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STUDIES ON THE BIOLOGICAL EFFECTS OF THERMAL DISCHARGES FROM NUCLEAR REACTORS TO THE COLUMBIA RIVER AT HANFORD[1]

William L. Templeton

Charles C. Coutant[2]

Battelle Memorial Institute
Pacific Northwest Laboratories
Richland, Washington, U.S.A.

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(2) Present address: Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee.

DISCLAIMER

Introduction

Studies on lethal temperature effects, and requirements for optimal temperatures by aquatic organisms have increased in the last decade due to a national concern about water quality and preservation of the environment. Population growth, demands for electrical energy and the introduction of nuclear generated power have contributed significantly to this concern. Despite the significant increase in research in this area, our ability to predict or assess the biological cost or benefits of increasing the temperature of a river system to a fishery resource, or to the aquatic ecosystem as a whole has not been sufficiently demonstrated. The problem is complex and while the general effects of elevated temperature in increasing metabolic rates and oxygen requirements, modifying sensitivity to toxic materials and fish diseases are well known, the sum of these effects, usually inferred from laboratory studies where death is the primary criteria, often contradicts the continued perpetuation of fish populations in certain areas under natural conditions.

Dams have inundated most of the spawning grounds in the main stem of the Columbia, and virtually all of the salmon spawning now occurs in tributary streams. Hence, most of the adult fish entering the Hanford reach of the Columbia are transients bound for areas upstream. A small spawning area still remains in the only free-flowing stretch in south central Washington, between Priest Rapids Dam and Ringold (20 km downstream from the reactor areas). Anadromous species found in the Hanford reach are chinooks (<u>Oncorhynchus tshawytscha</u>), sockeye (<u>O. nerka</u>), coho (<u>O. kisutch</u>), steelhead (<u>Salmo gairdneri gairdneri</u>), shad (<u>Alosa sapidissima</u>), white sturgeon (<u>Acipenser transmontanus</u>) and Pacific lamprey

(Lampetra tridentata). Over thirty other species of freshwater fish have been identified in the Hanford reach.

The approach taken at Hanford in studying the potential effects of heated reactor discharges to the Columbia River has involved an integrated program of laboratory and field studies in order to develop temperature criteria for the species of concern. Our research has emphasized the chinook salmon and the rainbow trout (Salmo gairdneri) because of their dominant economic importance to commercial and sport fisheries and their sensitivity to warm waters. The chinook salmon are of particular interest since they spawn and develop immediately above and below the reactor discharges; as juvenile fish migrate downstream through the Hanford reach of the Columbia River; and as adults return to spawn in the Hanford reach or pass as transients to spawn in the upper tributaries of the Columbia River.

There are, however, many other complex factors, man-made and natural, that affect and control the perpetuation of anadromous fish populations; temperature is but one of those. For the last two years the program has been coordinated with the U.S. Federal Water Quality Administration and the U.S. Bureau of Commercial Fisheries programs under the Columbia River Thermal Effects Study Committee.

Reactor operations and river temperatures

One of the primary reasons that the Hanford Reservation was selected for the siting of the plutonium production reactors was the availability of large volumes of cold river water in the Columbia River. The reactor areas are located along the right bank of the river near the eastern boundary of the 620 square mile reservation (Figure 1). A history of the operation shows that there were a total of six reactors operating prior to 1955, eight from 1955 to 1964, and a maximum of nine during 1964. At present, there are only two reactors operating (Figure 2).

A review of the history of Columbia River temperatures shows that with the construction of dams and multiple water use, there has been a reduction in the maximum temperatures during the summer months, an elevation in the minimum temperatures during the winter months, with very little change in the annual mean temperature (Jaske and Goebel, 1967). However, the operation of the dams has created a shift in the timing of the seasonal cycle towards the later months by lengthening the time of water passage. Maximum temperatures formerly observed in early August have moved some 30 days and are now seen in early September. With the completion of dams on the Columbia River in Canada the maximum temperatures are expected to occur in late September.

The difference in river temperatures between Priest Rapids Dam (20 km above the reactor area) and Richland (45 km downstream from the reactor area) is the result of not only reactor operations, but also of heat input from other sources. In 1965, the reactors were shutdown for over 40 days in July and August (Figure 3). The thermal increment of 2-3 F seen during this period is the result of natural heat input as the water flows from Priest Rapids Dam to the head of the McNary Pool at Richland.

The effluent discharge outfalls of the Hanford production reactors are typically located on the river bottom at nearly mid-channel, which may average 20 feet in depth. Battelle-Northwest is employing several advanced techniques to evaluate the interaction of these discharges with the highly regulated regime of the river (Jaske, Templeton and Coutant, 1969-1970). Infrared imagery plus the coordinated processing of tape recorded signals from the primary infrared system are the latest techniques being employed to determine the zone of prompt mixing which normally extends less than 300 yds from the point of discharge.

A hydroelectric plant at Priest Rapids Dam causes routine variations in river flow from lows of 36,000 ft^3/sec, the regulated minimum, to daily peaks of 160,000 ft^3/sec. The temperature pattern in the mixing zone of one reactor discharge point taken by remote imagery at river flows of 41,000 ft^3/sec, 80,000 ft^3/sec, and 110,000 ft^3/sec are shown in Figure 4. Estimates of the cross section area of the plume 60 ft below the discharge point at the lowest flow rate indicate that only about 5% of the total river area is enclosed by the ΔT 10 C isotherm.

<u>Effects of temperature on adults</u>

a) Tracking of migrating salmon and trout

Blockage of spawning migrations is an oft-speculated effect of thermal discharges on river fishes. The Columbia at Hanford is an important migration route for chinook salmon and steelhead trout during July through October when water temperatures are highest and to determine if any significant thermal blockage occurs at this point, a cooperative field study was undertaken by Battelle-Northwest (BNW) and the U.S. Bureau of Commercial Fisheries, Seattle Biological Laboratory (BCF).

Sonic tags and tracking equipment developed by BCF were used to follow fish movements. The tags consist of a battery-powered, ultra-sound transmitter housed in a polystyrene capsule. The capsule is inserted into the fish's stomach through its mouth and esophagus. The tags emit a sequence of sound pulses which can be heard through the receiving system at distances up to 3 km under certain river conditions. Separate groups of fish carry tags of differing pulse patterns, which make it possible to tell whether the fish being tracked was a salmon or steelhead trout, and approximately when it had been tagged. The tag life is approximately 12 weeks. Portable tracking equipment designed for use in a small boat consists of a directional hydrophone, transistorized receiver and earphones. BNW crews recorded locations or migration paths of 70 tagged fish in August and September of 1967 and 368 between May and October 1968.

Both species migrated principally along shore lines, and the summer run fish were found most often along the left bank opposite the reactors. This tendency was strongest during the peak temperature period of August and September. Additional attention was given in 1968 by both Battelle-Northwest and Bureau of Commercial Fisheries crews to determining the extent of the shore line preference in stretches of the river further downstream. The data indicate strong preference for the left bank in the entire area where the reactors are located. Additional data suggest that this basic pattern also exists from Richland to Priest Rapids Dam.

Two analyses were used to aid identification of possible migration blockage by reactor outfalls or other river features. These were 1) rate of migration during the period of most active fish movement through the area in May and in July and August, and 2) frequency of occurrence of stationary or slowly-moving tagged fish per river kilometer per day of observation during the period of slow migration in August, September and October.

Figure 5 illustrates average migration rates and the daily frequencies of 1968 fish records per river kilometer plotted below the corresponding sections of river illustrated at the top. The river outline also indicates the primary pathway of fish migration. The bottom histogram indicates a distinct nonuniform distribution of fish in this stretch of river during the period of analysis. Two areas are notable for an abundance of fish, 1) immediately downstream of the K-reactor outfall, and 2) opposite the inactive D reactor area. Notable for a paucity of records are areas immediately below the N-reactor and a 1 km stretch below the D area. Fish distribution underwent conspicuous shifts downstream of the K-reactor during the study period, as illustrated in the top two histograms. In late August a concentration of fish appeared in about the first kilometer below the discharge, with few fish being found for four kilometers downstream of that point (top histogram). This concentration shifted downstream in September until maximum abundance occurred between 2 and 3 km below the outfall between 11 and 18 September (middle histogram).

Migration rates, although more difficult to analyze on a river kilometer basis, indicate changes which appear to correlate with frequencies noted above. The average migration speeds for both species indicated on the line graph of Figure 5 show peaks which occur within or at the end of a zone with relatively few stationary fish (e.g., kilometers 29, 32.5, 36.5). One area of slow migration, km 35, corresponds an area with high fish abundance. More meaningful correlations can be identified from the incremental migration speeds of individual fish. Differences in both distribution and migration speed may be reasonably attributed to shore line features such as swift, unprotected zones (km 37-38) or backeddies (km 28), or they may be related to reactor operations. While insufficient data are available at present to positively identify the reasons for the anomalies in distribution and migration rate, the study indicates that migration is not affected to any significant degree. A temperature-sensitive sonic tag under development for use this summer will enable us to relate rates of migration to specific water temperatures.

b) Population census of Hanford fall chinook salmon

One of the initial field studies started on the Hanford reach in 1947 was an annual aerial census of fall chinook spawning (Watson, 1970). The major spawning areas are both upstream and downstream of the reactor areas (Figure 6). The data of the number of salmon nests observed each year for the last 22 years are perhaps the best circumstantial evidence of the continued viability of the fall chinook population that spawns within the Hanford Reservation (Figure 7). Spawning was observed in several years within 100 meters downstream from an effluent outfall. The marked rise in numbers of spawning salmon during 1965 to 1969 is not considered to be related to the decrease in reactor operation during that period, but due to other factors such as displacement from other inundated main stem spawning areas. Analysis of the data indicated that the rate of increase in the upstream area was similar to that at the next downstream area. Relation of the estimated numbers to environmental variables such as river temperature, flow and water elevation at spawning and to the number of operating reactors and construction of dams indicates that the critical factor is probably the construction of dams and inundation of main stem spawning areas. Operation of the reactors would appear to have had no adverse effect on this population of salmon.

c) Thermal resistance of adults

Summertime temperatures of Columbia River water at McNary Dam, about 113 km (70 miles) downstream from Hanford reactors usually reach 22 C for a few days in August. This peak temperature is well below the incipient lethal temperature for juvenile chinook salmon (about 25 C) established by Brett (1952). The applicability of this thermal criterion was questionable, however, for adult chinook migrating upriver at this time, or for adult coho and steelhead trout migrating in September. No data were available on thermal resistance of adults, so experiments were initiated in our laboratory (Coutant, in press).

