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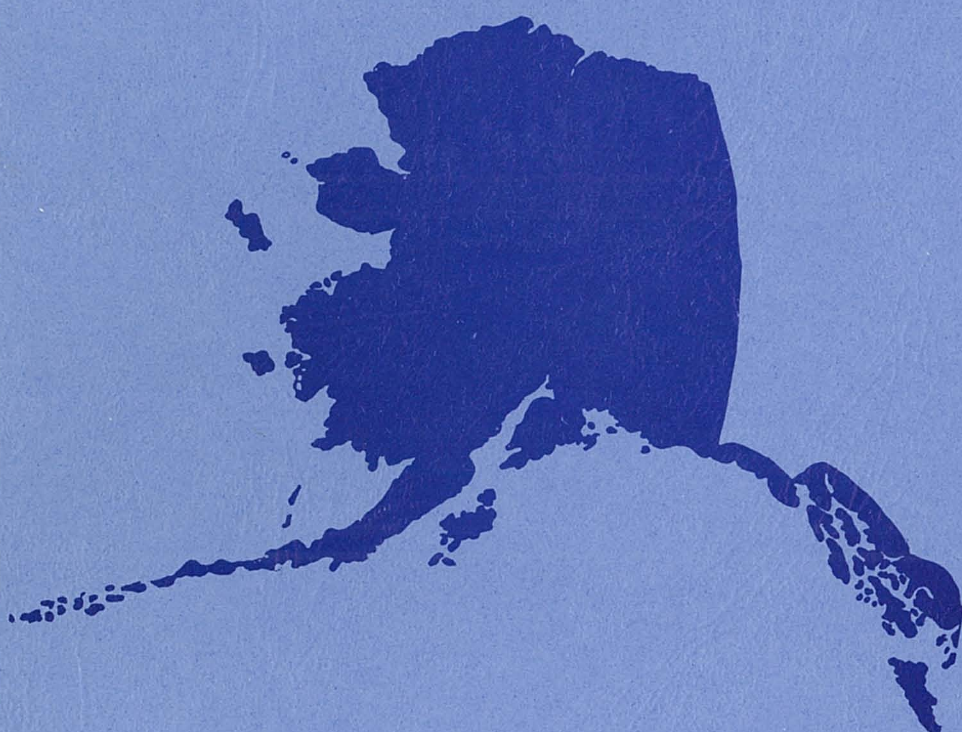

Analysis of Salmon Capabilities in
Steep Fish Ladders

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ANALYSIS OF SALMON CAPABILITIES IN STEEP FISH LADDERS*

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Abstract

Short, steep fish ladders of the continuous type, such as the Alaska Steeppass or the Oregon pipe fish ladders, are very high energy dissipation hydraulic devices which can be constructed for a fraction of the cost of the more conventional pool-type ladders.

Fish in continuous, steep ladders encounter significant additional drag forces which are not present in the conventional pool-type ladders. These additional drag forces are of the pressure gradient type in enclosed steep ladders and of the body-forced type in open channel ladders. These forces may be as much as an order of magnitude greater than the normal fluid-dynamic drag forces.

This paper presents the basic mechanics of fish passage in steep, continuous ladders and points out that the total drag force, power, and total energy requirements of the fish in passing through such ladders are each important and interrelated. The apparent limits of the continuous type of ladder are presented.

Sketches of both the Alaska Steeppass Ladder and the Oregon pipe ladders are presented in the paper together with figures on those prototype ladders which have thus far proved to be successful passage devices.

Introduction

The development of rivers for productive purposes often result in increments of project costs which have no associated benefits. The costs of fish ladders as passage devices for migratory fish, through man-made structures, is an excellent example of such costs without benefits. In most cases, fish are able to move freely in the river prior to the construction of the structure. Fish ladders have been a necessary adjunct to river control projects to maintain, at least partially, the freedom of fish to move in the river. The relative costs of fish ladders associated with power projects in the western United States, have been enormous. As an

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example, the cost of the Pelton Dam and Powerhouse on the Deschutes River in Oregon was approximately $20 million while the price of the fish ladder associated with this project was approximately $5 million. The fish run which this ladder maintains is of almost infinitesimal proportions. The cost without benefits aspect of fish ladders is not limited to Western power projects. The East is also feeling the fish ladder fiscal problem.

Many streams which have not been developed for other purposes appear to have developmental possibilities for migratory fish runs if relatively low-level waterfalls could be traversed by upstream migrating fish. Such streams are frequently small and have a limited, though quite valuable, fish producing capacity.

The desire by engineers to reduce nonbenefit-associated costs in various water projects, and the desire of biologists to develop fish runs on streams which present natural barriers to fish, has led to various studies directed toward the development of relatively cheap fish ladders. The developments of the Alaska Steeppass Ladders, which are essentially baffled, continuous open channels having rather small cross-sectional areas, and the Oregon Ladder which is essentially a baffled 36-inch pipe, have resulted from one or the other of these two needs.

