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EFFECTS OF HEATED DISCHARGES
ON ANADROMOUS FISHES^{1,2}

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EFFECTS OF HEATED DISCHARGES

ON ANADROMOUS FISHES

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The physical and biological aspects of Columbia River water temperatures have been studied at Hanford for more than 20 years. Much of the research in the first decade centered on the problems related to the consequences of releasing radioactive materials in the heated reactor effluent discharged to the River and to the relationships between reactor production efficiency and River temperatures [1]. The emphasis in early years on the radiological aspects rather than the heat aspects was necessary due to the paucity of radiological information. However, the effects of elevated temperatures, particularly on Columbia River fishes [2,3], were always studied along with the radioactivity and chemical toxicity features of the effluent.

While Hanford has accrued much information and experience in water temperature problems through the years, only relatively recently has national attention been focused on the biological effects of heated discharges into aquatic systems. The growth of the U.S. population concomitant with demands for more electric power, the advent of thermal nuclear power plants, the passage of the "Federal Water Quality Act of 1965" are all important factors in our national concern about the water quality and preservation of the aquatic environment.

Investigations on the effects of water temperature on aquatic organisms, including effects on anadromous fishes, have attracted much interest and research activity. Recently, V. S. Kennedy and J. A. Mihursky published an extensive bibliography listing 1,220 references on the effects of temperature in the aquatic environment [4]. E. C. Raney and B. W. Menzel provided additions to this list [5]. H. Harty et.al., reported on the nuclear power plant siting in the Pacific Northwest for the Bonneville Power Administration in a voluminous report evaluating possible sites from geological, hydrological, seismological, meteorological, socio-economical and ecological standpoints [6]. J. R. Brett has excellent review articles on the thermal requirements of fish, particularly for salmonids [7,8]. R. E. Burrow reported on the water temperature requirements for maximum productivity of salmon [9]. Perhaps no other single environmental parameter in the aquatic environment, i.e., water temperature, has received so much attention by aquatic biologists.

Despite this wealth of biological information on temperature effects, a salmon biologist faced with the pressing pragmatic problem of predicting or assessing the biological costs or benefits to a fishery resource of super-imposing some heat increment of a few degrees on a specific river system encounters an extremely complex and difficult task. He finds gaps in our knowledge which do not permit him in a practical sense to integrate and apply laboratory and field findings to his particular problem. Part of the difficulties arise because many excellent studies were not specifically designed to help resolve his complex field problem of a specific river ecosystem. Further, the extrapolation of laboratory findings to field situations always poses problems. He may also find field studies related to thermal plants located in another river system helpful (e.g., a steam-electric plant on the Delaware River), but not representative of a salmon river. While he turns to fundamental biologists for basic biochemical, physiological, behaviorial, and

ecological information, and recognizes the importance of basic scientific studies, he finds insufficient information. The general effects of increased water temperatures on fish are well known. Increases in metabolic rates and oxygen requirements, in reduction in stamina, in sensitivity to toxic materials and fish diseases, are but some of the effects (usually inferred from laboratory experiments) associated with increased temperatures, but these generalizations in our present state of knowledge are no substitute for extensive on-site studies and evaluations. Thus, he is likely to use the direct observational approach of investigating the effects of elevated temperatures on salmon or other desired species on site; using local fish and on-site water. This approach has been essentially used at Hanford.

The purpose of this paper is to review some of the highlights of Hanford's biological research related to the effects of elevated water temperatures, especially on salmonids. About 30 species of freshwater fishes have been identified in the Hanford reach. They are all exposed to reactor effluent in varying degrees, but our research has emphasized the Pacific salmon, Oncorhynchus, and rainbow trout, Salmo gairdneri, because of their sensitivity to warm waters and their well-known dominant economic importance to commercial and sport fisheries.

