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Thermal Resistance of Adult Coho (*Oncorhynchus kisutch*) and Jack Chinook (*O. tschawytscha*) Salmon, and Adult Steelhead Trout (*Salmo gairdneri*) from the Columbia River

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(2) Ecosystems Department, Pacific Northwest Laboratory, operated by Battelle Memorial Institute for the U. S. Atomic Energy Commission, Richland, Washington.

ABSTRACT

Resistance times to upper lethal temperatures were determined for adult coho (Oncorhynchus kisutch) and "jack" chinook (O. tschawytscha) salmon, and adult steelhead trout from the Columbia River near Richland, Washington. Incipient lethal temperatures for steelhead and chinook appeared to be near 21 to 22 C. Resistance times were longer for chinook than for coho or steelhead. Relative resistances of juvenile and large fish varied with test temperature--juveniles were more resistant at low lethal temperatures up to about 28.5 C and adults were more resistant above that level.

INTRODUCTION

Upper lethal temperatures for juvenile salmonids are documented in several studies. Experiments have been conducted with Pacific salmon, Oncorhynchus gorbuscha, O. keta, O. kisutch, O. nerka, and O. tschawytscha (Brett, 1952), with kokanee or landlocked sockeye salmon, O. nerka kinnerlyi (Black, 1953), with different races of rainbow trout, Salmo gairdneri (Black, 1953; Craigie, 1963; Alabaster and Downing, 1966; Bidgood and Berst, 1969), with brown trout, Salmo trutta (Bishai, 1960; Alabaster and Downing, 1966), with Atlantic salmon, Salmo salar (Bishai, 1960), with brook trout, Salvelinus fontinalis (Fry, Hart and Walker, 1946; McCauley, 1958), with lake trout, Salvelinus namaycush (Gibson and Fry, 1954), with two subspecies of Arctic char, Salvelinus alpinus alpinus and S. alpinus willaughbii (McCauley, 1958), and with hybrids of S. fontinalis and S. namaycush (Gibson and Fry, 1953). These data, obtained initially to promote understanding of fish physiology and taxonomy, are now proving to be valuable for assessing the potential and existing ecological effects of thermal loading of aquatic environments.

The experimental fish used in previous studies were generally juveniles due to availability and to ease of handling. Definitive data on the thermal resistance of adults of most salmonid species are lacking. Several workers have examined the effects of fish size on thermal resistance, and concluded that there was little demonstrable effect (Tsukuda, 1960; Doudoroff, 1942; Fry et al., 1946; Hart, 1947). Size ranges of the investigated species were small, however, compared to the extreme size differences between fry and adult Pacific salmon.

This paper reports thermal resistance times and estimates of upper incipient lethal temperatures for three species of large salmonids during their spawning migrations into the central Columbia River, Washington State. Experiments were conducted on adult coho salmon, "jack" chinook salmon, and adult steelhead trout, an anadromous race of rainbow. All test fish were from the summer or early fall runs which enter the central Columbia near seasonally peak river temperatures. They are thus ecologically adapted to migration under near maximum thermal conditions in nature. Fulton (1968) explains, adequately, the migration features distinguishing the various "runs" of salmon into the Columbia; Watson (1969) describes salmon spawning in the vicinity of the collection point.

MATERIALS AND METHODS

Adult coho and steelhead were used in the experiments, for both species were relatively abundant and of manageable size. Chinook (or king) salmon, however are extremely large and difficult to handle when mature. Thus, "jacks" were used exclusively in tests of this species, i.e., sexually maturing but undersized males returning after one year at sea

(Rather than two or three). Recent chinook spawning runs to the central Columbia have included large numbers of jacks which are considered of little value to fish management when larger males are available.

Experimental fish were obtained from trapping facilities at Priest Rapids Dam, located at river mile 370, operated by the Washington State Departments of Fisheries and Game. Transportation to the Pacific Northwest Laboratory aquatic ecology facilities, 27 river miles (43.4 km) downstream, was by an insulated, spray-recirculating fish tank of 757 liter capacity. Ten to fifteen fish were carried at one time, depending upon size in relation to tank capacity. There were no significant temperature increases (< 1 C) during transport.

Circular, fiber glass tanks, 1.22 or 1.83 m in diameter with water depths of about 65 and 80 cm, respectively, (0.76 and 2.1 m^3 water volume) were used for pretest holding and the tests. All tests greater than 6 hours in duration were conducted in the larger tanks. An exchange of water of about 15 liters per min was maintained from heated and unheated sources entering at the perimeter surface and leaving via a double standpipe from the center bottom. Desired tank temperatures were maintained within 0.05 C by a Model 71 YSI (Yellow Springs Instr. Co.) thermistor temperature control coupled to a solenoid valve on the cool-water inlet. Untreated water was supplied by pump directly from the Columbia River.

Tests were conducted in the following sequence, when possible. On Day 1, trapped fish were transported to holding tanks, containing unheated river water, at our laboratory. Ten to fifteen fish were held in the large tanks, while five to ten were held in the small tanks.

Any fish showing damage or lethargy during collection and transportation were rejected. The "acclimation" temperature, Days 1-3, was that of the river, Figure 1. On Day 3, a test temperature was established in another tank and about ten fish were transferred to it. Times to equilibrium loss, (EL) (fish unable to remain upright) and death (cessation of opercular movement under stimulation) were recorded for various temperatures between 26 and 30 C. At temperatures below 26, checks were made for dead fish at intervals of about 2 hours and no data were obtained on loss of equilibrium. All tests were made with "control" fish held at river temperature and were terminated after about 1 week, when other factors than temperature (e.g. disease) might cause death and bias test results. Dead fish were weighed, measured and sexed prior to disposal. Geometric mean times for EL and death were calculated with 95 percent confidence limits.

Some special conditions should be noted. Due to extensive facilities required for testing large fish, the experiments were conducted over a 3-year period. Acclimation temperatures thus varied over the full range of tests for chinook. In 1967, chinook were held before testing at two differing temperatures, one that of the river supply water and the other two degrees below. These different "acclimation" conditions were maintained for a holding period up to 21 days. Five fish were tested from each group at three test temperatures. In 1968, chinook and coho were tested simultaneously in the same experiments, and data at these temperatures could be compared. Since few coho were available at Priest Rapids Dam in 1969, the resistance pattern for this species was not completed. In addition, our laboratory was situated downstream of operating plutonium production reactors which use water from the Columbia for cooling.

A temperature differential of about 2 C exists in the river between Priest Rapids Dam and the laboratory. Test fish thus migrated upstream through a thermal decrease of 2 C to reach Priest Rapids Dam, and were then held at slightly elevated temperatures at the laboratory.

RESULTS AND DISCUSSION

Steelhead

Adult steelhead were tested in 1969 at temperatures of 21, 22, 23, 24, 26, 27, 28 and 29 C, Table 1. Geometric mean times to death and EL, with 95 percent confidence limits, are illustrated in Figure 2. The graphical orientation established by earlier investigators (e.g., Fry *et al.*, 1946; Brett, 1952) for thermal resistance testing was retained despite the reversal of dependent and independent variables from normal statistical orientation. Regression equations for these responses (excluding 21 and 29 C) are shown on the respective lines. At the lowest test temperatures, 21 and 22 C, all fish did not die within one week. Here, the time for half of the fish to die (without confidence limits) is given instead of the geometric mean death time. The incipient lethal temperature was estimated to be near 21 C.