It is not the purpose of this paper to discuss the geometry of the Alaska Steeppass Ladder or the Oregon Ladder; these two ladders are indicated in Figures 1 and 2 for those who are interested in their designs. However, it is rather the purpose of this paper to bring to the attention of fisheries biologists and hydraulic engineers, the basic mechanics of steep, relatively short fish ladders, as well as some of the approximate limitations of these ladders though such limitations are not, at this time, well defined. To accomplish this purpose a comparison will be made of short, steep fish ladders with the conventional pool-type of ladder.

Review of Pool-Type Fish Ladders

The Pool-Type Ladder usually consists of a large number of pools arranged as stairs from the headwater to the tailwater of an obstruction. Adjacent pools usually have water levels differing by one-foot increments and are connected by orifices or by overflow weirs which allow a water passage from the upper pool to the lower one and allow a passage space for fish moving either upstream or downstream. Most ladders have combinations of orifices and weirs. A fish entering such a ladder must exert discrete spurts of energy as he passes from pool to pool. However, he is free to remain in an individual pool for as long a time period as he desires. This type of ladder allows a fish to make a very slow passage from the tailwater to the headwater of the dam. If the fish run is small, the individual pools need not be very large, but if the fish run is large, the pools have considerable numbers of fish stored in them at any instant during the run and must, therefore, be relatively large. Capabilities of fish to travel through such ladders appear to be quite considerable. Experimental results obtained by the U.S. Fish and Wildlife's Bureau of Commercial Fisheries, Bonneville Fish Laboratory (1) show that at least one Sockeye Salmon was able to climb through an elevation distance of 6,648 feet in a five-day period using this type of ladder. It is not known what the salmon's ultimate climbing capability might have been since the laboratory personnel gave up before the fish did. However, it is quite apparent from the above