Hanford Reactors and the Biological Problem

One of the primary reasons Hanford reactors were sited on the Columbia River was the availability of large volumes of cold river water for reactors' coolant. Potential hazards to fishery resources caused by discharging heated effluents into the Columbia River were recognized, even before the reactors were built [10]. As early as 1945, young salmonids were reared from "green" eggs to fingerling size in different concentrations of reactor effluent to observe their growth and mortality [11]. Three characteristics of reactor effluent are of major biological

importance. These are, heat, radioactivity, and certain chemicals (mostly sodium dichromate, used routinely as a corrosion inhibitor in reactor cooling tubes). The review of the research on the radioactivity and chemical toxicity features of effluent is beyond the scope of this paper, but it is noteworthy that biological reasons were largely responsible for modifying reactor operations to reduce the amount of phosphorous-32 and sodium dichromate discharged in effluent water.

Figure 1 shows the Hanford Reservation with the reactor areas along the right bank of the River near the northern boundary of the 600-square-mile Reservation. Our main experimental hatchery and wet laboratory located at 100-F area downstream from all reactors use untreated Columbia River water; hence it functions as a "built-in" continuous monitoring station. Clearly, our hatchery fish are exposed to effluent contaminated river water, and the stress of any major release would obviously wipe out our stock. For planned monitoring tests, we have another smaller hatchery located at a reactor farther upstream where effluent at controlled levels may be used for rearing salmon and trout.

Detailed information about Hanford's reactor effluent or the actual heat contribution is classified, and the public and the fishery agencies receive only the strong impression of "thermal pollution" from observing the towering columns of steam which rise several hundred feet above each retention basin in the Hanford reactors areas. However, a study of the heat contributed by Hanford reactors to the Columbia shows immediately that Hanford adds only a relatively small heat increment on the widely variable seasonal river temperatures and flow. During much of the year, the temperature changes caused by variation in flow, the natural heating and cooling of the river within the Hanford stretch from solar radiation, evaporation, and air currents exceed the Hanford effect [12]. The history

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of the operation of Hanford reactors summarized in Figure 2 shows a total of six reactors operating during 1944-1955, eight during 1955-1964, and the maximum of nine, during 1964. At present, there are only four reactors operating.

The biological problem is to evaluate the effect of Hanford's heat increment on fishes, especially on the valuable salmon populations. This problem defies a direct, definitive answer, and much of the evidence on Hanford effect or lack of effect is circumstantial or inferred from limited field studies, laboratory experiments, and the literature. Although Hanford temperature effects are emphasized because of the interest of this meeting, it must be remembered that many other complex factors control the health of the salmon populations. Hanford temperature effects need to be kept in context with the major factors which contribute to the mortality of the salmon throughout its life cycle and recent history.

River Temperatures

Before discussing the temperature effects of reactor effluents, water use upstream from Hanford needs examination. On the main stem of the Columbia River upstream from Hanford, there are seven dams, viz, Priest Rapids, Wanapum, Rock Island, Rocky Reach, Wells, Chief Joseph, and finally, Grand Coulee. Obviously, the variation in the methods of operation of these dams, especially the pattern of daily and seasonal discharges, greatly influence the base river temperatures experienced at Hanford and also the temperature regimes below Hanford.

The notion that dam construction invariably raises the water temperature of the Columbia is questionable, if not erroneous. R. T. Jaske and J. B. Goebel have shown that the erection of low-head reservoirs on the main stem of the Columbia River have not produced significant changes in the average temperature of the River, and that dams and reservoirs actually decrease the expected seasonal variances in water temperatures [13]. A review of the history of Columbia

River temperatures by Jaske and Goebel shows that, with the advent of dams and multiple water use, there has been a suppression of the maximum temperatures during the summer months, an elevation of the minimum temperatures during the winter months, and little change in the annual mean temperatures. Further, they demonstrated that construction of impoundments has created a shift in the timing of the seasonal temperature cycle towards the later months by lengthening the time of water passage. The maximum temperatures formerly observed in early August are shifted about 30 days, and are now seen in early September. The shift has caused a gradual increase in the fall temperatures of the main-stem river, and a corresponding decrease in spring temperatures.

Temperature Effects on Adults - Transients and Residents.

