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EXPERIMENTAL DRIFTS OF JUVENILE
SALMONIDS THROUGH EFFLUENT
DISCHARGES AT HANFORD
PART II. 1969 DRIFTS AND CONCLUSIONS

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EXPERIMENTAL DRIFTS OF JUVENILE SALMONIDS
THROUGH EFFLUENT DISCHARGES AT HANFORD.
PART II. 1969 DRIFTS AND CONCLUSIONS⁽¹⁾

By

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ABSTRACT

Field investigations were conducted from March to September, 1968 and 1969 to determine the effect of heated reactor effluents on juvenile salmonids passing through the central Columbia River. The fundamental approach was to drift groups of fish held in liveboxes through areas representing maximum thermal increments while monitoring exposure temperatures and subsequently comparing survival or mortality among test and control groups. Drifts were conducted either through shoreline areas, which received heated water via intragravel seepage from shoreline retention basins (peculiar to the Hanford site), or through midriver effluent plumes that issued from subsurface point discharges. Mortalities attributed to thermal dose (i.e. intensity and duration of exposure) were generally low. Shoreline drifts resulted in significant mortalities among only a few test groups whereas midriver drifts (primarily through the K reactor plume) resulted in losses only under unfavorable late summer conditions. The relative intensity of thermal dose for any set of river conditions depended largely upon onsite mixing patterns. Shoreline areas were characterized by reduced river flows, relatively low effluent mixing rates and persistence of heated water close inshore. In contrast, plume discharges were characterized by fast river flow, relatively high effluent mixing rates and rapid dispersal of heated water.

The most important environmental features regulating thermal dose were river temperatures and river discharges, which ranged from about 2.0 to 20° C and 40,000 to 280,000 cf/sec, respectively, throughout the year. During the migration season, four combinations occurred with increasing potential for thermal damage: low temperature-low

discharge (early spring), low temperature-high discharge (late spring), high temperature-high discharge (early summer) and high temperature-low discharge (late summer). The last situation exists from mid-July to August when river temperatures peak near 20° C and discharges drop below 100,000 cf/sec. Most chinook migrants produced in the Hanford area have departed seaward by this time. However, the migration timing of juvenile salmonids from above Hanford is retarded by the reservoir complex until July and August when river conditions are more hazardous. Nevertheless, the disproportionate ratio of effluent volume to total water mass and the rapid decline of plume temperatures after discharge tend to minimize the actual proportion of migrating juveniles that are exposed to sublethal and lethal thermal shock.

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EXPERIMENTAL DRIFTS OF JUVENILE SALMONIDS
THROUGH EFFLUENT DISCHARGES AT HANFORD
PART II. 1969 DRIFTS AND CONCLUSIONS

INTRODUCTION

Routine operation of plutonium production reactors on the Atomic Energy Commission's Hanford Reservation above Richland, Washington involves the use of Columbia River water as a coolant. The diverted water, when returned to the river, has been heated to an extent that prolonged exposure to the undiluted effluent would be lethal to most species of freshwater fish. However, the central Columbia with its relatively large flow volumes and cold currents has the physical capacity to absorb vast amounts of heat. As a result, temperatures of the river at Priest Rapids Dam (above Hanford) and at Richland 93 km below differ less than a few degrees. The areas of greatest hazard to juvenile salmonids lie in the immediate vicinity of the effluent discharges, the "zone of prompt mixing".

Heated effluents at Hanford issue primarily from submerged outfalls located near midstream. Some areas along the south bank of the river also receive heated water via intragravel seepage from shoreline retention basins and from test disposal of reactor effluent into the ground. Temperatures rise sharply near the discharges before the effluents mix and disperse in the river. These areas are potentially lethal to young salmonids by exposing a portion of the migrating fish to "thermal shock" as they pass seaward through the central Columbia. Resulting mortalities could occur in three ways, depending on the extent of thermal exposure and the thermal resistance of the species involved, namely: 1) immediate, direct losses, 2) delayed, latent losses, and 3) indirect losses through predation, disease, and lowered resistance to environmental stress.

Under experimental field conditions, only immediate and delayed mortalities could be determined.

The initial experiments were conducted in 1968 with the dual objectives of 1) determining if, under simulated natural conditions, passage through areas of thermal discharge killed young salmonids and 2) examining the physical parameters, i.e., temperature levels and exposure durations that were encountered in situ by the fish (Becker and Coutant, 1969). Objectives for 1969 remained essentially the same. These studies, of necessity restricted to the field, have been supported by many other investigational phases including the effects of thermal shock under controlled laboratory conditions (Coutant, 1969; Dean, 1969), thermal exposure and fish predation (Coutant, 1970), predatory activity of gulls (Prentice, 1969), the relationship of temperature to seaward migration (Becker, 1970), and the food and feeding of young chinook (Becker, 1971).

This report presents data assembled during livebox drifts of juvenile salmonids through effluent discharges at Hanford in 1969. It represents a continuation of work conducted in 1968, and incorporates results of the 1968 study in the Conclusion section.

As in 1968, the drifts were grouped into two general periods, the first in the spring and the second during the summer. Whereas in 1968 the annual spring runoff of the Columbia followed a normal pattern and occurred between drift periods, in 1969 it began about six weeks earlier and was sustained for over three months. This abnormal discharge pattern resulted from operations at Grand Coulee Dam that required the lowering of Lake Roosevelt for installation of additional turbines. The excess water was passed downriver over spillways at dams above Hanford, resulting in supersaturation of atmospheric gases in the river. Consequently,

"gas bubble" disease in experimental fish from dissolved nitrogen adversely effected the 1969 spring data. Techniques in 1969 were modified in order to improve collection and validity of the data. Greater effort was made to correlate the drifts with low river discharges, since the importance of low flow volumes in intensifying thermal experience was clearly recognized after the first year of study.

Mr. E. F. Prentice directed field operations and maintained field equipment in 1969. Drs. C. C. Coutant and C. D. Becker jointly planned the operations and participated in field work. Messrs. E. W. Lusty, E. G. Tangen, R. G. Genoway and A. J. Scott assisted in various capacities as required. Stocks of experimental fish were supplimented by the Washington State Department of Game and the U. S. Fish and Wildlife Service.

MATERIALS AND METHODS

General procedures for in situ field operations involved the placement of juvenile salmonids in liveboxes, which were designed to retain the fish while permitting efficient diffusion of river water, and then drifting test fish through areas of effluent discharge. Control groups were treated similarly, but the fish were drifted along the north shoreline to avoid the effluent mixing zones. Experimental fish used in 1969 were egg-sac fry and 0-age chinook salmon (Oncorhynchus tshawytscha), yearling coho salmon (O. kisutch) and yearling rainbow trout or steelhead (Salmo gairdneri). The sites where the drifts were conducted are shown in Figure 1.

FIGURE 1. LOCATION OF LIVEBOX DRIFTS WITH JUVENILE SALMONIDS IN RELATION TO HEATED DISCHARGES AT HANFORD, CENTRAL COLUMBIA RIVER, 1969

Operations in 1969 can be summarized as follows: 1) young salmonids were placed in floating acclimation pens above the reactor discharges for several days to permit predrift acclimation to river temperatures above Hanford. 2) Samples of test fish, usually consisting of 20-25 individuals, were placed in liveboxes attached to each side of a drift boat. 3) Samples of control fish were proportioned similarly in a second drift boat. 4) The drifts were conducted by guiding test fish through areas representing maximum thermal increments and control fish along a path avoiding the discharges, while monitoring exposure temperatures. 5) Immediate mortalities at the end of the drifts were noted. 6) Test and control fish were retained for a six day postdrift period in floating pens well below the effluent mixing zones and examined daily for delayed mortalities. 7) Survivors were released into the river.

Drifts in 1969 differed from those in 1968 primarily by providing a predrift acclimation period rather than by transferring the fish directly from the 100-F area hatchery, by using a 6-day postdrift retention period rather than 24 hours, by drifting control fish rather than holding them in containers aboard the drift boat, and by utilizing juvenile coho and rainbow in addition to young chinook.

The acclimation pens for the spring drifts were positioned near the south shore above the BC reactor area (Figure 1). Spring drifts were conducted through the south shoreline seepage below BC, the south shoreline through KE-KW, and the K and N plumes. Since the C reactor ceased operation after the spring drifts (the B reactor was closed in 1968), the acclimation pens were positioned above the KE-KW reactor area for the summer drifts (Figure 1). Summer drifts were conducted through the K and N plumes as well as an inshore leak near the end of

the K jetty. The postdrift retention pens were positioned in the D reactor (inactive) pumphouse intake (Figure 1), below and away from the path of mixing effluent.