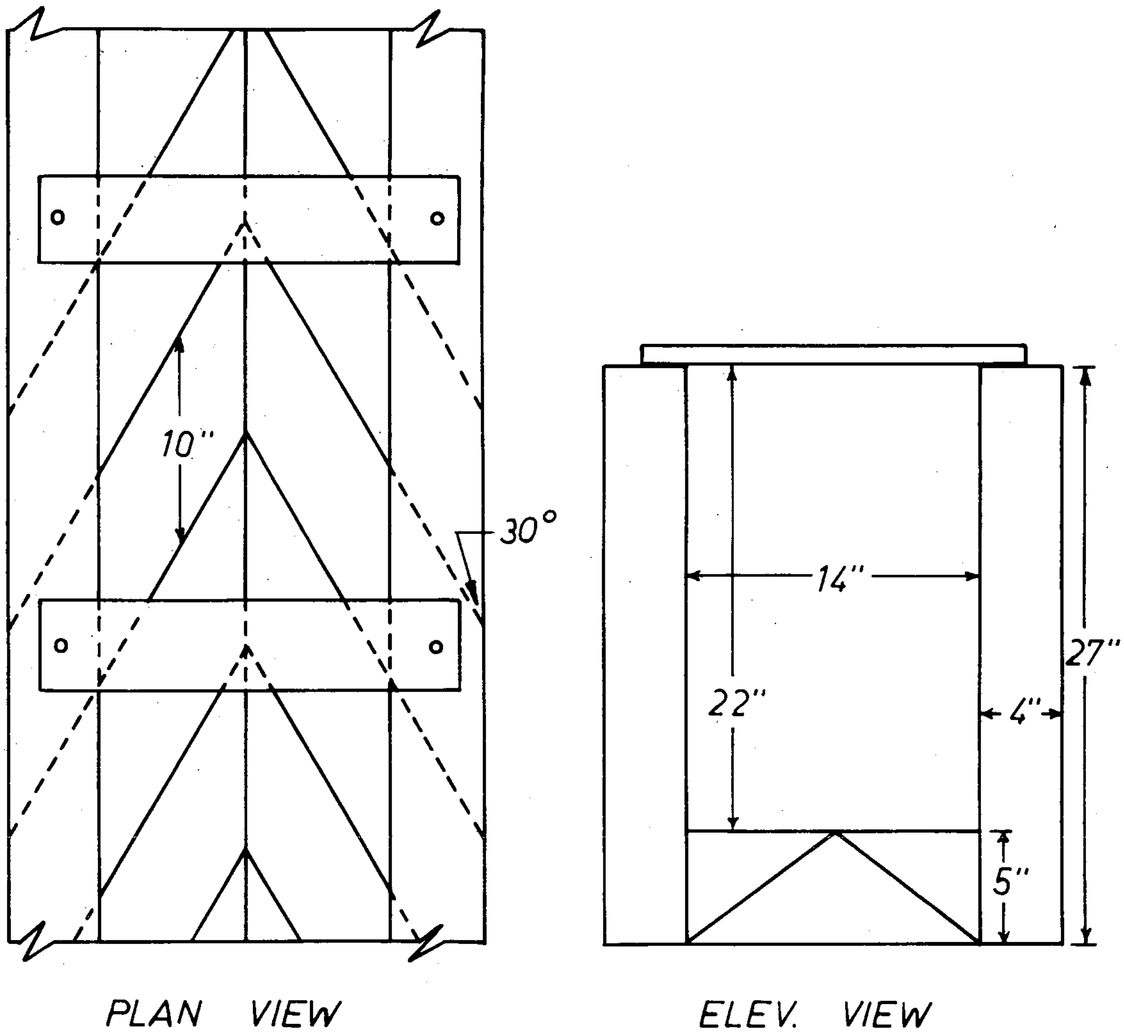

Figure 1. Typical section of the Alaska Steeppass fish ladder

experiment and several others carried on by the same laboratory, that salmon are probably not severely over-taxed in passing through a normal ladder of this type.

The energy requirements for a fish to travel through a pool-type ladder can be approximately computed. If it is assumed that the hydrodynamic coefficient of drag of a live fish is quite small, then the net energy expended by the fish in traveling from one pool to another is essentially that of lifting his weight from the lower pool level to the upper pool level. This expenditure then approximately equals the weight of the fish multiplied by the difference in elevation between the two pools. The total energy expenditure of the fish in traveling completely through this type of a ladder would exceed by a small percentage the product of the fish's weight and the difference in elevations of the tailwater and headwater of the dam or other barrier. Though buffeting forces and other unknown, but