Both salmon and steelhead trout (Salmo gairdneri gairdneri) spawn in freshwater, and the progeny spend varying periods in freshwater before migrating to sea where they obtain most of their growth, and return as mature adults to their home stream to start the cycle again. Dams have inundated most of the spawning grounds in the main stem of the Columbia, but a small spawning area still remains in the only free-flowing stretch of about 42 miles from Priest Rapids Dam to Ringold (15 miles upstream from Richland). Some 33 miles of this reach are within the confines of the Hanford Reservation. Virtually all of the salmon spawning now occurs in streams tributary to the Columbia, and thus most adult fish entering the Hanford reach are transients bound for areas upstream from Hanford. Anadromous species in the Hanford reach are chinooks (O. tshawytscha), sockeye (O. nerka), silver or coho (O. kisutch), steelhead (Salmo gairdneri gairdneri), shad (Alosa sapidissima), white sturgeon (Acipenser transmontanus), and Pacific lamprey (Lampetra tridentata).

In a particular year, 50,000 to 100,000 adult sockeye salmon migrating to spawning areas in Osoyoos Lake and Lake Wenatchee may pass the Hanford reach during July. A study of the sockeye counts at different dam sites as the fish progress upstream does not indicate delays in the Hanford reach [14]. Most of the sockeye counted over McNary Dam (below Hanford) are accounted for by summation of subsequent counts at Ice Harbor Dam (Snake River) and Priest Rapids Dam (above Hanford). On the other hand, counts of summer run steelhead at these dam sites show significantly high and as yet unaccountable losses above McNary Dam. The welfare of these summer steelhead population is of deep concern to fishery agencies.

A direct approach to determine the migration behavior of adult salmon and steelhead trout near reactor plumes in the Hanford reach was started in the fall of 1967 in cooperation with the Bureau of Commercial Fisheries [15]. A sonic fish tag developed by the Bureau was used to track fish movements. The tag emits a high-frequency signal which can be monitored with hydrophones mounted on a boat. Some 70 adult salmon and steelhead trout were tracked in the Hanford reach. The data showed no temperature block of fish, but most fish migrated upstream in relatively shallow waters (4-9 ft. depth) along the opposite bank from reactor sites. (Figures 3 and 4).

At a recent meeting of the Ben Franklin Technical Committee of FWPCA, engineers discussed the presence of a cooler "wedge" of water along the shore opposite the reactors and speculated that this cooler "wedge" provides the route for migrating salmon. However, our data show that fall chinook salmon are not limited to the cool wedge. Even when the number of reactors discharging effluent

into the river was much greater than it is at present, spawning occurred year after year near the reactor side of the river in waters in which complete mixing of the effluent had not taken place. The implication that the routes of travel of migrating salmon is influenced solely, or nearly so, by water temperatures in the Hanford Reservation is not supported by field observations. Since it is known that salmon are extremely responsive to variance in water velocity, some effort will be made next season to obtain detailed velocity measurements on the migration route along the banks.

An aerial census of fall chinook spawning in the Hanford reach has been made annually, since 1947 [16]. These records of the number of salmon nests observed each year for over 20 years are perhaps the best circumstantial evidence of the continued viability of the fall chinook population that spawns within the Hanford Reservation. Of the total escapement of fall chinook salmon above Bonneville Dam, about 6-13% spawn here. This race of chinook salmon enters the Columbia and migrates to its spawning grounds during the late summer when the river temperature is near its annual peak. The eggs and young are certainly much more subject to any effects of the Hanford Plant than races that spawn elsewhere. There is no evidence, however, that the local race has been adversely affected. On the contrary, the numbers of salmon nests observed has increased from about 300 prior to 1950 to a record number of over 1700 in 1965, 3100 in 1966, and to a 21-year record high of 3300 in 1967 (Figure 5). This increase in spawners is most likely related in part to displaced spawners when Priest Rapids Dam was completed in 1959, but it is interesting that even though most chinooks have a four-year cycle, we have seen a continual increase for eight years since 1959. Five of these years coincide with maximum reactor operation. This increase

in local spawners has occurred during a period of years when the runs of fall chinooks to other parts of the river system, e.g., the Snake River, have declined appreciably.

