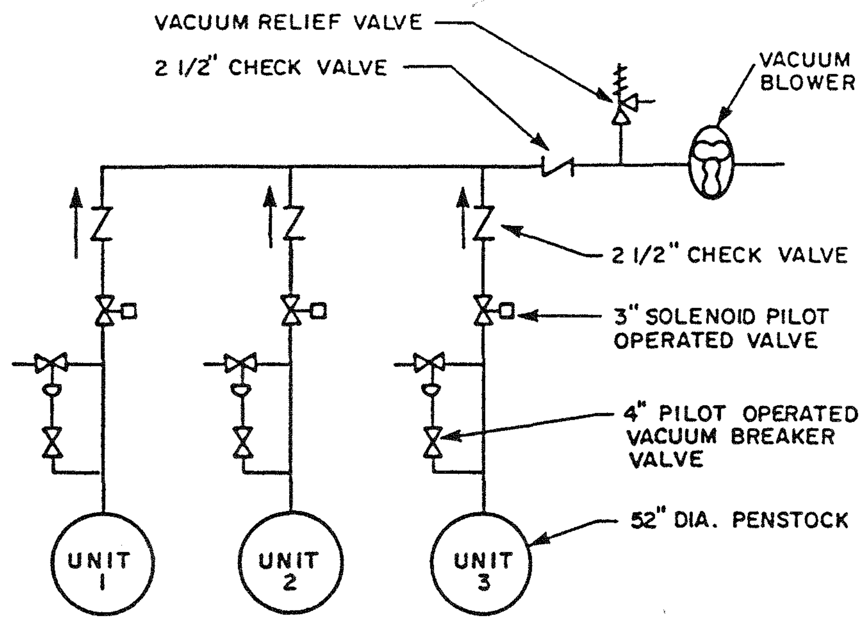
TABLE 1
PROJECT DATA SUMMARY

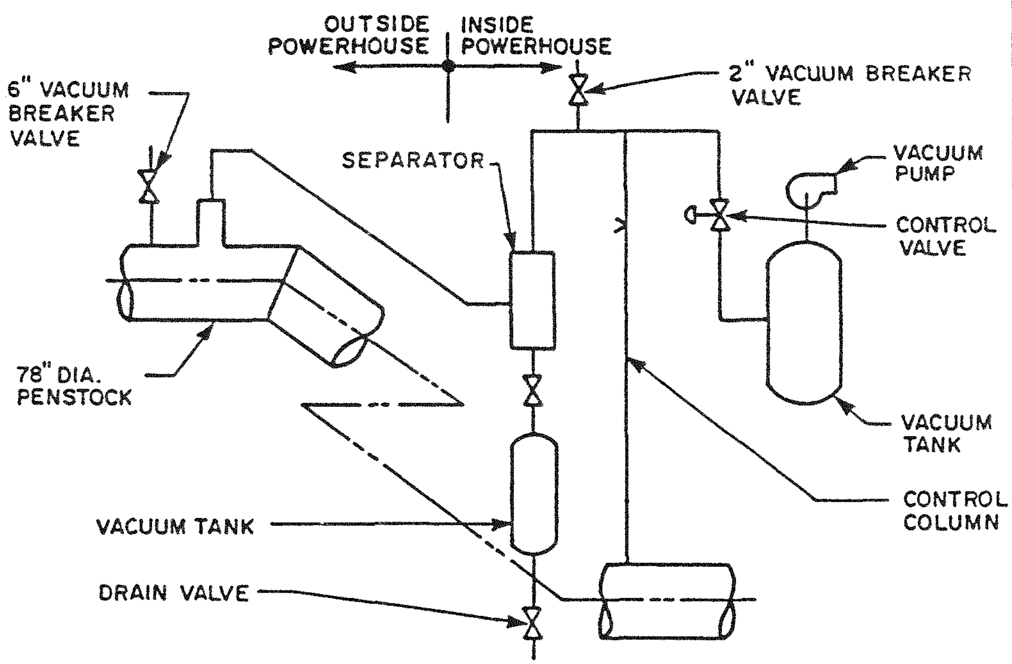
Project	Plant Capacity (kW)	Head (ft)	Plant Flow (cfs)	Number of Units	SIPHON PENSTOCKS No.	Diameter (ft)	Length Overall (ft)	Length Intake to Siphon Crown (ft)	Maximum Siphon Lift (ft)(2)	Intake Configuration(3)
Columbia Mills	417	17.2	334	1	1	9.8 x 13.8(1)	83.1	23.8	12.3	V
Jim Falls	500	30.4	240	1	1	6.5	89	27	8.5	V
Lac Courte Oreilles	3,450	30.0	1500	3	2	9.0	261	121	25.5	H
Ontelaunee	530	35.0	210	1	1	6.0	130	45	8.1	I
Pine Grove Dam	478	39.0	175	1	1	6.0	1390	149	22.0	V
Pocono Lake	285	24.0	180	3	1	5.0	73	17	5.3	I
Schaads Reservoir	240	97.0	42	3	1	2.5	717	71	10.0	I
Second Broad River	288	21.0	246	3	3	4.3	44.5	14.5	9.4	I
Superior Dam	570	14.0	567	1	1	8.0	150	56	13.0	H
Tierckenkill Falls	70	100.0	11.9	2	1	1.4	532	12	3.8	H
Traicao	8,570	21.3	8333	4	4	12.4 x 33.4(1)	107	63.5	19.9	H