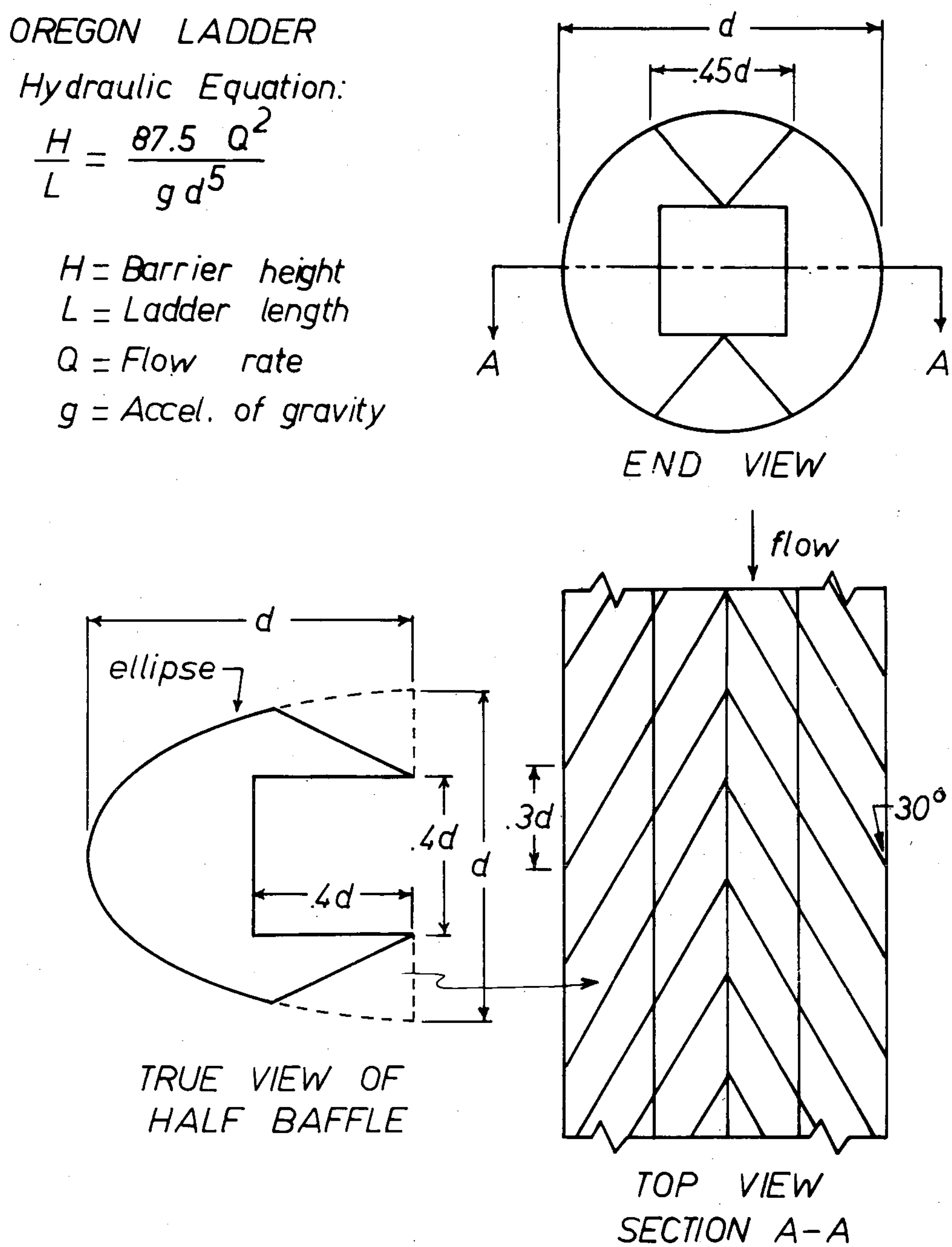

Figure 2. Typical section of the Oregon Pipe-Type fish ladder

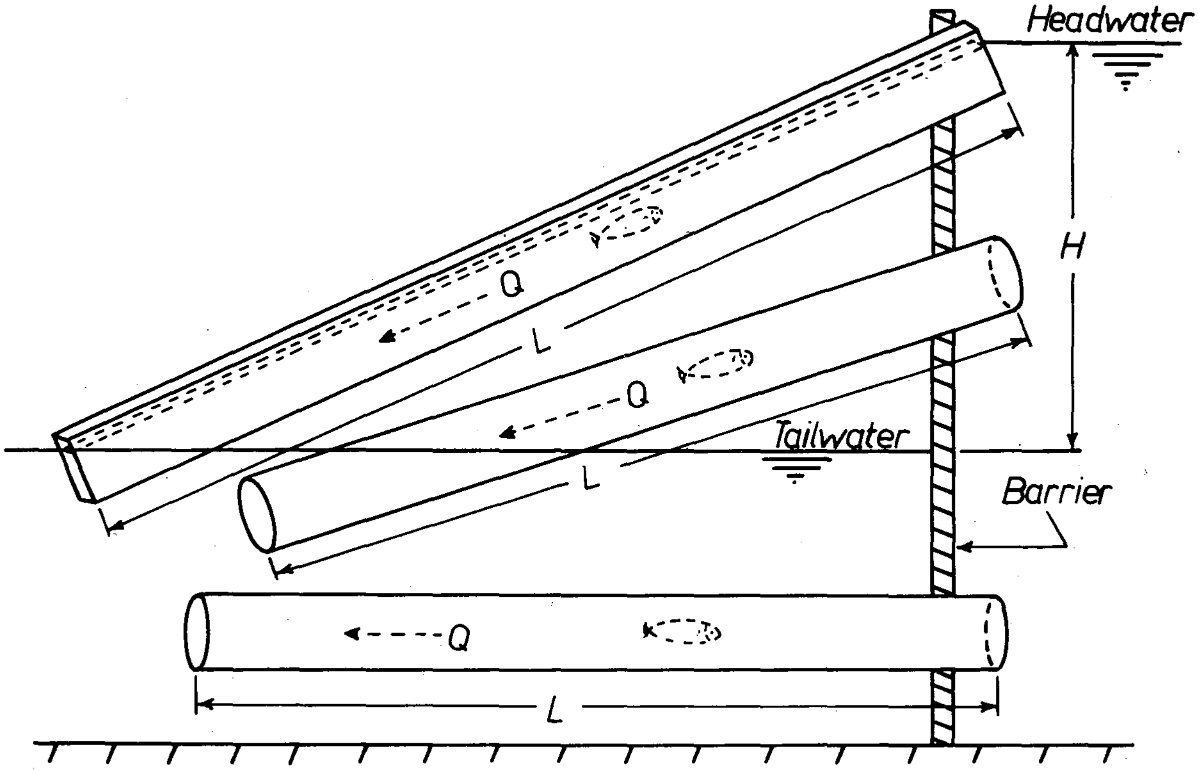

Figure 3. Installation possibilities for open and enclosed, steep fish ladders

certainly existent, taxes of the fish's energy have been neglected, it is felt, by the writers, that such forces will be approximately the same in the two types of ladders to be compared. Accordingly these forces are neglected as it is assumed, though perhaps with some error, that they cancel out of the comparison.

