THE LOW-TEMPERATURE THRESHOLD FOR PINK SALMON EGGS IN RELATION TO A PROPOSED HYDROELECTRIC INSTALLATION

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ABSTRACT

A proposed hydroelectric installation in southeastern Alaska would alter the seasonal pattern of stream temperatures and pose a threat to the natural production of pink salmon, *Oncorhynchus gorbuscha*. Analysis of experiments reported in the literature indicated that such an installation might lower stream temperatures below the threshold normal for the embryonic development of pink salmon. Our experiments with pink salmon eggs incubated in refrigerated water showed that the eggs required initial temperatures above 4.5° C for normal embryonic development. An increase in mortalities and in alevins with spinal deformities occurred when initial incubation temperatures were 4.5° C and lower; initial incubation at 2° C resulted in complete mortality. The proposed hydroelectric installation could result in temperatures as low as 4.5° C during spawning and initial incubation and could therefore be expected to cause an increase in mortality and the occurrence of deformed alevins. The low temperature would be followed by higher than normal winter incubation temperatures, which would have an unknown effect on the time of emergence of fry. A tunnel intake designed to draw water of a desirable temperature on demand would be required to protect salmon.

In 1964 the Bureau of Reclamation (now the Alaska Power Administration) started feasibility studies on a hydroelectric installation on Lake Grace, 51 km northeast of Ketchikan, Alaska. Grace Creek, the lake's outlet stream, enters the sea 4 km from Lake Grace. An impassable falls 2 km above tide water prevents migrating fish from reaching Lake Grace. Below the falls, the creek provides important spawning, incubation, and rearing areas for salmonids, especially pink salmon, *Oncorhynchus gorbuscha*.

The proposed dam would divert practically all of the water from Grace Creek through a hydroelectric plant and back into Grace Creek about 1.2 km from tide water. Because of the design of the dam and of the water intake, the temperature of the lower 1.2 km of the creek could be changed to lower than normal in summer and fall and higher than normal in winter.

Analysis of the studies by Combs and Burrows (1957) and Combs (1965) on the relation between temperature and the development of salmonid embryos indicated that when the hydroelectric facility is constructed, water temperatures in the principal spawning areas of Grace Creek might be too low for normal embryonic development. We therefore estimated the temperatures likely to occur in Grace Creek. Because these temperatures seemed critically low, we conducted laboratory experiments to determine precisely the low-temperature threshold or minimum temperature for the normal development of embryos of pink salmon, the major species in Grace Creek.

In this report we analyze the effects of the proposed installation on the temperature regime of Lake Grace and Grace Creek and describe the threshold temperatures for development of pink salmon embryos, and then relate the two studies and discuss their implications.

EFFECTS OF PROPOSED INSTALLATION ON TEMPERATURE REGIME OF LAKE GRACE AND GRACE CREEK

To consider the effects of the installation on the temperature regime, we compared the seasonal temperature pattern of Grace Creek under normal conditions with the temperatures likely

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Manuscript accepted February 1971.

to occur when the proposed power plant is in operation.

The daily maximum and minimum temperatures for Grace Creek (U.S. Geological Survey, 1966: 15; 1967: 17; 1968: 16) for the first and second half of each month between April 16, 1965, and March 31, 1967, were averaged to determine the annual temperature pattern under normal conditions (Figure 1). The highest temperature for this period was 17.8° C and the lowest was 0.6° C. Normally, Grace Creek temperatures reach a maximum of about 15° C at the start of the spawning season in mid-August, and decline to 10° C at the end of the spawning season the first week of October. After the spawning season, stream temperatures continue to fall, reaching about 6° C by late November and about 1.5° C in midwinter, when ice cover forms on Lake Grace during most years. The average stream temperature is about 1.5° C from the end of December until the end of March.

If the proposed power development on Lake Grace is completed, it would significantly change the physical dimensions and waterflow of the lake. The dam at the outlet of Lake Grace would raise the lake surface from the present elevation of 131.1 m (mean sea level) to a maximum elevation of 152.4 m and increase its surface area from 668 to 1,046 ha. Water would be diverted through a pressure tunnel and exposed penstock to a powerhouse on Grace Creek, 1.21 km downstream from the dam. The intake elevation of the diversion tunnel would be constant at 125.0 m, but the elevation of the reservoir surface would change from 131.4 to 152.4 m as the active reservoir capacity of 1.84×10^8 m^3 is used. The maximum depth of the natural lake is 129.5 m.