There were indications that a linear model may not be appropriate for describing these thermal deaths. First, resistance was greater at 29 C than one would expect for adult steelhead. This is also true at 28 C, although the deviation is within the confidence interval. The apparent increase in resistance at these high temperatures may result from relatively slow rates of heat transfer to the sensitive tissues, presumably the central nervous system of large fish. There was, consequently, a longer "warm-up" lag in large fish compared to small ones. Second, the resistances at 21 and 22 C were not markedly different. This may have signified the action of a secondary variable (e.g., disease) causing the observed mortality. Control fish died soon after the tests were completed, apparently due to fungal and bacterial infection. These factors would cause the model to deviate from linearity before reaching the incipient lethal level.

Equilibrium loss times varied from 48 to 79 percent of the death times, Table 2. The highest percentage was at the lowest temperature for which equilibrium loss data were recorded, similar to observations on juvenile rainbows and chinook (C. C. Coutant and J. M. Dean, unpublished).

Adult steelhead were significantly less resistant to elevated temperatures than were jack chinook tested the same year, although the chinook data were obtained only for the lower lethal temperatures. Male steelhead were more resistant than females at 26 and 27 C, but the difference was not significant with the number of fish tested.

Chinook

Thermal resistance of jack chinook was first tested in 1967 at 26, 28 and 30 C, Table 1. One half of the fish were held prior to testing in water chilled to 2 C below the inlet temperature to simulate conditions at Priest Rapids dam. Results are shown in Figure 3. There was apparently no difference between groups held at the two temperature levels, based on overlapping confidence intervals, and because the cooler group was less resistant at two temperatures, but more resistant at the third. EL time was a high percentage of death time at all three temperatures (Table 2). No regression analyses were made on these data due to the few temperatures studied.

More chinook jacks were available in 1968 so the resistance series was repeated, but with more fish in the 28 and 30 C test groups, and with an additional test at 27 C (Table 1). The results are illustrated in Figure 4. Death and EL times were nearly identical to those obtained the previous year and again, EL times were high percentages of death times at all temperatures.

Since the correlation among chinook resistance data proved to be similar for 2 years, death times at lower temperatures were determined in 1969 as a continuation of the series started previously. Tests at temperatures of 22, 24, 25 and 26 C were successfully conducted (a test at 23 C was aborted by equipment failure). The results were significantly different from the earlier tests, with resistance being greater by nearly a factor of 10 (Figure 4). This was true, also, at 26 C, the one temperature tested each year. Normal river temperatures (Figure 1) did not account for this difference, since the highest "acclimation" temperatures (theoretically giving longest thermal resistance) were in 1967, an unusually hot year. There were no significant differences due to size or sex. One possible contributing factor was the use of larger diameter tanks in 1969. The incipient lethal level would appear to have been between 21 and 22 C in 1969, for at 22 C only nine of fourteen test fish died at the end of 1 week. All control fish were still alive and active.

At 24 and 25 C, tests were conducted with two sizes of chinook, large jacks (as were the other tests) and smaller ones (Table 1). The small fish were significantly more resistant at the 95 percent confidence level.

Chinook jacks were more resistant than steelhead tested the same year and at the same temperatures, based on separation of 95 percent confidence intervals. Chinook were estimated to be 1.8 times as resistant at 22 C and 3.0 times at 24 C. If the 1969 chinook data could be extrapolated to higher temperatures, chinook would be more resistant by a factor of 10 at 29 C.

Coho

Adult coho salmon were tested in 1968 at 26, 27, 28, 29 and 30 C (Table 1, Figure 5). The resistance of coho was significantly less than that of jack chinook, which were tested simultaneously in the same experiments. Equilibrium loss occurred at about 80 percent of the death time, except at 28 C where it occurred sooner (Table 2). Coho were not available in 1969 for extension of the series to the incipient lethal temperature. Comparison of resistances of coho and steelhead from 1968 coho tests and 1969 steelhead tests would not seem appropriate, due to differences in results of chinook tests in 1968 and 1969.

Comparison of Tolerance of Juvenile and Large Fish

Thermal resistances of juvenile chinook and coho have been determined in our laboratory (J. M. Dean and C. C. Coutant, unpublished) and can be compared with the data presented above. Chinook were raised in our hatchery from eggs obtained from adults captured at Priest Rapids Dam. Coho were obtained from the Leavenworth National Fish Hatchery, Leavenworth, Washington. Figure 6 summarizes the respective thermal resistances at temperatures between 26 and 30 C.

Between 26 and 28 C, juveniles of both coho and chinook were generally more tolerant than large fish of either species. The difference was slight and insignificant for chinook, based on the error of the regression analysis. For coho, however, the difference was significant throughout the temperature range.

Resistances of juveniles of both species deviated from single straight lines near 28 C, thus changing the relative tolerances of juveniles and large fish (Figure 6). Chinook juveniles exhibited resistance times similar to jacks at 28 C, but above that temperature the resistance of juveniles was considerably less. The difference was estimated as a factor of 10 near 29.6 C. The greater tolerance of coho juveniles than adults decreased up to about 28.8 C, where young and adults became similar. Above that temperature, coho juveniles were less resistant. At 30 C, adults were more than three times as tolerant.

In summary, these tests have defined thermal resistance times, hitherto unknown, for adult steelhead trout, adult coho salmon and jack chinook salmon. Since the tests were conducted over three years and under varying thermal conditions, direct comparisons of resistance could be made only in some instances. Data for coho and chinook, tested simultaneously in 1968, indicate that coho were less resistant between 26 and 30 C. Data for steelhead and chinook, tested together in 1969, indicate that steelhead were less resistant than chinook between 22 and 26 C. Relative tolerances of steelhead and coho remain unclear because of variations in chinook data between years. Incipient lethal temperatures for steelhead and chinook appeared to be near 21 to 22 C. The relative thermal resistances of juvenile and large fish varied with test temperature--juveniles were more resistant at low lethal temperatures up to about 28.5 C and adults were more resistant above that level.

These data may be useful in evaluating the ecological effects of thermal discharges to salmonid environments, and for defining boundary conditions for thermal waste disposal that will assure continuation of the salmonid resources. They suggest that elevation of general environmental temperatures above 21 C would be directly lethal to adult salmon and steelhead. They also provide resistance times at higher temperatures that are necessary for modelling thermal death responses in the fluctuating temperature regimes of thermal mixing zones (Jaske, Templeton and Coutant, in press).