The experimental procedures were similar to those used for juveniles by Brett's (1952). Mature adult coho and steelhead were used, for they were relatively abundant and of manageable size. However, only undersized male chinook ("jacks") were used due to the extreme size and difficulty of handling of mature females. Test fish were obtained from the river at Priest Rapids Dam.

Acclimation temperature was that of the river, 18-19 C. Due to extensive handling facilities required for testing large fish, experiments were conducted over a three-year period. Following transfer of fish to the test temperature, times to equilibrium loss (EL) and death (D) were recorded for various temperatures between 26 and 30 C. Below 26 C, observations were only made for dead fish at intervals of about 2 hrs; and, therefore, no data were obtained on EL. All tests were made with "control" fish held at river temperature and were terminated after 1 week.

Incipient lethal temperatures for steelhead and chinook appeared to be near 21 to 22 C (Figure 8). Data were insufficient to obtain an estimate for coho. 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. The relative thermal resistances of juvenile and large fish varied wtih test temperature (Figure 9). Juveniles were more resistant at low lethal temperatures up to about 28.5 C, and adults were more resistant above that level.

Effects of temperature on eggs and juveniles in the Hanford reach

The need for investigating the hazards to fishery resources from discharging heated effluents into the Columbia River was recognized before the reactors were built (Foster, 1959). As early as 1945, young salmonids were reared from egg to fingerling size in different concentrations of reactor effluent, to observe their growth and mortality. The predominant characteristics of the reactor effluents of biological importance were shown to be heat, radioactivity and certain corrosion-inhibitor chemicals added to the cooling water. These studies indicated that effluent concentrations greater than 4 percent resulted in mortality, though acceleration of growth occurred in all concentrations up to 6 percent due to the thermal increment. Over 7 percent concentration growth depression occurred due to the toxicity of the corrosion-inhibitor hexavalent chromium in the effluent. No radiation damage could be demonstrated at these effluent concentrations (Nakatani, 1969).

Since the eggs and young stages of salmon and steelhead trout are sensitive to temperature changes, considerable research has been conducted on the effects of thermal increments above base river temperature on the rate of development, growth and mortality (Olson and Foster, 1955; Olson and Nakatani, 1968). For example, in the 1966-67 season, eggs were developed and young chinook salmon reared over 170 days under seven temperature regimes. Each test series followed the seasonal temperature patterns of the river with an increment of 2 F over the next lower temperature, giving an overall range of 12 F. Four groups of spawned eggs were tested from October through December. Temperature increments exceeding 4 F above the base river temperature of 54 F caused significant mortality in fish hatched from spawn collected in October. By December, however, when the base river temperature was 48 F, the spawn tolerated an increment of 12 F without significant mortality. The increased water temperatures accelerated fish growth in all lots, those in the +12 F test being as much as eight times heavier than those in the +2 F test. Similar tests series were conducted in 1969-70 with a single spawn from steelhead trout with similar results. These studies indicate that a significant thermal increment can be tolerated by eggs during lat fall and winter seasons without detrimental effects. Additionally, the results show that the warmer conditions favor the survival of young salmon from the late spawners of fall run chinook salmon. The question of whether larger-sized migrants have better survival is still open to question though there is some evidence that they have higher survival rates if other conditions are equal (Nakatani, 1969).

Effects of temperature on downstream migrating juvenile salmon.

a) Resistance of juveniles

The Columbia River at Hanford contains juvenile chinook salmon, for adults spawn both upstream and downstream of reactor plumes. Juveniles migrating downriver may experience the high temperatures of the plumes for brief periods, if their path coincides with the effluent mixing zone. Studies have considered several related questions concerning lethal temperature relations of juvenile chinook, in order to define responses that could be damaging to our fishery resource. These were:

(1) How does the resistance to acute thermal shock of local chinook compare with stocks studied by others?

(2) Does the developmental temperature regime (e.g., warmer, as in spawning areas downstream of reactors) affect the response of juvenile chinook to acute thermal shock?

(3) Does fish size (within the range of out-migrating juveniles) affect the response to thermal shock?

(4) How do the results of two types of tolerance tests compare, e.g., 48-hr TL_m (mean lethal temperature) and thermal resistance?

(5) What are the relationships between times to loss of equilibrium and physiological death under thermal stress?

(6) To what extent does delayed mortality follow equilibrium loss (initially reversible) at various shock temperatures?

(7) How do exposures to increasing or decreasing temperatures, as experienced in a thermal discharge area, compare with exposures to constant temperatures?

Summaries of these studies have been published (BNW 1968, 1969).

One example, however, will indicate the approach we have taken. It is a comparison of times to equilibrium loss and death. Fish subjected to thermal shock above the lethal level characteristically show equilibrium loss before the generally accepted thermal death point. Heat death of cold-blooded organisms has been observed to follow a common pattern which includes, in sequence, loss of equilibrium, coma, and physiological death. These observations have been made with several species of fishes and with amphibians and reptiles. They probably hold, in essence, for lower forms as well. The early stages of heat death, while not "death" in themselves, may lead to death through (1) immobilization in the area of adverse temperature (which may prolong exposure until death results) or (2) stimulation of predatory activity upon the heat-injured organisms. Both results have been observed in the field and in laboratory experiments. For field application, therefore, the thermal dose which will induce equilibrium loss is perhaps more important than is the dose required for death. Equilibrium loss data, however, have not generally been reported in thermal resistance experiments. This prompted us to examine our data for a possible consistent relationship between equilibrium loss and death. It was hoped that this relationship might be applied as a conversion factor to obtain equilibrium loss times from death times available in the literature.

Geometric mean times to equilibrium loss (EL) and death (D) did not fit the linear, semilog model of Brett (1952). Cubic models provided a much better fit for all pooled data for juvenile chinook (Figure 10). They were also more appropriate for groups of sibling chinook with identical rearing history (Coutant and Dean, in press). The ratio $\frac{EL}{D}$, was not constant, but varied with test temperature (Figure 11). A cubic model was also fitted to this variation, providing a quantitative description that is suitable for inclusion in mathematical models of potential effects in thermal plumes.

b) Thermal shock and predation

Loss of equilibrium is an obvious behavioral response to a sublethal exposure to a lethal temperature, with potentially lethal results in a predation situation. The behavioral changes of shocked fish at fractions of thermal doses sufficient to cause loss of equilibrium might not, however, be detectable visually, but might be reflected by the degree of predation when compared to untreated control fish.

A series of experiments was devised to test differential predation rates. Two groups of fish, one thermally treated and the other not, were offered simultaneously to a group of active predators at the acclimation temperatures. When about half of the initial charge of prey fish remains, the fish are separated and percentages of shocked and control fish remaining are determined. This sequence of exposure at high temperature and predation at lower temperature simulated in simplified form the sequence at Hanford, where juveniles passing through the thermal plume may be subjected to predators lurking the cooler reaches immediately downstream.

Results of repeated tests allow calculation of a ratio of instantaneous predation rates (Bams, 1967). High ratios indicate significantly increased succeptibility of treated fish to predation. Figure 12 illustrates ratios for juvenile chinook, shocked at 28 C, with and without recovery before predation (A and B, respectively). Regression lines quantify the response for predictive purposes. The thermal dose that first initiates differential predation was about 10% of the median equilibrium loss dose, when no recovery was allowed (Coutant, in press).

The thermal exposures just initiating differential predation at three temperatures were determined for rainbow trout in another set of experiments (Figure 13). Geometric mean times to equilibrium loss and death were determined for the same group of fish, and the pattern of time-dependency with various temperatures held for all three responses. These differential predation tests indicated a stress reaction at about 11% of the duration of exposure needed for death. Thus, the same predictive model developed from thermal death could be used to set plant operating limits based upon sublethal stress condition.

c) Effects of reactor plumes.

Fore predictive purposes, it is convenient to consider juvenile downstream migrants being carried in deep water by the flow of the river to the outlet of the effluent pipeline and thence through the centerline of the plume being exposed to maximum temperatures. The undiluted effluent of the reactors is hot enough to be lethal to fish; however, it is not obvious whether significant numbers of downstream migrants actually experience exposures that are extreme enough to kill them because of the nature of the hydraulic characteristics of the plume. The effluent does not exist in a smooth flow condition (Figure 4), but appears at the surface over a relatively wide area as periodic and turbulent upwellings. Each of these upwellings expands at a rate comparable to the rate of flow downstream. These upwellings of warm water can be identified in Figure 4, particularly at the lower flow rates.

Since fish may be distributed throughout the river cross section, a few might be swept into the mixing transition zones and be exposed to sudden thermal increases. In 1968 and 1969 field experiments were initiated with the objectives of determining if, under conditions of natural migration, passage through the areas of reactor discharge killed young salmon, and to examine the temperature levels and exposure durations, which are encountered by the fish.

In one such study young chinook salmon, the progeny of adult stock from the Columbia River and subsequently reared from eggs in the Battelle-Northwest hatchery, were drifted through the reactor plume area in live boxes. Test and control fish were subsequently held for 24 hours in 1968 and 7 days in 1969 at ambient river temperatures downstream from the operating reactors, checked for mortalities and released. In the spring series the ambient river temperatures are low and the extent of temperature rise does not appear to be sufficient to cause mortalities. Even in the late summer and early fall when ambient river temperatures are higher, mortalities were not significant. Only in one test, carried out in 1969 at a very low flow (40,000 cfs) was significant mortality recorded. The maximum temperature increment on this occasion was in excess of 22 C in the mixing zone (Figure 14).