Not only do we have a census of spawners, but we also have annual records on the distribution of the nests in the Hanford reach. Figure 6 summarizes the number observed in areas above and below the reactors. Before 1959, the area above the reactors had an average of 17% of the total count, but after 1959, this increased to 42%. The extent and distance of "fall-back" from the dam is unknown, but it could also be responsible for increased spawning below the reactors. In other words, the greater utilization of the Hanford reach for spawning may be related to unfavorable spawning areas upstream or downstream from Hanford. Nevertheless, for over 20 years, the Hanford reach has been an acceptable area for salmon spawning.

It is well known that a female adult salmon is normally highly sensitive to the environmental requirements necessary for successful nest building, spawning, and incubation of eggs. Much work has been done to understand these requirements, such as gravel size, water flow and water temperatures, especially in the interests of construction of artificial spawning channels [17,18]. Since spawning normally occurs only on a limited range of sites, we have considered the possibility of displacement of our local spawners in the Hanford reach due to reactor plumes. No data on the distribution of spawning areas prior to the Hanford operations are available, but a comparison between the distribution of the spawning areas during operations of eight reactors in 1962 and four reactors in 1967 should indicate some measure of the influence of reactor plumes on spawning behavior.

Figure 7 shows the distribution of salmon nests of fall chinooks counted by aerial survey in 1962. A total of 712 nests shown in Figure 6 are clearly in Hanford effluent zones. The main river channel between the 100-H outfall (River mile 371 to 373) and the end of Locke Island has attracted salmon spawners

from 1947 to the present. During much of this time, these fish were in a zone of incompletely mixed effluent from 100-H reactor. Similar observations have been made in the river immediately below 100-D and 100-F, during periods when these reactors were in operation. The distribution shown is typical of many years of observation. It is of interest to note that last fall, when 100-D, 100-H, and 100-F were no longer operating, the distribution in this reach showed little change. The reactor plumes apparently are not a significant controlling factor in the distribution of the spawning areas in this reach. The spawning areas appear to be determined more by gravel size, current velocity, and water depth.

Temperature Effects on Eggs and Young Salmon Resident in the Hanford Reach

The experiments on rearing young salmonids in reactor effluent are reported in over 20 A.E.C. reports through the years since 1946. This work, reported by P. A. Olson and R. F. Foster in earlier years and more recently by P. A. Olson and R. E. Nakatani, provided estimates on critical concentrations and gave some assurance that the average concentrations of reactor effluent found in the river will not induce growth depression or cause excessive mortality. These laboratory tests have been continued through the years because of variations in upstream water use and technical changes in reactor operations. Usually, effluent concentrations greater than 4% resulted in excessive mortality, but acceleration of growth occurred in all concentrations up to about 6% because of the warmer water. When concentrations exceeded about 7% effluent, growth depression occurred because of the toxicity of hexavalent chromium in the effluent. No radiation damage could be demonstrated at these levels of effluent concentrations.

Because the eggs and young of salmon are especially sensitive to warm waters, considerable research has been done at Hanford on testing the biological response of young salmon and trout reared under various heat increments above base river temperatures [19,20]. For example, during the 1966-67 season, young chinook salmon were reared for over five months under seven temperature regimes, each treatment following the Columbia River seasonal pattern, but differing by 2° F. and encompassing a range of 12° F. The results on growth and mortality are summarized in Table I. Temperature increments exceeding 4° F. above the base river temperature caused excessive mortality, i.e., greater than 20%, in fish hatched from spawn collected in October. The December spawn tolerated an incremental addition as much as 12° F. without significant mortality. In the river, however, most of the spawning is over by mid-November with few December spawners. The particular numbers on heat increments tested in the laboratory are not important in themselves, except as a demonstration that more heat can be added during late fall and winter seasons without significant detrimental effects. Furthermore, they show that warmer waters favor the survival of young salmon from the later spawners of fall-run chinook salmon.

Increased water temperatures clearly accelerated fish growth in all lots. Fish in the warmest lots were as much as eight times heavier than those in the coldest lots at the conclusion of the test. Do larger sized migrants have better survival? There have been several extensive studies which attempt to answer this question [21]. The general conclusion has been that there is some evidence that larger downstream migrants do in fact have higher survival rates if other conditions are equal.