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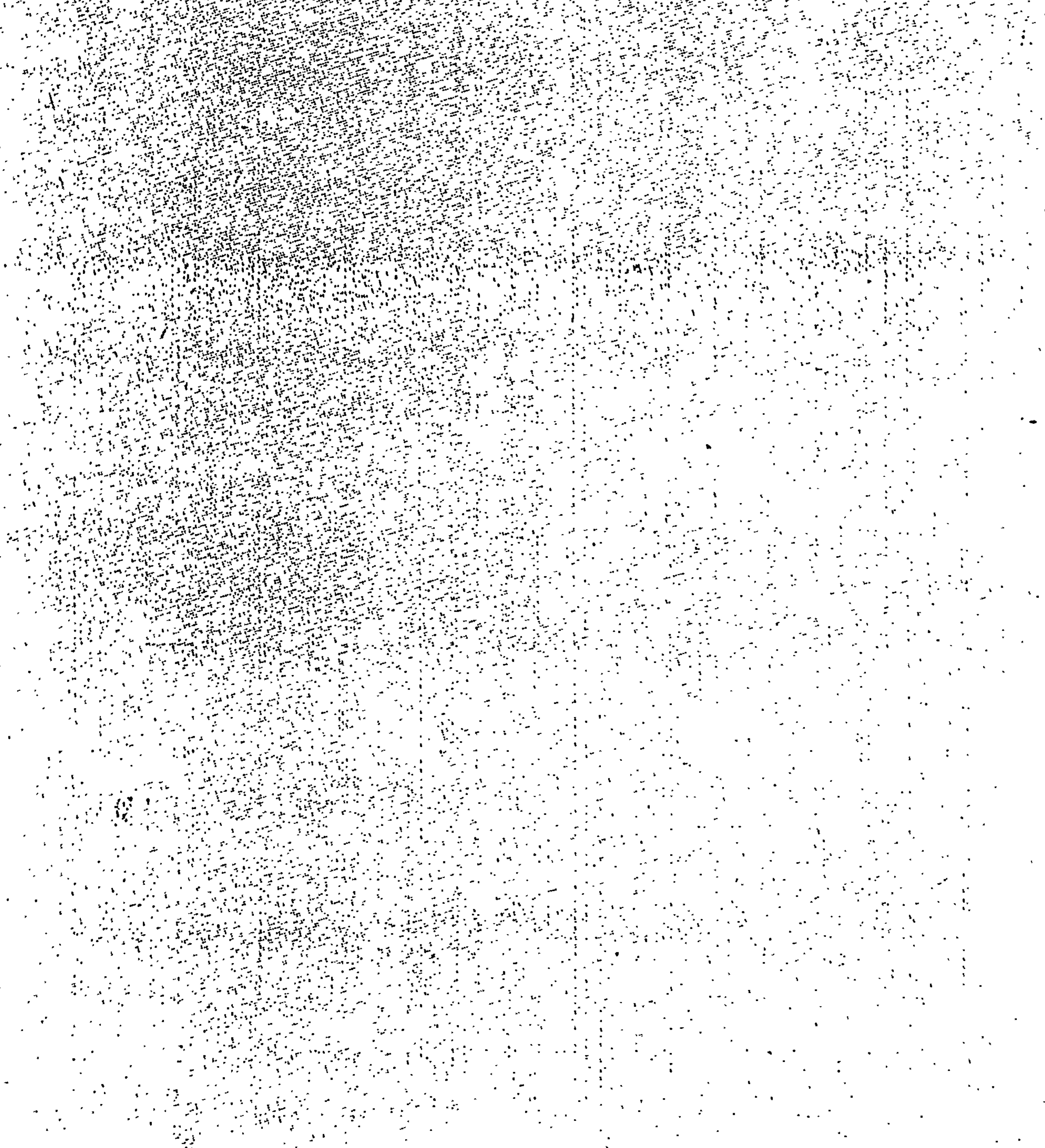
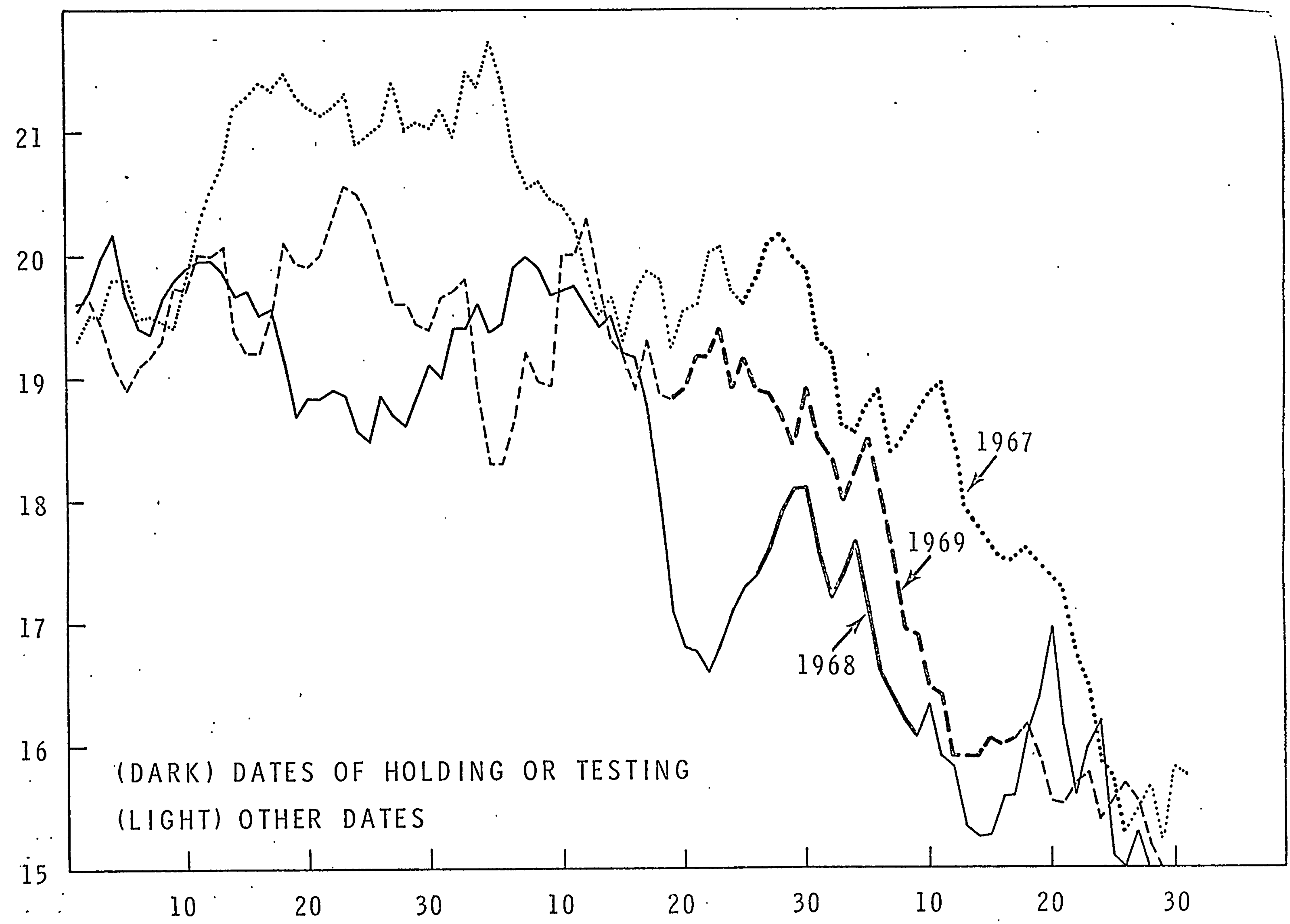


Figure 1. Temperature of hatchery supply water (approximates Columbia River temperature) during the period of fish migration and thermal tolerance testing, 1967, 1968 and 1969.