In certain reactor areas shore line intergravel seepage of heated water from the effluent retention basins does occur, and drift tests through these areas showed significant mortalities. We have no evidence, however, that young river fish actively swim into these areas of high temperature and low current velocities.

Effects of temperature on fish diseases

Columnaris has been endemic in the river many years prior to Hanford Operations, the etiological agent, Chondrococcus columnaris being positively identified in 1942 (Fish and Rucker, 1943). Studies were initiated in 1959, to determine effects of temperature and radiation on the incidence and infectivity of C. columnaris (Fujihara, Olson and Foster, 1960). Laboratory and field studies have shown that the infection of fish with columnaris becomes evident when the water temperatures rise above 10 C (50 F) and declines when the temperature decreases. Basic laboratory studies on antibody production and immune response to C. columnaris indicated that agglutinating antibodies in fish blood sera against columnaris provided a technique for field surveys (Fujihara, Olson and Nakatani, 1965). Measurement of agglutinating titres in blood sera of Columbia River fish showed a cyclic pattern during the year. Residual antibodies are carried by fish during the cold period of winter and spring with a sharp increase in titres and infection in the summer and fall. The field studies indicated that the fish ladders at Columbia River dam sites may be focal points for exposure and infection since resident coarse fish in the ladders show higher incidence and infection of columnaris. Since the anadromous salmon have to pass through the ladders, their potential for exposure is extremely high. Data on the incidence of columnaris in the Snake River, a tributary entering the Columbia River below Richland, above the reactors and directly below the reactors all indicate a similar seasonal cycle. There is no evidence of an enhanced degree of incidence or infection in those samples taken below the reactor operations area.

Thermal effects modelling

The laboratory data on the thermal resistance of fish is predominately concerned with temperature exposure, and together with the temperature data in the mixing zone below the discharge point is being developed into a predictive model of the potential hazards to downstream migratory fish. The model can predict the mortality of juvenile salmon under conditions of fluctuating temperatures, such as those that occur in many reactor plant outlets.

Early attempts in developing the model considered incremental death rates to be additive over the range of the fluctuating thermal experience. This was refined so that the rate of temperature change of fish tissue was considered relative to the external water temperature. Since we have now demonstrated that behavioral stress can be significant at temperature regimes near to 10% of that required to kill fish, the model can now reflect this factor. It is important to remember, however, that at this level we have no evidence to quantify this as a rate of predation, but rather as a measured stress that could have ecological consequences.

These models can be used in the initial planning stages of industrial and municipal release structures to predict the potential loss of fishery resources as a result of a proposed engineering design. It is proposed to extend this system to examine other aspects of ecological damage besides that of fish. Ultimately, these studies will permit the delineation of desired boundary conditions of an effluent discharge, not only as regards thermal releases, but also chemical and agricultural toxicants, since similar resistance patterns have been shown by fish exposed to toxic materials.

Summary and discussion

This review of the pertinent laboratory and field studies and their findings on the effects of thermal discharges from the plutonium production reactors at Hanford indicates that there is no demonstrable effect on the fishery resource. Consideration of the laboratory experiments and field data in the light of the seasonal thermal cycle of the river temperature (Figure 3) and in relation to the seasonal life stage of salmon and trout present in the river indicates that the river temperatures could be higher during the periods of late fall, winter and spring without causing significant damage to the development of young salmon. The uninhibited migration of salmon and trout past the reactors and the continued increase in the size of the spawning populations near the reactors indicate that the reactor discharges have not adversely affected the environment for the fish species of most concern. During the summer months, the temperature of the Columbia River has always been above the optimum for salmonids, especially in relation to the generalized "optimum" temperatures derived from laboratory experiments. Although a temperature of 60 F is often recommended as an upper limit for adult salmon in route to their spawning grounds (U.S. Fish and Wildlife, 1967), recorded temperatures for the Columbia show that 60 F has always been exceeded during the summer months.

Even though the studies outlined here indicate that there is little or no evidence of direct damage from a cluster of reactors on a large river, the problem of evaluating and assessing the total ecological effect of small increments of heat added to rivers, lakes, estuaries and coastal waters defies a direct definitive answer because of gaps in our knowledge about the effects of subtle perturbations of temperature on other ecological parameters.

We hope that the basic principles that we have developed for studying the direct effects in reactor mixing zones will be applied on a broader basis, since we believe that the best practical method of investigation of these problems is the direct approach of working on-site with local fish species and local water.

However, studies on the direct effects of thermal increments are basically only required for mixing zones and to enable more efficient outfalls to be designed and developed in order to protect both resident and migratory species of fish. With more and more of the world's available water resources being used to satisfy the demands of increasing populations, greater emphasis in the future will have to be given to the sum of the effects of total water use upon the ecosystem. The return of heated water from energy plants is but one of these.

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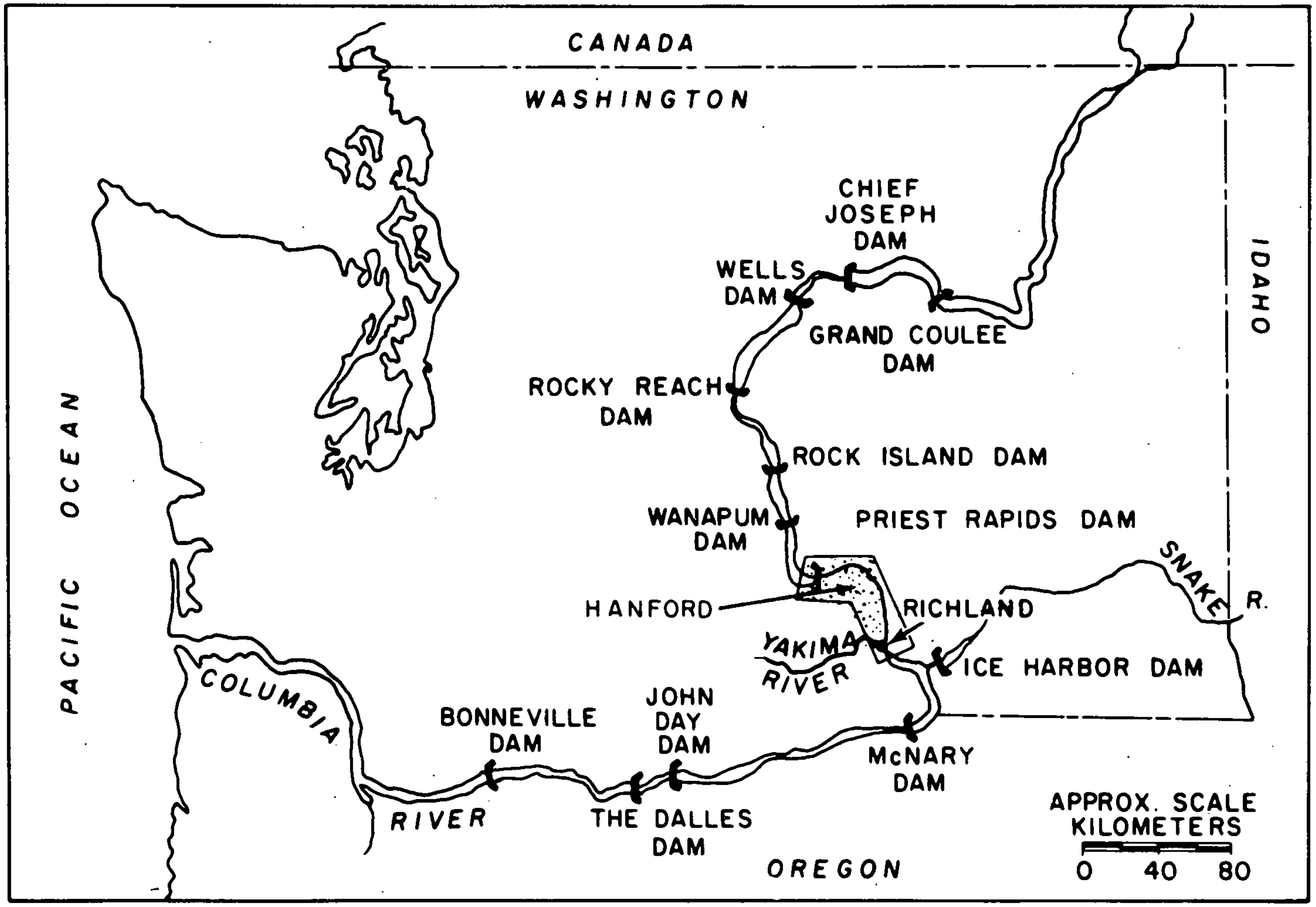

Figure 1. Hanford Reservation and the Columbia River, Washington, U.S.A.