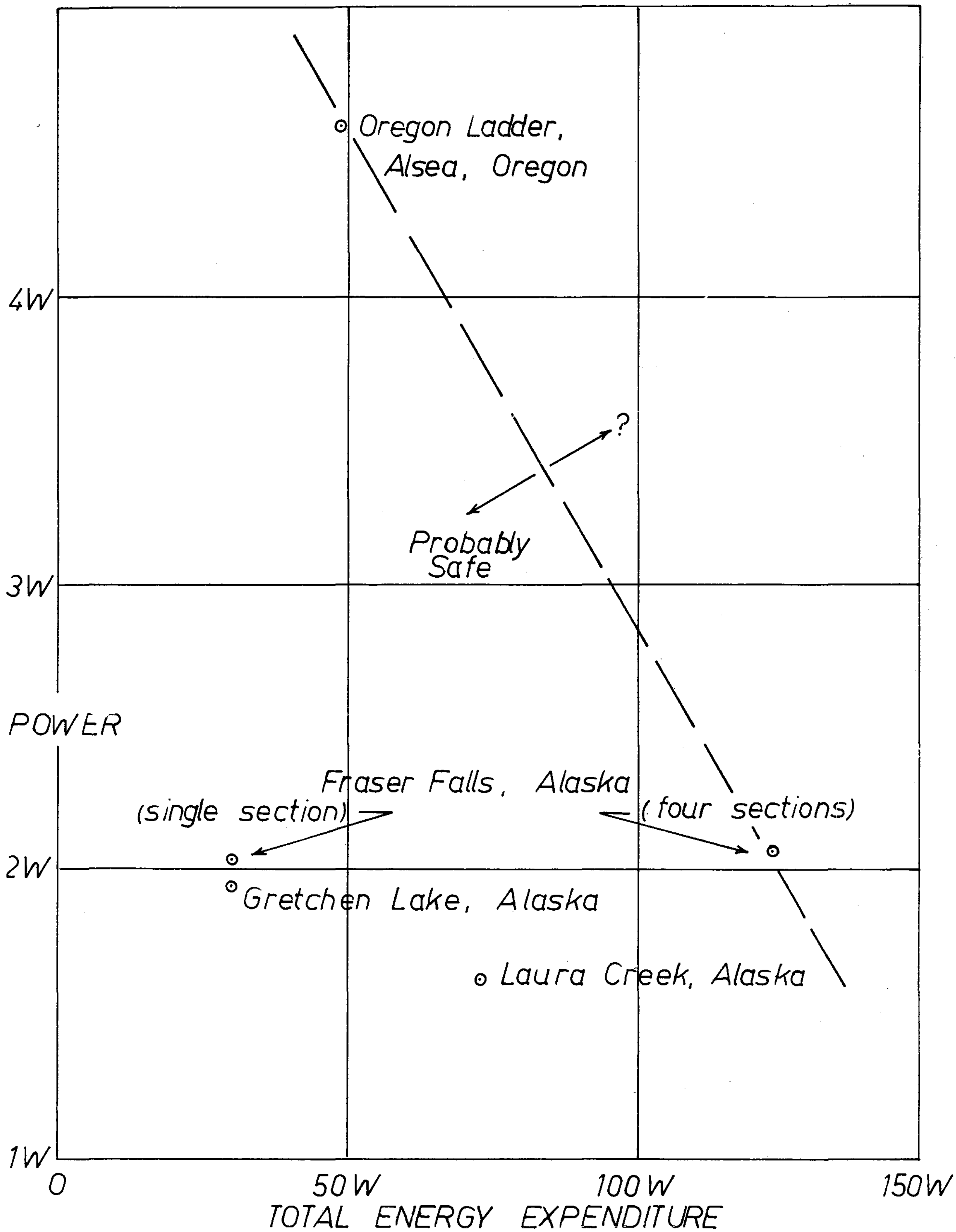

Figure 4. Approximate, and quite incomplete, power and total energy expenditure capabilities of salmon in steep ladders

If pool ladders are to be compared with steeper types of ladders, power requirements, i.e., energy expenditure rates, also must be considered. As the fish travels through the pool-type ladder, it generates a considerable degree of power for very short, discrete periods of time while traveling from one pool to another. However, the Sockeye Salmon which traveled for 6,648 feet upward in five days at the Bonneville U.S. Fish and Wildlife Laboratory, exerted an average power rate of only .0154W foot-pounds/second, where W is the weight of the fish--3 pounds 4 ounces in the Bonneville experiment.

Analysis of Pipe-Type Ladder

For the purposes of this discussion, it will be assumed that the pipe-type of ladder will be oriented in a horizontal direction. The pressure drop through this type of ladder will be considered to be Δp pounds per square foot. The length of the ladder will be L, so the rate of pressure drop through the ladder will be $\Delta p/L$. The pressure drop through the ladder is related to the difference between the elevation of the water surface at the upstream and downstream ends of the ladder by the equation

$$\Delta p = \gamma H, \qquad (1)$$

where γ is the specific weight of water (62.4 pounds per cubic foot) and H is the drop in elevation experienced by the water in moving through the ladder (the gain in elevation of the fish in moving up through the ladder).