Most of the local fall chinook spawn in water temperatures from 50 - 59° F., but the late spawners in a cold year may deposit their eggs in temperatures of about 41° F., well below the optimum. The importance of the time of deposition of eggs or spawning of fall chinook salmon was indicated by the mortalities of spawn taken in December, 1965. Eggs incubated in river water in 1965 showed higher mortalities than did those incubated in water warmed by addition of reactor effluent. Therefore, warming the colder waters of early winter might actually be beneficial for egg incubation.

From November, 1954 to May, 1955, temperatures were measured in the river bottom gravel of a simulated salmon nest approximately 1/2 mile downstream from 100-F reactor effluent outfall [22]. This location was chosen to obtain information on the thermal contribution of incompletely mixed reactor effluent. Temperatures were taken at positions 6" above the river bottom and at 6", 15", 21", and 30" below the surface.

During the period of salmon incubation (November - February), there was seldom more than 1° C. (1.8° F.) difference between the river gravel and the water above. There was generally a lag (and this was substantiated the following year with continuous temperature records) in temperature change between the water below and above the river bottom; and temperatures ranged from 1 to 4° C. (1.8 to 7.2° F.) higher in the simulated nest than in the river immediately upstream from the effluent outfall.

It should be borne in mind that measurements were made in an area of incompletely mixed effluent and are not necessarily typical of salmon spawning areas near Hanford.

Temperature Effects on Seaward Migrants

Information on the distribution (in time and space) of the young seaward migrants passing through the Hanford reach is necessary for assessment of effects of Hanford discharges. A question is often raised about the possibilities of seaward migrant kills in reactor plumes. Is this a source of mortality? We need to know the distribution and behavior of the fish in relation to the distribution of water velocity and temperatures of the plumes to answer this question.

The most thorough work to date on distribution and movement of seaward migrants passing Hanford is reported by E. M. Mains and J. M. Smith of the Washington State Dept. of Fisheries [23]. The work was done with large fyke nets rigged to five different river barges covering a transect across the Columbia River at Byer's Landing (downstream about 25 miles from 100-F). They found the seaward migration of chinook salmon occurred between March and July, during the high flows. A peak in April was mostly fry or 0-age chinooks (mean length, 39 mm), while peaks in June and July were largely yearlings (mean length, 72 mm in June).

Although numerous fish were taken at all stations, 50 to 60% of the catch per unit effort occurred near the banks. The seaward migrants also exhibited a preference for the surface zone. About 44% of the catch was within 30 inches depth from the surface.

Currently, we are testing the possibilities of kills in reactor plumes by drifting juvenile chinook salmon (0-age) in live boxes through the plumes and warmed shoreline areas. Water temperature is recorded continuously. Immediate and latent mortalities are scored. An inclined plane scoop-trap is also being used in the River downstream from a reactor outfall to sample the natural run of seaward migrants. In both the live box drifts and the trap collections, no mortalities attributable to heat have been observed this spring.

This lack of thermal mortalities is not surprising because of the lack of extreme warm temperatures experienced. The water temperatures observed during the period May 3 - 16, 1968, at the fish trap anchored about 400 meters downstream in the center of a reactor discharge plume showed a range of 53° F. (11.5° C.) to 60° F. (15.5° C.). During this period, the upstream temperatures at Priest Rapids Dam averaged 51° F. (10.5° C.).

The lethal temperature relations of the local stock of young chinook salmon are being studied in the laboratory to define better those conditions of temperature and duration of exposure which may cause mortalities [24]. Some of the questions posed for the work were as follows:

1. How does the resistance to thermal shock of local chinook compare with published data?
2. How does the developmental temperature regime affect the response to thermal shock?
3. Is fish size a significant source of variation?
4. What are the relationships between initial loss of equilibrium and times to physiological death under thermal stress?

Our preliminary laboratory work suggests our local chinooks may be slightly more sensitive to heat than chinooks studied by Brett [7,8]. The thermal history of rearing under elevated temperature conditions similar to areas downstream from reactors does not significantly change thermal resistance. Within the range (1.6 to 10.8 g) studied, size had little effect. Loss of equilibrium for groups of fish occurs at a predictable time prior to death; however, studies on individual fish were inconclusive. Loss of equilibrium may be a more valid and useful ecological death point than the commonly used physiological death.