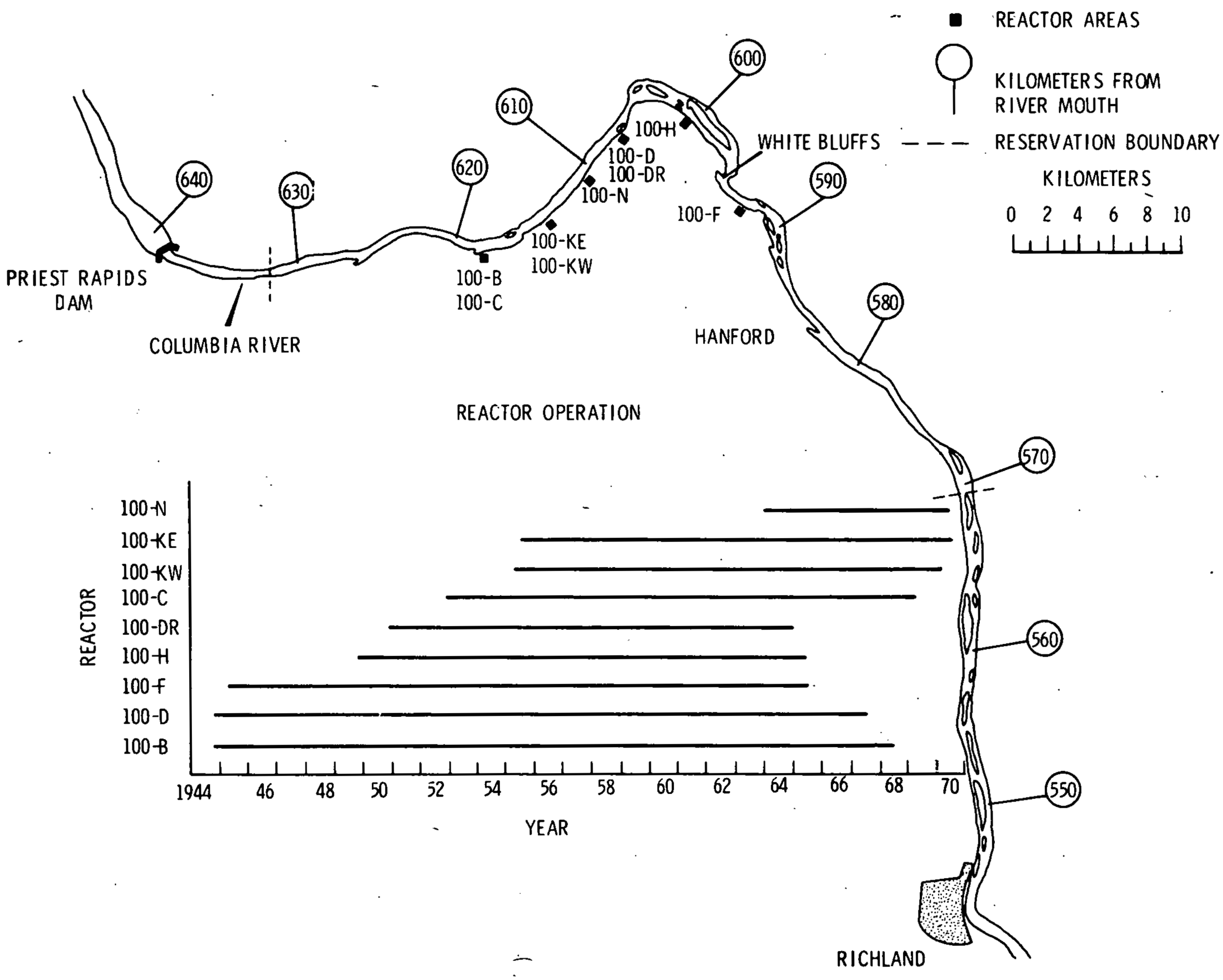

Figure 2. Locations and periods of operation of reactors at Hanford.

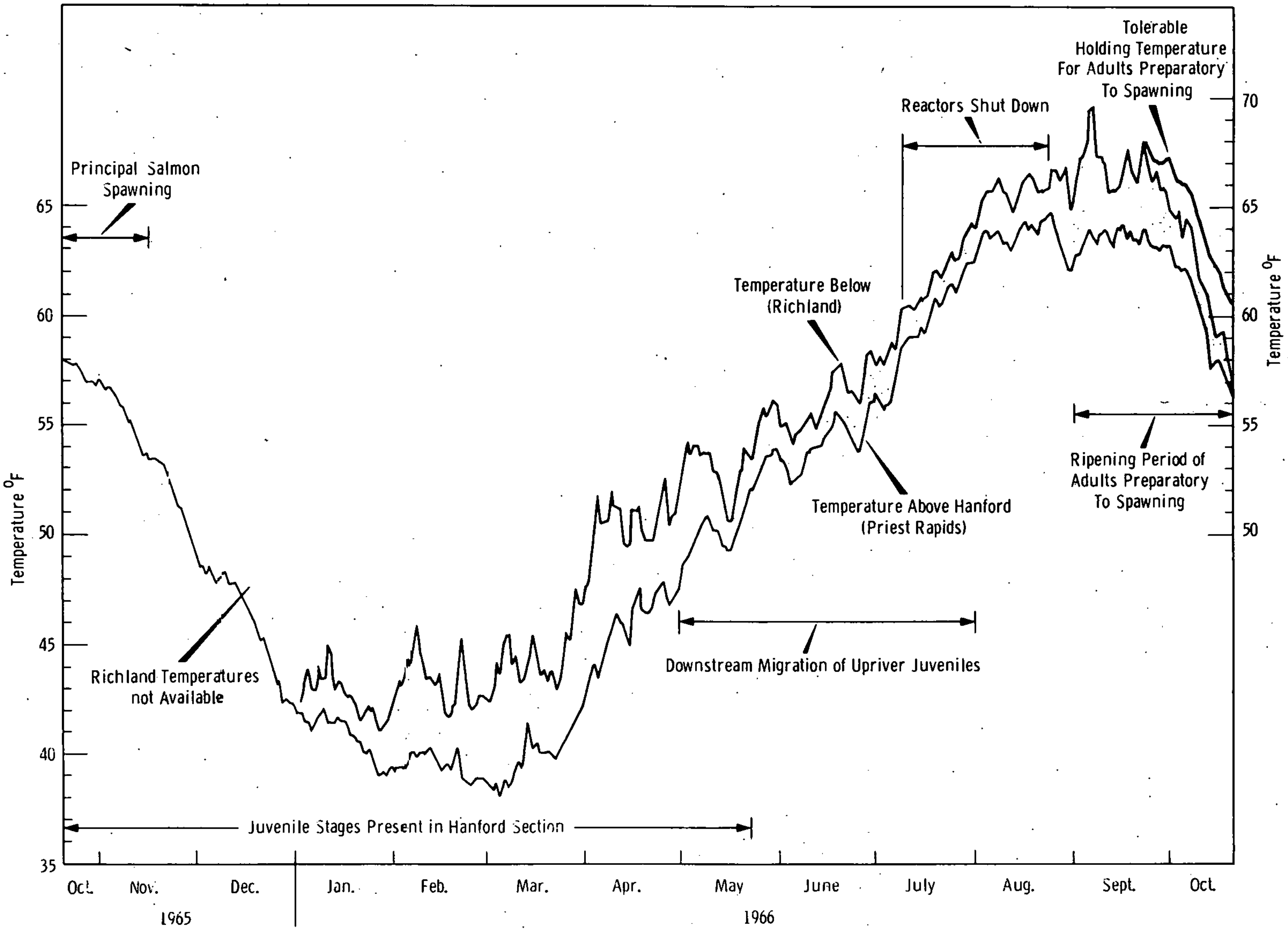

Figure 3. Seasonal cycling of Columbia River temperature above and below Hanford (1965-1966), and relationship with chinook salmon.

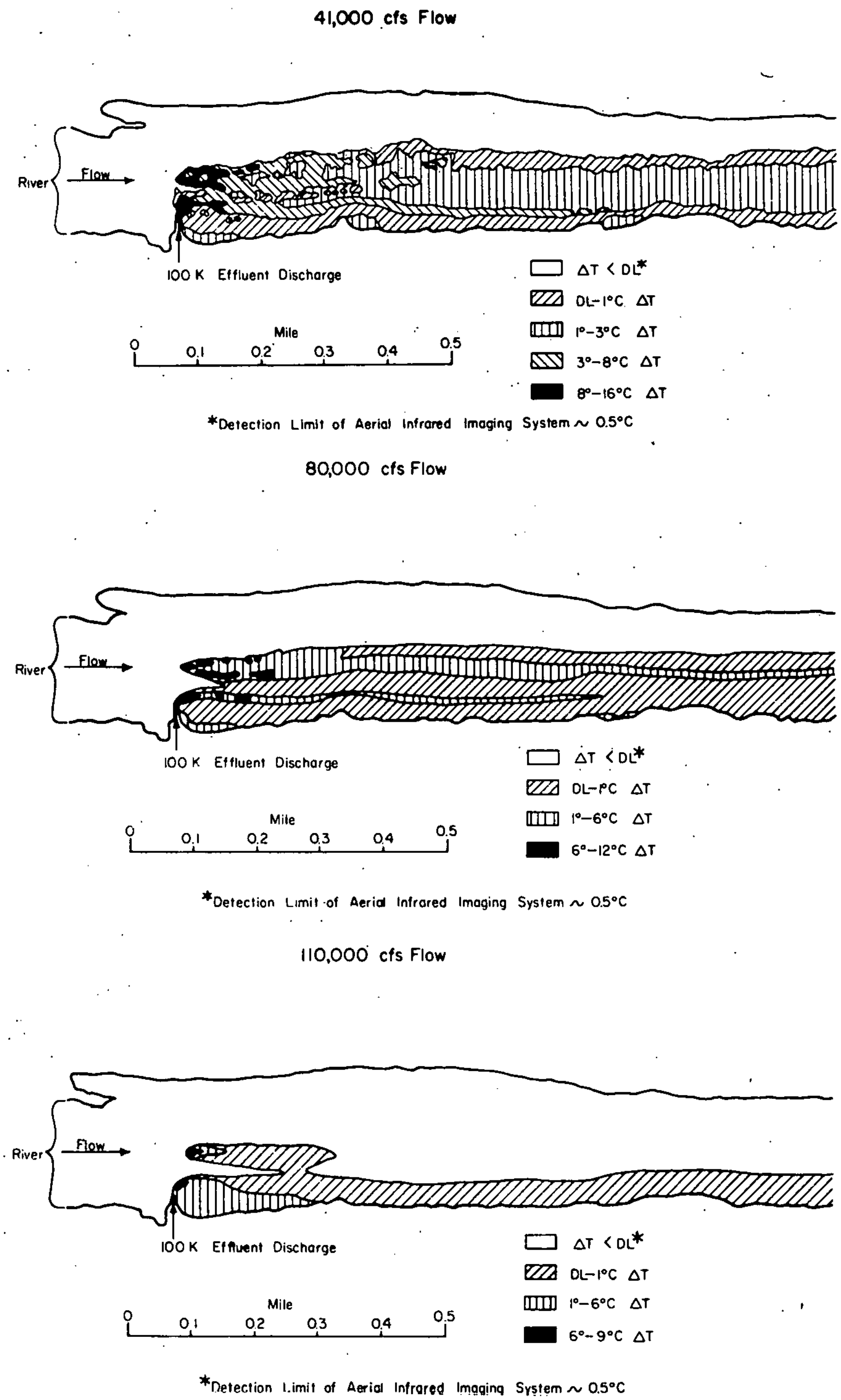

Figure 4. Columbia River surface temperature patterns at three flows: a) 41,000 cfs, b) 80,000 cfs and c) 110,000 cfs.