Other modifications of technique were adopted in 1969. First, the fish were drifted both at the surface and at a 3 meter depth, rather than only at the surface. The depth of a subsurface drift was controlled by installing a 20 foot pipe, which could be shifted from a horizontal to a vertical position, to the side of each drift boat; a livebox was lowered or raised along the pipe by a rope and pulley apparatus. Second, fluorescent red floats were anchored above the midstream effluent plumes to facilitate control of drifts through the approximate discharge focus. Third, the redesigned liveboxes consisted of an open metal frame about 46 cm^2 covered by rubberized mesh with 1/2-inch diamond perforations. Egg sac fry and advanced fry were placed in small containers constructed of plastic window screen within each livebox (since they could pass through the rubberized mesh), whereas yearlings were left free to move at random. Fourth, more sensitive temperature probes were used to monitor conditions within the liveboxes.

The new probes (No. 409, Yellow Springs Instrument Co.) had a time constant of 1.7 seconds, i.e., the time required to register 63% of a sudden temperature change. (According to specifications, about 4 time constants were required for the probe to respond to 99% of the total temperature change.) Since the probes were delicate, they required protection from mechanical damage and careful handling during field operations. Temperatures were read directly on multirange Tele-thermometers (Model 46 TU, YSI), and permanent records of temperature fluctuations were made on chart recorders. Power for instrument operation was provided

by batteries. (In actual field operation, excessive malfunctioning of recording equipment occurred from rapid loss of battery power and for unknown mechanical reasons).

Drifts commenced above the effluent discharges and terminated below where "thermal pulses", which indicated fluctuating temperatures resulting from exposure of test fish to mixing discharges, were no longer recorded. Drifts were conducted at rates roughly equivalent to surface flow. Outboard motors were occasionally operated at low speed to keep shoreline drifts from grounding or to guide drifts through areas of apparent maximum discharge temperatures. Discharge plumes in midchannel were visible as intermittent boils breaking the surface, while shoreline seepages were evident as areas of trickling water and rising vapors. In order to test the most stringent conditions, most of drifts were conducted during the early morning at times corresponding to minimum river discharge as regulated upriver at Priest Rapids Dam.

For evaluation of "thermal experience" in the livebox drifts, the following terms are defined:

Thermal Shock - The maximum rise in temperature experienced by test fish when they pass through an effluent discharge. Thermal shock reflects the highest thermal increment above base river temperature encountered during a drift.

Thermal Dose - The temperature increment plus the duration of exposure. Thermal dose is a precise measure of thermal effect because it includes not only the peak temperature (thermal shock), which may be very brief, but also the length of exposure to various increment levels.

Thermal Experience - A general term referring to temperature conditions encountered by test and control fish during the entire drift from start to completion.

Base Temperature - The temperature of the Columbia River above the Hanford area prior to a drift. Base temperatures approximate those recorded at Priest Rapids Dam, and were equivalent to acclimation temperatures.

Mixed Temperature - The temperature of the Columbia River below an effluent discharge where thermal pulses were no longer recorded and mixing was largely complete. Drifts were normally terminated at this point.

River Discharge - The discharge in cf/sec at the approximate time a drift was conducted. Discharge volumes were determined from gauge readings at the K reactor pumphouse, which had been previously correlated with known discharge volumes.

A hypothetical example of the thermal experience of fish passing through a midstream plume is given in Figure 2, which represents a permanent record obtained on a monitoring tape in the chart recorder. Entrance into a discharge plume initiates an abrupt rise in temperature. "Thermal pulses" of decreasing magnitude portray the mixing of the heated effluent with the cooler river at progressive points within the plume. In the transition zone, temperatures become stabilized somewhat above the base river level. Examples of thermal experience of certain test fish are given in Figures 7-11. For these illustrations, the tape was separated into 30-second intervals and the mean temperature for each interval was plotted. Because temperature levels fluctuated with successive pulses, exposure to a given thermal level was never continuous.

FIGURE 2. HYPOTHETICAL ILLUSTRATION OF THERMAL EXPERIENCE OF TEST FISH DRIFTED THROUGH A MIDRIVER PLUME, AS PERMANENTLY RECORDED ON STRIP CHART TAPE. (DOTS INDICATE THE MEAN EXPOSURE TEMPERATURE, ABOVE BASE RIVER TEMPERATURE, PER 30 SEC INTERVAL.)

RESULTS

Drift Timing in Relation to Seaward Migration

The drifts were grouped into two periods, the first in the spring and the second in the summer. These periods were separated by the annual period of maximum river discharge (above 200,000 cf/sec) when larger volumes of river water functioned to rapidly dilute and dissipate the heated effluents (Figure 3).

As in 1968, the drifts were conducted during two crucial periods for evaluation of possible thermal effects. In early spring, water temperatures were well below preferred levels (12-14° C) for the fish, juvenile chinook (and other young salmonids) were abundant but small in size, and river discharges were low but rising. In the summer, water temperatures were near the annual maximum (18-20° C), the remaining fish were large in size and physiologically aged to migration, and river discharges were low.

Determining the timing of the natural migration of juvenile salmonids from the central Columbia in relation to possible effects of heated discharges was important to clarifying the problem. This relationship has been explored (Becker, 1970) and is essentially as follows. In 1955, juvenile salmon passed through the Hanford environs during the spring and early summer (Mains and Smith, 1964) and the migration showed two peaks, the first in March and April (mostly fry) and the second in June and July (mostly fingerlings). At the present time, however, fish originating above Priest Rapids Dam pass through Hanford at a later date, in July and August (Park, 1969). Development of the upriver reservoir complex during the past decade is assumed to be responsible for this delay

FIGURE 3. MEAN WEEKLY WATER TEMPERATURES IN THE CENTRAL COLUMBIA RIVER AT PRIEST RAPIDS DAM AND RICHLAND, PLUS DISCHARGE VOLUMES AT PRIEST RAPIDS DAM, 1969. (KNOWN PERIODS OF SEAWARD MIGRATION OF JUVENILE CHINOOK ARE INDICATED.)

by reducing migration rates in the relatively slack water habitat of impoundments (Raymond, 1968, 1969). Juvenile chinook produced in the 93 km free-flowing section of the Columbia at Hanford apparently retain the normal migration pattern detected 15 years ago by Mains and Smith, and most have passed downriver into the forebay of McNary Dam by mid-July. This phenomenon was revealed by extensive beach seining efforts in connection with studies on food and feeding of young chinooks in 1968 and 1969 (Becker, 1971).

Juvenile chinook now leaving the central Columbia River, therefore, can be separated into two distinct components on the basis of migration timing (Figure 3). Those produced in the free-flowing Hanford environs retain their natural timing, whereas those originating above Hanford in tributaries, hatcheries and spawning channels are delayed up to 2 months. The delayed migrants are exposed to late season environmental conditions (i.e. warmer temperatures and lower river flows), which they did not encounter in earlier years when passing through the Hanford area.

Temperature and Discharge Volumes, 1969

Environmental conditions prevailing in 1969 (Figure 3) were essentially similar to those in 1968. However, increasing river discharges began about 6 weeks earlier, because of storage releases at Grand Coulee Dam to permit installation of additional turbines, and high flows were sustained for a longer period. Discharges decreased sharply in July and low flows were maintained throughout August and early September.

The spring rise in river temperatures entering the Hanford area followed a normal pattern. Temperatures were well below preferred levels

for juvenile salmon in March and April, entered the preferred range of 12-14° C (where thermal conditions are presumably near optimum) in late May and early June, and were sustained above preferred levels in July and August. Maximum daily temperatures briefly reached 19.7° C at Priest Rapids and 20.6° C at Richland during the summer. In 1968, the 12 monthly water temperature profiles show a rise of 0.5-3.5° C between Priest Rapids and Richland, of which 1-2° C in June and July was due to summer warming from the atmosphere (Moore, 1968, 1969).

Temperatures at Priest Rapids did not exceed 20° C during the summer or fall of 1969. Temperatures above this level, although well below the apparent upper incipient lethal limit of 25.1° C for young chinook and coho (Brett, 1952), may be considered suboptimum for survival of juvenile salmonids in the river ecosystem. Brett (1960) later proposed that the upper limit of required temperature for any species of fish should not exceed that which would curtail activity below 3/4 of optimum, and recommended a "freedom" of 3° C (5.5° F) below the ultimate lethal level.