(1) Rectangular
(2) Maximum siphon lift equals distance from minimum headwater level to top of siphon crown
(3) V = vertical; I = inclined; H = horizontal.



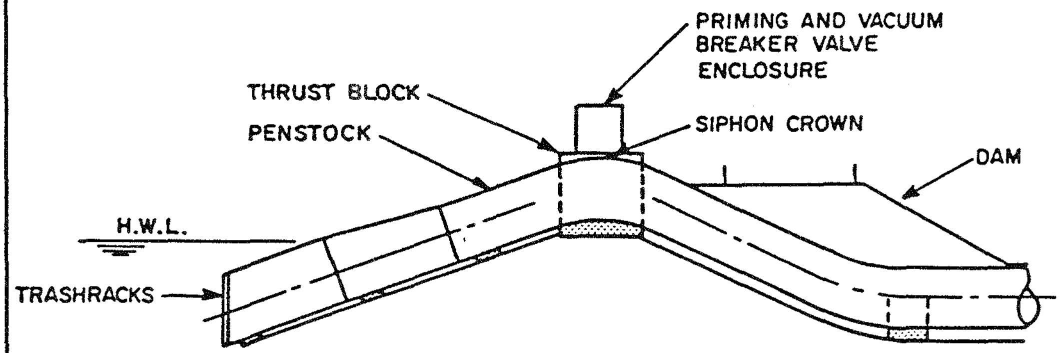
VACUUM SYSTEM - SECOND BROAD RIVER HYDROELECTRIC PROJECT

FIGURE 1



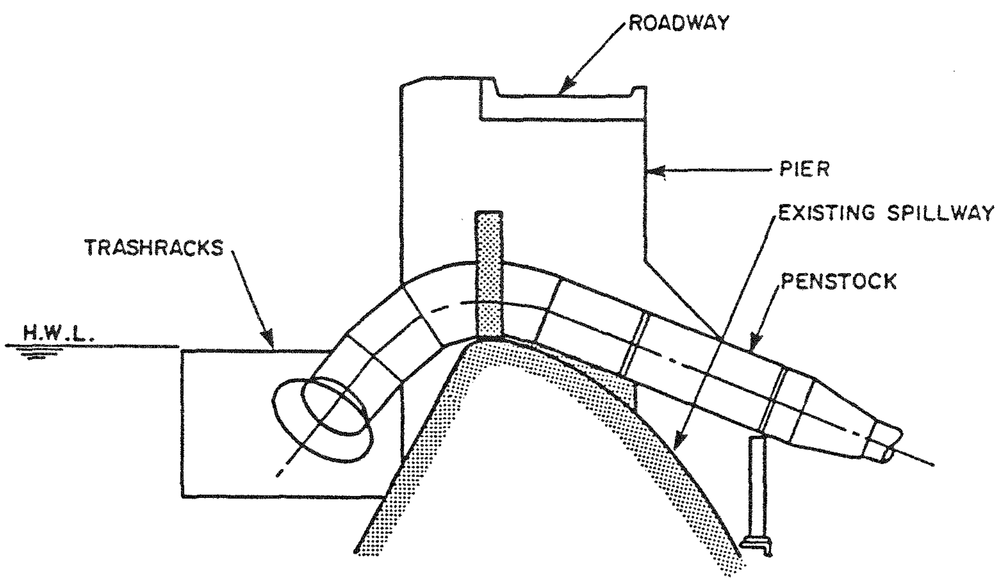
VACUUM SYSTEM - JIM FALLS MINIMUM FLOW UNIT HYDRO DEVELOPMENT

FIGURE 2



HORIZONTAL INTAKE-SUPERIOR DAM PROJECT

FIGURE 3



INCLINED/VERTICAL INTAKE- POCONO LAKE PROJECT

FIGURE 4