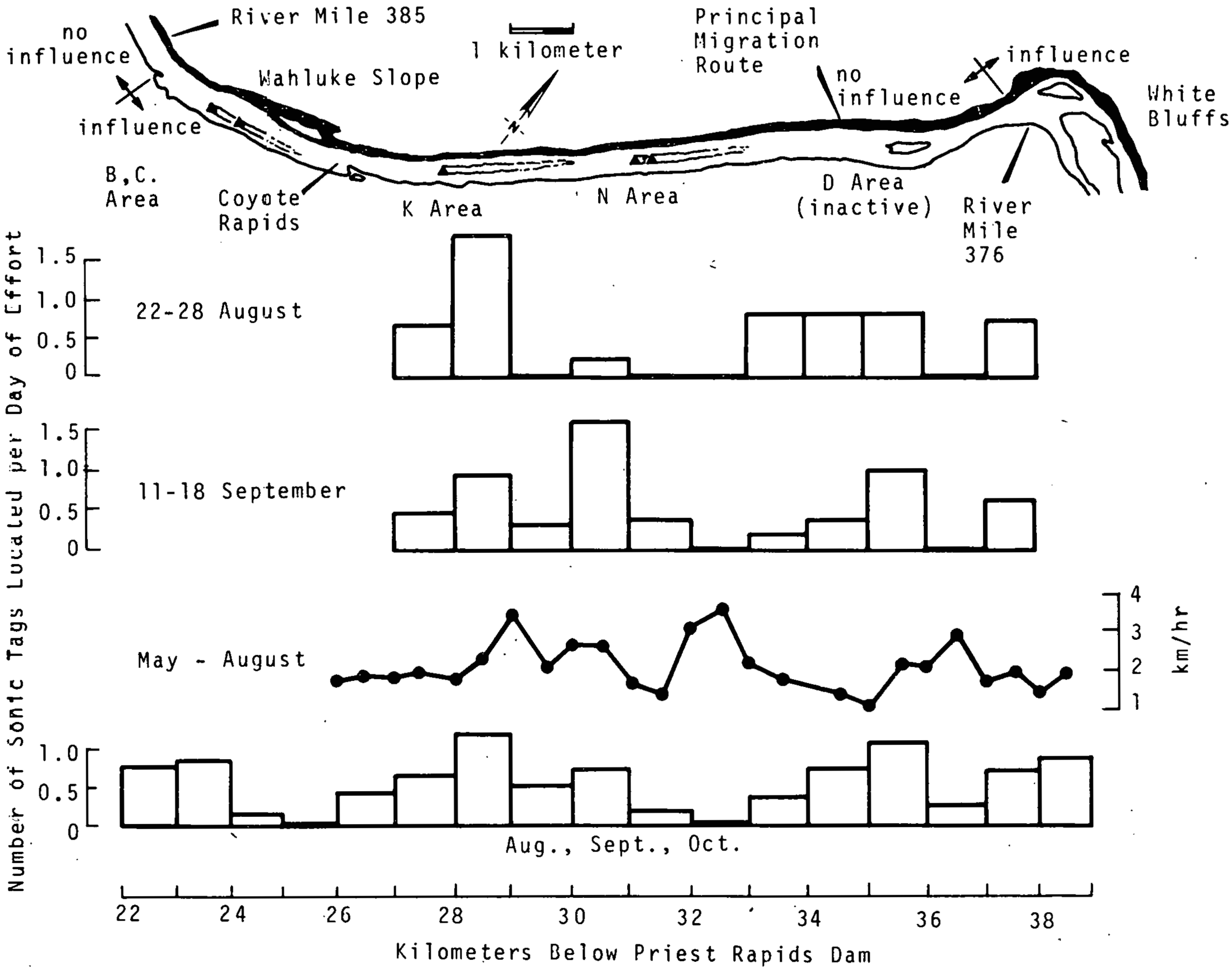

Figure 5. Principal migration route of sonic tagged chinook salmon and steelhead, frequencies of point locations, and average migration speeds.

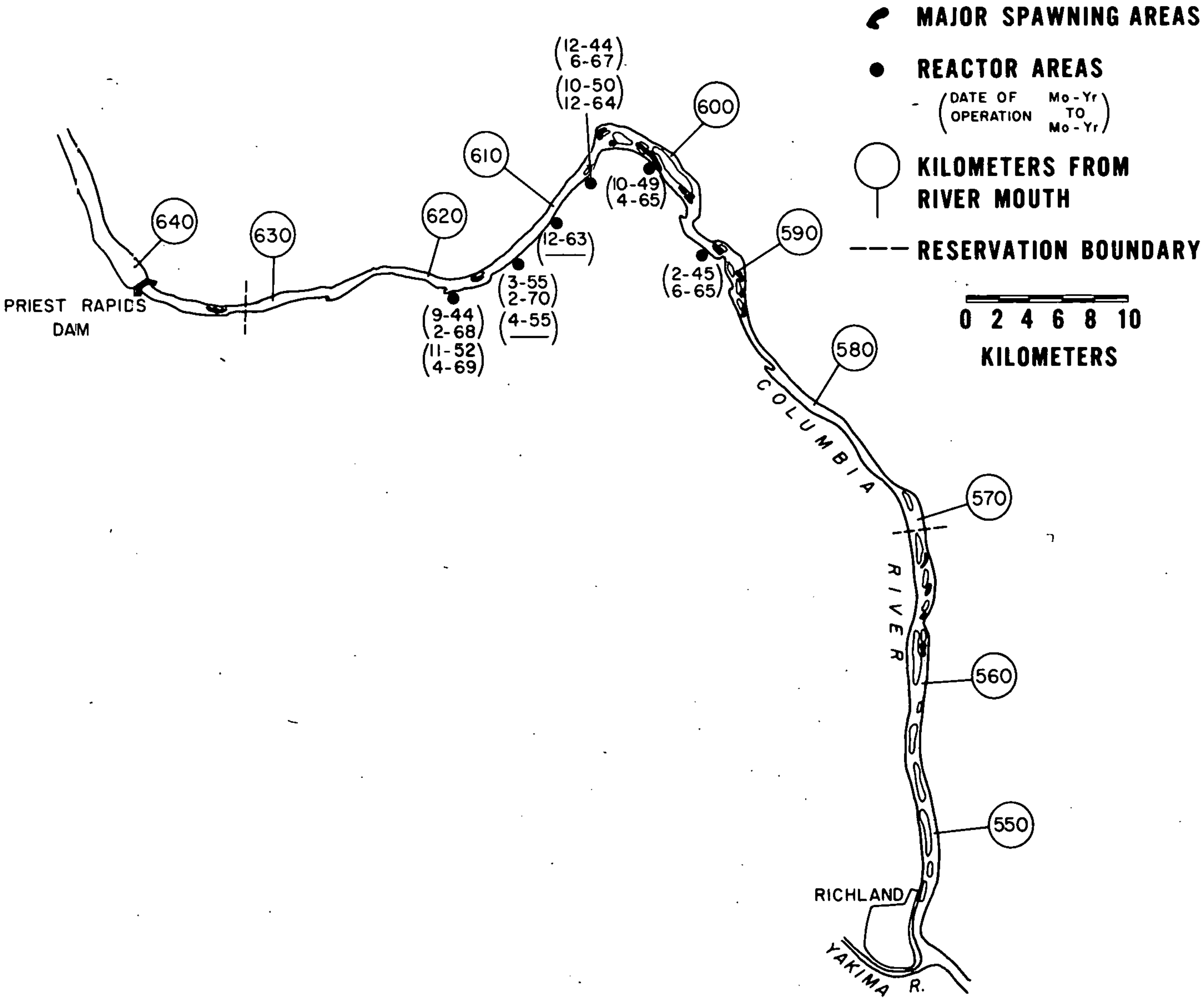

Figure 6. Spawning areas of chinook salmon in the Hanford area.