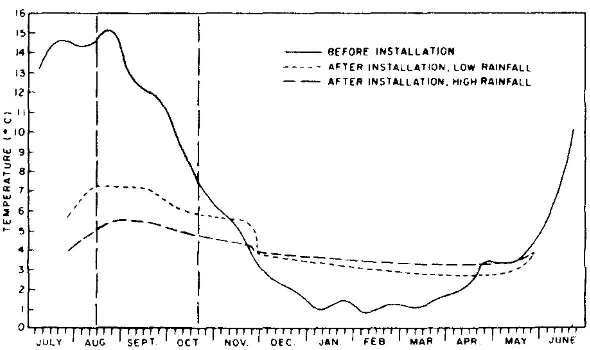

FIGURE 1.—Average annual temperature pattern of Grace Creek, based on temperature records from April 16, 1965, through March 31, 1967, and temperature patterns that might prevail during years of extreme high and low rainfall if water is drawn from a reservoir at the 125.0-m elevation.

Most of the water in the stream below the powerhouse would come through the powerhouse and would therefore be similar in temperature to the water at the tunnel intake level of the lake. To predict the temperature of this water, we obtained temperature-depth profiles from Lake Grace during the freshwater phase of the reproductive cycle of pink salmon. Profiles were taken on July 27, 1961, August 12, 1965, September 16, 1965, October 8, 1965, November 18, 1965, and March 25, 1965 (Figure 2). In addition to the temperature-depth profiles, we obtained thermograph records which indicated surface water temperatures attained 4° C November 28, 1965, and again May 28, 1966. These thermograph records provide our best estimate of the dates of autumn and spring overturn of Lake Grace. Although these data were not all taken during a single reproductive cycle of pink salmon, we feel they are representative. These predicted estimated temperatures of the lake waters that would enter the intake are probably higher than would actually occur because increasing the depth of the lake increases its thermal capacity and results in colder deep water (Hutchinson, 1957). No correction was made for the cooling effect of deeper water.

The actual surface elevation of the reservoir and therefore the depth of the tunnel intake would depend on operational requirements of the power plant and the flow of water into Lake Grace. The fixed tunnel intake at the 125.0-m elevation could be under 6.4 to 27.4 m of water because the proposed active reservoir elevation varies from 131.4 to 152.4 m. We allowed for these fluctuations in using the temperature-depth profiles as an indication of water temperatures at tunnel intake depth.

The project development plan for Lake Grace included a graphic model of simulated reservoir water surface elevations for each month from

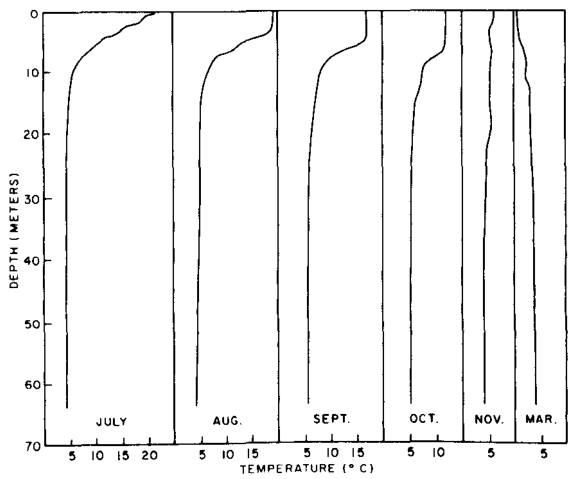

FIGURE 2.—Temperature-depth profiles from Lake Grace during months of the freshwater reproductive cycle of pink salmon.

January 1928 through December 1964.[3] The basis of the model included records of streamflow and climate from Grace Creek and several nearby streams and also a computer study of the monthly operation of the power plant. We have chosen the year of lowest water level (1948) and the year of highest water level (1934) from the surface elevation model to illustrate the range of temperature patterns that might be caused by fluctuating water levels (Figure 1). The simulated water levels and depth of water above the entrance to the intake tunnel at 125.0 m used to predict water temperatures are shown in Table 1.