Weekly and Daily Fluctuations in Discharge Volumes

The data illustrated in Figure 3 are based on weekly means and do not reveal the extent of either daily or hourly fluctuations that occur from flow regulation at Priest Rapids Dam. Flows were usually reduced on weekends and increased during the week to satisfy consumptive demands for hydroelectric power. For similar reasons, flows were lowered at night and raised during the day. Weekend variations occasionally resulted in changes of the water level in the river, measured at drift locations, of up to 8 feet in 12 hours.

The mean daily discharges at Priest Rapids Dam from March through August 1969 are illustrated in Figure 4. Daily fluctuations were less pronounced in April, May, June and early July because increased runoff from snow melt (combined with Grand Coulee releases) provided a surplus of river water. In March and later in August, however, a seasonal need to conserve available water behind upriver dams existed and weekend decreased in daily discharges were extreme.

Hourly fluctuations in discharge volumes at Priest Rapids during days that the drifts were conducted are shown in Figures 5 and 6. Drift Series I was conducted during sustained low flows in the morning by agreement with the Grant County Public Utility District (operators of Priest Rapids Dam). The other series of spring drifts were conducted without prior agreement and discharge volumes reflected the typical hourly flows prevailing (Figure 5). The fall drifts were conducted in the early morning hours to correspond with regulated low flows during August (Figure 6). Correlation of Priest Rapids data with water levels recorded at the K reactor pumphouse indicated that approximately two hours were required for changes in regulated discharge volumes to appear downriver at the drift sites (Priest Rapids is about 25 km above the K reactor area).

River discharges prevailing during the time young migrating salmon pass through the Hanford area influence the extent of thermal exposure in mixing zones. For relatively constant effluent volumes, high river flows disperse and dilute the heated effluent more effectively than low river flows. Moreover, with high discharge volumes, the migrating population spreads over a wider horizontal area and the actual proportion of fish that enter effluent mixing zones is presumably reduced.

FIGURE 4. DATES LIVEBOX DRIFTS WERE CONDUCTED IN RELATION TO DAILY COLUMBIA RIVER DISCHARGES AT PRIEST RAPIDS DAM, MARCH THROUGH APRIL, 1969.

FIGURE 5. DAILY FLUCTUATIONS IN COLUMBIA RIVER DISCHARGES AS REGULATED AT PRIEST RAPIDS DAM DURING LIVEBOX DRIFTS, SPRING 1969.

FIGURE 6. DAILY FLUCTUATIONS IN COLUMBIA RIVER DISCHARGES AS REGULATED AT PRIEST RAPIDS DAM DURING LIVEBOX DRIFTS, SUMMER 1969.

Drift Series I (23 March)

Discharges from Priest Rapids Dam were sustained at minimum flows (about 40,000 cf/sec) during the morning when the drifts were conducted (Figure 5). In the initial series, 180 chinook egg-sac fry and 200 yearling cohos were drifted in groups of 20 fish each (Table 1). Base river temperatures averaged 4.5°C for the day. The maximum thermal increase (thermal shock) was recorded for test groups 5 and 6, which were drifted along the south shoreline near the BC reactor. The thermal increment of $\Delta T\ 26.5^{\circ}\text{C}$ was due largely to intragravel seepage. An increase of $\Delta T\ 12.4^{\circ}\text{C}$ was the maximum briefly experienced by test fish (groups 13 to 19) drifted in midchannel through the K reactor plume.

Postdrift mortalities were insignificant in each drift group. Chinook losses were due to trauma from mechanical injury of the weak-swimming fry, whereas coho losses (accompanied by growth of fungus in the mouth and palatine area) probably resulted from poor physical condition. Based upon these data, no losses could be attributed directly to thermal dose. Presumably the relatively cold base river temperatures and brief exposures to thermal increments mitigated against excessive mortality.

Drift Series II (22 April)

High river flows (about 200,000 cf/sec) commenced in April (Figure 3) and were accompanied by supersaturation of water with air. Nitrogen levels exceeded 120 percent of saturation in many determinations. Experimental fish consisted of 130 chinook fry, drifted in two composite groups of 60 control and 70 test animals, and 50 yearling coho drifted in two groups of 25 (Table 2). River discharges during the drifts were about 195,000 cf/sec (Figure 5) and base river temperatures averaged 8.0°C

TABLE 1. Series I. Drifts of juvenile salmonids through areas of thermal discharge, Hanford environs, 23 March 1969

Group	Number and Species ⁽¹⁾	Area and Depth of Drift	River Flow cf/sec	Temperature, °C			Mortality, day:							
				Base	Maximum	Shock ⁽²⁾	0	1	2	3	4	5	6	Total ⁽³⁾
1. Control	20 chinook	North Shore, K to N, Surface	40,000	4.0	4.0	0.0	0	0	0	0	0	0	0	0
2. Control	20 chinook	"	"	"	"	"	0	0	0	0	0	0	0	0
3. Control	20 coho	"	"	"	"	"	0	0	0	0	0	0	0	0
4. Control	20 coho	"	"	"	"	"	0	0	0	0	0	1	0	1
5. Test	20 chinook	South Shore, below B C Surface	40,000	4.0	30.5	26.5	0							
6. Test	20 coho	"	"	"	"	"	0	0	1	0	0	0	2	3
7. Test	20 chinook	Midchannel, K to N, Surface	40,000	4.0	12.0	8.0	0	0	0	0	0	0	0	0
8. Test	20 chinook	"	"	"	"	"	0	0	0	0	0	0	0	0
9. Test	20 coho	"	"	"	"	"	0	0	0	0	0	0	0	0
10. Test	20 coho	"	"	"	"	"	0	0	0	0	1	0	0	1
11. Test	20 chinook	South Shore, below K, Surface	39,000	6.0	6.0	0.0	0	0	0	0	1	0	0	1
12. Test	20 coho	"	"	"	"	"	0	0	0	0	0	0	0	0

TABLE 1. (Continued)

Group	Number and Species ⁽¹⁾	Area and Depth of Drift	River Flow cf/sec	Temperature, °C			Mortality, day:							
				Base	Maximum	Shock ⁽²⁾	0	1	2	3	4	5	6	Total ⁽³⁾
13. Test	20 chinook	Midchannel, K to N, Surface	39,000	4.2	16.6	12.4	0	0	0	0				
14. Test	20 chinook	Midchannel, K to N, 3 meters	39,000	"	"	"	0	0	0	0	0	1	0	1
15. Test	20 coho	Midchannel, K to N, Surface	39,000	"	"	"	0	0	1	0	1	0	0	2
16. Test	20 coho	"	"	"	"	"	0	0	0	0	0	0	1	1
17. Test	20 chinook	Midchannel, K to N, 3 meters	40,000	4.2	16.6	12.4	0	0	0	0	0	0	0	0
18. Test	20 coho	"	"	"	"	"	0	0	0	0	0	0	0	0
19. Test	20 coho	"	"	"	"	"	0	0	0	0	1	0	0	1

(1) Chinook were egg sac fry reared at BNW's 100-F Area hatchery; coho were yearlings from Ice Harbor Dam, U.S. Fish and Wildlife facilities.

(2) Calculated as the degrees increment above base river temperature.

(3) Mortalities due primarily to trauma from mechanical injury.

TABLE 2. Series II. Drifts of juvenile salmonids through areas of thermal discharge, Hanford environs, 22 April 1969.

Group	Number and Species (1)	Area and Depth of Drift	River Flow cf/sec	Temperature, °C		Mortality, day:					
				Base	Maximum Shock (2)	0	1	2	3	4	5 6 Total (3)
1. Control	60 chinook	North Shore, CB to N, Surface	195,000	8.0	11.2	3.2	4	4	1	1	1 2 13
2. Control	25 coho	"	"	"	"	"	4	10	2	1	5 2 24
3. Test	70 chinook	South Shore (seepage), Surface	195,000	8.7	14.1	5.4	0	2	2	0	1 0 5
4. Test	25 coho	"	"	"	"	"	11	13	1		

(1) Chinook were fry (34-40 mm fork length) and coho were yearlings (95-130 mm fork length) seined from the Columbia River above Hanford.

(2) Calculated on the degrees increment above base river temperature.

(3) Chronic mortalities due largely to air supersaturation, i.e. nitrogen or "gas bubble" disease.

for the day. Test groups were drifted at the surface along the south shoreline in the seepage near the BC reactor area. Due to the prevailing high river discharge, the maximum thermal shock briefly experienced by test groups was ΔT 5.4° C. Control fish experienced a ΔT 3.2° C increment along the north shore.