21
20
19
18
17
16
15
10
20
30
10
20
30
10
20
30
1967
1969
1968
(DARK) DATES OF HOLDING OR TESTING
(LIGHT) OTHER DATES

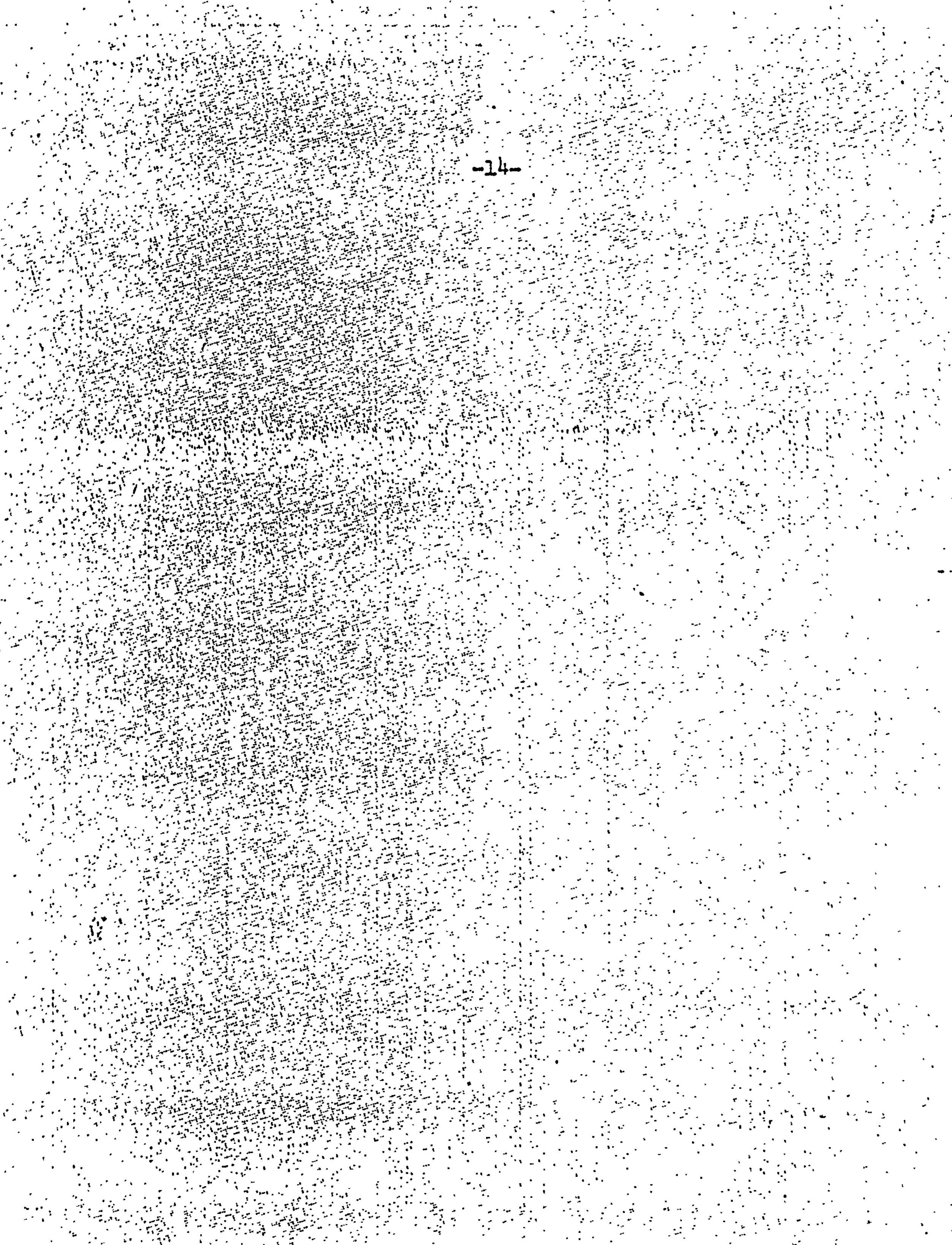
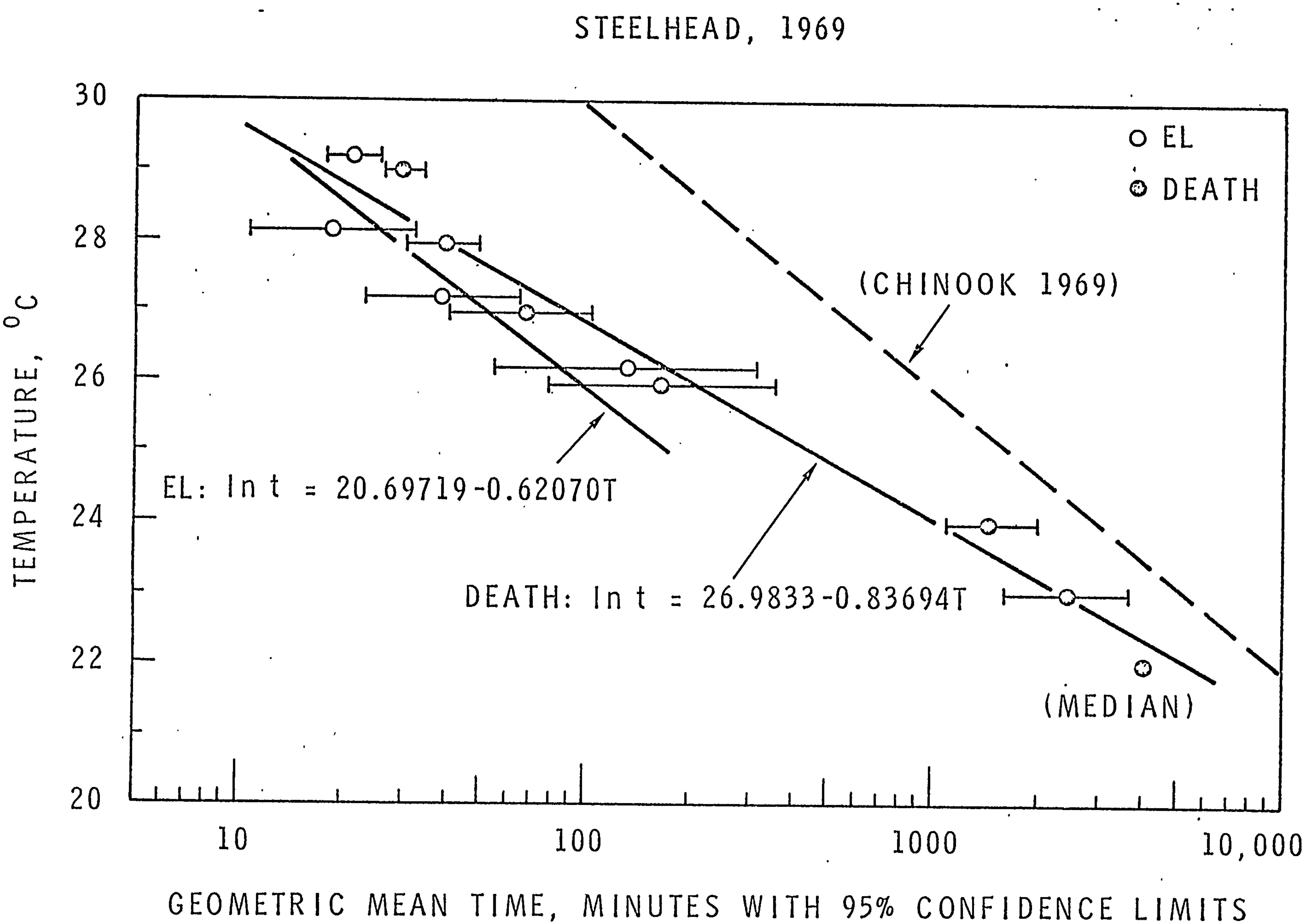


Figure 2. Geometric mean times (t) to equilibrium loss (EL) and death of adult steelhead trout, 1969, with 95% confidence limits. The extended regression line for 1969 chinook data (Figure 4) is included for comparison.


