Northwest Fisheries Center Auke Bay Fisheries Laboratory

Processed Report

SALMON RANCHER'S MANUAL

by

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ERRATA NOTICE

FOREWORD

The North Pacific Ocean is a vast nursery ground for the Pacific salmon that spawn in streams and lakes in North America and Asia. These salmon reproduce in fresh water, but most of their growth occurs at sea. When mature they return to their freshwater ancestral spawning grounds, where tens of thousands of genetically separate stocks segregate for reproduction.

Man has helped to precipitate a general decline of salmon by overfishing and by polluting spawning and nursery grounds. Even though the oceanic waters where salmon spend most of their life are vulnerable to pollutants, there are encouraging indications that such pollution has not seriously impaired the capacity of the ocean to grow salmon. The problem then is to restore the runs themselves--something that might be accomplished through aquaculture.

Public agencies now produce most of the juvenile Pacific salmon through artificial propagation (hatcheries and spawning channels). However, recent advances in technology for salmon aquaculture and removal of legal barriers to private ownership of salmon in California, Oregon, Washington, and Alaska have combined with a scarcity of wild stocks to stimulate private investments in the ocean ranching of Pacific salmon. Several pioneering business ventures are now in the process of evaluating the economic feasibility of ocean ranching.

Despite a long history of artificial propagation of salmon, the causes of the success or failure of ocean ranching are not fully understood, and many problems remain unresolved or only partially resolved. Therefore, this manual does not attempt to provide answers to all questions. Instead, it attempts to identify the more serious impediments to successful ocean ranching and the precautions that will reduce the risk of failure.

Production of healthy fry is the "core" of any salmon aquaculture system because the success of ocean ranching will depend largely upon the quality of juvenile fish released into the ocean. The primary purpose of this manual is to assist salmon ranchers with planning, constructing, and operating systems for artificial propagation of salmon fry. The methods described are not necessarily the only suitable ones available, and considerable latitude usually exists for modification of equipment and techniques. Salmon ranchers will soon adapt their systems to suit their specific requirements.

Some comments on the use of chemotherapy to control disease in salmon hatcheries is pertinent here because federal, state, and local agencies have rigid regulations governing the use of chemicals in controlling disease in animals raised for human consumption. In fact, only a few of the chemicals recommended in publications that discuss treatment of diseased fish are approved by the federal government. Those approved for salmon include salt, glacial acetic acid, sulfamerazine, and oxytetracycline. In most instances, proper control of the environment and observance of high standards of sanitation are the only means of minimizing mortality from disease.

To simplify the organization and content of the text, publications are not cited in the manual, although many statements are based largely on interpretations of and conclusions from the voluminous pertinent literature (more than 400 reports were reviewed). The authors recognize that alternative interpretations are often possible and also that the conclusions given are subject to change. Trade names are frequently used in the text, but the National Marine Fisheries Service does not endorse any of the products mentioned.

Preparation of this manual would not have been possible without the technical support of staff members at the Auke Bay Laboratory. Those deserving special recognition are Jerrold M. Olson (photography), Elmer Landingham (drawings), Betty Miller (typing), and Helen Fleischhauer (technical editing). Valuable suggestions from a number of reviewers have allowed us to develop the organization and content of this manual, and we welcome any further suggestions readers might wish to provide. Appropriate suggestions will be used if an opportunity arises to revise and update this first edition of "Salmon Rancher's Manual."

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SALMON RANCHER'S MANUAL

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INTRODUCTION

Man has precipitated a serious decline of Pacific salmon over most of their natural range. In Japan, chum salmon stocks had dwindled to low levels by the early 1900's --probably as a result of overfishing. Another of man's activities contributing to the decline early in the century occurred between 1914 and 1917 when the upstream migration of sockeye salmon at Hells Gate in the Fraser River, British Columbia, was blocked by rock debris dumped into the river during railroad construction. Dam construction on the Columbia River in Washington and Oregon in the 1930's started a downward trend in numbers of chinook salmon as a result of the loss of major natural spawning and nursery grounds. Once abundant southeastern Alaska pink salmon runs began a serious decline in the 1950's, followed by a similar decline in numbers of Asian (primarily Russian) pink and chum salmon in the 1960's and of Bristol Bay sockeye salmon in the 1970's. An intensive Japanese high seas fishery that began in the mid-1950's appears to have contributed substantially to the large reductions in numbers of Asian pink and chum salmon and Bristol Bay sockeye salmon. Numerous other examples could be cited where overfishing, construction of dams and water diversion facilities, water pollution, and poor land use practices have been detrimental to salmon.

Examples can also be cited, however, where man has successfully applied technology to arrest, and in some instances reverse, the decline of salmon. The specific application of technology to accomplish restoration of salmon runs has varied considerably because of the specific requirements for particular problems. In some instances fish passage facilities such as those that were constructed at Hells Gate in the Fraser River have reduced mortality of brood fish and thus allowed the reestablishment of natural spawning stocks. More frequently, it has been necessary to propagate salmon artificially in order to make efficient use of a limited number of brood fish by reducing the high (usually greater than 80%) egg-to-fry mortality in natural spawning beds. Techniques for artificial propagation of salmon have ranged from complete control over the processes of reproduction through the use of hatcheries to the improvement of environmental conditions for spawners in their natural spawning areas by constructing artificial spawning channels.

The propagation of salmonid fishes in hatcheries dates back at least to the 15th century in Europe. In North America, the U.S. Fish Commission established the first hatchery for Pacific salmon on the McCloud River, California, in 1872. A second federal hatchery was built on the Clackamas River, Oregon, in 1877. Also in 1877, the first private hatchery was established on the Rogue River, Oregon, by an early pioneer of the salmon industry, Mr. R. D. Hume. These three early hatcheries were used primarily to propagate chinook salmon. The first Canadian salmon hatchery was constructed in 1884 on the Fraser River at New Westminster, British Columbia, to propagate sockeye salmon.

The Japanese began to build hatcheries in 1876 to replenish dwindling supplies of chum salmon. The Japanese used a technology similar to that which evolved in North America before the turn of the century, where fertilized eggs were hatched on screen trays immersed in water-filled troughs. Variations of this basic technique are still useful for certain hatchery applications.

Interest in hatcheries remained high in North America until the 1930's. Public and private hatcheries from Northern California to western Alaska annually released hundreds of millions of salmon fry during this early period of hatchery development. However, evidence of success was often lacking and optimism that hatcheries would compensate for overfishing waned by the 1930's.

A crisis engendered by the damming of major rivers on the west coast of the United States, especially the Columbia, rekindled interest in hatcheries in the Pacific Northwest in the 1940's and 1950's, and massive investments were made in hatcheries for coho and chinook salmon. Nevertheless, the contribution of hatchery stocks remained doubtful for several years because of the problems associated with nutrition, disease, and handling of fish. Modern advances in technology now appear to have relieved these problems enough to ensure an important role for artificial propagation in the restoration and maintenance of Pacific Northwest salmon.

The Japanese hatchery system for chum salmon also underwent a major reorganization in the early 1950's, when certain private hatcheries on Hokkaido Island were placed under government management. A rapid expansion of hatchery production of chum salmon has occurred in Japan and further expansion is planned. The approximate number of chum salmon fry released from Japanese hatcheries since 1940 and number planned for future release are as follows:[1]

Years	Honshu Island	Hokkaido Island
1940-49	25 million	175 million
1950-59	50 million	250 million
1960-69	150 million	350 million
1970-79 (Planned)	200 million	650 million
1980- (Planned)	>280 million	>840 million

By the early 1970's, the harvest of chum salmon on Hokkaido Island had surpassed the harvest in Alaska (Figure 1). Alaska production is dependent on wild stocks of chum salmon, whereas 90% or more of Hokkaido chum salmon come from hatcheries.

In seeking suitable alternatives to hatcheries, fish culturists began in the 1950's to experiment with spawning and egg incubation channels. Favorable results from the early tests have prompted the Canadian Government and the International Pacific Salmon Fisheries Commission to construct several large spawning channels for sockeye, pink, and chum salmon in British Columbia.

The Soviet Union undertook a large-scale pink and chum salmon hatchery program in the 1960's to compensate for overfishing by the Japanese high seas fishery. The Soviets now release hundreds of millions of pink and chum salmon from a hatchery system which may be as large as Japan's.

If the productivity of wild stocks of salmon continues to decline because of the combined effects of natural stressing factors, overfishing, and harmful land and water use activities, increased reliance on artificial propagation can be anticipated. Although most modern hatcheries are operated by public agencies, private hatcheries are returning in California, Oregon, Washington, and Alaska. A salmon ranching industry is now in its formative stage on the Pacific coast, and active and prospec-

[1] Statistics from Japan Fisheries Resource Conservation Association and Japan Fishery Agency.

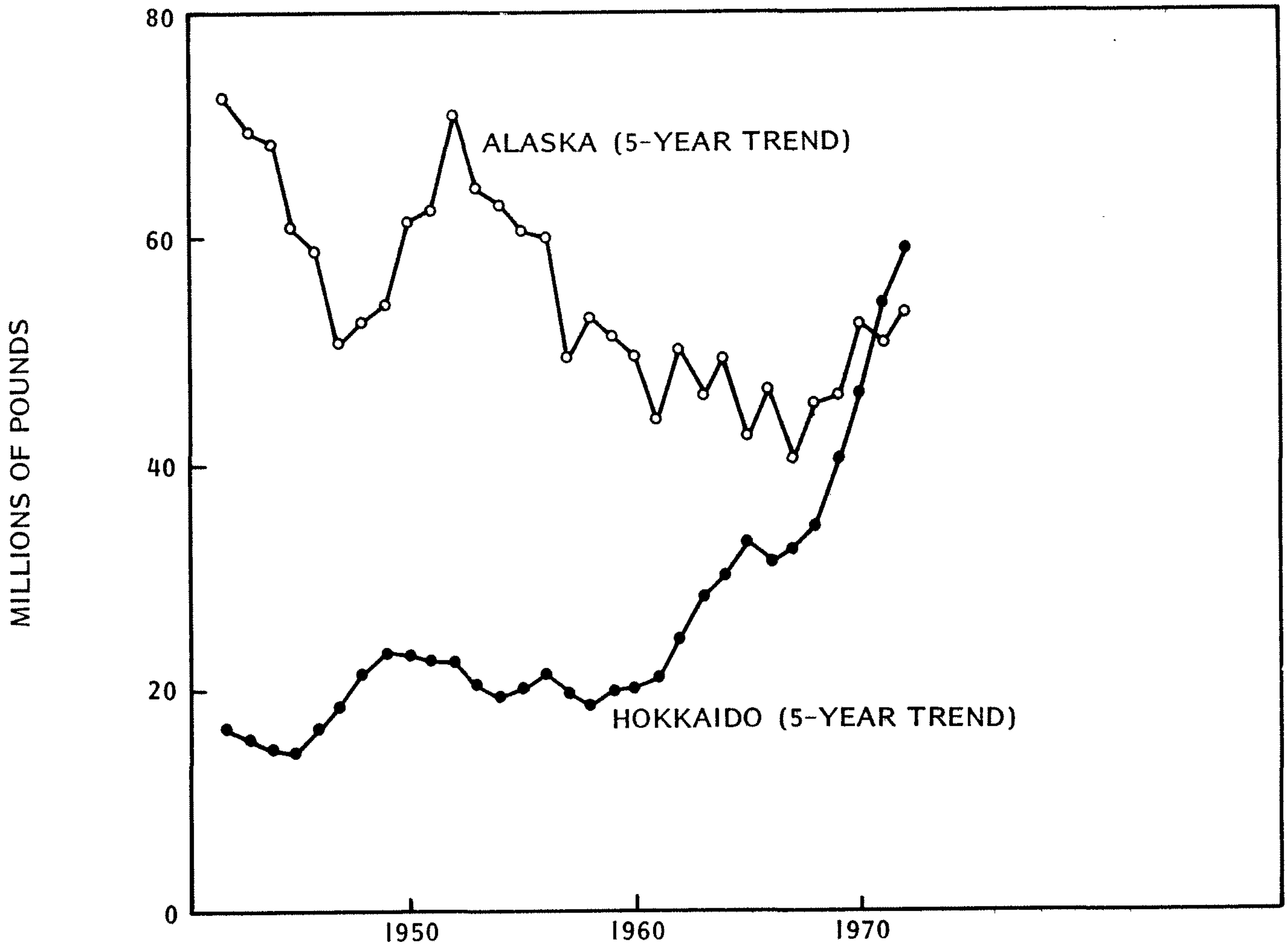


Figure 1--Trends of production of chum salmon on Hokkaido Island and in Alaska.

tive salmon ranchers are seeking technical assistance on how best to propagate salmon by artificial means.