In Grace Creek, the probable result of the power plant would be lower than normal temperatures during summer and fall when salmon eggs are beginning their development and higher than normal temperatures during the winter when eggs and alevins are completing their development. Temperatures of Grace Creek during the normal spawning season currently range from 15° to 10° C, but under the conditions of power plant operation, temperatures would be from 7° to 5° C. During the first month after spawning, temperatures normally range from 10° to 6° C, but under the altered conditions they may be reduced to only 6° to 4.5° C. The predicted temperatures for the winter incubation period, 3° to 4° C, would be consistently higher than the 1° to 3° C in the unaltered stream.

[3] Alaska Power Administration. 1968. Lake Grace Project, Alaska. On file, Alaska Power Administration, Federal Building, Juneau, Alaska 99801.

LOW-TEMPERATURE THRESHOLD FOR NORMAL DEVELOPMENT OF EMBRYOS

Several workers have studied the low-temperature threshold for normal development of embryos of fishes. In this section we review their findings and describe our laboratory experiments with pink salmon.

EXPERIMENTS BY OTHER WORKERS

An important aspect of the effects of low temperatures is the stage of development at the time the critical temperature is imposed on the embryo. Combs and Burrows (1957) associated high mortalities and gross anomalies in embryos of chinook salmon with low temperatures during the pregastrula stages; they used a significant rise in mortality in defining the low-temperature threshold. Combs (1965), Efimov (1962), and Price (1940) found that salmonid eggs were most sensitive to low temperature in the blastula and early gastrula stages. These authors demonstrated that once gastrulation is well underway, the embryos can tolerate temperatures close to freezing.

TABLE 1.—Estimated water temperatures that would have prevailed at the 125.0-m elevation (mean sea level) of the proposed tunnel intake of Lake Grace if the proposed power plant had been in operation during the year of lowest water level (1948) and the year of highest water level (1934) from 1928 to 1964.

Month	Water surface elevation (m)		Depth of water above tunnel intake (m)		Water temperature at tunnel intake (° C)	
	1948	1934	1948	1934	1948	1934
July	135.6	152.4	10.4	27.4	5.6	3.9
August	134.1	152.4	9.1	27.4	7.2	5.0
September	137.2	150.9	12.2	25.9	7.2	5.6
October	141.7	152.4	16.8	27.4	6.1	5.0
November	143.2	152.4	18.3	27.4	5.6	4.4
March	135.6	149.4	10.7	24.4	2.8	3.3

Adverse effects of low temperatures during certain stages of development were also observed for other fishes. Kinne and Kinne (1962) exposed embryos of the cyprinodont *Cyprinodon macularis* to different temperature-salinity-oxygen combinations and found a period of "low thermal stability," which we presume to mean low resistance, in embryos exposed to critically low temperatures during early development (fertilization to gastrulation). Stockard (1921) conducted a number of experiments with eggs of the cyprinodont *Fundulus heteroclitus* which he placed in a refrigerator at 5°, 7°, and 9° C for various lengths of time and at various stages of development. Development was almost, if not completely, stopped at 5° C and greatly slowed at 9° C. Exposure to 5° C just after gastrulation commenced was not noticeably injurious, but exposure to low temperatures during earlier stages resulted in increased mortalities and gross anomalies among survivors.

Piavis (1961) incubated sea lamprey eggs at various constant temperatures and learned that viable burrowing larvae could be produced at 15.6° C but not at 12.8° C. McCauley (1963) also explored the lethal temperature limits of embryonic sea lamprey. He found that the narrow range of constant temperature, 15.0° to 25.0° C, necessary for successful hatching may be extended to 12.2° to 25.6° C if gastrulation is completed before the eggs encounter temperature extremes.

The work of Tåning (1952) on the effects of temperature on the development of *Salmo trutta trutta* supports Stockard's conclusion that the earlier the stage of development is arrested, the more severe will be the effect.

The lowering of temperatures in Grace Creek by the proposed hydroelectric plant would be greatest just before and during gastrulation of the pink salmon embryos (Figure 1).