The force in the direction of flow on a unit volume of water (1 ft^3), passing through the ladder is $\Delta p/L$, which is from Eq. 1, also $\gamma H/L$. If it is assumed that the fish has the same weight as a similar volume of water, the force on the fish produced by the pressure gradient is equal to the force per unit volume multiplied by the volume of the fish. That is,

$$F = \frac{\gamma H}{L} \times (\text{Vol. of fish}) = \frac{\gamma H}{L}\frac{W}{\gamma} \cdot$$
$$= \frac{HW}{L} \qquad (2)$$

The fish experiences the force of Eq. 2 if he moves through the ladder in either direction or if he simply maintains his position in the ladder. This force has nothing to do with the relative velocity of the fish and the surrounding water. In addition to this force the fish also experiences a frictional drag force which is due to the relative motion of the water past the fish's body.

J. R. Brett (2) has performed extremely interesting drag experiments on yearling Sockeye Salmon. The writers' analysis of his results indicate that if the drag equation for a swimming fish in the fluid having a relatively small pressure gradient is written as:

$$D = C_d \frac{\zeta l^2 \, V^2_{fw}}{2} \qquad (3)$$

where

D = the drag force on the fish

C_d = a coefficient of drag

l = the length of the fish

ζ = the mass density of the fluids through which the fish swims

V_{fw} = the velocity of the fish with respect to the surrounding water

then C_d becomes approximately:

$$C_d = \frac{3.3}{N_R^{.417}} \tag{4}$$

Where N_R is the Reynolds Number with, l, the fish's length, being the scale parameter. It should be emphasized here that Eq. 4 represents the coefficient of drag for a yearling Sockeye Salmon. If it is assumed the yearling Sockeye Salmon is geometrically similar to an adult salmon, and if the equation can be extrapolated to a Reynolds Number of less than an order of magnitude higher than that measured by Brett on the yearling salmon, this same equation can be used for the drag coefficient of adult salmon. It should also be noted that any extra drag which is induced by intense turbulence associated with high fluid pressure gradients, or any other energy requirements not present in Brett's simplified experiments, has not been studied in this analysis and would make an excellent area for future work. However, since the authors feel that these extraneous forces are probably relatively small and are certainly unknown, it is a matter of simple expediency to neglect them here.

Combining Eqs. 2, 3 and 4, the total force on the fish at any time during its passage through the ladder is

$$F_T = F + D = \frac{HW}{L} + C_d \frac{\zeta l^2 V^2{}_{fw}}{2} \tag{5}$$

As an example, to indicate the relative magnitudes of the drag and pressure gradient forces a Sockeye Salmon having a weight of 3.25 pounds and length of 20 inches will be assumed to swim through a pipe-type fish ladder at a speed of 1 ft./sec., with respect to the ladder, while the velocity of the water with respect to the ladder will be assumed to be 4.5 ft./sec. It will also be assumed that the pressure gradient in the ladder is such that the hydraulic gradient slopes at 0.55 ft./ft. From Eq. 5 it is found that:

$$F_T = 1.79 \text{ pounds} + .9 \text{ pounds}$$

The first term of this result evolves directly from the considerable slope of the hydraulic gradient. The last term is a function of the velocity of the fish with respect to the water. It is obvious that for the conditions just sited, the major portion of drag on the fish is that due to the pressure gradient in the ladder. The simple fact that the velocity in the ladder has been kept as low as 4.5 ft./sec., certainly does not mean that the fish should have an easy time traveling through the ladder.

A most important aspect of this discussion is the mode in which a fish produces the force required to pass through the ladder. According to the discussion above (see Eq. 5) a force against the fish, parallel to the axis of the ladder, exists whether the fish moves upstream, downstream, or just maintains his position in the ladder. This force must be overcome by means of the fish's swimming through the water which passes around him. To stand still in the ladder he cannot "hold on" to the sides of the ladder. If he maintains his position in the ladder, he must still swim and move with respect to the water passing around his body. So, to simply maintain his position in the ladder he must continuously swim hard enough to exert a force equal to that indicated by Eq. 5. He cannot rest in the ladder without losing his position. This is a contrast to the situation in the pool type of ladder where he may rest in each pool.

The rate at which the fish expends energy is equal to the product of the force given in Eq. 5 and the velocity of the fish with respect to the moving water, V_{fw}. This can be replaced by the sum of the water velocity down the ladder, V_w, and the velocity of the fish up the ladder, V_f. So, $V_{fw} = V_f + V_w$. The rate at which the fish expends energy is then,

$$P = F_T\ (V_{fw}) = F_T\ (V_f + V_w) \qquad (6)$$

where P is the power expenditure of the fish in foot-pounds per second (or other dimensionally correct terms).