Artificially propagated salmon fry must have qualities of stamina and growth which maximize their opportunity to survive the numerous natural and man-caused stresses they will be exposed to. In some ranching procedures, young salmon from hatcheries will be released as fry into natural nursery grounds; in others, they will be held in captivity for a few days to a year or longer and raised on artificial diets before they are released.

Aquaculture, which involves the release of artificially propagated juvenile fish into marine waters to grow on natural foods to harvestable size, is called "ocean ranching" in this manual. Pacific salmon are particularly well suited for ocean ranching because they migrate widely over the North Pacific Ocean and Bering Sea in search of food; they grow rapidly and have relatively good survival; and their strong homing instinct and natural herding behavior cause the mature fish to concentrate in or near their home stream or lake of origin for harvesting as adults.

This manual provides information about hatchery systems and describes procedures to aid the salmon rancher in producing juvenile salmon for ocean ranching. General background information on salmon is briefly discussed, followed by discussion on (1) water requirements, (2) design and operation of hatchery systems, (3) selection of brood stock, (4) care of brood fish, eggs, alevins, and fry, (5) genetic problems, and (6) economic and legal perspectives for private hatcheries.

BIOLOGY OF SALMON

An account of the life of Pacific salmon is a story of struggle for survival. Events in the story unfold in fresh water and at sea, but the locale of the beginning and the end is a spawning ground in a cold-water stream or lake. The spawning salmon has already survived against odds of at least 1,000 to 1 that it would die before becoming a mature adult. It is destined to die, nevertheless, within a few days after the new generation of fertilized eggs has been buried in the ancestral spawning ground.

Species of Salmon

Of the six species of Pacific salmon, all but one (*Oncorhynchus masu*--a native of Asia) are discussed in this manual. The most-often used common names and the scientific names for the five species are pink or humpback salmon (*O. gorbuscha*), chum or dog salmon (*O. keta*), sockeye or red salmon (*O. nerka*), chinook or king salmon (*O. tshawytscha*), and coho or silver salmon, (*O. kisutch*). Although these five species have many similarities in their biology, there are also differences, which are important to the design, operation, and application of hatchery systems.

This section summarizes only general aspects of the biology of salmon. Readers requiring more detailed information are referred to the section "Selected References."

Pink Salmon

Although pink salmon (Figure 2) are the smallest of the Pacific salmon, (3 to 7 pounds), they make up about 40% of the total poundage of salmon harvested in North America. They have a more rapid growth rate than the other species of Pacific salmon but are small because their life span is only 2 years (Figure 3). Young pink salmon typically migrate immediately to sea as fry and do not require freshwater streams or lakes for nursery areas. The adults usually migrate fewer than 200 miles inland from the sea and often spawn in intertidal areas at the mouths of streams.

Pink salmon are abundant from Puget Sound to western Alaska, are scarce in coastal streams of Washington, and occur only rarely in coastal streams of Oregon and northern California. They are harvested extensively in commercial net fisheries and are sometimes caught on hook and line by commercial trollers and sport fishermen. Most pink salmon are canned. Current annual landings in North America are less than one-half of their earlier levels.

Chum Salmon

Chum salmon (Figure 4) typically weigh between 5 and 20 pounds, although some may approach 30 pounds. Most fry migrate immediately to salt water after emerging from spawning gravels, but some feed in fresh water for a month or so (Figure 5). Chum salmon usually mature in their third to fifth year (occasionally in their second or sixth year). They commonly spawn in streams close to the sea, although some migrate more than 1,500 miles to their spawning grounds. Small creeks and large rivers from northern Oregon to the Arctic coast of Alaska provide the spawning grounds for North American chum salmon. This species is also widely distribu-

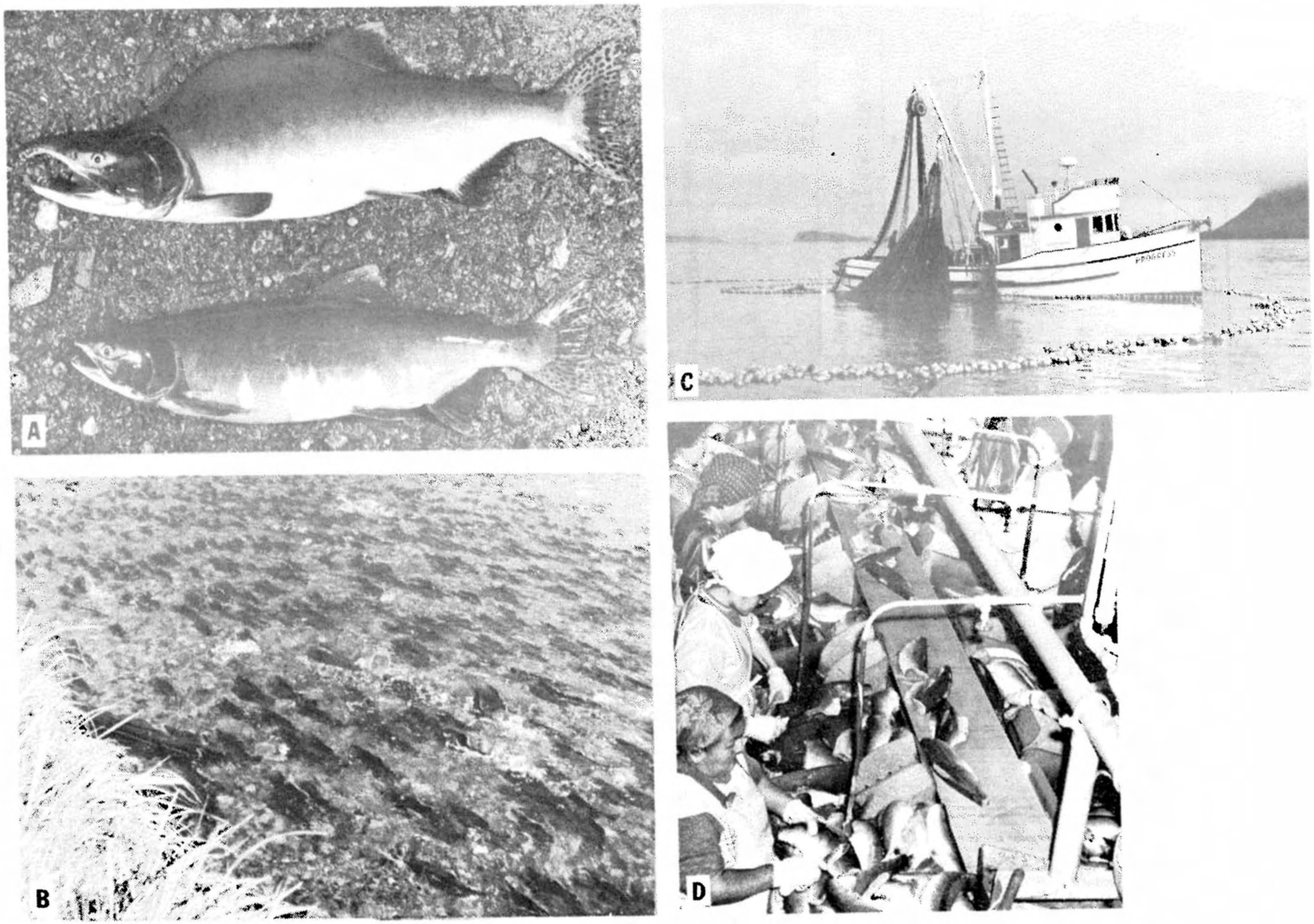


Figure 2.--Pink salmon: (A) mature male (upper) and female (lower), (B) mass spawning, (C) purse seine vessel, (D) butchering adult fish.

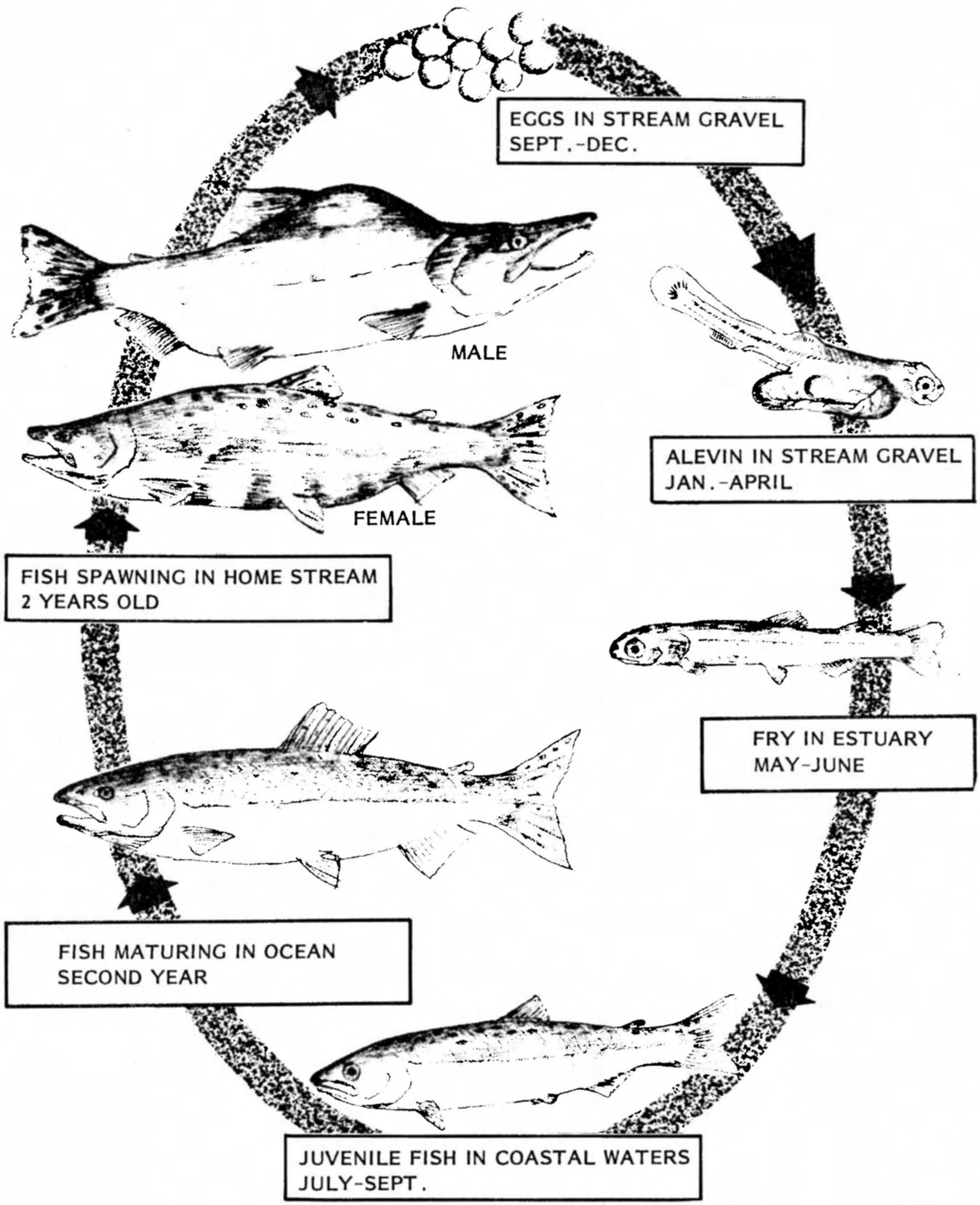


Figure 3.--Life cycle of pink salmon.