Our laboratory work in lethal temperatures is directed toward providing empirical data as input for developing a model to predict the likelihood of fish mortalities under fluctuating thermal conditions encountered in a heated discharge plume. Our initial attempts to program on a computer a preliminary model simulating fish death in fluctuating temperatures has been encouraging, but considerable more work needs to be done to improve the model [25].

Apparently, Hanford temperatures have minimal effect on the downstream chinook migrants because of the relationship between time of the migration past Hanford and prevailing river temperatures. Two waves of downstream migration occur between March and late July, during a period of rising river temperatures from about 43 to 60° F. (6 to 15.5° C.). Several factors help to temper Hanford thermal effect. Bulk of the migration occurs during the spring months during cool waters. Some migrate later in the season during warmer, but still satisfactory temperatures. The yearly freshet, which peaks during late May or early June, also helps to minimize any Hanford effects at this season. The critical tests must be carried out in late August and September, during the warm water period.

Columnaris - A Warm Water Fish Disease

Our columnaris research, initiated in 1959, investigates the possible aggravation of columnaris disease by the introduction of the reactor effluent into the Columbia River. Columnaris has been endemic in the river for many years prior to Hanford operations, and the etiological agent, Chondrococcus columnaris, was positively identified in the River system in 1942 [26]. Because reactor effluent is thermally hot and radioactive, some biologists have speculated that Hanford might be a serious focal point for the columnaris disease [27]. Some of the

speculations follow:

1. Radioactivity and warm waters seriously aggravate the columnaris problem and induce higher mutation rates which could lead to more virulent strains of columnaris.
2. Initial infection of fish and development of the disease occurs in the warm water sloughs of the Hanford Reservation.
3. Columnaris is a serious threat to the salmon populations and may be responsible for the declining runs.

Early work in our laboratory showed that columnaris exposed to radiation levels many orders of magnitude higher than the radiation levels in undiluted reactor effluent did not affect mutation rates or increase virulence of the organism [28]. Mutants of columnaris were induced readily at 10k R x-ray dose; however, the virulence of these mutants were no greater than the parent strain.

Monthly field sampling of coarse fish, mostly largescale sucker (Catostomus macrocheilus), for an entire year at sites upstream and downstream from Hanford provided evidence that coarse fish serve as reservoirs for columnaris, especially during the winter months when the disease is apparently dormant. We found the number of "incidences" (positive, but fish not in a disease state) and diseased fish at Hanford differed little from other sites on the main stem of the River. Incidence ranged from 6 to 9%, and diseased fish ranged from 1.9 to 2.2% for all sites in 1965.

Although high temperatures are often associated with columnaris, experience with our hatchery trout maintained throughout the year in Columbia River waters indicates the further complexity of the problem. Columnaris disease is well established when the water temperatures reach 63-64° F. (17 to 18° C.) in early July. The fingerlings suffer mortalities for a few weeks, but mortalities taper

off sharply, and few deaths occur despite the continual rise in the river water temperature to about 70° F. (21° C.) in late August. Serious problems may arise however, when salmon are confined and crowded in warm waters as exemplified by the serious loss suffered at Oxbow Dam in the Snake in 1961. Laboratory work has demonstrated that severe crowding and high temperatures can cause serious columnaris mortalities.

Our recent studies suggest fish ladders at Columbia River dam sites which have a heavy population density of fishes may be major focal points of columnaris exposure and infection. The resident coarse fish in the ladders showed 37% "incidence" and 24% infection. These ladders present a potentially serious columnaris disease problem for anadromous salmon as they pass through ladder facilities heavily saturated with the pathogen. Monthly water samples taken near the top and bottom of fish ladders at four sites, Bonneville, McNary, Priest, and Rocky Reach Dams, determined the incidence of the pathogen in the water before, during, and after the warm water season. Figure 7 summarizes the results.

A columnaris population becomes evident in the ladder when water temperature rises above 50° F. (10° C.), and starts to decline when the temperature starts to decrease. The counts represent organisms released to the water by infected fish in the ladder, rather than organisms entering the ladder from the river. This is indicated by the large increase of organisms in the lower section of the ladder when compared to the upper section.