STEELHEAD, 1969
30
28
26
24
22
20
TEMPERATURE, °C
O EL
DEATH
(CHINOOK 1969)
EL: ln t = 20.69719-0.62070T
DEATH: ln t = 26.9833-0.83694T
(MEDIAN)
10
100
1000
10,000
GEOMETRIC MEAN TIME, MINUTES WITH 95% CONFIDENCE LIMITS

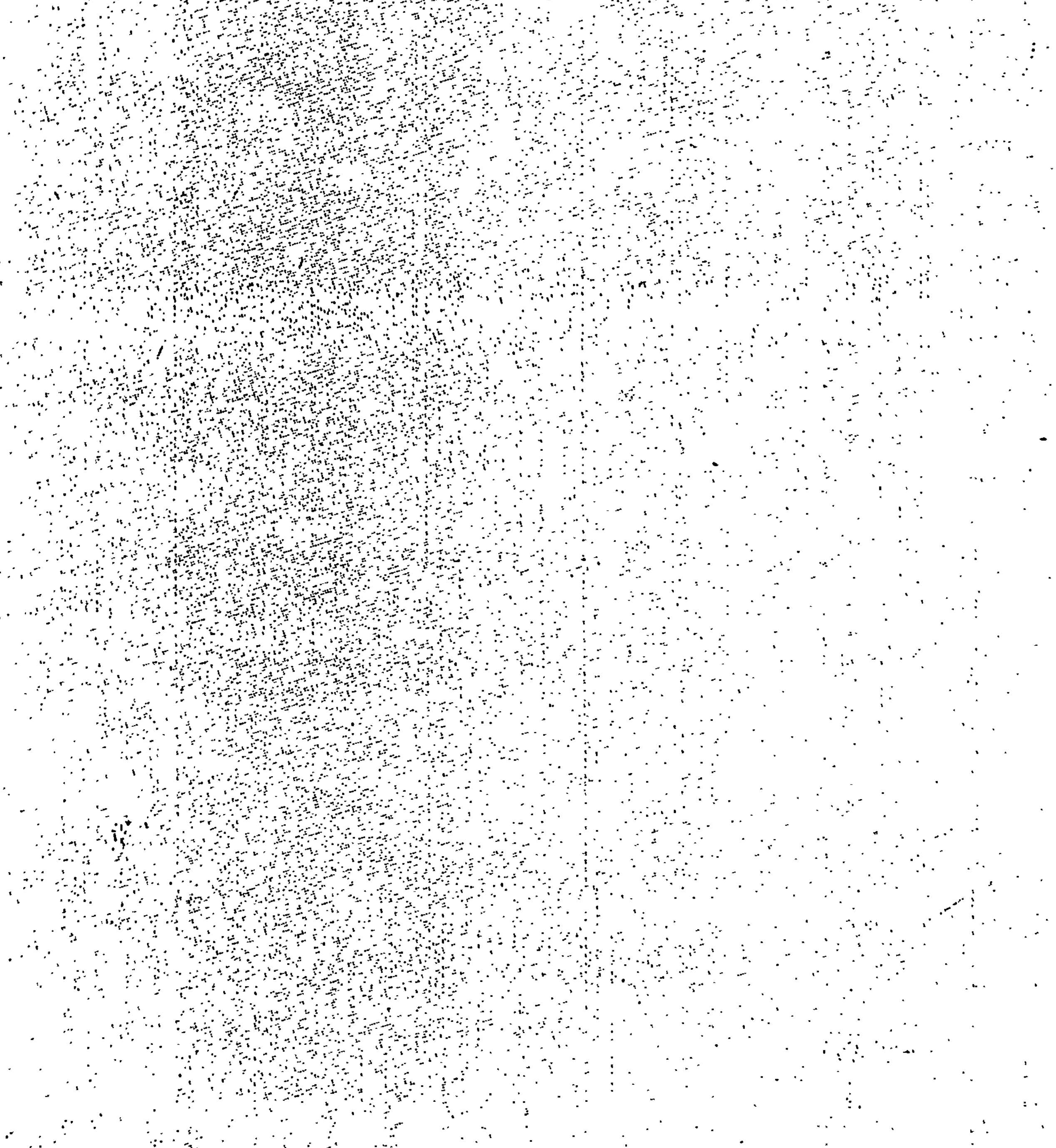
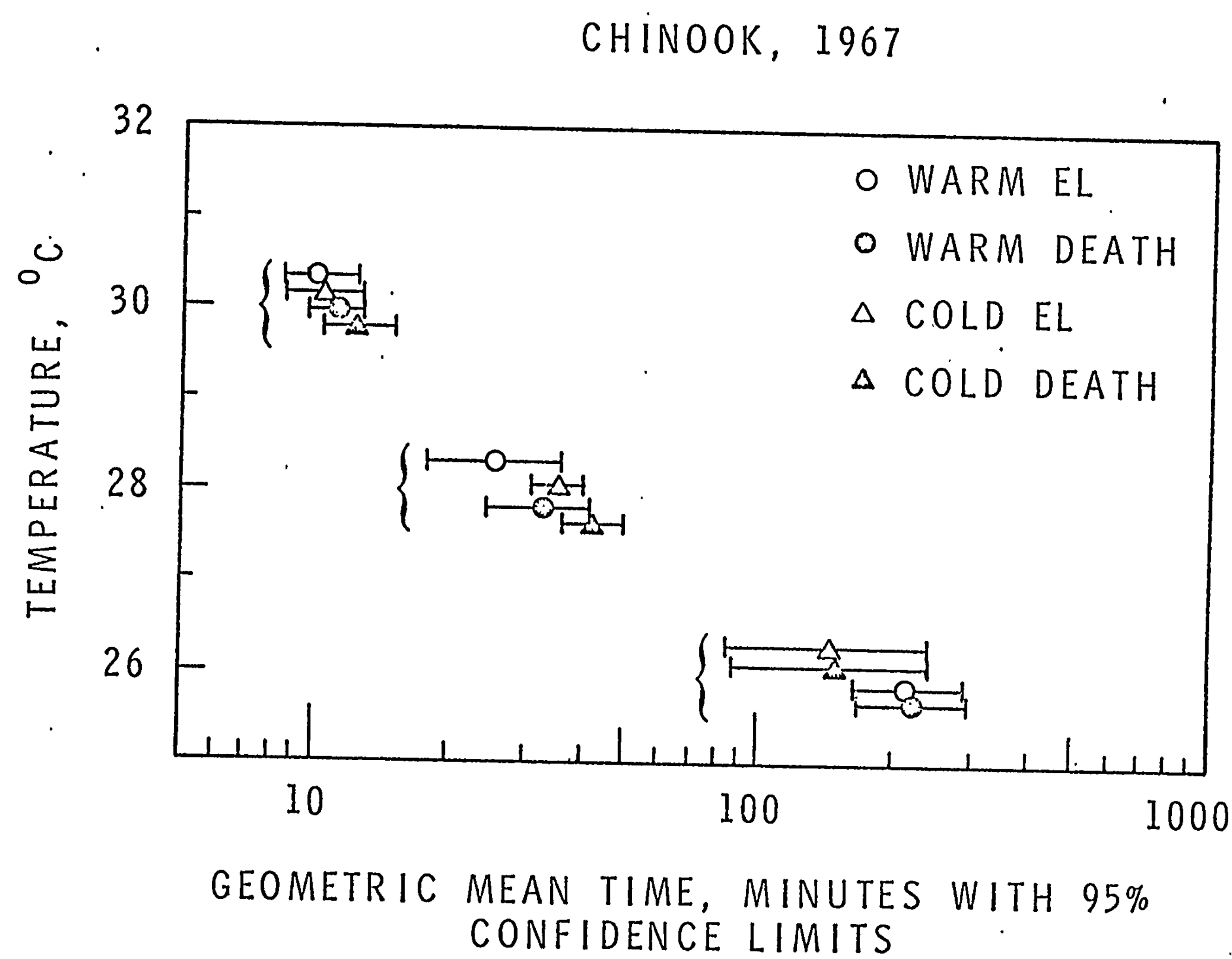


Figure 3. Geometric mean times to equilibrium loss (EL) and death of "jack" chinook salmon in 1967, held at hatchery temperature and hatchery temperature minus 2 C (approximate Priest Rapids temperature), with 95% confidence limits.