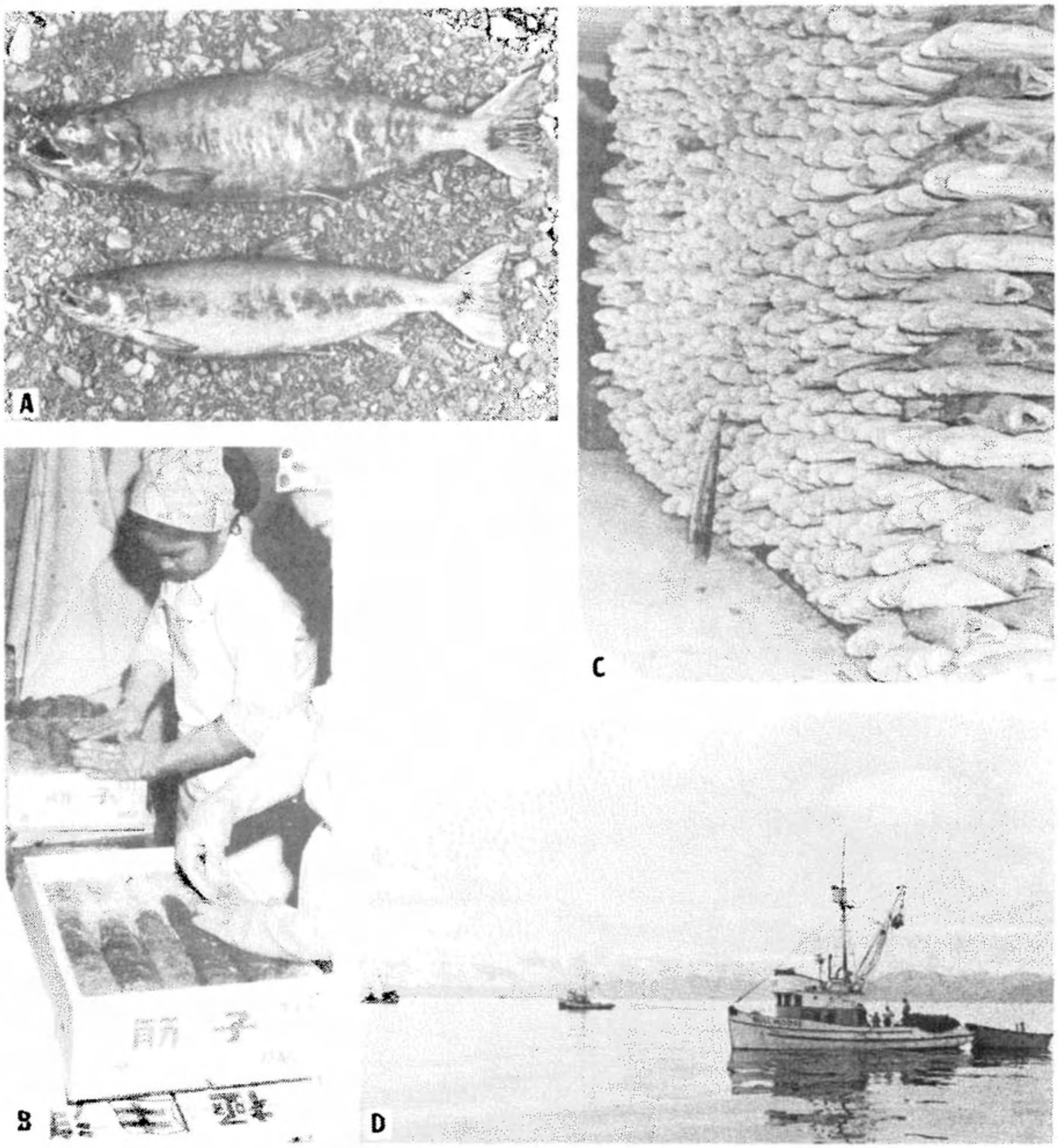


Figure 4.--Chum salmon: (A) mature male (upper) and female (lower), (B) eggs being packed for shipment, (C) frozen carcasses, and (D) fishing ground.

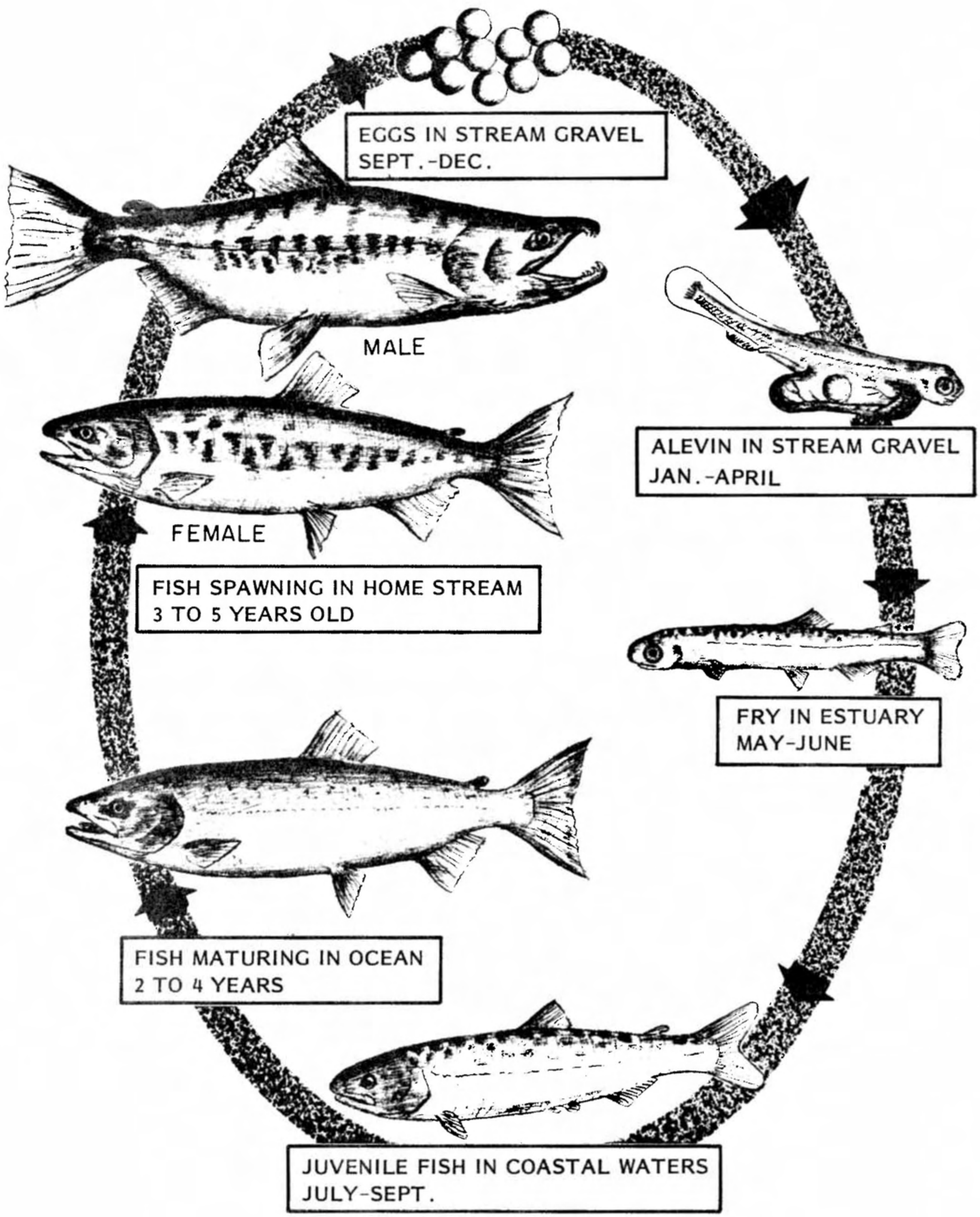


Figure 5.--Life cycle of chum salmon.

ted in Asian streams that enter the Arctic and Pacific oceans and the Bering, Okhotsk, and Japan seas.

The decline of North American chum salmon stocks has not been as precipitous as the pink salmon decline. Pacific Northwest stocks are nevertheless badly depleted. Japanese stocks would probably also be in very poor condition were it not for an extensive hatchery program. Chum salmon stocks in the Soviet Union have been seriously depleted, and the Soviets have initiated an extensive hatchery program to replenish stocks on Sakhalin Island.

Chum salmon are seldom caught on hook and line and are not popular with sport fishermen. They are valuable commercial fish, however, and are used extensively for canning. Fresh and frozen chum salmon are increasing in demand, and the eggs of this species bring a premium price as caviar in Japan.

Sockeye Salmon

Sockeye salmon (Figure 6) inhabit lake systems from the Columbia River drainage to western Alaska. Most sockeye salmon develop through the alevin stage in the gravel of their freshwater spawning areas. They then move into nursery lakes where they spend 1 to 3 more years in fresh water before migrating to sea (Figure 7). Sockeye salmon mature and spawn between their second and eighth year, usually in their fourth or fifth year. Adults typically weigh 5 to 8 pounds (occasionally as much as 15 pounds). They spawn in streams or in lakes, sometimes to depths of 100 feet.

The sockeye salmon is the second most abundant species of salmon in North America. It is a commercial fish, and the value of the catch frequently exceeds that of the more abundant pink salmon because of the higher unit value of sockeye salmon. Because of the deep red color of its flesh, the sockeye salmon is preferred for canning. The demand for fresh and frozen sockeye salmon is increasing, however.

Chinook Salmon

Chinook salmon (Figure 8) are known for their large size and long migrations to spawning grounds. They have been known to approach 100 pounds at maturity, but weights of 15 to 40 pounds are more typical. Some Yukon River chinook salmon spawn 2,000 miles from the ocean, and before dams were built on the river Columbia River fish also made long migrations.

Chinook salmon mature between their second and eighth year, usually in their fourth or fifth year. The young fish feed in fresh or brackish water for periods of a few months to a year or longer before they migrate to sea (Figure 9). Because of this long period in fresh water, chinook salmon are particularly vulnerable to damage from dams, pollution, irrigation, and other land and water use activities. Some of these losses have been mitigated through the use of hatcheries.

In North America, chinook salmon are found from the Sacramento River to the Yukon River. The species is not as abundant in Asia as in North America. Premium prices are paid for chinook salmon on the fresh fish market because of their large size and outstanding eating qualities. They are prized by sport anglers for these same reasons.

Coho Salmon

Coho salmon (Figure 10) are found in large and small streams and in lakes from northern California to the Yukon River. They spawn at locations up to several hundred miles from the sea. Juvenile coho salmon typically remain in fresh water

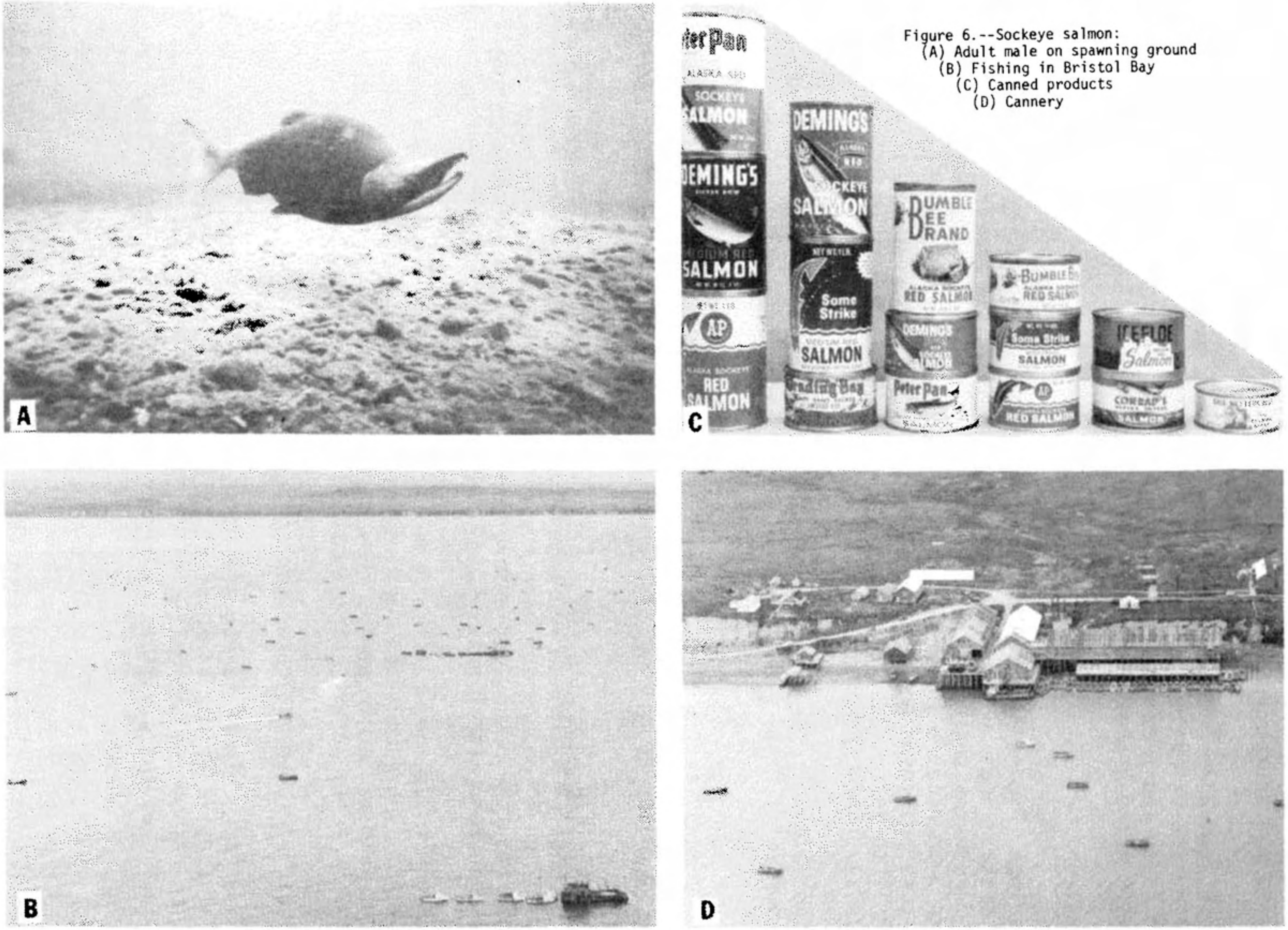


Figure 6.--Sockeye salmon:
(A) Adult male on spawning ground
(B) Fishing in Bristol Bay
(C) Canned products
(D) Cannery