Our basic laboratory studies on antibody production and immune response of rainbow trout to C. columnaris gave the basis for the development of our technique of measuring the agglutinating antibodies in fish blood sera against columnaris [29].

Measurements of agglutinating titers in blood sera of over 900 suckers sampled at four sites, Hanford, McNary Dam, Wenatchee, and Bonneville Dam, showed a single cyclic pattern during a year. Residual antibodies are carried by the fish during the cooler waters of winter and spring, but a sharp increase in the average agglutinating titers occurs during September to November, the warm water period. Last year, both the downstream and upstream migrant sockeye salmon were sampled along their migration routes. The downstream migrants showed little change in titers during their migration in water temperatures of 45-57° F. during April to June; however, the adults migrating in warmer waters of 51-66° F. during the summer showed progressively higher titers with upstream migration [30].

These columnaris studies illustrate the probable critical significance of fish ladders in the etiology of the columnaris disease in the Columbia River. Maximum concentration of columnaris organisms occurs in ladders during periods of warm water temperature when concentration of river fish and passage of anadromous salmon through the ladders are at the peak. These salmonids are not only repeatedly subjected to columnaris exposure at each dam site, but may constitute a major vector for spread of the disease throughout the river system.

Discussion and Summary

In discussing the effects of Hanford's heated discharges on salmonids, it is convenient to think of the Hanford reach as two areas, namely the area of the reactor plumes and the area of "mixed" zones farther downstream. While the temperature of the undiluted reactor effluent is obviously lethal to fish, it is not so obvious whether any significant number of fish actually experience such extreme exposures because of the swimming behavior of fish and the nature of the hydraulic

characteristics near the outfall. Observations from a boat over the reactor outfalls show periodic upwellings of considerable turbulence surging from the discharge pipe on the river bottom. Hence, more likely many of the seaward migrants will be swept away like inert bodies into cooler waters. The outfalls are in fast waters of about 5 fps and the small migrant of say 38 mm length can hardly swim against 1 fps velocity.

Estimates on the average temperatures in the mixed zones downstream from reactor plumes are essential references; however, what the fish actually experiences may vary considerably from the averages. The adults with swimming ability to avoid unfavorable temperatures may experience cooler temperatures significantly different than the average. On the other hand, the tendency of the young fish to hug shoreline waters may expose them to higher temperatures. Although we can discuss about the average temperatures of the River or about some extreme temperatures of an effluent plume, at present, the actual temperature experiences of a salmon migrating past Hanford is mostly unknown.

The laboratory and field findings presented in previous sections need to be discussed in light of the seasonal temperature regime of the Columbia River near Hanford. Figure 8 shows the river temperature profile above and below Hanford in 1965-66. The difference between Priest Rapids and Richland temperatures is the result of not only Hanford reactors, but also includes heat gains or losses from all sources. In fact, for over 40 days starting in early July, the reactors were shut down because of a labor strike. Hence, the increment of about 3° F. seen during this period is the result of natural heat gains during the summer as the water flows from Priest Rapids to Richland. Clearly, the River temperatures increase during the summer even when the reactors are not operating.

Extrapolation of laboratory data to field situations must be treated cautiously, but this step must be taken because of little field data. A curve of maximum temperatures experienced in our laboratory with a total mortality no greater than 20% from egg to migrant size is plotted for reference in Figure 8. The curve immediately shows more heat can be added during the cooler periods of late fall, winter, and spring without a threat to young salmon.

The migration of seaward chinooks based on the work of E. M. Mains and J. M. Smith in 1955 [23] occurred before the warm water season of August and September; however, more recent work of Bureau of Commercial Fisheries' sampling of seaward migrants from turbine intake gatewells at Priest Rapids Dam showed sockeye, coho, yearling chinook, and steelhead trout migrated in May and June, whereas 0-age chinook migrated primarily in July and August [31]. This shift in the migration time of 0-age chinooks from early spring to summer months exposes the fish to warmer waters. The reason for this shift is not clearly understood, but there are some indications that reservoirs of upstream low-head dams delay their rates of movement [31].