CHINOOK, 1967
WARM EL
WARM DEATH
COLD EL
COLD DEATH
TEMPERATURE, °C
32
30
28
26
10
100
1000
GEOMETRIC MEAN TIME, MINUTES WITH 95%
CONFIDENCE LIMITS

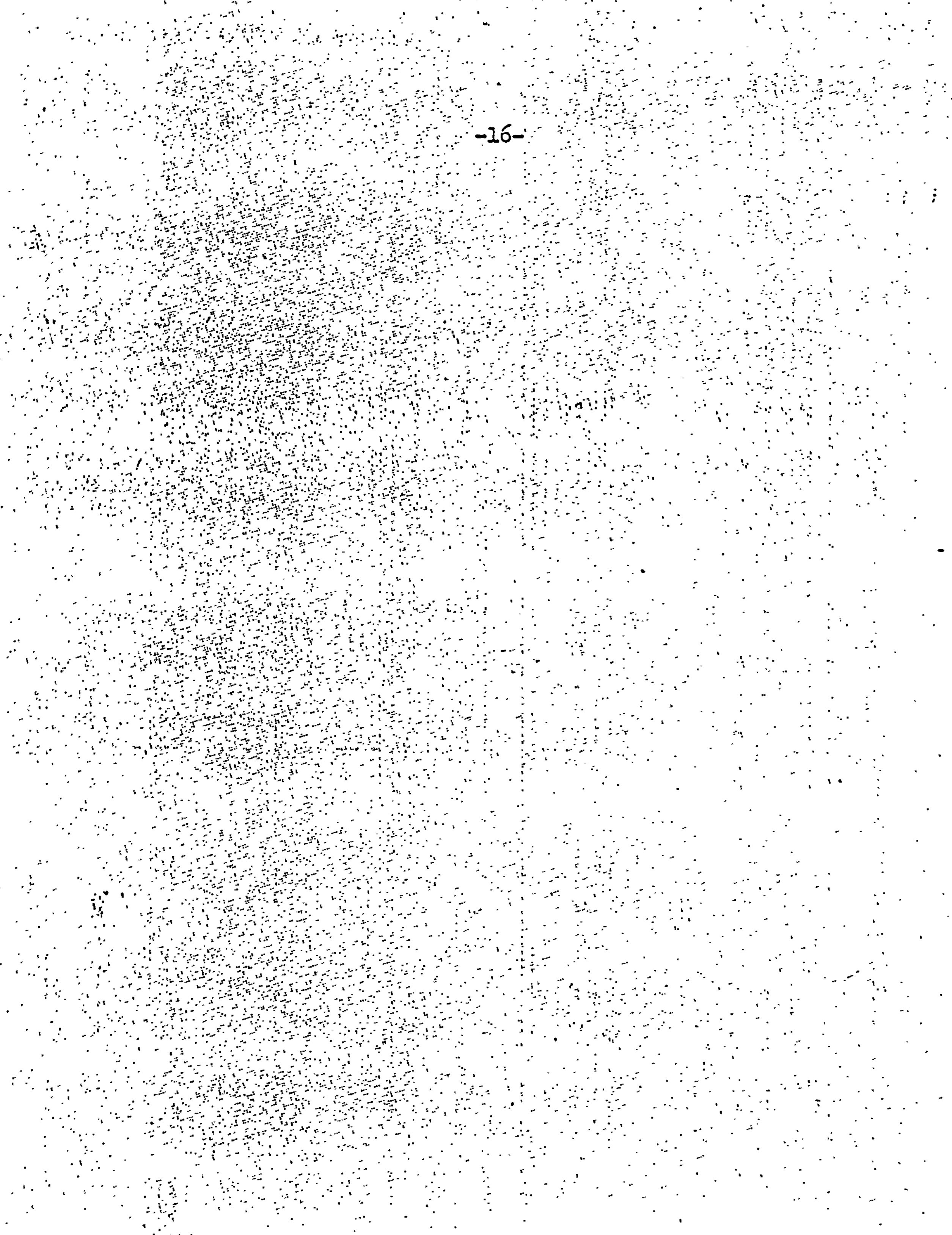
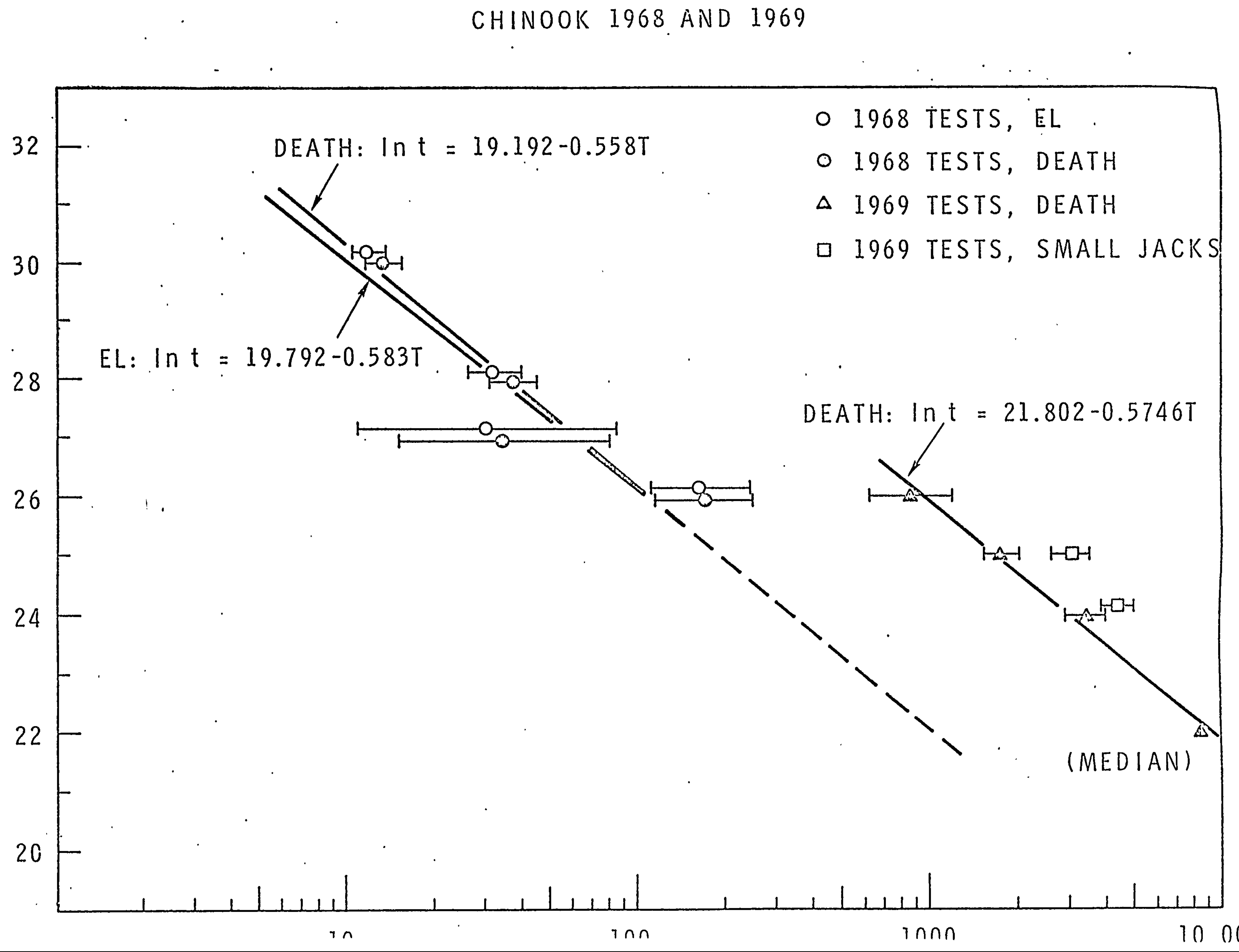


Figure 4. Geometric mean times (t) to equilibrium loss (EL) and death of "jack" chinook salmon, 1968 and 1969, with 95% confidence limits.