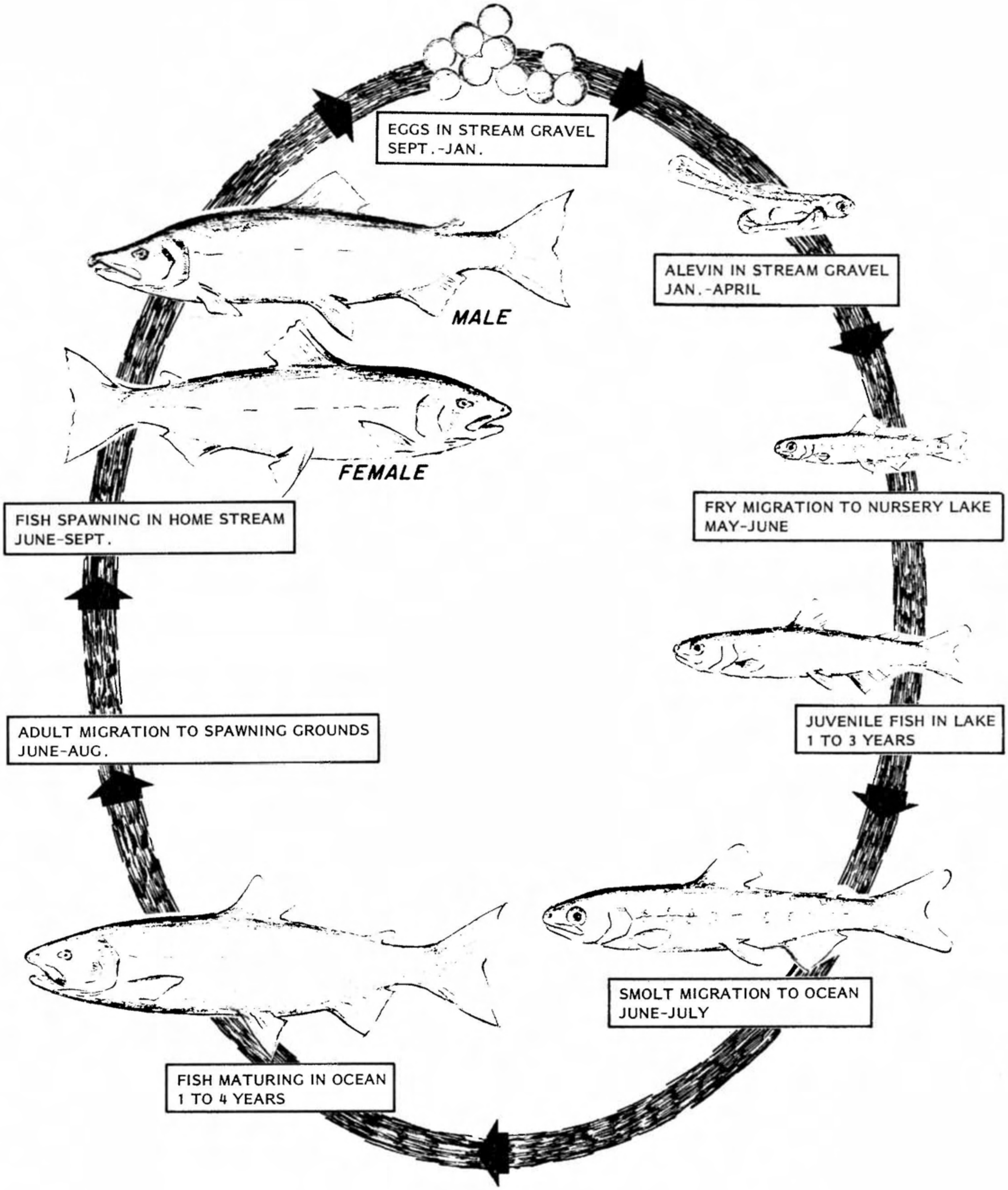
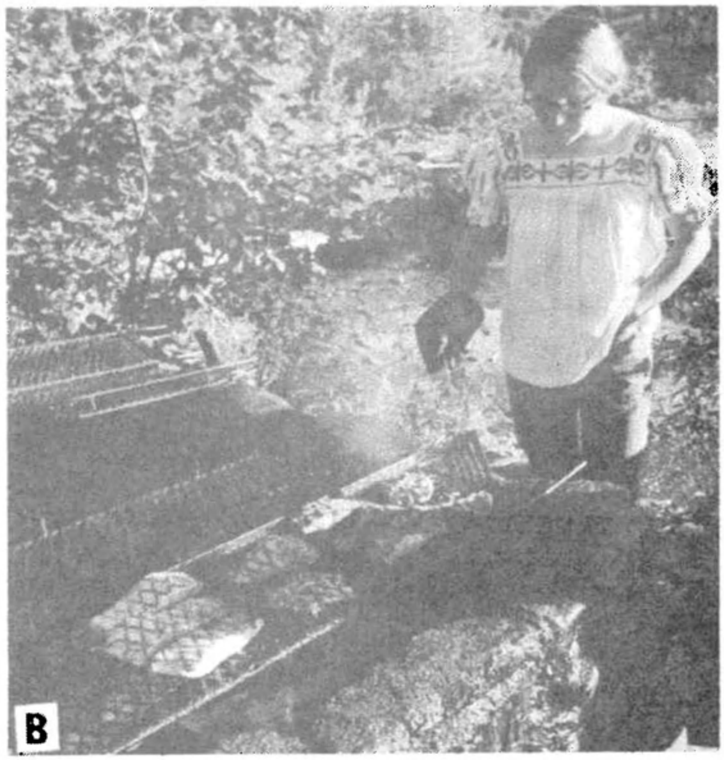


Figure 7.--Life cycle of sockeye salmon.



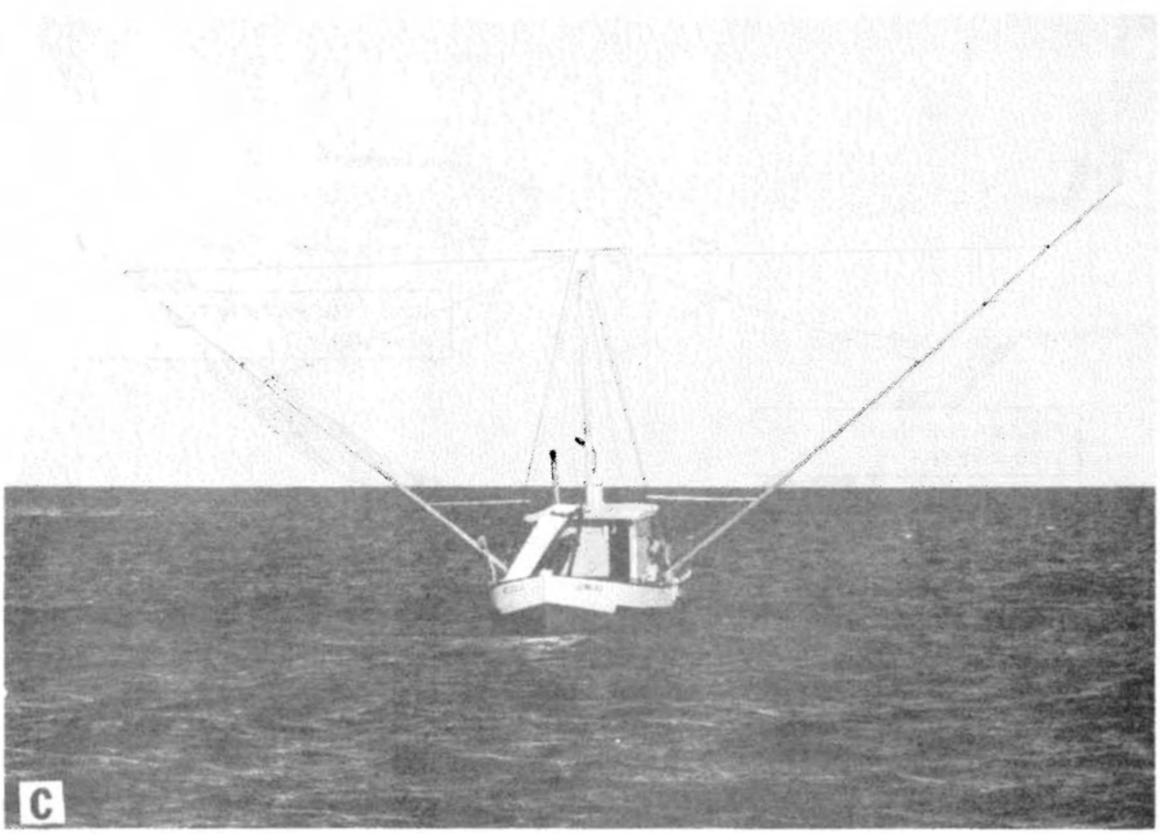


Figure 8.--Chinook salmon:
(A) a sport-caught fish
(B) fresh steaks
(C) troller

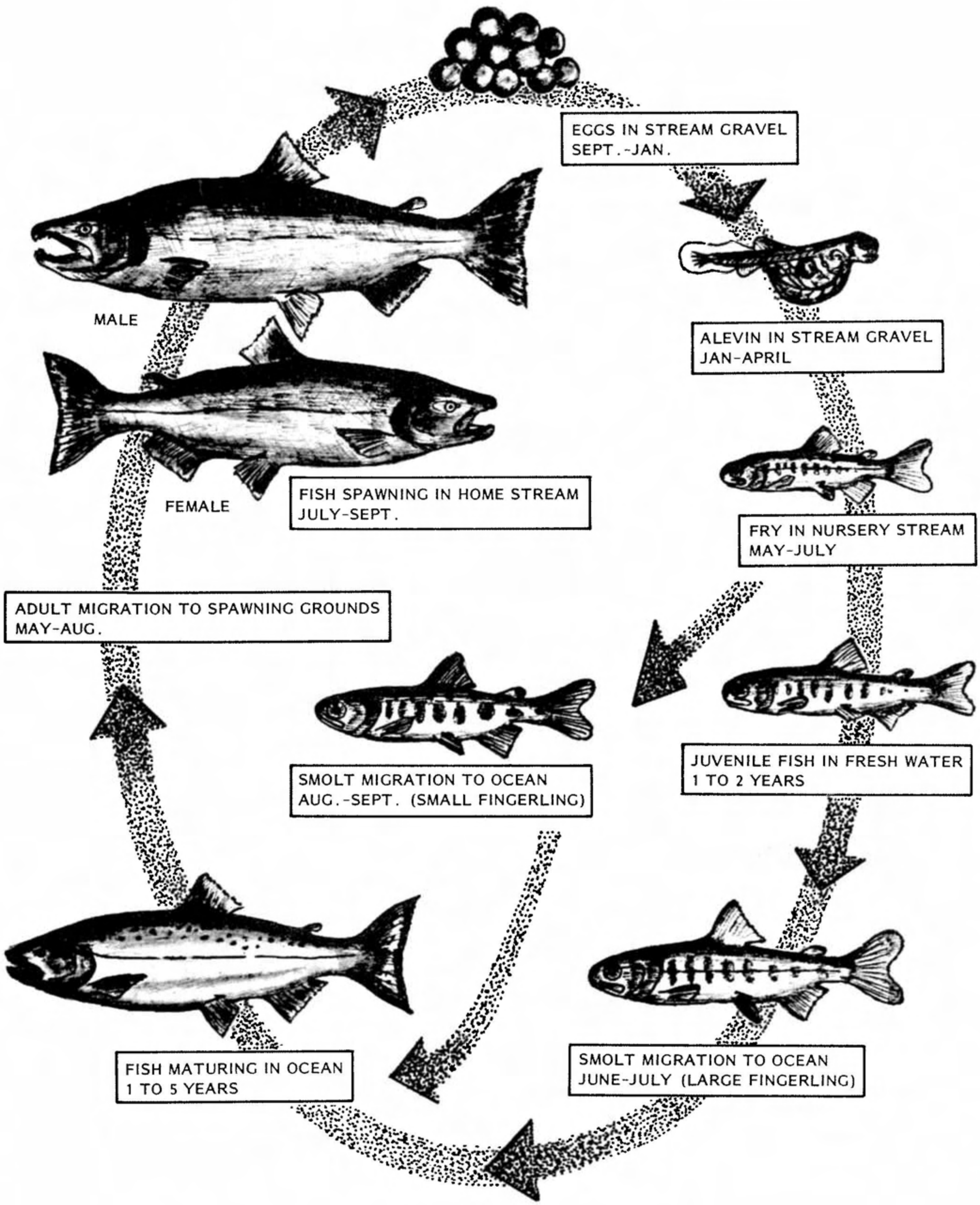


Figure 9.--Life cycle of chinook salmon.