EXPERIMENTS IN LABORATORY ON PINK SALMON

We conducted an experiment in the laboratory to determine if pink salmon eggs could survive and develop normally under the projected thermal regime for Grace Creek. The eggs for the study came from two pink salmon collected September 7, 1966, from Grace Creek. The eggs were thoroughly mixed and fertilized by sperm from two males in the field.

Embryonic development had begun before the eggs were placed in the experimental array because the temperature in the transporting container ranged from 7° to 12° C (average, 10.8° C) during the 10-hr trip to the laboratory. According to Soin (1954) the first cleavage division occurs in pink salmon eggs about 7 hr after fertilization at 11° C. Knight (1963) showed that about 2.5 hr elapse between successive cleavage divisions in rainbow trout eggs at 12.2° C. Therefore, we estimate, but did not confirm, that the Grace Creek pink salmon eggs completed two cleavage divisions before they were transferred to the controlled temperatures of the experiment.

The eggs were incubated in 55- and 42.5-mm diameter Buchner funnels with perforated plates. Each of the large funnels was stocked with 120 eggs and each of the small ones with 25 eggs. The water was introduced through the stem of the funnel to produce an upwelling flow through the plates that supported the eggs. The water was not recirculated, and flow rates[4] were set to deliver an apparent velocity of about 200 cm/hr to the eggs. Dissolved oxygen content of the water as it entered the funnels was above 8 ppm at all times.

The experiment involved 16 treatments consisting of four initial incubation temperatures each with four exposure periods. The four temperatures were ambient,[5] 4.5°, 3.0°, and 2.0° C; and the four exposure periods were 15, 27, 37, and 103 days. All of the exposure periods began 10 hr after fertilization on September 7, 1966. When the experimental cold treatment for each lot was completed, the eggs were transferred to ambient temperature to complete their incubation. Temperatures were recorded continuously; the daily means (Figure 3) were usually within ±0.5° C of the planned levels. In-

[4] Apparent velocity was obtained by dividing the rate of flow to the egg container in cubic centimeters per hour by the cross-sectional area of the container in square centimeters.

[5] Ambient temperature is the unmodified temperature of the laboratory water supply. See Figure 3.

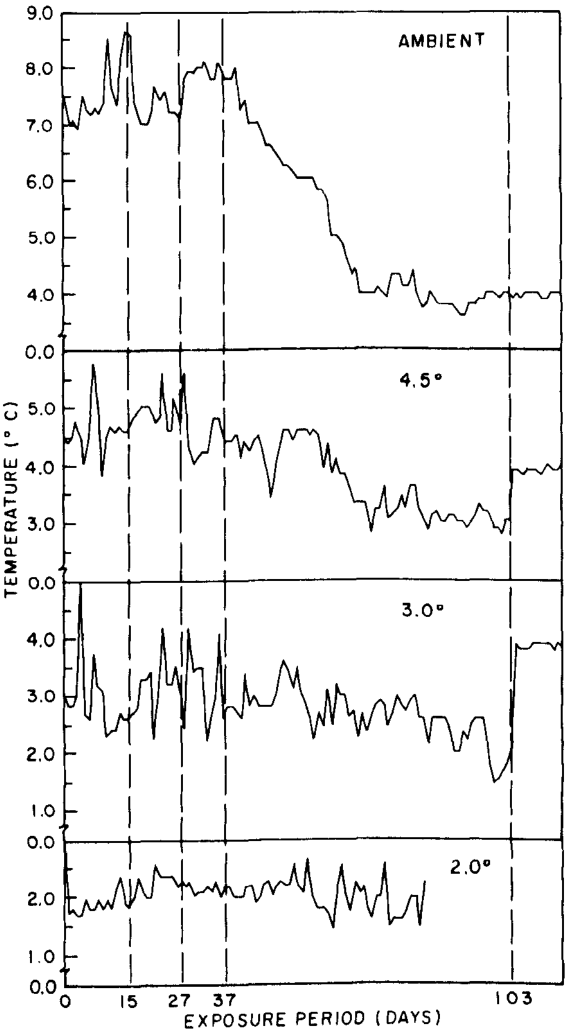

FIGURE 3.—Four initial incubation temperatures to which pink salmon eggs were subjected for four exposure periods in laboratory experiments on effects of low temperature on growth and development. Dashed lines indicate when individual lots were transferred to ambient temperature (see footnote 5).

frequent variations as great as ±2° C for 1 day were observed. Mean temperatures for the 37-day period September 7 through October 14 were within ±0.2° C of the planned levels. Ambient temperature, initially 6.9° to 8.7° C, dropped gradually to the usual winter level of 4.0° C by mid-November.