Significant mortality occurred among both control and test groups during the posttest holding period (Table 2). In the controls, 13 chinook (of 60) and 24 coho (of 25) died whereas 5 chinook (of 70) and 25 coho (of 25) died among the test fish. Mortalities were chronic and highest during the initial days after the drifts. No correlation was apparent between losses and relatively mild thermal doses. About two thirds of the dead fish (control and test) showed external blisters symptomatic of "gas bubble" disease.

The influence of nitrogen was also evident during the pretest acclimation period in the river above Hanford. Substantial losses (about 50 percent) of the coho occurred prior to the drifts. Although chinook were less severely affected, they also appeared to be under stress. Symptoms among coho were more pronounced than among chinook.

Drift Series III (30 April)

Priest Rapids discharges remained high (210,000-220,000 cf/sec) during the day. Chinook fry, 80 control and 100 test, were drifted in groups of 20 fish each (Table 3). Test groups were drifted at the surface along the south shoreline near the BC reactor area. Maximum thermal shocks briefly encountered (adjusted data) were ΔT 20.7 and ΔT 21.3° C. All test fish were drifted simultaneously, but in drift boxes secured to opposite sides of the boat. Mortalities resulting

TABLE 3. Series III. Drifts of juvenile salmonids through areas of thermal discharge, Hanford environs, 30 April 1969.

Group	Number and Species ⁽¹⁾	Area and Depth of Drift	River Flow cf/sec	Temperature, °C			Mortality, day:							
				Base	Maximum	Shock ⁽²⁾	0	1	2	3	4	5	6	Total ⁽³⁾
1. Control	20 chinook	North Shore, CB to K, Surface	210,000	8.1	8.1	0.0	0	1	0	0	0	0	0	1
2. Control	20 Chinook	"	"	"	"	"	0	0	0	1	0	0	1	2
3. Control	20 chinook	"	"	"	"	"	0	0	0	0	0	1	0	1
4. Control	20 chinook	"	"	"	"	"	0	0	0	0	0	—	—	0
5. Test	20 chinook	South Shore, CB to K, (seepage) Surface	220,000	8.1	28.8	20.7 ⁽⁴⁾	13	3	0	0	0	1	0	17
6. Test	20 chinook	"	"	"	"	" ⁽⁴⁾	19	0	1	—	—	—	—	20
7. Test	20 chinook	"	"	8.1	29.4	21.3 ⁽⁴⁾	0	0	0	1	0	0	2	3
8. Test	20 chinook	"	"	"	"	" ⁽⁴⁾	0	0	0	3	0	1	0	4
9. Test	20 chinook	"	"	"	"	"	0	0	—	—	3	0	3	6

(1) Chinook were reared from eggs at BNW's 100-F Area hatchery.

(2) Calculated as the degrees increment above base temperature.

(3) Chronic losses due largely to air supersaturation, i.e. nitrogen or "gas bubble" disease; accute losses due to thermal dose.

(4) Thermal experience is graphed in Figure 7.

from thermal dose relative to position (port or starboard) were significantly different.

Mortality among 40 fish held on the starboard side were high and occurred prior to termination of the drift, whereas immediate mortality among 60 fish held on the port side were nil. Mortalities during the postdrift holding period were minor and were attributed to nitrogen because the fish displayed typical external symptoms of "gas bubble" disease. Only four fish died in six days among the control groups.

Since the maximum temperatures experienced by test fish on the starboard (ΔT 20.7° C) and port side (ΔT 21.3° C) were essentially similar, the mortalities cannot be explained on the basis of thermal shock. The losses probably resulted from differences in exposure time (thermal dose) to temperature fluctuations below maximum levels. The starboard fish received a longer exposure to increments in the ΔT 18-20° C range (Figure 7), although temperatures in both liveboxes varied widely in response to inshore effluent mixing patterns.

Drift Series IV (15 May)

River discharges were reaching the annual peak during May (Figure 4). The drifts were conducted under high flows (210,000-225,000 cf/sec) and a daily mean temperature of 10.1° C (Figure 5). Nitrogen saturations reached 130 percent. The experimental fish consisted of 160 0-age chinook and 130 yearling rainbow (steelhead), and were drifted in lots of 20 fish except for one group of rainbow (Table 4). Test drifts were conducted in midchannel at the surface and the 3 meter depth near the KW and N reactor plumes, and near the south shoreline below K. Maximum thermal shocks briefly encountered were ΔT 3.9° C and ΔT 0.3° C during two separate drifts.

FIGURE 7. THERMAL EXPERIENCE OF TEST FISH IN GROUPS 5-6 (STARBOARD) AND 7-9 (PORT) IN DRIFT THROUGH SHORELINE SEEPAGE AREAS, SERIES III

TABLE 4. Series IV. Drifts of juvenile salmonids through areas of thermal discharge, Hanford environs, 15, May, 1969

Group	Number and Species ⁽¹⁾	Area and Depth of Drift	River Flow cf/sec	Temperature, °C			Mortality, day:							
				Base	Maximum	Shock ⁽²⁾	0	1	2	3	4	5	6	Total ⁽³⁾
1. Control	20 chinook	North Shore, K to N, Surface	225,000	9.5	10.0	0.5	0	3	3	-	1	2	-	9
2. Control	20 rainbow	"	"	"	"	"	0	8	12	0	—			20
3. Control	20 chinook	North Shore, 3 meters	225,000	9.5	10.0	0.5	0	1	1	-	1	0	-	3
4. Control	20 chinook	"	"	"	"	"	0	12	0	-	1	0	-	13
5. Control	20 rainbow	"	"	"	"	"	0	1	12	-	7	—		20
6. Test	20 chinook	Midchannel, K to N, Surface	220,000	9.5	12.4	3.9	0	2	0	-	2	0	-	4
7. Test	20 chinook	Midchannel, K to N, 3 meters	"	"	"	"	0	3	0	-	3	0	-	6
8. Test	20 chinook	"	"	"	"	"	0	8	6	-	1	1	-	16
9. Test	20 rainbow	Midchannel, K to N, Surface	"	9.5	12.4	3.9	0	3	17	—				20
10. Test	20 rainbow	Midchannel, KW to N, 3 meters	"	"	"	"	0	1	11	-	8	—		20
11. Test	20 chinook	South Shore, K to N, Surface	210,000	10.9	11.2	0.3	0	4	5	-	3	—		13
12. Test	20 chinook	"	"	"	"	"	0	4	6	-	4	1	-	15
13. Test	20 rainbow	"	"	"	"	"	0	1	12	-	7	0	-	20
14. Test	30 rainbow	"	"	"	"	"	0	5	16	-	9	—		30

(1) Chinook were reared at BNW's 100-F Area hatchery; rainbow were yearlings reared at the Ringold hatchery, Washington State Department of Game.

(2) Calculated as the degrees increment above base temperature.

(3) Chronic mortalities largely due to air supersaturation, i.e. nitrogen or "gas bubble" disease.

No immediate mortality was evident at the termination of the drifts (Table 4). Test and control groups of chinook suffered chronic mortality during the postdrift retention period. Losses among rainbow were most severe. All rainbow (control and test) were dead after 5 days and most fish revealed distinctive symptoms of gas bubble disease. Since temperature increments were low, it was apparent that nitrogen and not thermal shock or thermal dose was the primary lethal cause.

Results of drift Series II to IV, conducted under environmental conditions of high river flow and nitrogen saturation, indicated the existence of a species and/or size relationship to nitrogen sensitivity. Generally, 0-age chinook appear to be less severely affected by high nitrogen levels than yearling coho and rainbow. This phenomenon requires experimental confirmation under controlled conditions.

Drift Series V (1 August)

River discharges in August were near the seasonal minimum (Figure 4), temperatures neared the seasonal maximum, and levels of dissolved gases were normal. The C reactor was closed after the spring drifts were completed, eliminating the intragravel seepage area near the BC reactor. Weekly beach seining at established stations indicated that nearly all young chinooks produced in the Hanford environs had departed seaward by mid-July (Becker, 1970).

River discharges ranged from 80,000-90,000 cf/sec during the morning when the drifts were conducted and base river temperatures averaged 17.7° C for the day (Figure 6). The experimental fish consisted of 200 0-age chinook drifted in groups of 25 (Table 5). All test fish were passed in midchannel through the K reactor outfall at the surface or

TABLE 5. Series V. Drifts of juvenile salmonids through areas of thermal discharge, Hanford environs, 1 August 1969.