1 or 2 years before entering the sea (Figure 11). The adults, which mature in their second to fourth year, commonly weigh between 6 and 12 pounds, occasionally 20, at this stage of their life.

Coho salmon have resisted heavy fishing pressure and environmental changes induced by man better than any other salmon species. Moreover, they have responded well to enhancement programs, especially in hatcheries designed to raise juvenile fish to smolt size.

Coho salmon are mostly caught by hook and line, both in the commercial and sport fisheries, although gill nets are used on some commercial fishing grounds. Like chinook salmon, coho support important recreational fisheries.

Life in Streams and Lakes

As the time for spawning approaches, salmon transform from silvery streamlined fish and become colored and sometimes misshapen. The transformation is usually more pronounced in males than females. Spawning males of all species develop an enlarged and hooked nose. Mature pink salmon become darker color and the male develops a pronounced hump on its back. Chum salmon become yellowish and their pelvic fins are tipped with white; the male has jagged crimson streaks on its sides and the female dusky bars. Sockeye salmon turn to a deep crimson, but have a greenish head and tail. Male coho salmon also turn reddish but not as vividly as the sockeye. Chinook salmon turn dark or reddish.

There are similarities in spawning behavior among the five species. Eggs are deposited in three or four pits that the female digs in the gravel bed of a stream or a lakeshore. Where spawning occurs in large rubble, eggs are sometimes deposited in natural crevices in the surface of the bed. However, in most cases the female excavates an elliptical area about 3 feet wide by 6 feet long; the entire excavation is called a redd. One or more males fertilize the eggs as soon as the female releases them, and she then covers them with at least 6 inches of gravel. After spawning is completed, a female remains in the vicinity of her redd until she weakens and dies, usually within 2 weeks after spawning. Males do not remain with spent females.

The spawning ground appears lifeless after spawning. Life remains, however, among the eggs and alevins, which repose beneath the surface of the gravel for 4 to 8 months, the length of time depending primarily on water temperature. The success of the new generation often depends on survival during this critical period between spawning and emergence of fry.

Salmon eggs are orange or red spheres 0.20 to 0.36 inch in diameter. Sockeye salmon have the smallest eggs and chinook salmon the largest. Fertilized eggs are clustered together in the spawning bed in groups of several hundred to a thousand or more. Even if natural survival should be relatively high, no more than 20% of the eggs will produce fry and survival to the fry stage is usually less than 10%.

Spawning usually occurs in summer in northerly spawning grounds and in autumn in southerly grounds, although there are exceptions to this among late-spawning northern stocks that utilize warm spring water sources for spawning. Fry emergence coincides with the annual spring cycle of increased food production in nursery waters.

Many circumstances enter into the struggle for survival in natural spawning beds. Some relate to the behavior of spawners, which sometimes crowd too densely into a limited area of spawning ground. When such crowding occurs, late-spawning females use the same redds as early-spawning females and excavate many of the fertilized

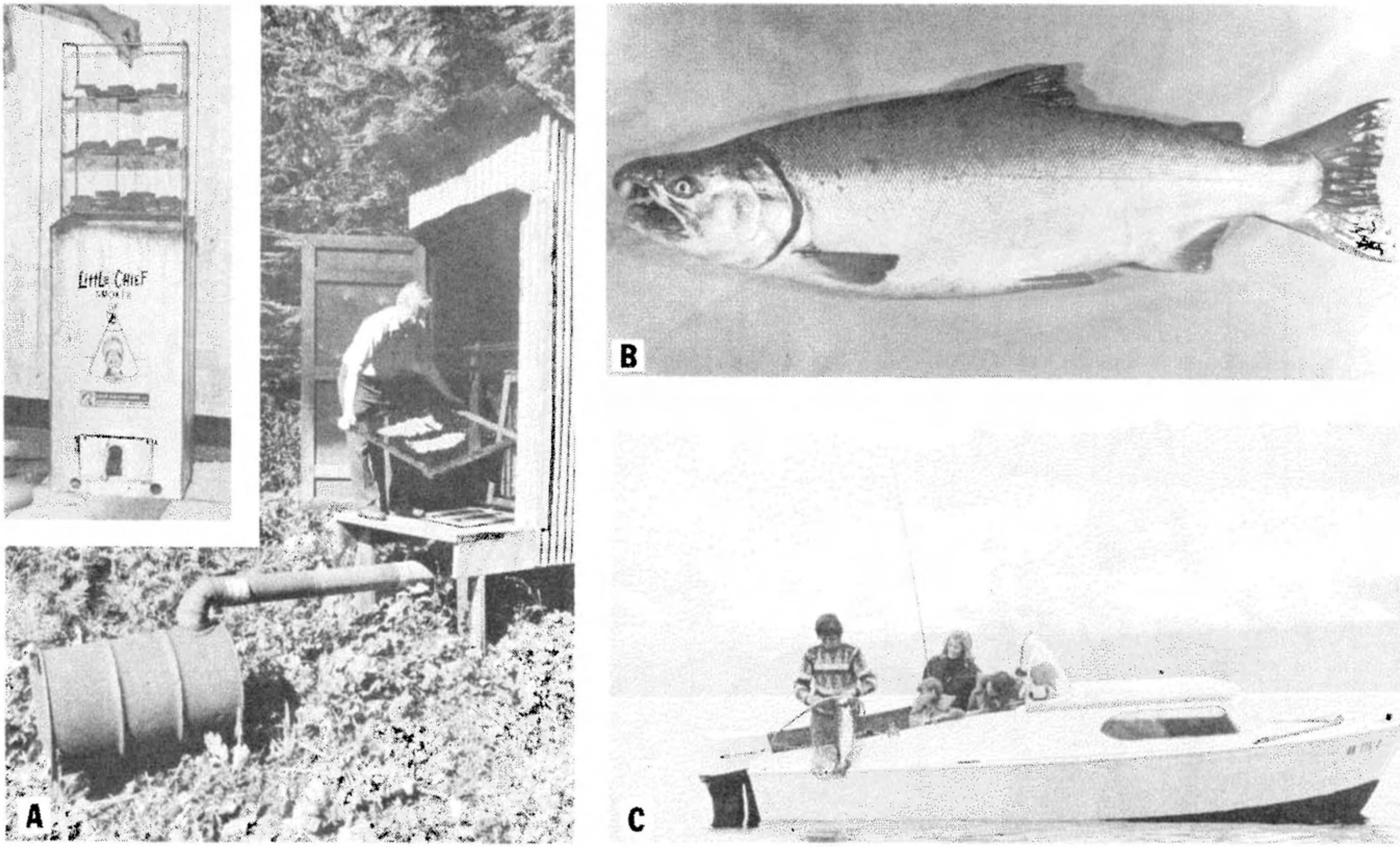


Figure 10.--Coho salmon: (A) smoked coho, (B) maturing male, (C) sport fishing.

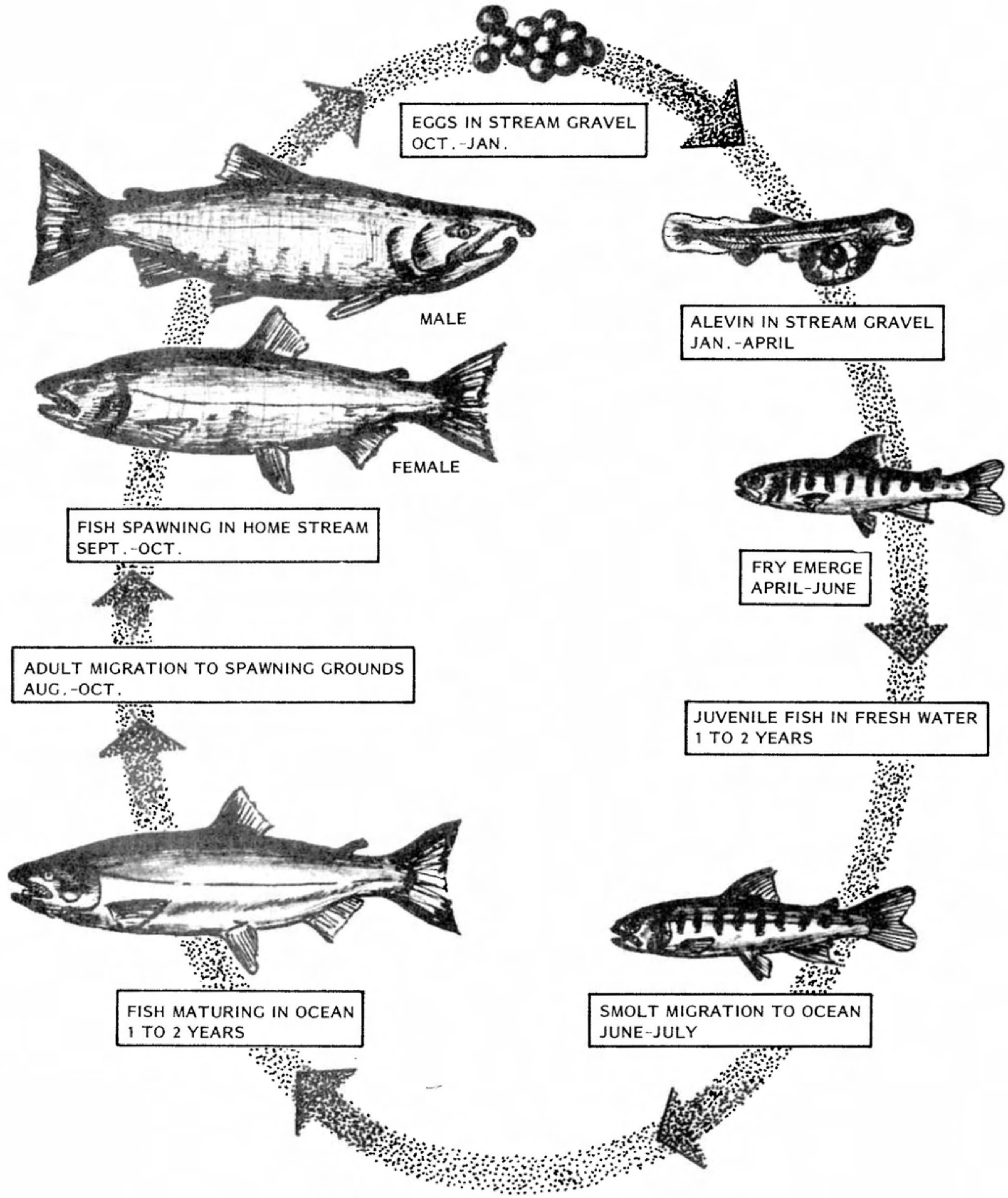


Figure 11.--Life cycle of coho salmon.

eggs already in the redd. There have been instances, especially with pink salmon, where extreme crowding has killed large numbers of unspawned fish. Fertilized eggs in redds face many dangers before the fry emerge: (1) suffocation or desiccation from low water, (2) gravel shift during freshets, (3) siltation, (4) freezing, and (5) predation.

The eggs do not depend upon the environment of the spawning bed for food because this is supplied by the yolk; they do depend upon it, however, for suitable water. Water flowing within the spawning bed (intragravel water) must transport oxygen to the developing embryo or alevin and carry away waste products such as carbon dioxide and ammonia gas. The velocity of intragravel water is commonly less than 3 feet per hour, whereas that of stream water may be 3 feet per second.

Salmon fry emerge from the spawning bed when their yolk is nearly absorbed, usually during hours of darkness. Pink and chum salmon fry begin an immediate seaward migration which may require minutes, hours, or days, depending on how near they are to salt water. Sockeye salmon fry begin an immediate migration to a nursery lake. Some have to migrate upstream or downstream to reach the lake, but those that are spawned on the shore of a lake make no migration. Chinook and coho salmon fry typically occupy feeding territories in the spawning stream or adjacent nursery streams, lakes, or marshes.

Juvenile sockeye and coho salmon remain in the freshwater nursery areas for 1 year or longer before they migrate to sea. Juvenile chinook salmon sometimes migrate to an estuary after feeding in fresh water for only a few months, although they also commonly remain in fresh water for a year or longer. Mortality of juvenile sockeye, chinook, and coho salmon while in fresh water commonly approaches 90% of the fry that emerge from spawning grounds. Freshwater mortality of juvenile pink and chum salmon is usually much lower because their period of residence in fresh water is typically very short. However, ocean mortality of pink and chum salmon is usually higher than for the other species because of their small size when they enter the sea. Most juvenile salmon migrate to sea in the spring of the year, but continue migrating into summer.