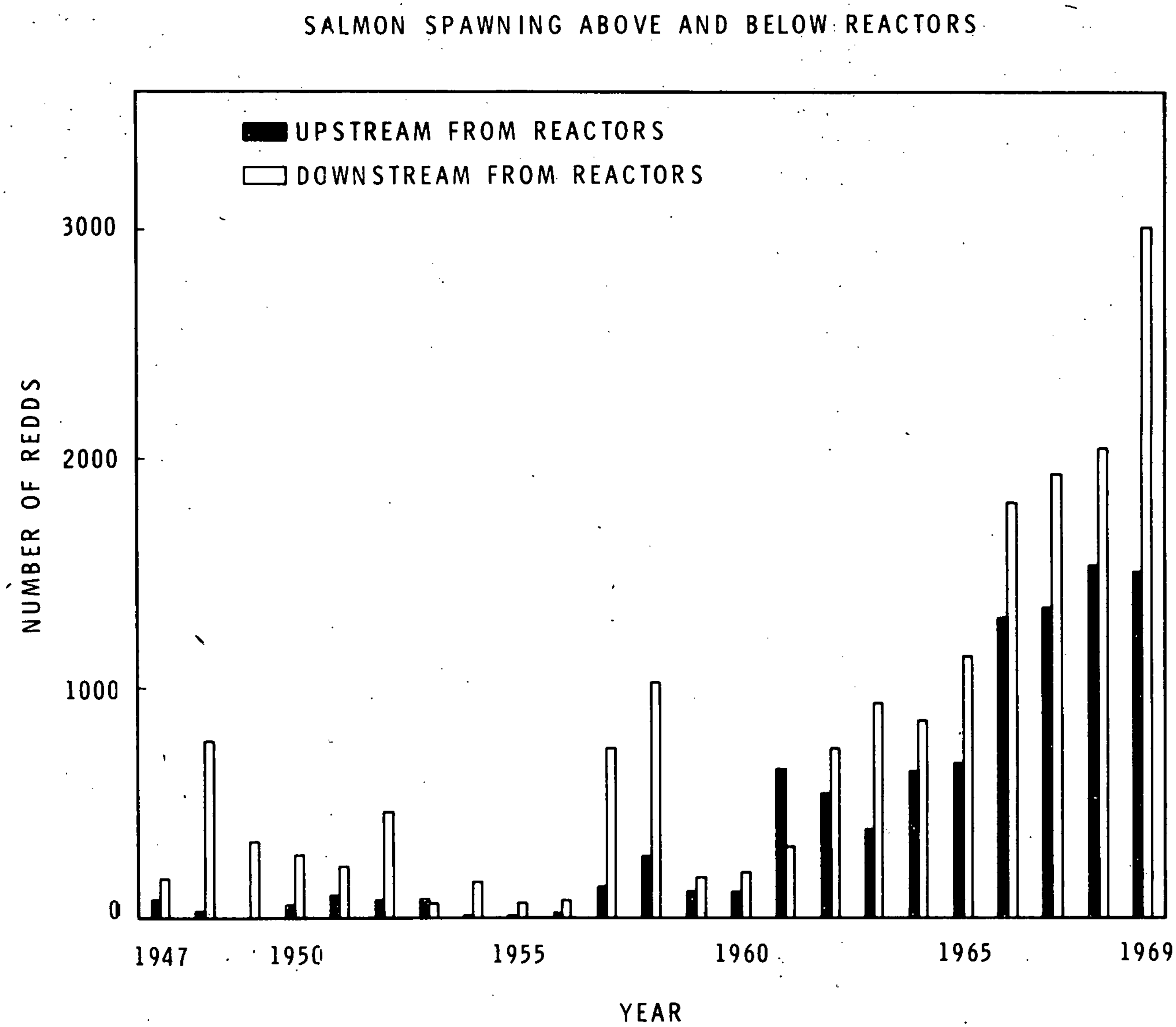

Figure 7. Chinook salmon census of redds above and below the reactor areas at Hanford.

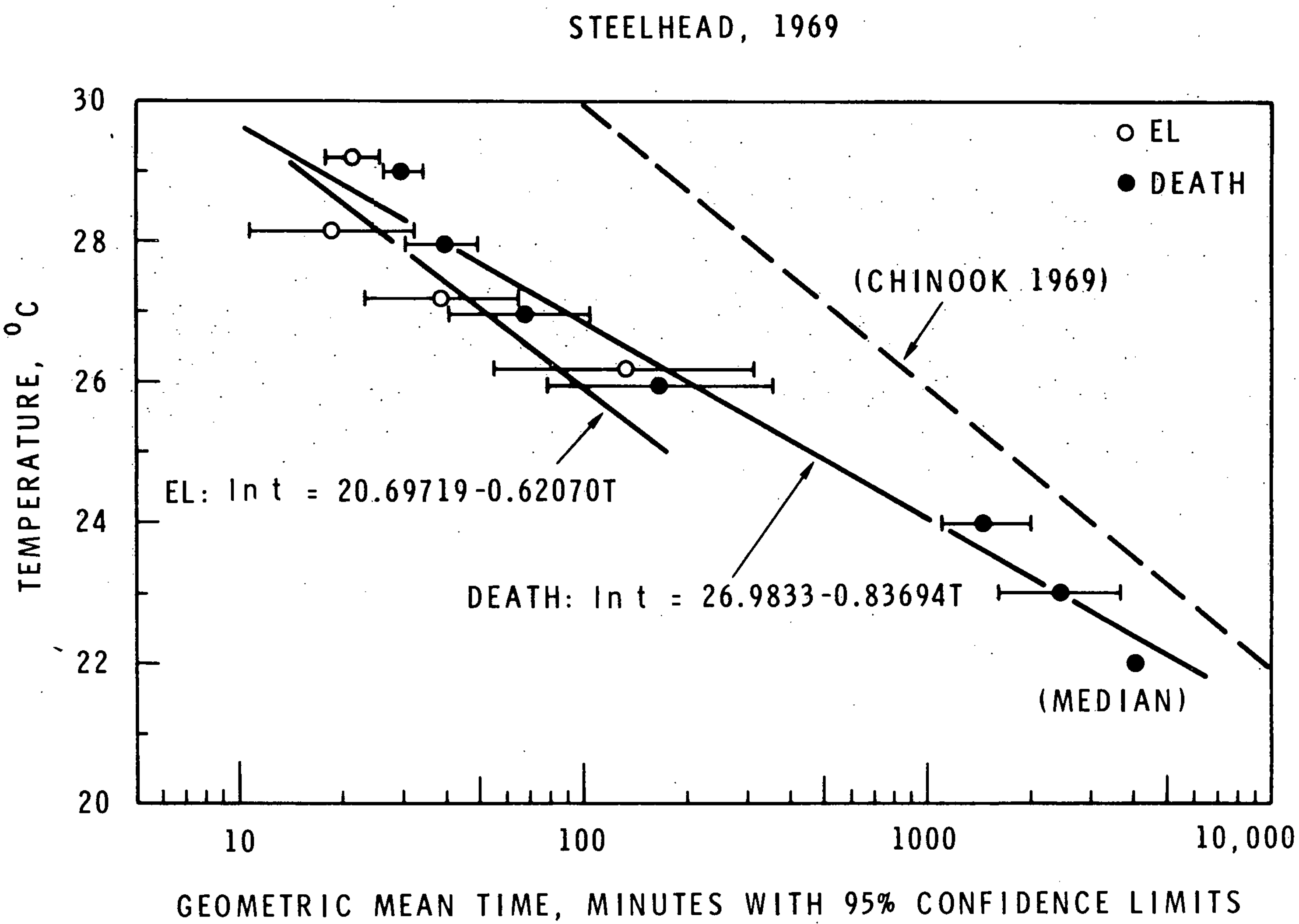

Figure 8. Geometric mean times (t) to equilibrium loss (EL) and death of adult steelhead trout, 1969, with 95% confidence limits. A regression line for 1969 chinook data is included for comparison.

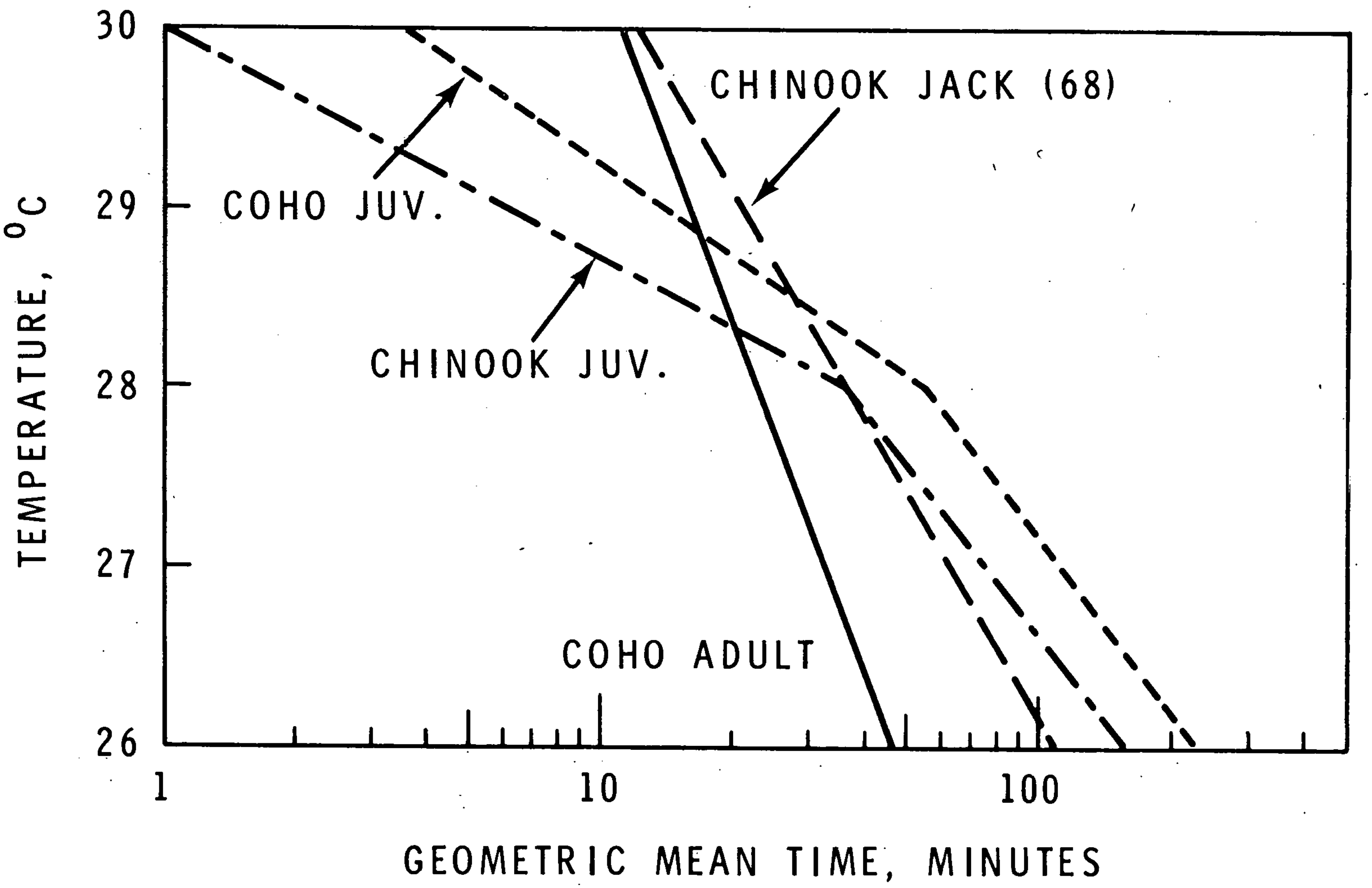

Figure 9. Summary of thermal resistance of juvenile and adult coho salmon and juvenile and "jack" chinook salmon.