Group	Number and Species ⁽¹⁾	Area and Depth of Drift	River Flow cf/sec	Temperature, °C			Mortality, day:							
				Base	Maximum	Shock ⁽²⁾	0	1	2	3	4	5	6	Total
1. Control	25 chinook	North Shore, K to D, surface	80,000	18.0	18.0	0.0	0	1	0	0	1	2	1	5
2. Control	25 chinook	North Shore, 3 meters	"	17.2	17.2	0.0	1	1	1	1	0	3	1	8
3. Test	25 chinook	Midchannel, K to N, surface	80,000	18.0	19.4	1.4	0	0	1	1	2	3	2	9
4. Test	25 chinook	Midchannel, K to N, 3 meters	"	17.2	18.4	1.2	0	0	0	2	0	3	3	8
5. Test	25 chinook	Midchannel, K plume, surface	90,000	(3)			0	0	0	1	1	1	0	3
6. Test	25 chinook	Midchannel, K plume, 3 meters	"	(3)			0	0	0	0	0	1	0	1
7. Test	25 chinook	Midchannel, K to N surface	90,000	18.0	21.4	3.4 ⁽⁴⁾	0	1	0	0	0	0	1	2
8. Test	25 chinook	Midchannel, K to N, 3 meters	"	17.4	22.3	4.9 ⁽⁴⁾	0	4	2	2	5	7	3	23

(1) Chinook were reared at BNW's 100-F Area hatchery.

(2) Calculated as degrees increment above base temperature. Exposure to peak temperatures was very brief.

(3) Recorders malfunctioned.

(4) Thermal experience is graphed in Figure 8. Fish in Test Group 8 were severely emaciated at time of death.

at 3 meter depth. Maximum thermal shocks briefly encountered by test fish ranged from ΔT 1.2 to ΔT 4.9° C.

Immediate mortality from exposure to effluent plumes were insignificant. Test group 8, drifted at 3 meters and receiving a brief thermal shock of ΔT 4.9° C, suffered a high delayed mortality (23 of 25) after 6 days. None of the other six lots were affected similarly. The thermal experience of test groups 7 and 8 (drifted simultaneously) is illustrated in Figure 8. There was little difference in thermal experience resulting from vertical configuration of the mixing plume. Mortality occurring at a depth of 3 meters was not explained on the basis of either thermal shock or thermal dose. Unknown factors probably caused the postdrift losses of these fish, which appeared to be severely emaciated at time of death.

Drift Series VI (8 August)

River discharges ranged from 75,000-80,000 cf/sec during the morning when the drifts were conducted and base river temperatures averaged 17.4° C for the day (Figure 6). The experimental fish consisted of 200 0-age chinook, drifted in lots of 25 fish (Table 6). All test fish were passed through the K reactor outfall at either the surface or at 3 meters depth. Maximum thermal shock briefly experienced by test fish ranged from ΔT 1.6 to ΔT 9.6° C. The thermal experience of test groups 3 and 4 (drifted simultaneously) is illustrated in Figure 9.

Immediate and delayed mortalities were low except for one lot where 5 fish (of 25) died during the postdrift holding period (Table 6). Thermal shock and thermal dose sufficient to kill significant numbers of test fish were not experienced despite efforts to direct all drifts through the focus of the main discharge plume.

FIGURE 8. THERMAL EXPERIENCE OF TEST FISH IN GROUP 7 (SURFACE) AND GROUP 8 (3 METERS) IN DRIFT THROUGH K PLUME, SERIES V

TABLE 6. Series VI. Drifts of juvenile salmonids through areas of thermal discharge, Hanford environs, 8 August 1969.

Group	Number and Species ⁽¹⁾	Area and Depth of Drift	River Flow cf/sec	Temperature, °C			Mortality, day:							
				Base	Maximum	Shock ⁽²⁾	0	1	2	3	4	5	6	Total
1. Control	25 chinook	North Shore, K to N, surface	80,000	17.6	17.6	0.0	0	0	0	0	0	0	0	0
2. Control	25 chinook	North Shore, 3 meters	"	"	"	"	0	0	0	0	0	0	0	0
3. Test	25 chinook	Midchannel, K to N, surface	80,000	18.2	22.2	4.0 ⁽³⁾	0	0	0	0	0	0	1	1
4. Test	25 chinook	Midchannel, 3 meters	"	17.4	27.0	9.6 ⁽³⁾	0	0	0	0	1	0	0	1
5. Test	25 chinook	Midchannel, K to N, surface	75,000	17.7	21.3	3.6	0	0	2	2	0	1	0	5
6. Test	25 chinook	Midchannel, 3 meters	"	17.4	21.5	4.1	0	0	0	0	0	0	0	0
7. Test	25 chinook	Midchannel, K to N, surface	75,000	17.4	19.0	1.6	0	0	0	0	0	0	0	0
8. Test	25 chinook	Midchannel, K to N, 3 meters	"	17.4	27.0	9.6	0	0	0	0	0	0	0	0

(1) Chinook were reared at BNW's 100-F Area hatchery.

(2) Calculated as degrees increment above base temperature. Exposure to peak temperatures very brief.

(3) Thermal experience graphed in Figure 9.

FIGURE 9. THERMAL EXPERIENCE OF TEST FISH IN GROUP 3 (SURFACE) AND GROUP 4 (3 METERS) IN DRIFTS THROUGH K PLUME, SERIES VI

Drift Series VII (20 August)

River discharges remained low (70,000-75,000 cf/sec) during the morning when the drifts were conducted and base river temperatures averaged 18.4° C for the day (Figure 6). Temperatures were near the annual peak for 1969. The experimental fish consisted of 116 0-age chinook and 72 0-age coho, and were drifted in small lots of variable numbers (Table 7). All test fish were passed through the K reactor outfall at either the surface or at 3 meters depth. Maximum thermal shock briefly experienced by test fish ranged from ΔT 1.7 to ΔT 4.8° C.

Immediate and delayed mortalities were low and insignificant (Table 7). As in the preceding series (Series VI), lethal exposures to thermal shock and thermal dose in the K plume were insufficient to cause mortality even though river discharges were low and water temperatures were high. Thermal experiences of test groups 5 and 6 are illustrated in Figure 10.

Drift Series VIII (1 September)

Monday, September 1, was Labor Day and low flows that prevailed during the preceding weekend were sustained an additional 24 hrs at Priest Rapids. River discharges were near the summer minimum (39,000-50,000 cf/sec) when the drifts were conducted and base river temperatures averaged 17.8° C for the day (Figure 6). The experimental fish consisted of 400 0-age chinook drifted in groups of 25 fish (Table 8). Test drifts were made through the K-reactor outfall and an inshore leak exposed at the prevailing low water levels near the end of the K jetty. Maximum thermal shocks received by the test fish were relatively severe, ranging from ΔT 6.8 to ΔT 30.0° C.

High immediate mortality was experienced in three test lots (Table 8) group 4 drifted through the main K plume at 3 meters depth (ΔT 22.7°

FIGURE 10. THERMAL EXPERIENCE OF TEST FISH IN GROUP 5 (SURFACE) AND GROUP 6 (3 METERS) IN DRIFTS THROUGH K PLUME, SERIES VII

TABLE 7. Series VII. Drifts of juvenile salmonids through areas of thermal discharge, Hanford environs, 20 August 1969.

Group	Number and Species ⁽¹⁾	Area and Depth of Drift	River Flow cf/sec	Temperature, °C			Mortality, day:							Total ⁽⁵⁾
				Base	Maximum	Shock ⁽²⁾	0	1	2	3	4	5	6	
1. Control	25 chinooks	North Shore, K to N, surface	70,000	18.4	0.0	0.0	0	0	0	—	—	—	0	
2. Control	25 chinooks	North Shore, 3 meters	"	"	"	"	0	0	0	—	—	—	0	
3. Control	16 cohos	North Shore, surface	70,000		(3)		0	0	0	—	—	—	0	
4. Control	16 cohos	North Shore, 3 meters	"		(3)		0	0	0	—	—	—	0	
5. Test	35 chinooks	Midchannel, K to N, surface	70,000	18.3	23.1	4.8 ⁽⁴⁾	0	0	0	—	—	—	0	
6. Test	31 chinooks	Midchannel, 3 meters	"	18.5	23.1	4.6 ⁽⁴⁾	0	1	0	—	—	—	1	
7. Test	20 cohos	Midchannel, Surface	75,000	18.3	20.0	1.7	0	0	0	—	—	—	0	
8. Test	20 cohos	Midchannel, 3 meters	"	18.5	20.2	1.7	0	0	0	—	—	—	0	

(1) Chinook and coho yearlings were reared at BNW's 100-F area hatchery.

(2) Calculated as degrees increment above base temperature. Exposure to peak temperatures very brief.

(3) Recorder malfunctioned.

(4) Thermal experience graphed in Figure 10.

(5) Lost fish after 3 days retention in a wind storm.