Life at Sea

Pacific salmon occupy waters of the North Pacific Ocean at about the 40° north latitude line, which intercepts northern California and Northern Honshu Island. They are found throughout the Bering Sea and enter waters of the Chukchi Sea and Arctic Ocean. Salmon from North America and Asia utilize an "oceanic pasture" more than twice the area of the continental United States.

Little was known about salmon on the high seas before the Second World War. Japan had exploited salmon in coastal waters of the Kuril Islands, Kamchatka, and Siberia before the war; but Russia denied Japanese fishermen access to these traditional coastal fishing grounds after the war. This caused the Japanese to seek salmon on the high seas, and Japan undertook the construction of a high seas salmon fishing fleet as a part of her postwar recovery effort. By 1952, the Japanese were actively fishing for salmon over much of the western Pacific Ocean and Bering Sea and had begun to show an interest in salmon occupying waters far to the east.

Tens of thousands of salmon have been tagged on the high seas since 1955, and movements of many of these tagged fish have been determined from their recapture at sea and in distant coastal waters. The results show that a salmon's journey at sea may carry it 2,000 miles or more from its home stream. Chum salmon tagged south of Unalaska Island in the Aleutians have been recaptured in coastal waters of Hokkaido Island, Sakhalin Island, Kamchatka, Siberia, western Alaska, and Vancouver Island

(Figure 12). These distant locations cover most of the range of chum salmon in coastal waters of Asia and North America. Sockeye salmon tagged in the Gulf of Alaska were recaptured from Bristol Bay to the Fraser River (Figure 13)--the entire range of commercially important runs of sockeye salmon in North America. Pink salmon are also widely distributed on the high seas, and Asian and North American stocks overlap extensively in the oceanic feeding areas. Although movements of chinook and coho salmon are not as well documented as those of other species, these two species are known to travel more than 1,000 miles from their home streams.

The distribution of salmon on the high seas changes with warming and cooling of surface waters. Salmon are mostly within 200 feet of the surface, and they move southward in winter and northward in summer. A narrow coastal belt of cold upwelling ocean water along the North American coast provides conditions suitable for salmon southward to central California throughout the year.

Survival of salmon at sea typically ranges from 1 to 5% for pink and chum, which enter the sea as fry; and 5 to 30% for sockeye, chinook, and coho, which enter as smolts. Predation is probably the most important natural mortality factor at sea, but parasites and diseases may also be significant.

Homing and Transplantation

Successive generations of genetically separate stocks of salmon ascend home streams to reach spawning grounds on well-defined schedules which may vary by only a few days to a few weeks each year, depending on the particular stock. Even though salmon may travel thousands of miles while at sea, they somehow manage to relocate the specific stream or lake of their natal spawning ground. This is an extraordinary accomplishment when one considers that these fish begin their homeward journey from many distant points scattered at sea.

A number of hypotheses have been advanced to explain this mysterious migration: Do salmon orient on the sun? celestial bodies? water currents? electrical gradients in seawater? Is this uncanny ability to navigate to the home stream an inherited trait or a learned (conditioned) response? We can only speculate about answers to these perplexing questions. It is well known that once salmon come within the influence of home waters, olfactory cues trigger recognition of the correct freshwater migration path. Salmon possess an acute sense of odor perception, and each stream and lake has a unique organic quality, possibly derived from soils and plant communities. Once exposed to these organic qualities, young salmon become imprinted and are able to recognize them throughout their lives.

Recognition of home waters appears in part at least to be a conditioned response of salmon rather than entirely an instinctive trait. Salmon that were transferred from their natal water to another body of fresh water as eggs or young fish, have been known to return as adults to the new stream or lake even though no ancestral ties existed. This behavior has allowed transplanted stocks to establish self-perpetuating populations.

Pacific salmon have also become established in natural streams, spawning channels, and hatcheries outside of their native range. Well-known examples include chinook salmon in New Zealand, coho and chinook salmon in the Great Lakes, and pink salmon on the Kola Penninsula of USSR near Murmansk. There are many examples where runs of Pacific salmon have been created or reinforced within their natural range through transplantation of stocks to hatcheries, spawning channels, and natural lakes and streams. Numerous attempts at transplanting stocks have failed, however. Some of these failures may have been caused by differences in ecological conditions between recipient and donor waters, others by improper handling of fish or over-

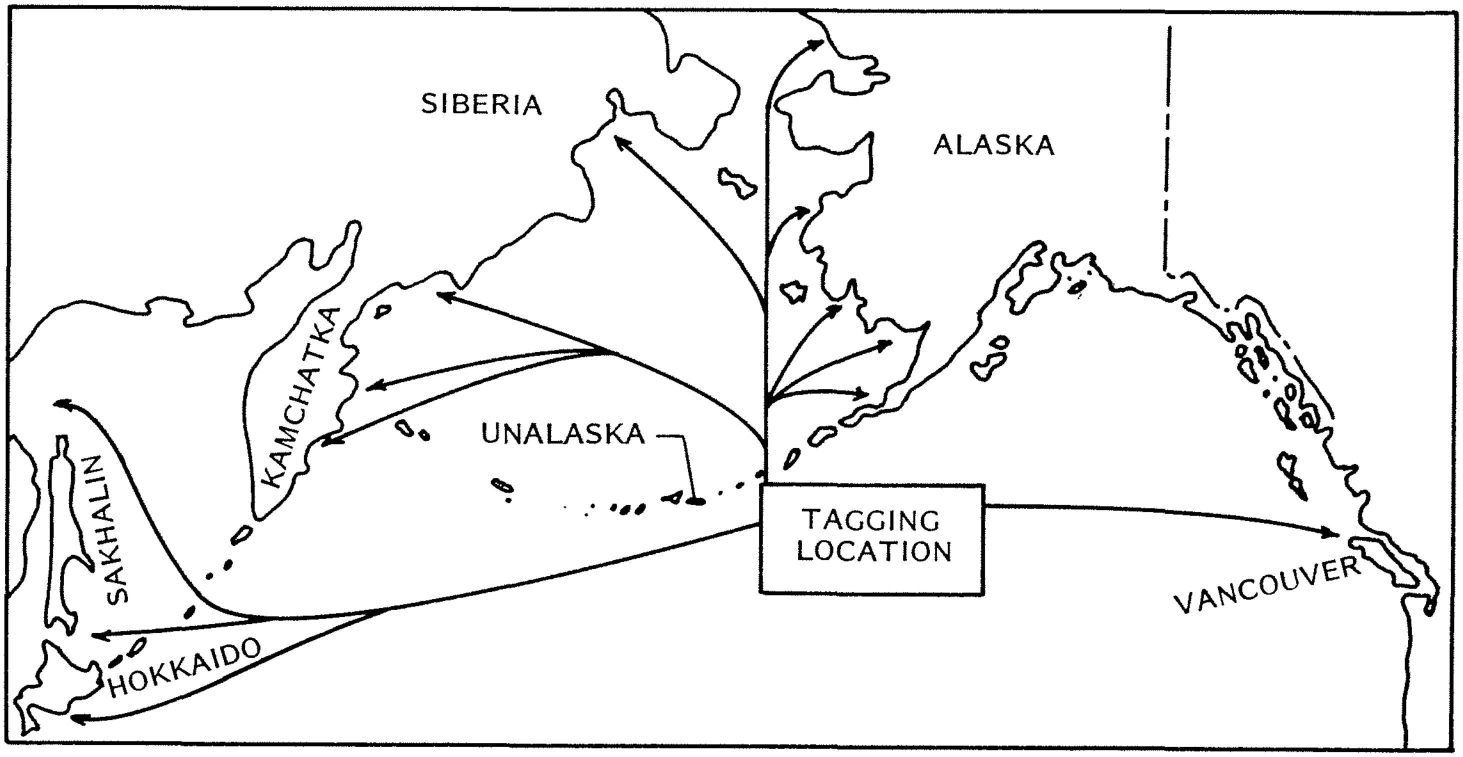


Figure 12.--Location of tagging of chum salmon south of Unalaska and locations of recapture (arrows) of tagged fish.

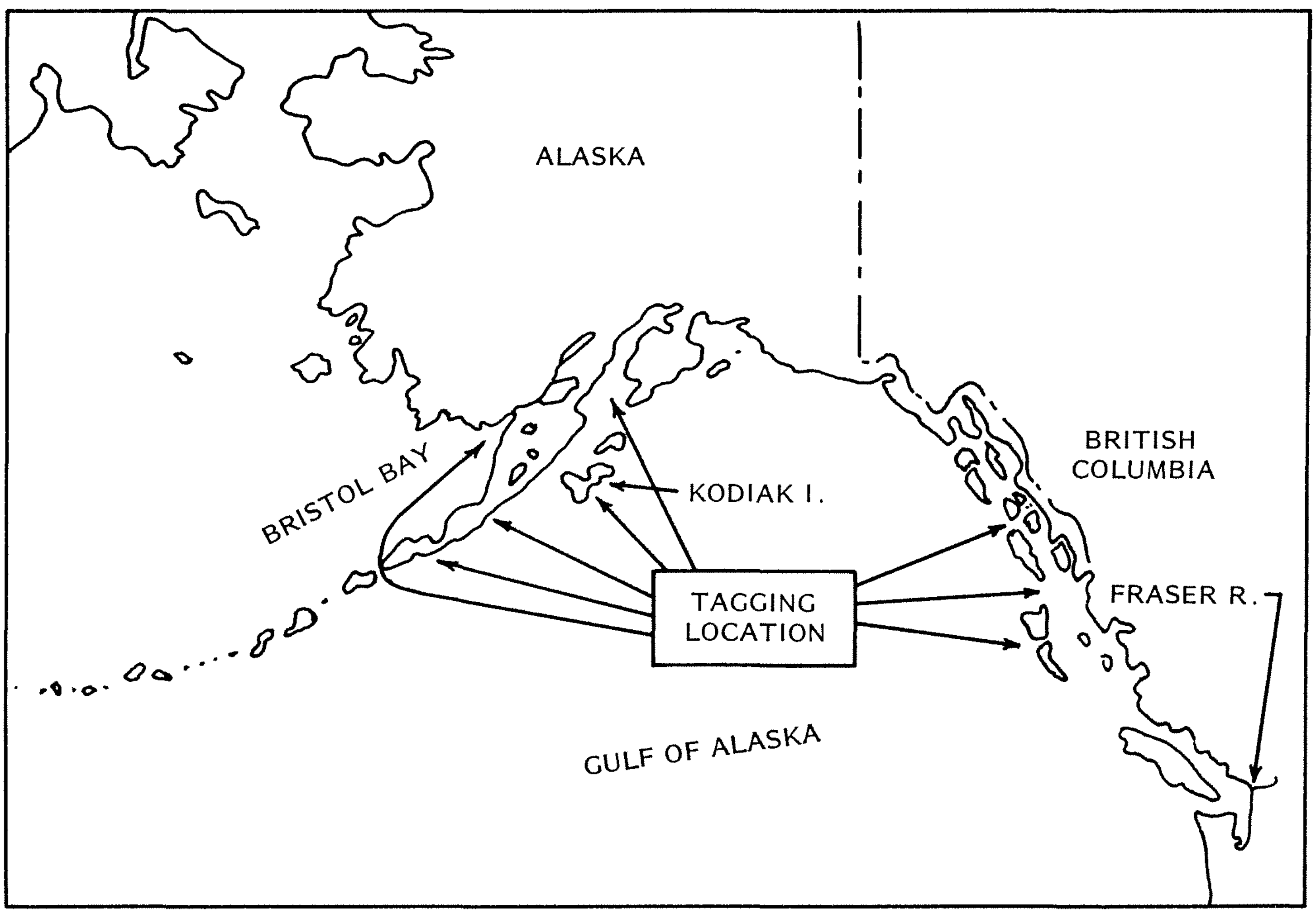


Figure 13.--Location of tagging of sockeye salmon in the Gulf of Alaska and locations of recapture (arrows) of tagged fish.

fishing. Perhaps some unknown genetic control over homing behavior has also played a role in the failure of transplanted stocks.

To increase the chances of success in transplanting stocks, the ecological characteristics of the donor and recipient waters should be similar and the two streams should be as close to one another as possible. If a recipient stream formerly held fish or still supports a remnant run, the timing of spawning of the donor stock should be similar to that of fish native to the recipient stream. Furthermore, the procedures of handling transplanted fish should take into account the natural behavior of the species in question. For example, with pink and chum and possibly sockeye salmon, it may be necessary to hatch the eggs in the recipient stream to ensure that the young fish, which migrate as newly emerged fry, become conditioned to recognize their new home waters. This precaution may be unnecessary for chinook and coho salmon, which commonly remain in a recipient stream for a period to feed. The necessity to evaluate and compare the ecological characteristics of donor and recipient streams and the behavior of transplanted stocks cannot be overemphasized because failure to establish a run might result from genetically determined inability of an introduced stock to adapt to a new environment.