We made no direct observations of the stages of development of the embryos when they were transferred to ambient temperature (on days 15, 27, 37, and 103), but in a separate experiment we observed development of pink salmon embryos in relation to temperature. At temperatures approximating ambient in the present experiment, the eggs began gastrulation about the 10th day and completed gastrulation about the 26th day. Eggs incubated initially at 4.5° C began gastrulation about the 21st day and completed gastrulation about the 45th day. Eggs incubated initially at 3.0° C began gastrulation about the 34th day and completed gastrulation about the 62d day.

We controlled water temperatures during incubation by mixing chilled and unchilled water in the intake line to each incubation funnel. A continuous flow of fresh water chilled to 1.0° ±0.3° C was obtained by operation of a 1/3-hp refrigeration unit. The cooling coils and agitator propeller were suspended in an insulated 20-gal fiberglass tank. Unchilled or ambient water was introduced through Y fittings to produce the required temperature for experimental lots of eggs.

Eggs incubated entirely at ambient temperature were first to hatch—the midpoint of hatching occurred December 9, 1966, 94 days after fertilization. The last eggs to hatch were from the group that was incubated initially at 3.0° C for 103 days. The survivors of the prolonged cold treatment hatched February 8, 1967, 154 days after fertilization.

Mortalities were inversely related to initial incubation temperatures. None of the eggs incubated at 2.0° C survived (Table 2); at 3.0° C, about 75% died; and at 4.5° C, about 10% died. Average mortality of eggs incubated entirely at ambient temperature was only 3%.

The occurrence of developmental anomalies was also associated with severity of the initial cold treatments. No alevins were produced in the 2° C treatment lots. Mild spinal deformities, various degrees of spinal curvature in the vertical plane, occurred in the 3.0° C and 4.5° C lots. The spinal flexures were not always severe enough to be easily recognized as deformities, but the deformity caused the lengths of alevins in these lots to be less uniform than the lengths of alevins in the ambient temperature lots.

TABLE 2.—Percentage mortality from fertilization to hatching of pink salmon in relation to initial incubation at low temperatures (number of eggs in each lot in parentheses).

Exposure period (*days*)	Percent mortality at temperature treatment[1] Ambient	4.5° C	3.0° C	2.0° C
15	4 (24)	12 (24)	71 (24)	100 (24)
27	0 (25)	12 (25)	77 (22)	100 (25)
37	5 (20)	10 (21)	60 (20)	100 (21)
103	2 (41)	7 (41)	82 (40)	100 (40)

[1] See Figure 3 for temperature regime for each treatment.

Range in lengths among alevins in the ambient temperature lots was 20.9 to 22.9 mm, but range in length in the 3.0° C lots was 15.1 to 22.3 mm (Table 3).

Because of the increased mortality and abnormal embryonic development of Grace Creek pink salmon eggs at temperatures of 4.5° C and lower, we conclude that initial incubation temperature for these eggs should be higher than 4.5° C. This is in agreement with the 4.4° to 5.9° C threshold for normal development of sockeye and chinook salmon eggs found by Combs (1965).

TABLE 3.—Ranges in lengths (millimeters) of alevins from eggs treated at four temperatures (number of alevins measured in parentheses).

Exposure period (*days*)	Ranges in total length (*mm*) at— Ambient temperature	4.5° C	3.0° C	2.0° C
15	21.3-22.6 (10)	20.8-23.2 (10)	18.4-21.9 (7)	--
27	21.1-22.8 (10)	21.0-23.1 (10)	20.5-21.7 (5)	--
37	20.9-22.3 (10)	19.3-22.3 (10)	19.4-22.3 (8)	--
103	21.0-22.9 (10)	20.2-22.4 (10)	15.1-20.3 (7)	--

DISCUSSION

The proposed Grace Creek hydroelectric power plant focuses attention on a fishery problem that may become increasingly important if more hydroelectric plants are to be built on Alaska streams. Where water for power generation is drawn only from the deeper and colder waters of reservoirs, the resulting stream temperatures would be lower than normal during the salmon spawning season and initial incubation period (Figure 1).