TABLE 8. Series VIII. Drifts of juvenile salmonids through areas of thermal discharge, Hanford environs, 1 September 1969.

Group	Number and Species ⁽¹⁾	Area and Depth of Drift	River Flow cf/sec	Temperature, °C			Mortality, day:							
				Base	Maximum	Shock ⁽²⁾	0	1	2	3	4	5	6	Total
1. Control	25 chinook	North Shore, K-N, surface	39,000	18.0	18.0	0.0	0	0	0	0	0	0	0	0
2. Control	25 chinook	North Shore, K-N, 3 meters	"	17.4	17.4	0.0	0	0	0	0	0	0	0	0
3. Test	25 chinook	Midchannel, K-N, surface	39,000	17.9	37.0	19.1 ⁽³⁾	0	0	0	0	0	0	0	0
4. Test	25 chinook	Midchannel, K-N, 3 meters	"	17.7	40.4	22.7 ⁽³⁾	10	10	0	0	3	1	1	25
5. Test	25 chinook	Midchannel, K plume, surface	39,000	18.1	29.1	11.0	0	0	0	0	0	0	0	0
6. Test	25 chinook	Midchannel, K plume, 3 meters	"	17.8	(4)		0	0	0	0	0	0	0	0
7. Test	25 chinook	Midchannel, K plume, surface	40,000	18.1	37.8	19.7 ⁽³⁾	0	0	0	0	0	0	0	0
8. Test	25 chinook	Midchannel, K plume, 3 meters	"	17.8	28.4	10.6 ⁽³⁾	0	0	0	0	0	0	1	1
9. Test	25 chinook	South Shore, K leak, surface	40,000	18.3	48.3	30.0	25	—————						25
10. Test	25 chinook	"	"	18.0	41.2	23.2	25	—————						25

TABLE 8 (continued)

Group	Number and Species ⁽¹⁾	Area and Depth of Drift	River Flow cf/sec	Temperature, °C			Mortality, day:							
				Base	Maximum	Shock ⁽²⁾	0	1	2	3	4	5	6	Total
11. Test	25 chinook	South Shore, K leak, surface	50,000	18.3	24.2	6.9	0	0	—————					0
12. Test	25 chinook	South Shore, K leak, 3 meters	"	17.8	(4)		0	0	0	0	0	0	0	1
13. Test	25 chinook	South Shore, K leak, surface	"	18.0	27.9	9.9	0	0	0	0	0	0	0	0
14. Test	25 chinook	South Shore, K leak, surface	"	18.3	25.9	7.6	0	0	—————					0
15. Test	25 chinook	Midchannel, K plume, surface	60,000	18.4	25.2	6.8 ⁽³⁾	0	0	0	0	0	0	0	0
16. Test	25 chinook	Midchannel, K plume, 3 meters	"	18.3	26.6	8.3 ⁽³⁾	0	0	0	1	0	0	0	1

(1) Fingerling spring chinook (40/lb) were obtained from the Little White Salmon hatchery, US Fish and Wildlife Service.

(2) Calculated as degrees increment above base temperature.

(3) Thermal experience graphed in Figure 11.

(4) Recorder malfunction.

(5) Fish lost in wind storm.

C), and groups 9 and 10 drifted through the inshore leak (ΔT 30.0 and ΔT 23.2° C). Delayed mortalities during the postdrift holding period were low but a few fish died of bacterial disease, presumably "columnaris" (Chondrococcus columnaris).

The thermal experiences of test groups 3-4, 7-8, and 15-16 are shown in Figure 11. Although high maximum temperatures were recorded during drifts through the focus of the K plume in the midchannel, the duration of exposure was usually so short that few fish died from thermal dose. One exception (group 4) occurred when test fish were drifted at 3 meters and received a maximum shock of ΔT 22.7° C.

Short exposure times presumably were the basis for the lack of mortalities in some drifts through the inshore leak. In contrast, exposure times and high temperatures were sufficient to cause mortalities in two drifts (groups 9-10) through the leak. In all leak drifts, the direction was manipulated by outboard motor to guide the fish through the maximally heated section of the discharge. This series of drifts demonstrate the potential hazard from the late summer combination of peak temperatures and low discharge volumes. Under such conditions, lethal exposure to temperatures may even occur in a midstream plume. The inshore leak, with its reduced mixing patterns and persistent inshore eddy behind the jetty, revealed lethal temperatures and effluent mixing patterns typical of shoreline seepages at seasonal minimum flows.

FIGURE 11. THERMAL EXPERIENCE OF TEST FISH IN GROUPS 3-4, 7-8, AND 15-16 IN DRIFTS THROUGH THE K PLUME, SERIES VIII

DISCUSSION

1969 Drifts in Relation to 1968 Drifts

The thermal experience of juvenile salmonids (chinook, coho and rainbow) under field conditions in 1969, when tests under low river discharges were emphasized, are summarized in Figure 12. Data for the 1968 drifts are summarized in Figure 13. In these illustrations, the base river temperature is given on the ordinate and the maximum temperature encountered by test fish is on the abscissa. The diagonal line represents an assumed ultimate incipient lethal temperature of 25.1°C (from Brett, 1952) and is the sum of any combination of ordinate and abscissa readings. Maximum temperatures (thermal shock) during the drifts fall either in the zone of thermal tolerance or the zone of thermal resistance. Young salmon can theoretically live in the zone of thermal resistance for a definite period of time, which is essentially a function of the distance of the exposure temperature beyond the incipient lethal level (Fry, 1964). However, various natural and experimental stress conditions may tend to reduce the inherited resistance of fish to thermal exposure, thereby resulting in mortalities at a more rapid rate or even at lower temperature levels.

The 1969 spring drifts are scantily represented in Figure 12 because of excessive mortalities during the postdrift retention period, a consequence of high nitrogen levels in the river. Peak temperatures during the drifts usually fell well within the zone of thermal tolerance. Exposures to lethal temperatures (thermal shock) occurred in three test drifts through the shoreline seepage below the BC reactor -- but the exposure duration (thermal dose) was sufficient to cause mortality in only one

FIGURE 12. MAXIMUM THERMAL EXPOSURES OF JUVENILE SALMONIDS (TEST) DURING LIVEBOX DRIFTS THROUGH EFFLUENT DISCHARGES AT HANFORD IN 1969. (TEMPERATURE CRITERIA ADOPTED FROM BRETT, 1952.)

FIGURE 13. MAXIMUM THERMAL EXPOSURES OF JUVENILE CHINOOK (TEST) DURING LIVEBOX DRIFTS THROUGH EFFLUENT DISCHARGES AT HANFORD IN 1968. (TEMPERATURE CRITERIA ADOPTED FROM BRETT, 1952.)

group. Temperatures and exposure durations in all drifts through the K plume and along the south shore through K were insufficient to cause death. These results agree essentially with data obtained in 1968, when no significant mortality occurred during the spring drifts (Figure 13). Mitigating environmental conditions, i.e. relatively low base river temperatures and high river discharges (Figure 4), appeared to be the major reason for the occurrence of few thermal mortalities during the spring (March, April, May). A hazardous area existed below the BC reactor where intragravel seepage of effluent raised inshore temperatures to potentially lethal levels.

The 1969 summer drifts exposed fish to thermal shock at temperatures falling in both the tolerance and resistance zones (Figure 12). Four drifts resulted in near total mortalities, two through the inshore K leak and two through the main K plume in midriver. However, a lethal thermal dose did not result in the majority of the drifts through the K plume, albeit environmental conditions were extreme, i.e. relatively high base river temperatures and low river discharges (Figure 4). Exposure durations were normally too short to cause excessive mortality even when maximum temperatures exceeded the arbitrary 25° C lethal limit. No summer drifts through midstream plumes in 1968 exposed test fish to a lethal thermal dose (Figure 13). In 1968 and 1969 combined, three drifts with maximum temperatures falling within the tolerance zone caused significant mortalities for reasons inadequately known.

Effect of Depth

Drifts were conducted both at the surface and at a depth of 3 meters in 1969, whereas only surface drifts were made in 1968. Subsurface drifts

were conducted primarily through the midstream plumes because mechanical damage to liveboxes resulted from intermittent bottom contact in shallow water near the shore. Base river temperatures at the surface and at 3 meters were similar during the spring, but were usually somewhat lower ($<0.5^{\circ}\text{C}$) in subsurface drifts during the summer. The thermal experience of test fish held in both positions while simultaneously drifted through the K plume proved to be somewhat different (Figures 8-11). This difference was expected on the basis of known effluent mixing patterns (Jaske, Templeton and Coutant, in press).