HATCHERY WATER SUPPLY

The suitability of any water supply for a salmon hatchery depends on its quantity, temperature, and concentrations of dissolved atmospheric gases, organic substances, and inorganic constituents. It is also essential for the salmon stock to be adapted to the environmental conditions which characterize the hatchery water supply.

Quantity

Water is the medium through which eggs, alevins, and juvenile fish receive dissolved atmospheric oxygen. The biomass of salmon embryos, alevins, and fry that can safely be held in a hatchery incubator is determined largely by the availability of dissolved oxygen. Water also removes the waste products of metabolism; the term "metabolism" refers to the vital processes involved in the release of body energy, the building and repair of body tissues, and the excretion of waste materials. It is essential that the water supply be relatively free of contaminants.

The capacity of water to absorb atmospheric oxygen is determined by temperature and atmospheric pressure. Saturation values of oxygen in water are higher at low temperatures than at high and decrease with an increase in altitude.

The approximate saturation values (in milligrams per liter) at four temperatures for atmospheric oxygen dissolved in fresh water at sea level and at 1,600 feet above sea level are as follows:

Water temperature (°F)	Sea level	1,600 feet
32°	14.6	13.7
41°	12.8	12.0
50°	11.3	10.6
59°	10.1	9.5

Although there has been considerable work on the water requirements of juvenile salmon in raceways, relatively little work has been done on the requirements in hatchery incubators. The present guidelines on delivery rates to hatchery incubators of water containing known quantities of dissolved oxygen are therefore incomplete and tentative.

The rate of consumption of dissolved oxygen by eggs, alevins, and fry is determined by water temperature and stage of development--metabolic activity increases with increased water temperature and stage of development. Salmon embryos begin to develop when the eggs are fertilized in summer and autumn (when temperatures are warm), but the total consumption of dissolved oxygen remains relatively low until after the eggs hatch in winter because there is only a small biomass of embryonic tissue before hatching. The egg is composed mostly of inert yolk, and only enough waterflow is needed to maintain oxygenated water at the surface of the egg and to remove the metabolic wastes produced by the embryo. Oxygen consumption approaches a maximum in hatchery incubators when yolk is mostly absorbed and as fry begin to swim. This usually occurs in the spring of the year as the fry approach the time of release from hatchery incubators. It also coincides with a warming of water.

Pink salmon alevins having a combined weight of 1,800 per pound have been observed to consume 60 mg O_2/pound of fish per hour at a water temperature of 40°F. At this temperature, fresh water becomes saturated near sea level with about 13 mg O_2/liter of water. If, for example, we should select a stocking density where respiring alevins reduce the oxygen content of incoming hatchery water by 3 mg/liter in the absence of aeration, we can easily calculate the amount of water required to produce a given poundage of fry. Suppose we wish to produce 1,000 pounds of fry[2] in water which is 40°F. The amount of water required under the above conditions is calculated to be 88 gpm (gallons per minute), viz:

$$1{,}000 \text{ lb fry} \times 60 \text{ mg } O_2\text{/hour per pound of fry} = 60{,}000 \text{ mg } O_2\text{/hour}$$

$$\frac{60{,}000 \text{ mg } O_2\text{/hour}}{3 \text{ mg } O_2\text{/liter}} = 20{,}000 \text{ liters/hour} = 88 \text{ gpm}$$

The following formula is convenient to use for the calculation of weight of alevins or fry that can be raised on 1 gpm of waterflow:

$$W = \frac{1.2\,(C - C_{min})}{O_2},$$

where W = pounds of fish per gpm.
C = mg/liter of dissolved oxygen in incoming water
C_{min} = minimum desired mg/liter of dissolved oxygen after passing water over fish
O_2 = oxygen uptake by fish, expressed as pounds of O_2/100 lb of fish per day.

In our previous example, the consumption of 60 mg O_2/hour per pound of fish is equivalent to 0.317 lb of O_2 per 100 lb of fish per day. Using the above equation, we calculate

$$W = \frac{1.2\,(13 - 10)}{0.317} = 11.4 \text{ lb of fry/gpm}$$

Thus, to raise 1,000 lb of fry, we need

$$\frac{1{,}000 \text{ lb of fry}}{11.4 \text{ lb of fry/gpm}} = 88 \text{ gpm}$$

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[2] Depending on the species, 1,000 to 3,000 unfed salmon fry typically weigh one pound.

Unfortunately, detailed information is lacking on oxygen consumption rates of different salmon species at various water temperatures. It is tentatively recommended that 1,000 pounds of unfed fry (advanced alevins) be supplied with 100 gpm or more of water where maximum temperature is 40°F and where incoming hatchery water contains at least 8 mg O_2/liter of water. If water temperature warms above 40°F, either the volume of water or the minimum dissolved oxygen content of incoming water should be increased.

The velocity of water flowing past eggs and alevins will be determined largely by configuration and dimensions of hatchery incubators, especially cross-sectional areas. In order to ensure sufficient velocity to deliver oxygen to eggs and to remove waste metabolites, it is recommended that average apparent velocity[3] be at least 200 cm/hour (79 inches/hour) in hatchery incubators. Thus, the configuration of hatchery incubators can have an important bearing on the amount of water required.

Temperature

The influence of water temperature will be alluded to frequently in sections of this manual where artificial propagation of the various life stages of salmon is discussed. Optimum temperature ranges reported in the literature for salmon are often based on physiological criteria such as metabolic and growth rates, but behavioral and ecological criteria may be of equal importance.

Because the rate of development and growth of salmon embryos and alevins is determined by water temperature, natural spawning in streams and lakes is timed for salmon fry to emerge from spawning gravels in the spring of the year when the availability of food in nursery waters is increasing and while water is warming to allow more rapid growth of young salmon. Where juvenile salmon are released from hatcheries into natural freshwater or saltwater nursery areas, the temperature regime in the hatchery should in most instances[4] be as nearly the same as that of the hatchery stream and perhaps other streams near the hatchery that support natural runs of salmon. Similarity in temperature between the hatchery water and natural streams will help to ensure that the physiological state of hatchery fry will compare closely to that of wild fry.

Temperatures which become too cold or too warm for salmon impart stresses on fish before lethal levels are reached. Resistance to cold or warm water varies among species of salmon in relation to their stage of development and according to their acclimation to particular temperature regimes. Here are some general guidelines for salmon aquaculture:

> Mature salmon generally ripen and spawn as water temperature declines from its summer maximum; the preferred range for spawning is 45° to 55°F.
>
> Exposure of eggs to water temperatures of 40°F and lower should be avoided for at least 10 days after fertilization, preferably 20 to 30 days.

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[3] Apparent velocity (V) is defined as the volume of waterflow (Q) divided by the cross-sectional area (A) perpendicular to the direction of waterflow, i.e. $V = \frac{Q}{A}$.

[4] Heated water is used in some hatcheries to accelerate development and growth artificially, especially where fish are to be raised in feedlots.

After the initial sensitivity to low temperatures has passed, embryos and alevins can tolerate temperatures as low as 32°F, as long as the water does not freeze.

Exposure of fry to water temperatures much above 60°F can impart stress, but fry are able to tolerate temperatures in the upper 60's and low 70's for limited periods.

pH

The hydrogen ion concentration of an aqueous solution is described by its pH value. Water becomes increasingly acidic as pH declines below the neutral value (pH 7.0 at 77°F) and increasingly basic as pH climbs above neutrality.

The role that pH plays in the quality of a hatchery water supply is largely indirect. Although pH serves as an indicator of acidity or alkalinity, the importance of either characteristic depends largely on other constituents in water--viz metals, alkalies, acids, and gases. In many instances the toxicity of these other constituents to salmon can be controlled by pH.

Rainwater has a low mineral content and is poorly buffered. It normally is weakly acidic (pH about 6.5). As rainwater becomes exposed to organic and inorganic matter, it picks up various ions which determine the acidity and alkalinity of natural waters.

Values of pH ranging from 6.0 to 8.0 are common for natural waters, and such waters are usually acceptable for use in hatcheries. Water with pH lower than 6.0 or higher than 8.0, although not necessarily unsuited for hatcheries, should be examined critically for possible harmful contaminants.

Water with pH less than 7.0 is usually poorly buffered with dissolved minerals. Such water can easily acquire toxic concentrations of heavy metals such as zinc, copper, cadmium, aluminum, and lead. Therefore, the use of galvanized steel, aluminum, copper, and brass fittings and pipe should be avoided in hatcheries with poorly buffered water of low pH. Water with low pH should also be examined for possible presence of free carbon dioxide, hydrogen sulfide, and certain toxic acids, including tannic acid (which is often found in natural waters). Bog waters with high acidity and pH much below 6.0 should be avoided as water sources for hatcheries.

Water with pH above 7.0 is usually buffered with dissolved minerals. Heavy metals precipitate from solution in well-buffered water with high pH and are not as toxic to eggs and alevins as poorly buffered water with low pH. Toxicity from free carbon dioxide and hydrogen sulfide is unlikely in natural waters with pH above 7.0, but ammonia gas (NH_3) is toxic in highly alkaline waters. Thus, to avoid a buildup of nitrogenous wastes in water of high pH, hatchery incubators must not be overcrowded with embryos and alevins. Recycling water through hatchery incubators placed in series and served by a common water supply should be approached with care in alkaline waters of pH 8.0 and above to avoid a progressive increase in ammonia nitrogen to toxic levels in incubators served last in the series.

Dissolved Gases

Nitrogen and oxygen are the two most abundant atmospheric gases dissolved in water. Although the atmosphere contains almost four times more nitrogen than oxygen on a volumetric basis, oxygen has twice the solubility of nitrogen in water. Therefore, fresh water usually contains only twice as much nitrogen as oxygen when in equilibrium with the atmosphere.

Carbon dioxide is also present in water, but it normally occurs at a much lower concentration than either nitrogen or oxygen because of its low concentration in the atmosphere. However, carbon dioxide has a much higher solubility in water than oxygen or nitrogen, and there are situations where concentrations of carbon dioxide can exceed those of nitrogen or oxygen. For this to occur, water must be exposed to a source of highly concentrated carbon dioxide. Water containing unusually high levels of carbon dioxide (say 5 mg/liter or more) could be unfit for use in hatchery incubators because of the contaminants sometimes associated with high carbon dioxide concentrations. The presence in a hatchery water supply of other naturally occurring gases such as ammonia, methane, or hydrogen sulfide also suggests unfavorable environmental conditions for salmon.

The toxicity of ammonia and hydrogen sulfide is determined by pH. The relation is direct for ammonia and inverse for hydrogen sulfide. Concentrations of un-ionized ammonia gas should not exceed 0.002 mg/liter. Concentrations of hydrogen sulfide above 0.5 mg/liter should be suspect in acidic waters.

Rather high concentrations of free carbon dioxide can be tolerated in hatchery water supplies, provided dissolved oxygen levels remain above 5 mg/liter and there are no other contaminating substances in the water. Although acidic waters with several milligrams of free carbon dioxide per liter are not necessarily harmful to eggs and alevins, the cause of high carbon dioxide levels should be identified to determine if there are associated water quality problems. For example, high carbon dioxide levels can occur from respiration of aquatic vegetation at night. Dense growths of aquatic vegetation in the hatchery water supply can deplete oxygen at night and can also raise the carbon dioxide levels. This type of problem can be corrected by aerating water.

It is not unusual for hatchery water supplies to be supersaturated with inert gases, especially nitrogen. Other inert gases which can occur in natural waters are zenon, krypton, argon, and neon. Even though these gases are biologically inert, there are circumstances where they can kill alevins in hatchery incubators. Some waters, especially those flowing from springs and artesian wells or those pumped from wells, are naturally supersaturated with dissolved inert gases. Nitrogen supersaturation can also be caused mechanically if water passing through a conduit under high pressure is suddenly exposed to the atmosphere. Sudden warming can also cause supersaturation of gases dissolved in water.

Alevins exposed to water supersaturated with inert gas absorb the gas into their body fluids. Because the total pressure of these dissolved gases exceeds the hydrostatic pressure (primarily atmospheric pressure), gas that is surplus to normal saturation values is released from solution and forms bubbles. These bubbles tend to accumulate in the abdominal cavity, behind the eyeballs, in fins, under the skin, and in the vascular system (gills, kidneys, heart). Death often results from an embolism. Another manifestation of "gas bubble" disease is "gas popeye" in alevins, which causes blindness.

Oxygen can also become supersaturated in water but is less likely to cause embolism or "popeye" than the inert gases because it is readily reabsorbed by body fluids.

Even very slight supersaturation of inert gases can cause embolism or "popeye" among salmon alevins. If supersaturation is suspected, the problem can be corrected by aeration.