It is readily seen in Eq. 6 that only if the fish moves downstream with the same velocity as that of the water is his power expenditure zero.

The power expenditure in itself does not mean a great deal so long as certain rather wide limits are not exceeded. Such limits would probably not be reached in a pipe-type ladder.

As the fish begins his passage through the ladder, he has probably no knowledge of how far he must travel to get through the ladder. He must make a choice among the alternatives of a particular sustained force, F_T, a sustained power expenditure rate, P, or a particular value of V_f or V_{fw}. Which of these the fish chooses and whether or not the same choice would be made under different circumstances of ladders is completely unknown to the writers.

After the fish has made its choice of force, power, or velocity, it must either continue on through the ladder or give up and fall back out of the ladder. If the ladder is long, the fish must continue to expend energy until the ladder has been completely negotiated if it is to be successful in its passage. So, not only is the fish's ability to produce a certain force and a certain power necessary for passage through the ladder, but it is also necessary that the fish be capable of creating a sustained force and power for a sufficiently long time period, thus giving rise to a total energy expenditure, which will be designated T.E.

The total energy expenditure is the product of the power, or energy expenditure rate, P, and the time period required for the fish to pass through the ladder. This time period is the length of the ladder divided by the fish's velocity with respect to the ladder, that is time, $t = L/V_f$. Thus, the equation for total energy expenditure becomes,

$$T.E. = Pt = \frac{P\ L}{V_f} \tag{7}$$

Substituting the value for power from Eq. 6, using F_T and Eq. 5 and simplifying somewhat, Eq. 7 becomes,

$$T.E. = \frac{L}{V_f}\left(\frac{HW}{L} + C_d \frac{\zeta 1^2\ (V_f + V_w)^2}{2}\right)(V_f + V_w) \tag{8}$$

From standard hydraulic relationships the velocity of the water in the ladder, V_w, is inversely proportional to the square root of the length of the ladder for a given barrier height, H, as follows:

$$V_w^{\ 2} = \frac{K}{L} \tag{9}$$

where K is a function of pipe geometry, Eq. 8 can be expressed as follows:

$$T.E. = \left(HW + C_d \frac{\zeta 1^2\ K^2}{2}\left(\frac{V_f}{V_w} + 1\right)^2\right)\left(1 + \frac{V_w}{V_f}\right) \tag{10}$$

It can be seen from Eq. 10 that the sum of the two terms in the final set of brackets is always reduced with a decrease in water velocity for a given fish velocity. The first term of the equation remains constant for a given H and W and the second term, which is the contribution of form drag due to the viscous effects of the fish's body, increases as the ratio $\frac{V_f}{V_w}$ increases. Fish ladders could, indeed, be made so long that this second term in Eq. 10 could become exceedingly large. Partial derivitives of F_T and P with respect to L indicate that these parameters are always reduced by increasing L. However, the partial derivitive of T.E. with respect to L indicates beyond a certain point, T.E. increases with L. Inspection of Eq. 10 indicates that if the second term of the equation is small as compared to the first, the value of T.E. is strongly effected by $\frac{V_w}{V_f}$. A strong fish may be able to swim faster than a weaker one. If the strong fish chooses to make use of his faster swimming capabilities, he would pass through the ladder with a smaller T.E. than that of a weaker fish of the same weight. Thus, this type of ladder can become an elimination process with the weaker fish losing strength much more rapidly than the stronger fish. Indeed, such a process could have something to do with the development of a stronger run of fish, but that is a biological matter which the writers only note but do not attempt to evaluate here.

It is apparent that there are two problems which face the user of pipe-type of ladder or the Denil type of ladder (the analysis of either the Denil type of ladder or the sloping, pipe-type ladder results in equations exactly the same as Eq. 6, 7 and 8), namely the simultaneous coupling of the rate of energy expenditure, P, and the total energy, T.E., which a fish is capable of expending. As far as the fish is concerned, these expenditures are certainly not independent.

The writers do not know of studies on adult fish conducted specifically to determine the relationship between P and T.E. This appears to be the next area into which research should be conducted if the limits of the Alaska Steeppass ladder and the Oregon ladder are to be determined.

Of the pool type of fish ladder studies which have come to the attention of the writers, none have resulted in high average values of power expenditure, P, although some have indicated very great values of total energy expenditure, T.E. The Sockeye Salmon, which ascended 6,648 feet (1) in 7,947 minutes, expended effective energy at the very small rate of only .0154W foot-pounds per second. Since the initial weight of the fish was 3 1/4 pounds, the average effective power produced by the fish was 0.044 ft.-pounds/sec. The total effective energy expenditure for this Sockeye was 21,160 foot-pounds. This is equivalent to raising a 200 pound man 106 feet vertically upward.