A difference in mortality associated with depth occurred in two tests. In the first (Drift Series V, groups 7-8), immediate losses were nil but delayed losses were severe among fish drifted at 3 meters; this case was atypical since death was preceded by emaciation. In the second (Drift Series VIII, groups 3-4), immediate and 24 hr mortalities were excessive among the 3 meter fish and apparently resulted from a lethal thermal dose during the drift (Figure 11). No data were obtained to demonstrate a persistent effect related to a combination of depth (pressure) and temperature.

Immediate vs Delayed Mortalities

Test and control fish were held 6 days postdrift in 1969 for identification of immediate and delayed mortalities, whereas only a 24 hour retention period was used in 1968. Mortality data (Tables 1-8) demonstrate that lethal effects from thermal dose among test fish usually appeared at the termination of a drift or within 24 hrs. Thus, data from the short postdrift observation period in 1968 were reasonably valid. Chronic mortalities from high nitrogen levels during the 1969 spring drifts that

involved both control and test fish usually appeared after the first day of retention. Sporadic mortalities from mechanical damage (injury followed by infection with fungi) appeared during the longer postdrift observation period.

Effects of Dissolved Nitrogen

Supersaturation with nitrogen in the Columbia River during the spring and summer, when large volumes of water are passed over spillways at dams, has become an environmental hazard to young salmonids (Ebel, 1970). Due to the separation in time of the livebox drifts into early spring and summer periods, excessive nitrogen levels were apparently avoided in 1968. The 1969 spring drifts were severely effected by nitrogen supersaturation resulting from early releases of stored water at Grand Coulee, which passed downriver over spillways at Priest Rapids Dam above Hanford. Losses of test fish from "gas bubble" disease occurred in the predrift acclimation pen (severity unrecorded) and during the postdrift retention period (Tables 2-4). These mortalities were largely chronic and involved both test and control fish. Although the data are admittedly limited, there was little evidence that excessive dissolved nitrogen combined with moderate thermal shock to increase mortalities of test fish above those of control fish.

Physical Characteristics of Shoreline and Midriver Discharges

The physical parameters of drifts conducted through shoreline seepage areas (and the K leak) contrasted with those through the midriver plumes. These differences were related to thermal effects among test fish. Peak temperatures were somewhat higher and exposure durations were somewhat

longer in shoreline seepage drifts, thereby resulting in greater mortality.

Shoreline drifts were generally characterized by 1) prolonged exposure to mixing effluent, because of relatively slow passage rates resulting from restricted downriver flow; 2) high thermal dose, because of reduced effluent mixing with the receiving river water along the shore; and 3) gradual temperature decline, because of the extended mixing zone passing downriver before dispersal. Inertial effects in shoreline areas contribute to reduced efficiency of the mixing process, and prolongs the exposure of test fish.

Midriver drifts through the main discharge plumes, in contrast, were characterized by 1) brief exposure to mixing effluent, because of relatively rapid passage rates resulting from unrestricted downriver flows; 2) low thermal dose, because of efficient effluent mixing with the receiving river water in midstream; and 3) rapid temperature decline, because of a short zone of prompt mixing extending downriver before dispersal to the transition and completely mixed zones. Exposures to peak temperatures in a plume usually occurs within a few minutes of initial contact. Exposures to fluctuating temperatures, which indicated the transition zone below a midstream plume, occurs within 10 minutes at minimum river flows. After initial contact, the intensity and fluctuation of plume temperatures drops rapidly to harmless levels.

The dissimilar thermal parameters of shoreline and midriver effluent discharges was clearly modified by differences in current patterns and river discharge volumes (which regulate mixing) between the two sites. Drifts in 1969 were closely correlated with daily and weekly periods of minimum river discharge (Figure 4). Drifts during the spring (23 March-14 May) occurred during rising discharges (40-225,000 cf/sec)

but low base temperature ($4-10^{\circ}\text{C}$). Drifts during the summer (1 Aug.-1 Sept.) occurred during seasonal minimum discharge volumes (40-60,000 cf/sec) but high base temperatures ($17-19^{\circ}\text{C}$). A wide range of temperature and flow conditions occur annually in the central Columbia River, and the effect of heated effluents on young salmonids clearly relate to these features.

CONCLUSIONS

The 1969 experimental drifts terminated two successive years of field studies dealing with the effects of heated effluent discharges on juvenile salmonids passing seaward through the Hanford area of the central Columbia River. The following conclusions, therefore, are derived from data collected in both 1968 and 1969 although only the latter are detailed herein.

As noted previously (Becker and Coutant, 1969), mortality of fish under simulated migration conditions is primarily a function of thermal experience, i.e., temperature increase and exposure duration (=thermal dose). These intergraded functions determine the lethal effect, if any, of "thermal shock" as migrating fish pass through the mixing zones. Clearly, if the temperature is sufficiently high and the exposure duration is sufficiently long, any species of fish experiencing thermal dose will be killed. The precise relationship can be determined in laboratory experiments (Coutant, 1969; Dean, 1969), but the data have not previously been extended to field conditions with confidence because of temperature fluctuations that occur randomly in the mixing zones before thermal stabilization occurs. Moreover, unknown intrinsic factors are operative

contributing to the "early seaward migration" detected by Mains and Smith (1964). Other fry appear in inshore areas for an indeterminate period of feeding and growth before departing seaward (Becker, 1971). Data from 1968 and 1969 drifts reveal only one instance of significant mortality, through a shoreline seepage area, during early spring; no losses from temperature exposure were evident in midriver plume drifts. The general lack of thermal deaths may be attributed largely to low base river temperatures.

Surface mixing patterns at the K plume under river flows of 41,000 and 80,000 cf/sec are shown in Figures 14-15. Maximum thermal increments above base river temperature cover a broader surface area behind the plumes at the lower flow, and the width of the 1-6° C ΔT mixing zone extending downriver is considerably wider. If base river temperatures are low, as in early spring, thermal increments sufficient to cause mortality exist only in the focus of the plume. If currents are rapid, as in the central Columbia, exposure to maximum temperatures would necessarily be brief and usually impart merely a sublethal thermal dose. Exposure (of confined fish) to high temperatures is apparently longer in the shoreline seepage areas and some deaths may result.

Low Temperatures--High Discharges

High river discharges normally occur in late spring and early summer (May-July), accompanied by a rise in river temperatures to about 16° C (Figures 3-4). Many juvenile salmon are moving seaward and fish are abundant in inshore feeding areas at Hanford. Although river temperatures are near optimum, dissolved nitrogen becomes an added environmental hazard when surplus water is passed over spillways of upriver dams.

*DETECTION LIMIT OF AERIAL INFRARED IMAGING SYSTEM $\sim 0.5^{\circ}C$

FIGURE 14. COLUMBIA RIVER SURFACE TEMPERATURE FLOW PATTERNS BY INFRARED IMAGERY AT 41,000 cf/sec FLOW (FROM JASKE et.al. ____)

*DETECTION LIMIT OF AERIAL INFRARED IMAGING SYSTEM $\sim 0.5^\circ C$

FIGURE 15. COLUMBIA RIVER SURFACE TEMPERATURE FLOW PATTERNS BY INFRARED IMAGERY AT 80,000 cf/sec FLOW (FROM JASKE et.al.)

Surface mixing patterns at the K plumes under river flow of 110,000 cf/sec are illustrated in Figure 16. Maximum thermal increments (6-9° C ΔT) occur only at the precise discharge focus and the width of the mixing zone extending downriver has narrowed. Actual river flows during spring runoff, however, normally exceed the illustrated 110,000 cf/sec and peaked above 270,000 cf/sec in both 1968 and 1969. Prevailing high flows provide protection for the migrants from thermal increments by rapidly mixing and dispersing heated effluents in the vast water mass.

High Temperatures--High Discharges

River temperatures reach and exceed the thermal preferendum (12-14° C) for young salmon in early summer (June and July). Discharge volumes remain relatively high until mid-July (Figures 3-4). High dissolved nitrogen levels in the river water remain a hazard. Most juvenile chinook salmon produced in the Hanford area apparently pass downriver by mid-July (Becker, 1971). Continuing high discharges apparently mitigate against excessive losses of migrants during this period. Our drift data, however, indicate that shoreline seepages remain potentially lethal even during relatively high river flows.