Probably the most critical temperature is the temperature at spawning which not only affects the adults but also the survival of the egg, especially during the early stages of development [9]. The tolerable holding temperatures of adults preparatory to spawning is not very well known for our local chinooks. However, those fish spawning earlier in October face a greater threat from heat than later spawners in November.

Salmon eggs and young are not so vulnerable to heat from the Hanford effluent today as they are to any significant shifts in the seasonal temperature cycles of the River. A marked shift in the temperature regime of the River, so that

temperatures now experienced in September occur in October, could affect the survival of salmon eggs now deposited during the early portion of the spawning period. Most of the local chinooks spawn from about mid-October through mid-November when the temperature is rapidly declining from about 57 to 48° F. (13.9 to 8.9° C.). Incubation of the eggs and development of the young occurs from October through April when the Columbia River is sufficiently cold that heat increments added by the Hanford reactors cannot raise the River temperature above the acceptable range. Initial temperatures above 60° F. (15.5° C.) appear critically high for incubation of chinook eggs. U.S. Fish and Wildlife Service recommended the following generalized temperature limits for salmon waters as "optimum" for the following activities:

Migration 45-60° F.

Spawning 45-55° F.

Rearing 50-60° F. [32].

These limits may be "optimal", but they are not very realistic for the main stem of the Columbia. During the warm summer months, the Columbia River has always been a marginal habitat for salmonids. The historical temperature data in the main stem, either before the period of accelerated dam construction or even the data of more recent years, show 60° F. was always exceeded. The Columbia River in its pristine state must have exceeded 60° F.

A review of the laboratory and field studies concerning the biological effects of Hanford heat on salmonids showed no demonstrable evidence that the present level of heat burden introduced by Hanford reactors creates damage to our valuable salmon resources. However, the problem of evaluating and assessing the biological

effect of the relatively small heat increments added by the Hanford reactors to the Columbia River or added heat from any source on the health of salmon populations defies a direct, definitive answer at this time because of large gaps in our detailed knowledge about the complex factors which determine survival.

We believe the best practical method to investigate the effects of elevated temperatures on salmon or other desirable species in the Columbia River is the direct approach of working on-site, using local fish and Columbia River water. We have the only hatchery that successfully uses Columbia River water. Ideally, we hope to develop basic principles from our findings which can be applied on a broader basis. At present, however, we hope the biological data obtained from these practical types of experiments will help to determine the quantity of heat which can be added to the river without significant damage to salmon.

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COLUMNARIS POPULATION IN FISH LADDERS¹⁻²

1. SAMPLES NEAR TOP OF LADDER
2. SAMPLES NEAR BOTTOM OF LADDER

Figure 9 RELATIONSHIP BETWEEN CHINOOK SALMON AND
COLUMBIA RIVER TEMPERATURES NEAR HANFORD

TABLE I. MORTALITY AND GROWTH OF YOUNG CHINOOK SALMON REARED UNDER ELEVATED RIVER TEMPERATURES

Date Spawmed	10/30/66	11/14/66	11/23/66	12/8/66					
Date Terminated	<u>4/24/67</u>	<u>5/9/67</u>	<u>5/18/67</u>	<u>6/2/67</u>					
Initial Base Temp. °F	56	54	53	48					
Lot	Temperature Condition	% Mor-tality	Mean wt, g	% Mor-tality	Mean wt, g	% Mor-tality	Mean wt, g	% Mor-tality	Mean wt, g
1	Control ^(a)	4.6	0.95	10	0.63	5.5	0.64	4.8	0.63
2	+2 °F	3.6	1.40	11	0.96	9.3	0.97	5.5	0.97
3	+4 °F	11	1.92	16	1.53	12	1.37	7.5	1.42
4	+6 °F	28	2.72	19	2.55	9.4	1.96	7.3	1.79
5	+8 °F	60	4.28	17	4.17	6.9	2.61	17	2.31
6	+10 °F	97	--	43	5.52	10	3.82	14	3.18
7	+12 °F	100	--	93	5.65	37	5.28	12	4.24

(a) Similar to temperature at Priest Rapids Dam