The obvious conclusion to be drawn from the above figures is that salmon probably would experience little difficulty in any fishway if the power, P, can be kept small.

T.E., P, and F_T of Alaska Steeppass and Oregon Prototypes

Some indication of the possibilities of the pipe type ladder can be obtained from the results obtained by the Alaska Department of Fish and Game in its Steeppass ladders and from the Alsea, Oregon pipe-type prototype which was briefly though quite inconclusively, tested in the fall of 1964.

Using the equations which have been developed for F_T, P, and T.E., the following values of these parameters have been computed. The Alaska Steeppass at Gretchen Lake, Alaska, has a rise, H, of 7.8' and has a slope of 26.2%. The writers have estimated a V_w of 3.0'/sec. and a V_f of 2.0'/sec. These numbers for a Sockeye Salmon of the length of that used for the 6,648 foot rise at Bonneville, result in F_T = 0.39W, P = 1.95W, and T.E. = 29.9W. (All foot-pound-second units.) This structure appears to be passing Sockeyes without difficulty.

The Laura Creek, Alaska, steeppass which is 90' long and rises 17.35' at a 19.7% slope worked successfully during the summer of 1964. This ladder passed Sockeye and Silver Salmon without difficulty. The fish appeared to behave the same at exit from the 90' continuous ladder as at entrance.

The writers again estimate V_w of 3.0'/sec. and V_f of 2.0'/sec. These numbers result in F_T = .324W, P = 1.62W, T.E. = 73W.

At the Alsea, Oregon Hatchery, small Jack Salmon passed successfully through the experimental pipe-type ladder. The mean velocity was 4.5'/sec., the head, H, was 6' and the effective length of the ladder was 10.8'. If V_f is assumed to be 1'/sec., then F_T = .83W, P = 4.6W, T.E. = 49.5W. Since larger fish are usually stronger than smaller fish, the writer concludes that the larger fish could have negotiated the ladder but chose not to enter it because of entrance conditions.

In the Fraser Falls, Alaska, fishway, Silvers, Sockeye, and Pink Salmon all were able to pass the 33 foot rise. This steeppass has three resting pools. However, many Pinks appeared in 1964 to pass through without resting. If this ladder, which has a total length of 120' and rises 33 feet at a 22.4% slope, is considered for some fish to be continuous it can be considered with the three ladders already discussed. If V_w = 3.0', V_f = 2.0'/sec., the F_T = .41W, P = 2.05W, T.E. = 123W. For a single section of steeppass, F_T and P remain the same, but T.E. = 123W/4.

Conclusions

It can be concluded that the slope of pool type ladders, which is the vertical rise per pool divided by the pool length, means little in the evaluation of a fish's climbing capabilities. Large pools are required for storage of fish as they rest between jumps, but the length of the pool has almost nothing to do with the energy expended by the fish or the power expenditure of the fish in its passing through the ladder.

Pipe-type fish ladders and Denil type ladders can be designed to pass fish adequately provided the power requirements and total energy expenditures of the fish are kept in mind. Some idea of the possibilities for P and T.E. of salmon have been given, but more information is required before accurate estimates can be made.

The limited information which the writers have available are shown in Figure 4 to give some (admittedly quite rough) indication of fish capabilities. This plot cannot be used for design purposes in "close" situations since the curve is only a guess based on little information. However, it can probably be used to indicate gross errors in design as well as to indicate situations which are quite safe.

Eqs. 2, 6 and 7 should be carefully kept in mind in any design of a continuous fish ladder. A careful study of these equations can lead to better design and should alleviate errors in thought which have been prevalent in the analysis of fish climbing capabilities.

It should be understood that this report deals with fish capabilities only. Whether the fish accepts a particular fishway is quite another topic. The theory reported here attempts to answer the question of whether or not it is physically possible for the fish to ascend the fishway.

If it is found that the fish are disposed to use the Oregon ladder, it may have advantages over the Alaska Steeppass ladders. Fish cannot jump out of this ladder. The Oregon ladder can operate under fluctuating headwater and tailwater elevations without appreciably effecting flow through the ladder. However, the writers do not think that the Oregon ladder will prove as successful in passing trash as the Alaska ladders.

The economics of small, relatively simple fish ladders are quite obvious. The number of parallel ladders can be made to correspond with an increase or decrease in the magnitude of the fish run. Temporary ladders can even be rushed to streams which experience an abnormally large run. Steep ladders can be installed quite inexpensively to move fish past existing dams or natural barriers. This type of ladder can be used with great economic success where fish move only in small numbers. New fish producing locations can also be tried with little capital outlay.

Since the steep ladders use only a few cubic feet per second of water, they become economic competitors of more conventional fish ladders simply on the basis of water saved while accomplishing their primary purpose.

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