High Temperatures--Low Discharges

A condition of high temperatures (near 20° C) and low river discharges (below 100,000 cf/sec) prevails (Figures 3-4) in late summer (Aug.-Sept.). Whereas most Hanford juveniles have departed, a delayed migration of young salmonids produced above Hanford may continue through August (Park, 1969). During periods of minimum flows on weekends, losses of

*DETECTION LIMIT OF AERIAL INFRARED IMAGING SYSTEM $\sim 0.5^{\circ}C$

FIGURE 16. COLUMBIA RIVER SURFACE TEMPERATURE FLOW PATTERNS BY INFRARED IMAGERY AT 110,000 cf/sec FLOW (FROM JASKE, et al.)

under field situations that are largely reduced or eliminated in controlled laboratory studies. Clearly an ideal evaluation program (for thermal effect studies) must combine laboratory and field data in order to obtain ecological meaning with respect to the survival value for a species, as noted by Mihursky and Kennedy (1967).

Environmental conditions in the central Columbia during the period juvenile salmonids are present play a dominant role in influencing thermal experience, potential or realized. The two most important features appear to be prevailing base river temperatures and river discharge volumes, which range from about 2.0 to 20.0° C and 40,000 to 280,000 cf/sec, respectively, over the year. Throughout the annual migration season (Figure 3), there exists a well defined sequence based on four combinations of temperature and discharge. These are, in succession, low temperature--low discharge (early spring), low temperature--high discharge (late spring), high temperature-high discharge (early summer), and high temperature-low discharge (late summer). The potential hazard to juvenile salmonids resulting from heated discharges tends to increase from March through August. Environmental conditions appear to be most severe during the late summer, after most chinook produced in the free-flowing river at Hanford have departed seaward.

Low Temperature--Low Discharge

During early spring (March-April), river temperatures and flow volumes are low (Figures 3-4). (High flows began early in 1969, due to releases at Grand Coulee Dam.) Chinook fry first emerge from the gravel of the river bed in the Hanford environs at this time. Many weakly swimming fry are apparently carried directly downriver, thus

test fish from thermal dose did occur during some livebox drifts. Surface mixing patterns prevailing in the discharge plumes approximate those of 41,000 cf/sec (Figure 14), but base river temperatures are high rather than low as in early spring. With river temperatures of 18° C, increments greater than 8° C will expose migrating fish to temperatures above the arbitrary upper incipient lethal limit of 25° C. The mixing zone with ΔT 3-8° C extends for a considerable distance downriver under low flow conditions. Consequently, a potential for lethal exposure among migrating fish exists at this time. Yet significant mortalities rarely occurred during the plume drifts and lethal temperatures were infrequently recorded. (These results may have been partly influenced by our inability to direct all test fish into the precise center of a discharge plume under field conditions.) Temperatures in the shoreline seepage areas were more excessive than in the plumes, and some mortalities of drifted fish did occur.

Physical parameters between mixing patterns in shoreline seepages and midstream plumes are clearly different. The following contrasting features of the two effluent disposal sites were evident.

Shoreline Seepages

Mortality occurs during some drifts through areas heated by intragravel seepage from effluent retention basins along the south shoreline. A particularly hazardous area existed below the BC reactor area in 1968 and early 1969, which was eliminated with closure of the C reactor after the 1969 spring drifts. Other shoreline seepages still exist in the Hanford area but these are limited in volume and area, and must be considered of minor consequence. Shoreline seepages are less affected by changing

river flows than midstream plumes, apparently because heated water persists along the inshore zone. This persistence is due to reduced flow and inefficient mixing (thermal inertia). Discharges from the leak near the end of the K jetty tend to move inshore at river flows below 120,000 cf/sec, since an eddy exists behind the riprap (Figures 14-16), that reduces mixing efficiency. This area is particularly hazardous at minimum flows of 40,000 cf/sec during late summer.

We have no evidence that unconfined fish are involuntarily carried into or voluntarily penetrate heated water areas near the shore. Voluntary entrance may occur in seepage areas during early spring when river temperatures are well below a thermal preferendum of 12-14° C for young salmonids. However, fish are known to be extremely sensitive to small temperature changes (Bull, 1936) and will avoid areas warmed in excess of their preferendum (Alabaster, 1963; Brett, 1952; Bardach and Bjorklund, 1957). Heavy concentrations of young feeding chinook occur near the banks in the Hanford area from April through mid-July, as demonstrated by seining activity (Becker, 1971). Concentrations of migrating chinook also pass near the banks, although these fish are generally well distributed throughout the entire horizontal area of the river (Mains and Smith, 1964).

The conclusion from these observations is explicit and inescapable--shoreline seepages represent a potentially lethal area to migrating juvenile salmonids regardless of the extent of fish avoidance or existing river temperature and flow. Shoreline seepages of heated water (peculiar to the Hanford site) are now greatly reduced. Clearly, shoreline discharge of heated effluents are to be avoided at facilities planned for construction on the Columbia River and other streams utilized by cold-adapted salmonid fishes.

Plume Discharges

Although mortality may also result among fish drifted through midstream plumes, these losses are limited and occur primarily under late season conditions of maximum temperatures and minimum flows. Most juvenile chinook produced by spawners at Hanford migrate seaward under protection of favorable river temperatures and flows exceeding 100,000 cf/sec. This migration timing has evolved as a natural phenomena over thousands of years. But now, after an extensive period of dam construction, young salmonids produced above Hanford pass Priest Rapids Dam during July and August (Park, 1969). These delayed fish may encounter plumes with mixing patterns shown in Figure 14 at a season when river temperatures are in the upper zone of thermal tolerance. (We obtained no catches of late migrating juveniles in an inclined plane trap fished behind the K plume in August and September of 1969).

The thermal hazard represented by a midstream plume appears to be less than a shoreline discharge. Potential harm depends upon ambient river conditions (temperature and flow) and whether or not the fish actually pass through the focus of a plume before mixing reduces temperatures to sublethal levels. During active migration, juvenile chinook in the central Columbia exhibit a preference for the surface zone (44 percent occur within 30 inches of the surface) and the fish are horizontally distributed across the entire river with greatest concentrations near the shore (Mains and Smith, 1964). The proportion of juvenile salmonids entering the transition mixing zone of a midstream plume is unknown, but is probably small due to the disproportionate ratio of effluent volume to total water mass. The proportion of fish that actually encounter lethal temperatures at the focus of a plume is presumably even less.

Plume temperatures generally lose 80 percent of ΔT within 5 seconds of discharge as measured at the river surface. Water leaving the submerged effluent pipes (that open upward) are discharged at high velocities and a shear plane initially exists between the heated discharge and the cool river water. Theoretically, this shear could reduce possible collisions of small fish passing downriver with maximum discharge temperatures.

Lethal temperatures exist only for a relatively short distance in the zone of prompt mixing before dispersal to sublethal levels of the transition zone even at low flows (Figures 14-16). Although lethal temperatures may be encountered in the initial moment of thermal shock, exposure time is apparently so brief that there is little effect on sensitive fish tissue in most field situations. Nevertheless, under environmental conditions in July and August (high temperature and low flow), mortality was evident in some plume drifts. Alabaster (1963) has pointed out that fish introduced into effluent outfalls in cages are deprived of the opportunity to escape unfavorable conditions thereby making survival minimum. In the Columbia River, with current velocities exceeding swimming speed of young salmon, collision with high effluent temperatures may well be unavoidable for at least some migrants.

Nevertheless, the disproportionate ratio of effluent volume to total water mass and the rapid decrease of plume temperatures after discharge tends to minimize the actual proportion of migrating juvenile salmonids that receive sublethal or lethal exposures.

The reactor effluents at Hanford issue primarily from single point discharge with a high exit velocity, which are carried upward and downriver during the mixing process. Horizontal spreading in the mixing zone, as well as the area of peak temperature near the outlet, decreases with

increased river flow up to 110,000 cf/sec (Jaske, et al., in press), as shown in Figures 14-16. The most successful diffuser for direct disposal of reactor effluent in the center of a large, cool and fast-flowing river like the central Columbia, for the purpose of reducing thermal effects on migrating juvenile fish, is not necessarily a single point discharge. There is ample reason to believe that a comprehensive hydraulic investigation on other types of midriver diffuser outlets would prove rewarding. Such outlets as a multiple port diffuser might facilitate the mixing process by providing a broader horizontal mixing zone while simultaneously lowering maximum temperatures near the discharge foci. An alternative would be to provide for minimizing effluent temperatures before release by onshore dilution with river water, by cooling towers or by cooling ponds.

If the undiluted effluent falls in the range of lethal temperature and mortalities of young salmonids can occur, there is reason for concern. We have demonstrated with our livebox drift experiments that this does not necessarily mean the risk of kill from thermal dose is excessive, only that losses may occur under certain conditions. We have attempted to clarify these conditions by defining environmental features prevailing in the central Columbia River in relation to the Hanford effluent discharges and the migration timing of the fish.

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