CHINOOK 1968 AND 1969
1968 TESTS, EL
1968 TESTS, DEATH
1969 TESTS, DEATH
1969 TESTS, SMALL JACKS
DEATH: ln t = 19.192-0.558T
EL: ln t = 19.792-0.583T
DEATH: ln t = 21.802-0.5746T
(MEDIAN)
32
30
28
26
24
22
20
10
100
1000
10 00

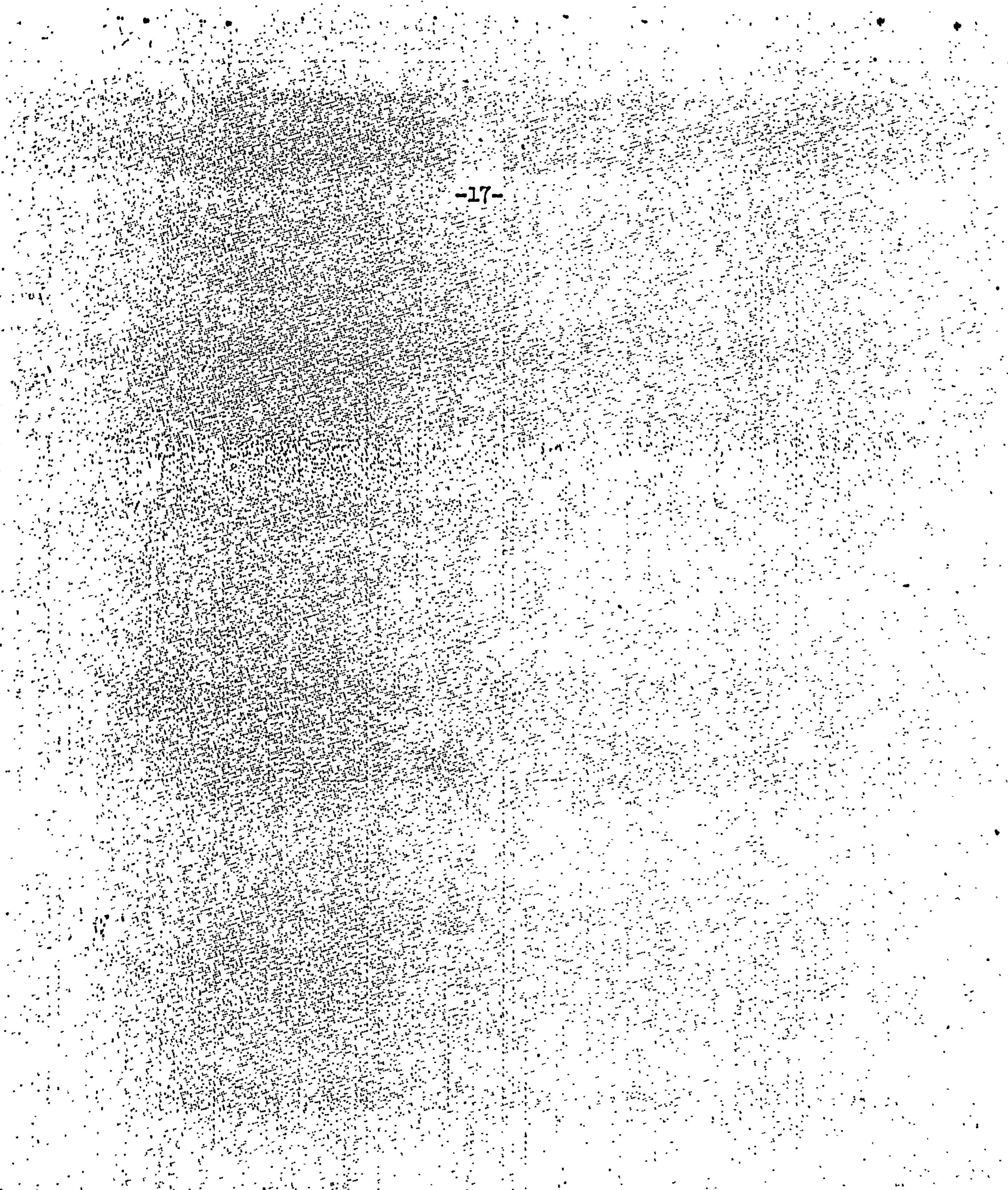
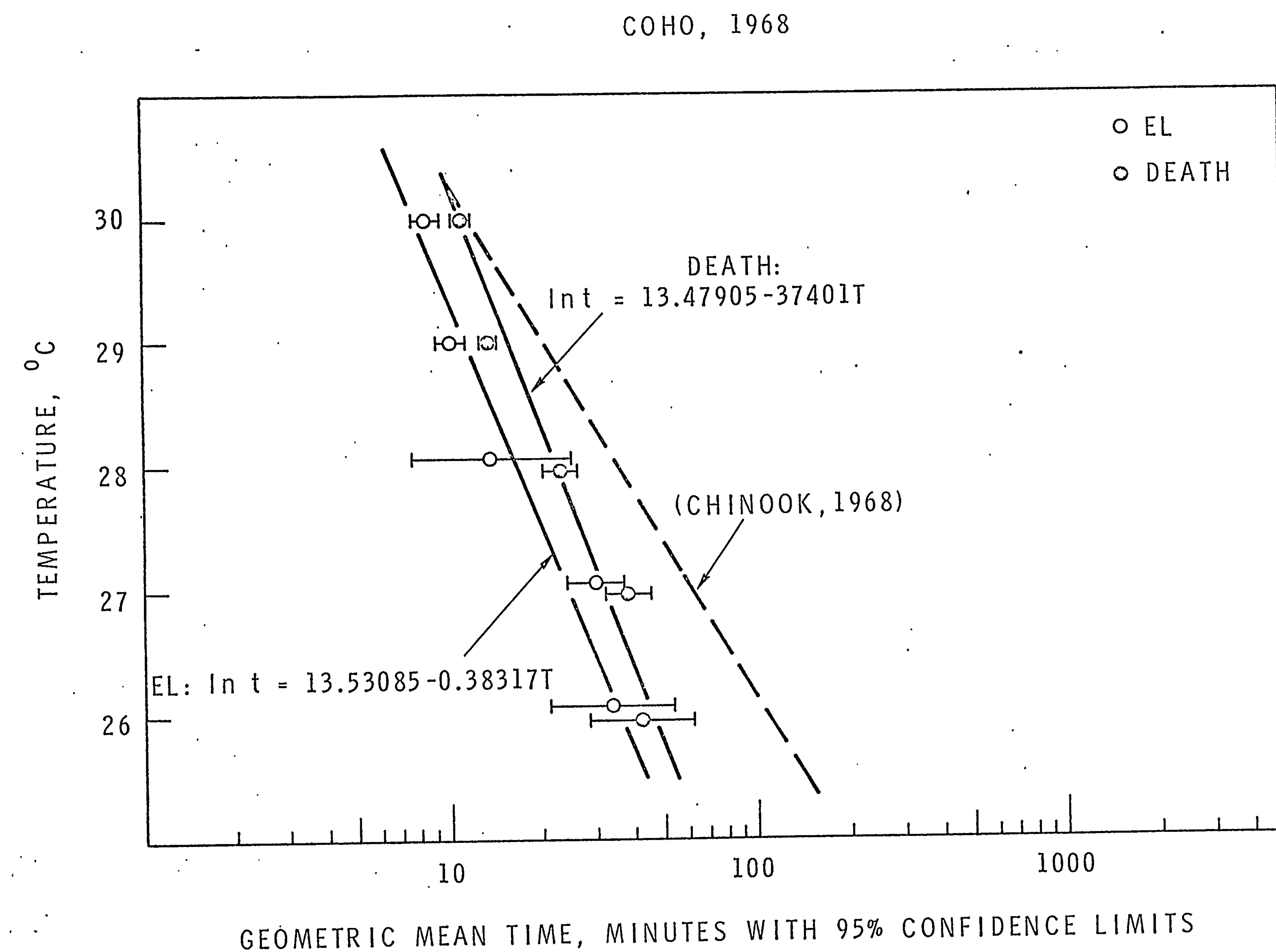


Figure 5. Geometric mean times (t) to equilibrium loss (EL) and death of adult coho salmon, 1968, with 95% confidence limits. The regression line for 1968 chinook data is included for comparison.