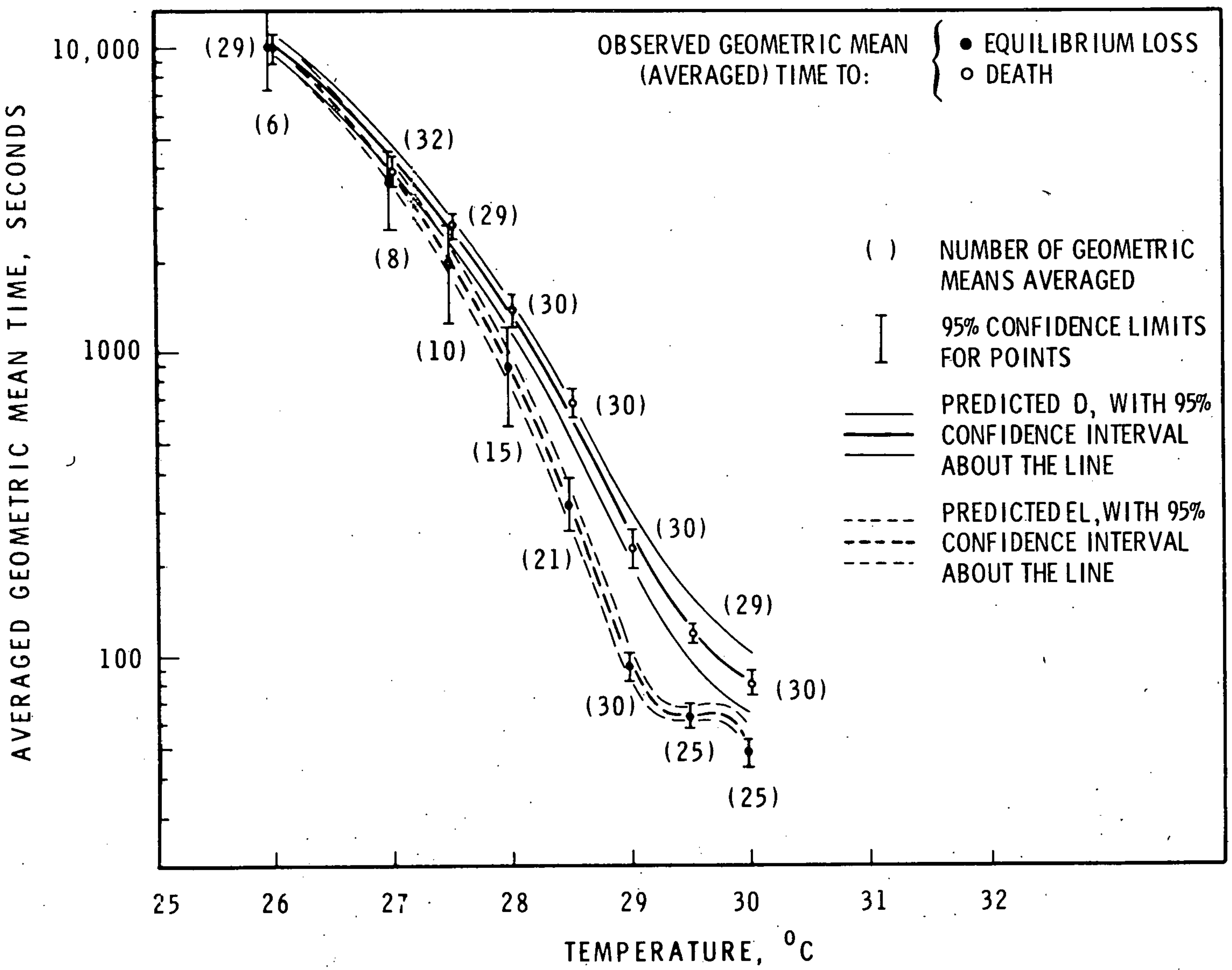

Figure 10. Cubic models of geometric mean times to equilibrium loss (dashed) and death (solids) of all juvenile chinook for which data were available. Confidence limits are shown for both points and lines.

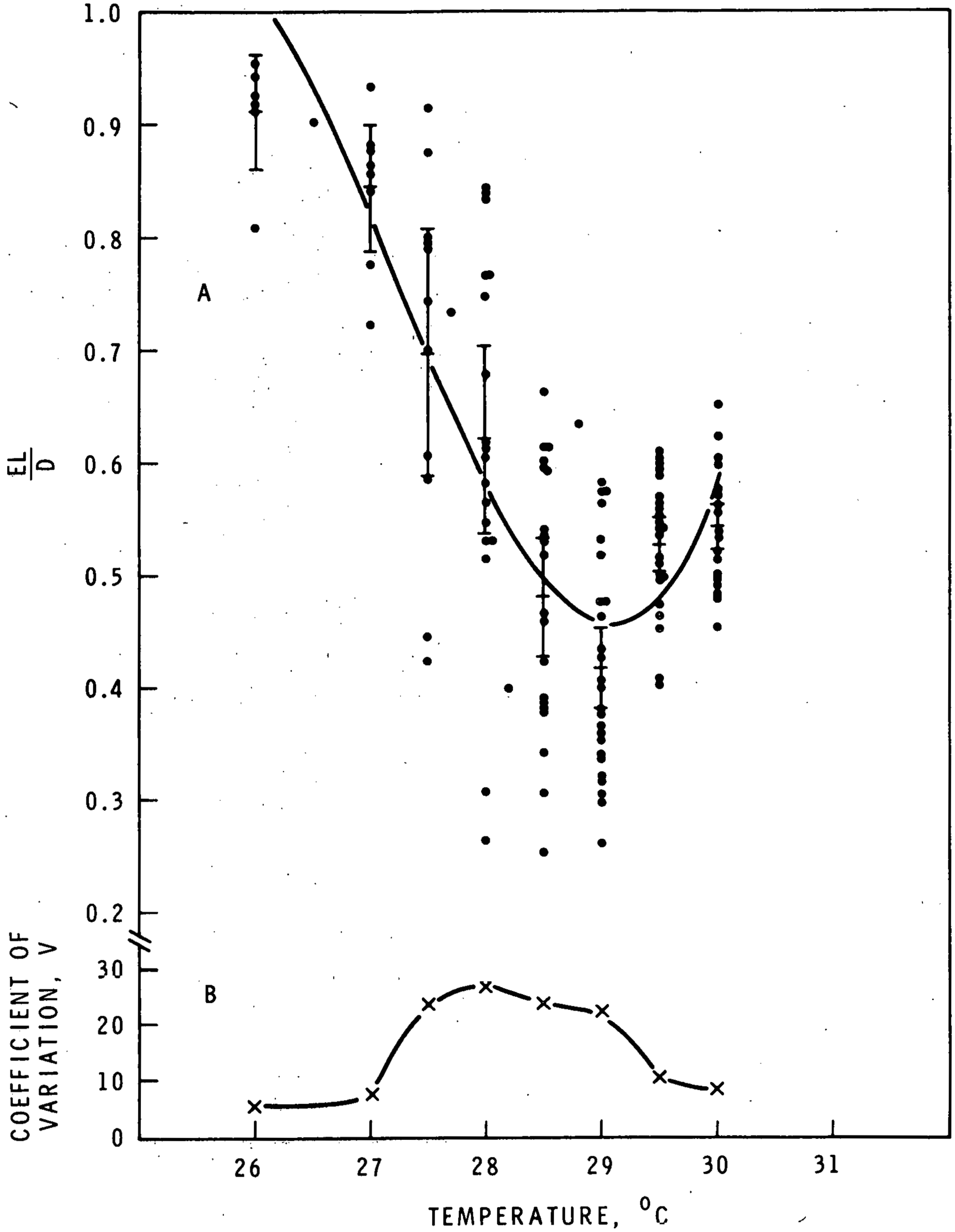

Figure 11. (A) Relationship between geometric mean equilibrium loss (EL) and death (D) times for all juvenile chinook for which data were available. Means and 95% confidence intervals are shown for most test temperatures. The curve represents a cubic model for the data. (B) Coefficient of variation for ratios at various test temperatures. (From C. C. Coutant and J. M. Dean, ms. submitted for publication).