At Grace Creek the expected changes in water temperature could affect salmon in several ways. Delay in ripening of gonads of the adults after they enter the streams because of the lowered temperatures (Reingold, 1968) might result in late spawning. The low initial incubation temperatures would further delay development of embryos, but if normal cleavage were not disrupted this delay could be offset by the higher winter temperatures. The net effect on time of emergence and seaward migration of the fry is not known. The predicted initial incubation temperature of 4.5° to 7.2° C (Figure 1) for pink salmon eggs at Grace Creek includes the temperature 4.5° C, at which we detected abnormal development and increased mortality of the embryos. Measures should therefore be adopted to prevent deleterious temperature changes. Provision of an intake designed to draw water of a desirable temperature on demand is suggested as minimum action to protect the salmon.

ACKNOWLEDGMENTS

Theodore R. Merrell, Jr., generously gave of his time and thoughts in discussions of the problem. Charles J. DiCostanzo critically reviewed the manuscript and made suggestions to improve clarity of presentation.

LITERATURE CITED

COMBS, B. D.
1965. Effect of temperature on the development of salmon eggs. Prog. Fish-Cult. 27: 134-137.

COMBS, B. D., AND R. E. BURROWS.
1957. Threshold temperatures for the normal development of chinook salmon eggs. Prog. Fish-Cult. 19: 3-6.

EFIMOV, V. I.
1962. Vyzhivaemost' gorbushi v period embrional'nogo razvitiya. (Survival rate of pink salmon (*Oncorhynchus gorbuscha*) during embryonic de-

velopment.) Polyarn. Nauchn.-issled. Inst. Morsk. Rybn. Khoz. Okeanogr., Nauchn.-Tekh. Byul. 4: 25-26. (Abstr. in Biol. Abstr. 45: 7142, Abstr. No. 89708.)

HUTCHINSON, G. E.
1957. A treatise on limnology. Volume I, Geography, physics, and chemistry. Wiley, New York, 1015 p.

KINNE, O., AND E. M. KINNE.
1962. Rates of development in embryos of a cyprinodont fish exposed to different temperature-salinity-oxygen combinations. Can. J. Zool. 40: 231-253.

KNIGHT, A. E.
1963. The embryonic and larval development of the rainbow trout. Trans. Am. Fish. Soc. 92: 344-355.

MCCAULEY, R. W.
1963. Lethal temperatures of the developmental stages of the sea lamprey, *Petromyzon marinus* L. J. Fish. Res. Board Can. 20: 483-490.

PIAVIS, G. W.
1961. Embryological stages in the sea lamprey and effects of temperature on development. U.S. Fish Wildl. Serv., Fish. Bull. 61: 111-143.

PRICE, J. W.
1940. Time-temperature relations in the incubation of the whitefish, Coregonus clupeaformis (Mitchill). J. Gen. Physiol. 23: 449-468.

REINGOLD, M.
1968. Water temperature affects the ripening of adult fall chinook salmon and steelhead. Prog. Fish-Cult. 30: 41-42.

SOIN, S. G.
1954. Zakonomernosti razvitiya letnei kety, gorbushi i simy. (Pattern of development of summer chum, masu, and pink salmon.) Tr. Soveshch., Ikhtiol. Kom. Akad. Nauk SSSR 4: 144-155.

STOCKARD, C. R.
1921. Developmental rate and structural expression: An experimental study of twins, 'double monsters' and single deformities, and the interaction among embryonic organs during their origin and development. Am. J. Anat. 28: 115-277.

TÅNING, Å. V.
1952. Experimental study of meristic characters in fishes. Biol. Rev. (Cambridge) 27: 169-193.

U.S. GEOLOGICAL SURVEY.
1966. Water resources data for Alaska, 1965. Part 2. Water quality records, 73 p.
1967. Water resources data for Alaska, 1966. Part 2. Water quality records, 81 p.
1968. Water resources data for Alaska, 1967. Part 2. Water quality records, 64 p.