COHO, 1968
EL
DEATH
DEATH:
ln t = 13.47905-37401T
(CHINOOK, 1968)
EL: ln t = 13.53085-0.38317T
30
29
28
27
26
TEMPERATURE, °C
10
100
1000
GEOMETRIC MEAN TIME, MINUTES WITH 95% CONFIDENCE LIMITS

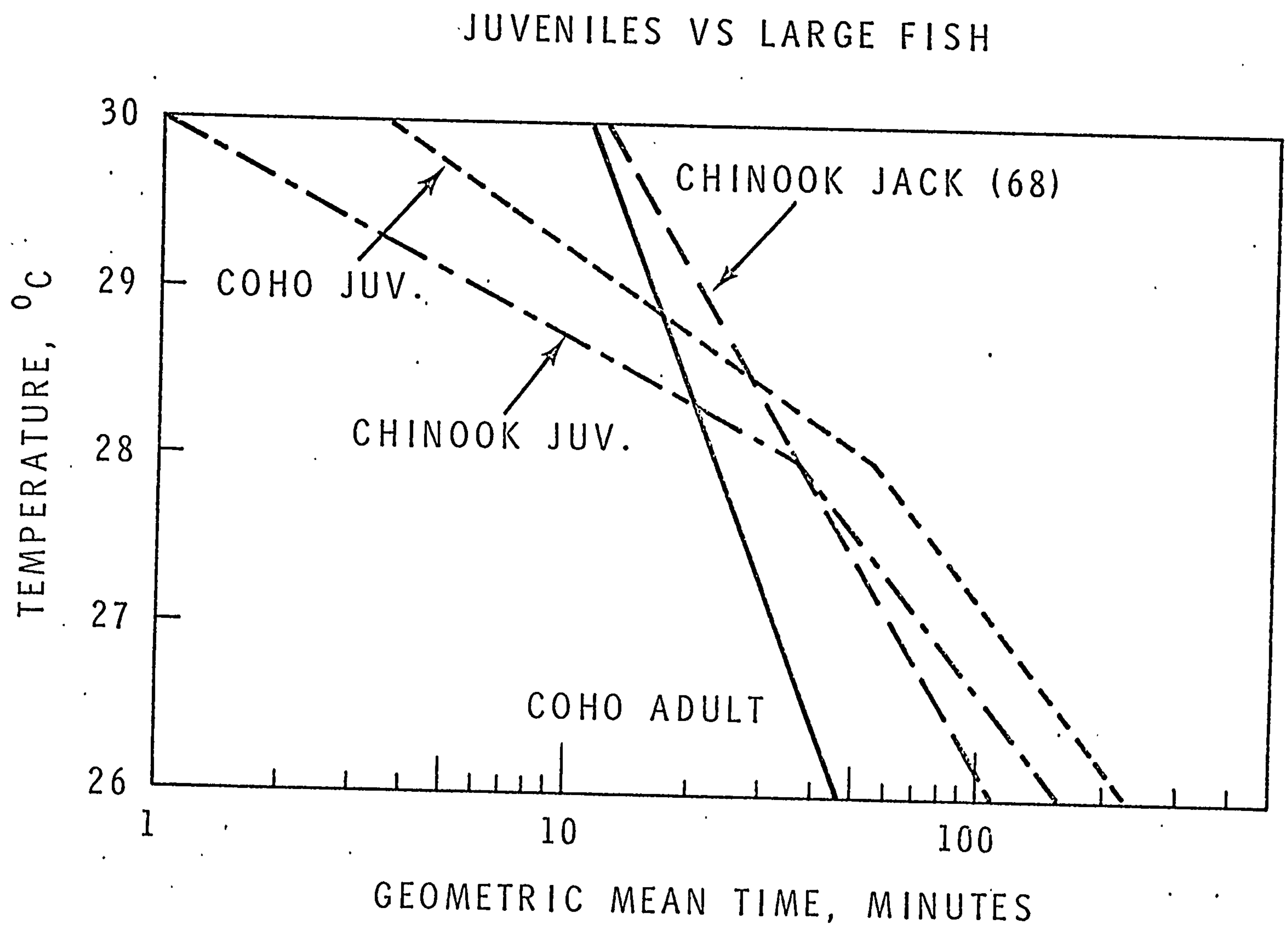

JUVENILES VS LARGE FISH
30
29
28
27
26
TEMPERATURE, °C
1
10
100
GEOMETRIC MEAN TIME, MINUTES
COHO JUV.
CHINOOK JUV.
CHINOOK JACK (68)
COHO ADULT

TABLE 1. Summary of Experimental Fish

	N	Weight (grams) Mean	Weight (grams) Standard Deviation	Length (mm)[a] Mean	Length (mm)[a] Standard Deviation	Sex
Steelhead, 1969						
22	10	4011	1056	639 (710)	56 (59)	5 M, 5 F
23	7	4322	1348	654 (725	78 (85)	2 M, 5 F
24	8	5117	1422	674 (752)	65 (74)	2 M, 6 F
26	10	4722	710	671 (760)	39 (48)	4 M, 6 F
27	10	3571	736	624 (699)	44 (47)	2 M, 8 F
28	10	4087	1081	651 (733)	54 (60)	4 M, 6 F
29	10	3569	1078	630 (709)	63 (72)	10 F
Chinook, 1967, warm						
26	5	1467	783	444	91	5 M
28	5	2182	964	506	87	5 M
30	5	924	181	386	23	5 M
Chinook, 1967, cool						
26	5	2116	1203	488	103	5 M
28	3	1504	742	438	86	3 M
30	5	1703	1037	463	97	5 M
Chinook, 1968						
26	5	1339	695	436	84	5 M
27	3	2640	746	551	46	3 M
28	10	1503	921	439	87	10 M
30	11	2091	962	495	91	11 M
Chinook, 1969						
22	14	1399	684	426 (466)	72 (76)	14 M
24 small	14	1092	325	384 (420)	35 (38)	14 M
24 large	6	2568	743	521 (573)	48 (52)	6 M
25 small	6	1056	429	378 (412)	56 (62)	6 M
25 large	10	2614	768	522 (577)	46 (48)	10 M
26	9	1538	466	441 (473)	58 (69)	9 M
Coho, 1968						
26	10	2554	443	579	27	(b)
27	10	2488	830	555	90	6 M, 4 F
28	11	2167	370	546	36	(b)
29	10	2737	557	585	38	3 M, 7 F
30	11	2588	905	554	36	(b)

(a) Measured from snout to hypural plate. Fork lengths in parentheses, when taken.

(b) Data not taken.

TABLE 2. Relationships between Equilibrium Loss (EL) and Death (D) Times

Test Temperature	EL/D
Steelhead	
26	.79
27	.60
28	.48
29	.72
Chinook, 1967 Tests, warm	
26	.98
28	.79
30	.92
Chinook, 1967 Tests, cool	
26	.97
28	.84
30	.84
Chinook, 1968 Tests	
26	.99
27	.88
28	.86
30	.88
Coho	
26	.81
27	.78
28	.59
29	.76
30	.76