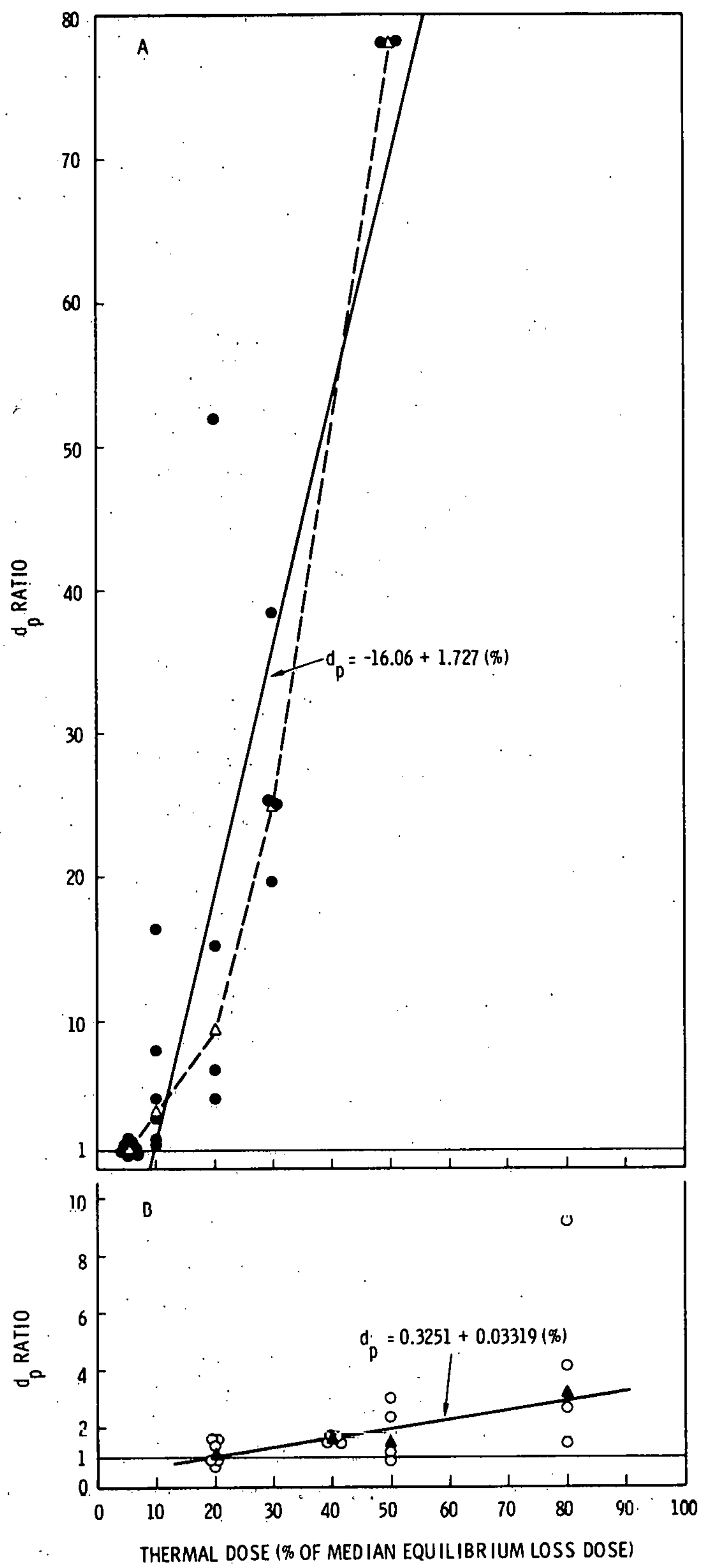

Figure 12. Ratios of instantaneous predation rates following various durations of exposure of juvenile chinook salmon to 28 C; (A) no recovery, (B) one-half hour recovery. Ratios are shown for individual tests and the combined ratios for each exposure duration.

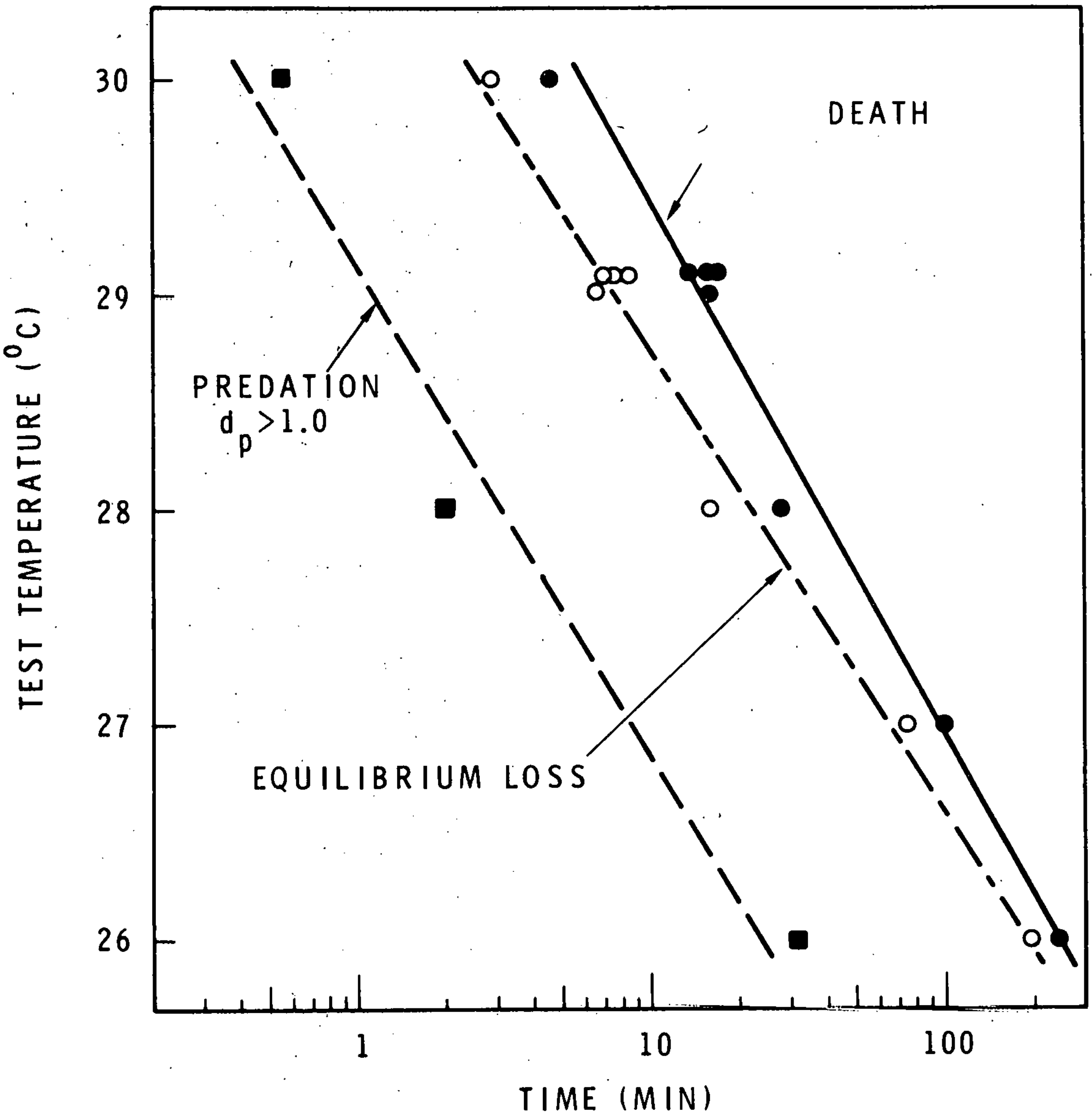

Figure 13. Relationships among three effects of acute thermal shock to 15 C acclimated juvenile rainbow trout.

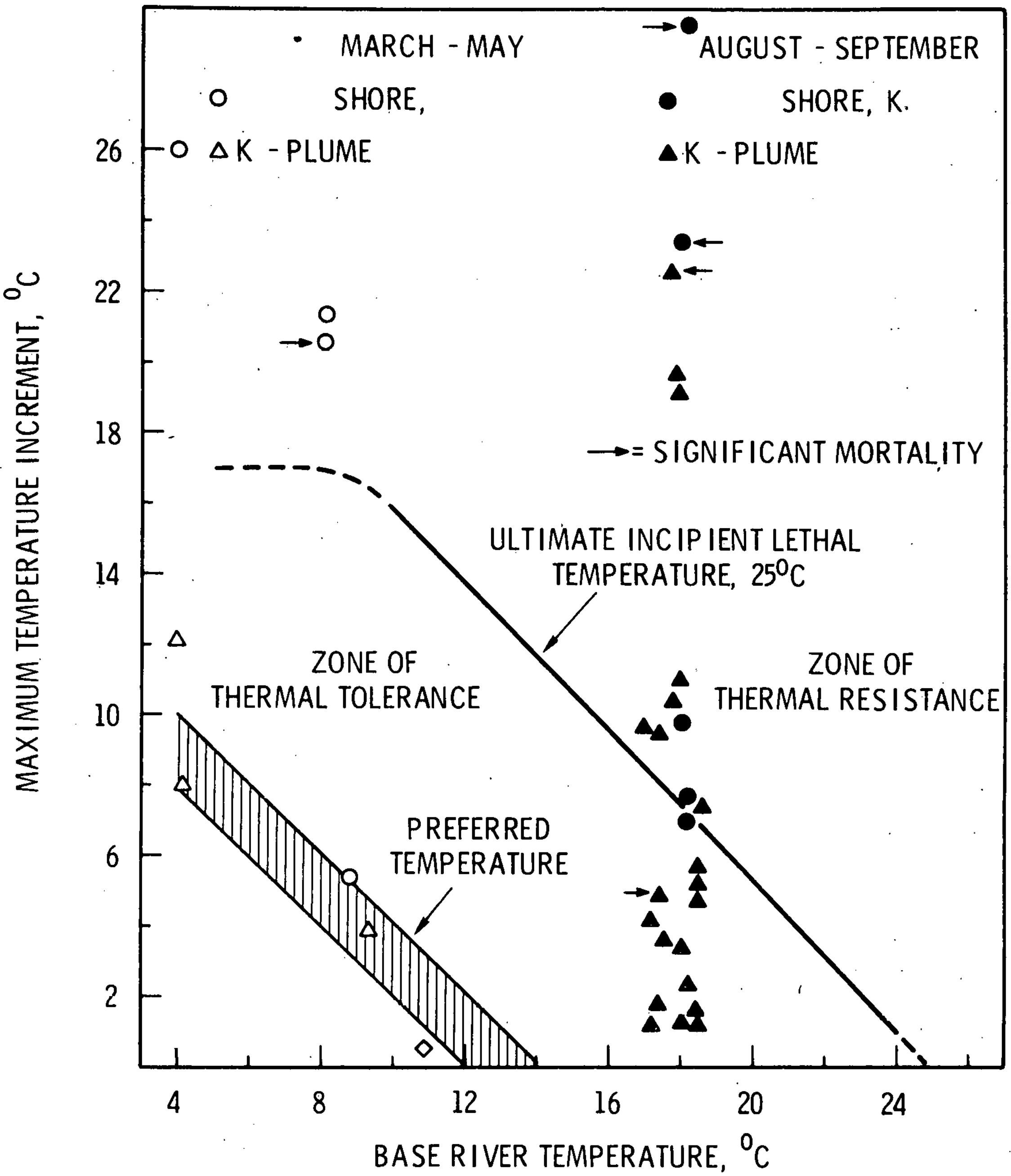

Figure 14. Maximum thermal exposure of juvenile salmonids during live box drifts through effluent discharges in 1969 (temperature criteria adopted from Brett, 1952).