Nitrogenous Wastes

Nitrogenous wastes in hatchery incubators are mostly excretions from respiring embryos and alevins. These wastes mostly consist of ammonia derivatives but also include urea and amine derivatives. Ammonia has an inhibiting effect on growth and development and is toxic at very low concentrations in highly alkaline water. Toxicity of ammonia is determined largely by the concentration of ammonia gas (NH_3) in solution. In water of 50°F and colder and at pH 8.0 or lower, at least 98% of ammonia gas is ionized to relatively nontoxic NH_4^+. The percentages of un-ionized ammonia gas in aqueous solutions at 41° and 50°F are as follows:

pH	41°F	50°F
6.5	0.04	0.06
7.0	0.12	0.19
7.5	0.39	0.59
8.0	1.22	1.83
8.5	3.77	5.55

Ionization to NH_4^+ increases with decreasing pH. Moderate crowding of eggs and alevins should not cause problems from nitrogenous wastes in acidic or slightly alkaline waters provided guidelines on waterflow through incubators are adhered to.

Dissolved Solids

Water is the universal solvent, and the amounts and kinds of solids dissolved in natural waters vary greatly among drainages. The solids most commonly dissolved in natural fresh waters are bicarbonate (HCO_3), calcium sulfate (SO_4), chloride, magnesium, sodium, and potassium. Some of these constituents, along with various trace elements (e.g. nitrogen and phosphorus), must occur at low concentrations to support life processes.

The extreme high toxicity of zinc and copper to fish warrants special attention. A salmon rancher should avoid the use of hatchery components (piping, valves, fittings, tanks, screens, etc.) constructed of galvanized steel, copper, or brass, especially if hatchery water is poorly buffered and has low pH. Because aluminum and iron are moderately toxic to fish, these materials should not be used for waterlines.

Other highly toxic metals which should be avoided in hatchery water supplies include lead, mercury, and cadmium. A listing of metals of medium toxicity would include nickel, cobalt, and titanium. Metals of relatively low toxicity include sodium, potassium, calcium, strontium, magnesium, manganese, and barium; concentrations of these metals in hatchery water would normally be too low to cause problems.

Suspended Solids

Suspended solids should be avoided in hatchery incubators if possible. Colloids and silts, which tend to collect on eggs, interfere with the exchange of oxygen and waste metabolites between the embryo and the water surrounding the egg. Alevins are able to expel some silt from their gill chambers after binding it with mucous, although they are vulnerable to suffocation if silt deposits become too deep. Juvenile salmon can tolerate suspended sediment concentrations of several hundred parts per million before their gills become damaged, but the resistance of alevins to gill damage from silt has not been evaluated.

Suspended solids can clog gravel incubators of the deep matrix type, in which eggs and alevins are buried in rock or gravel substrates. Also waterflow to incubators can be reduced below optimum levels if waterlines become constricted by deposited sediments.

Insecticides and Herbicides

Even if a hatchery should be located on a watershed with no industrial or domestic sources of pollution, the widespread use of insecticides and herbicides represents a significant threat to the quality of water.

The most toxic insecticides to fish are those that use chlorinated hydrocarbons. These insecticides can cause death at concentrations of active ingredients ranging from 0.0001 to 0.1 ppm. Mineral content, alkalinity, and acidity of water have little or no effect on toxicity of chlorinated hydrocarbons, and their toxic properties tend to persist in the environment for extended periods. The following chlorinated hydrocarbons are listed according to their approximate descending order of toxicity to fishes: endrin, toxaphene, dieldrin, aldrin, DDT, heptachlor, chlordane, methoxychlor, and lindane.

Another class of modern insecticides is formed from organic phosphates. These compounds are much less toxic to fish than chlorinated hydrocarbons and are also less stable in water and quickly hydrolyze to nontoxic compounds. The organic phosphates include parathion, malathion, guthion, EPM, TEPP, chlorthion, disyston, dipterex, OMPA, para-oxon, systox, and co-ral.

Herbicides are less toxic to fish than insecticides, but there is great danger in using herbicides to control aquatic vegetation because of the heavy concentrations required. Such applications should be avoided in hatchery water sources while the hatchery is in operation.

INCUBATION SYSTEMS

Because artificial propagation can increase recruitment of fry from a given number of brood fish by five times or more over natural spawning, it is not surprising that artificial incubation of salmon eggs and alevins is becoming popular. Several major salmon fisheries are already heavily dependent on artificially propagated fry:

> Japan--Hatcheries on Hokkaido and Honshu Islands produce 90% or more of chum and pink salmon harvested in coastal fisheries.
>
> USSR--Hatcheries produce at least 20% of pink and 85% of chum salmon on Sakhalin Island.
>
> United States--Hatcheries in Oregon and Washington produce a large percentage of the coho and chinook salmon harvested from northern California to southeastern Alaska. Artificial propagation of five species is under evaluation in major salmon-producing areas of Alaska.
>
> Canada--Spawning channels produce substantial numbers of pink and sockeye salmon for the Fraser River, sockeye salmon for the Skeena River, and chum salmon for the east coast of Vancouver Island. Hatcheries for coho and chinook salmon are also phasing into operation in British Columbia.

Even with these examples of large-scale applications of artificial propagation of salmon, the methods are still imperfect. There have been numerous failures of artificially propagated stocks of salmon, and the reasons for these failures have not always been understood. For artificial propagation to succeed, healthy juvenile fish must be released into marine waters at the proper time of year; the physiological state of juvenile fish must allow rapid acclimation to seawater; and the genetic composition of the stock must allow subsequent homing and maturation at the proper time so that artificially propagated stocks can be perpetuated.

Techniques for incubating salmon eggs and alevins have changed over the past 20 years. Early hatcheries used open troughs with baffles to direct water flow through baskets filled with eggs. This simple concept was modified in the 1950's by stacking trays vertically and allowing water to cascade downward from tray to tray. Incubation and spawning channels were also introduced in the 1950's. The gravel incubator hatchery is a recent innovation, and work is underway on incubators which use artificial turf as a substrate for alevins instead of gravel.

What are the advantages or disadvantages of various incubation systems? Although costs of construction and operation necessarily enter into an answer to this question, requirements of eggs and alevins have to be considered first. The incubation system must produce salmon fry that have a capacity for rapid growth and high survival. Not all incubation systems are equal with regard to these two essential criteria.

Soviet scientists were the first to determine that incubators with smooth substrates failed to satisfy fully the requirements of salmon alevins. The early Soviet studies have led to additional research in USSR, England, Canada, Japan, and the United States. A number of deficiencies in salmon fry raised on smooth substrates in conventional hatchery incubators can now be listed:[5] (1) injury to yolk sac (yolk-sac malformation), (2) deformation of gut, (3) translocation of liver, (4) fat distrophy, (5) small size (poor conversion of yolk to body tissue), and (6) poor stamina.

The Soviets were the first to recommend that salmon alevins be held on a gravel rather than a smooth substrate to increase their size and to avoid other problems listed above. In Soviet hatcheries, newly hatched alevins are transferred from conventional incubators to open channels with beds of gravel (incubation channels) to continue their development to the fry stage. In Canada, extensive use is made of spawning channels to ensure that the environmental requirements of alevins are fully satisfied. Gravel incubator hatcheries are designed to satisfy essential physiological, ecological, and behavioral requirements of alevins by simulating conditions in high-quality natural spawning beds.

Trough Incubator

Salmon eggs are commonly incubated on trays suspended in open troughs. Trough incubators (Figure 14) are constructed of wood, concrete, or metal. The egg trays are typically metal screen attached to wooden frames. The screen openings are small enough to retain eggs and may be large enough to allow alevins to pass through so that they can rest on the bottom of the trough.

Trough incubators equipped with opaque lids are suitable for incubating eggs, provided metalic components are not contributing metal ions to the water in toxic concentrations. Trough incubators may not be suitable for salmon alevins (especially pink, chum,and sockeye) without certain modifications in operating procedures.

[5] Most of the pertinent research has been done with pink, chum, and sockeye salmon. There are indications that chinook and coho salmon alevins are better adapted to conditions in incubators with smooth substrates than these three species.

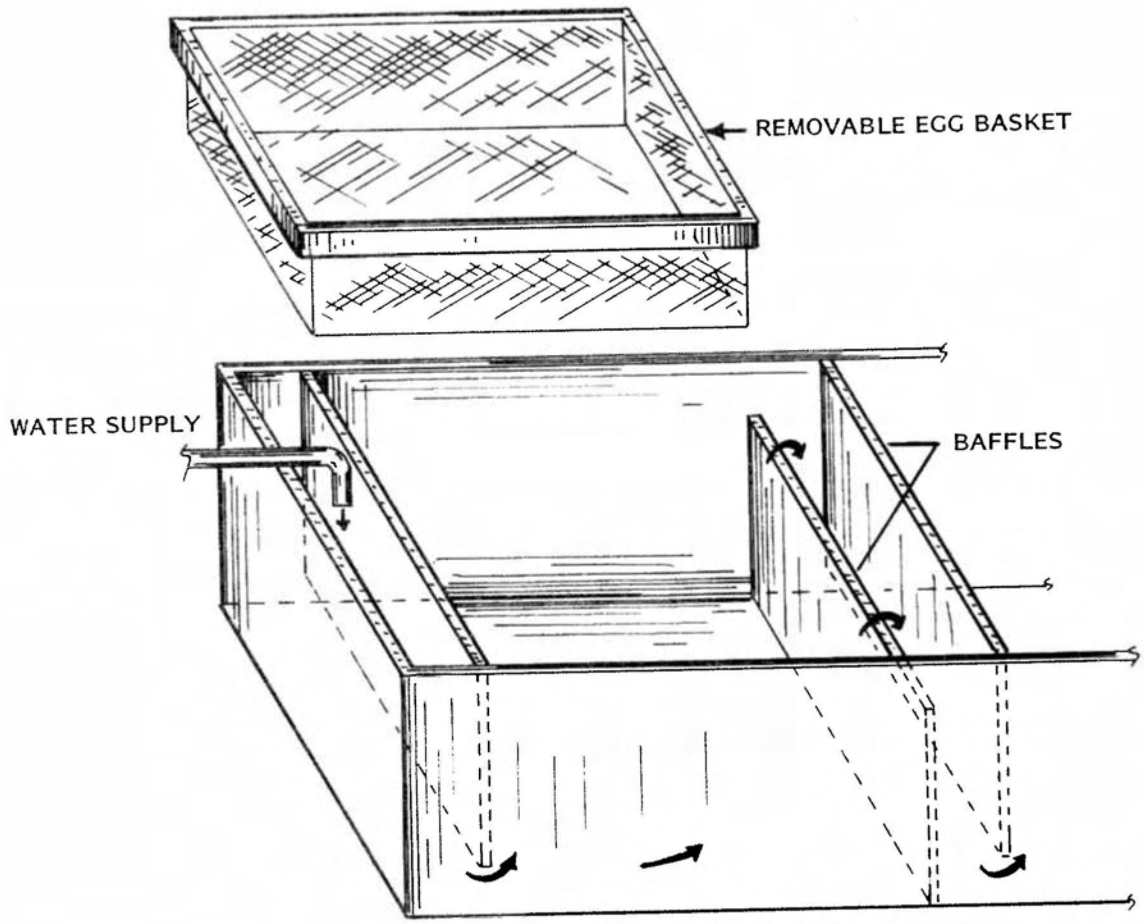

Figure 14.--Diagram of trough incubator with removable egg basket

Problems resulting from use of the typical trough incubator are:

Alevins usually bunch together on or near the smooth bottom of a trough at the head of each partition where the water enters.

Water flow is turbulent and velocities are much higher than in natural spawning beds.

Alevins consume much of the energy reserve in their yolks through premature swimming induced by turbulent water, smooth substrate, and light.

Fry are undersized because of poor conversion of yolk to body tissue.

Fry may suffer from internal anatomical deformities and fat dystrophy.

These problems can be corrected in large measure by providing a rock or other rugose substrate and by excluding light from troughs.

Vertical Tray Incubator

Major advantages of the vertical tray incubator are the convenience of inspecting and handling eggs and the small space required. Commercial models of this type of incubator are manufactured from plastics and fiberglass, so there is little or no risk of introducing toxic metal ions to the water supply. Figure 15 shows a bank of vertical incubators containing 1 million pink salmon eggs. In this instance, the incubators are used only to eye the eggs before they are transplanted to other incubators. Each tray holds about 25,000 eggs and a stack of 16 trays (400,000 eggs) is supplied with 6 gpm of water. These high densities are not recommended where salmon are raised to the fry stage. For this purpose, densities are reduced from 25,000 pink salmon eggs per tray to about 5,000. The capacity of the vertical tray incubator is governed by egg size and varies with species. Figure 16 illustrates construction details and the passage of water from one tray to the next.

Vertical tray incubators can be loaded to completely fill the space between the bottom and top screens of the trays if the only purpose is to eye the eggs. They are also commonly used to hold alevins, but stocking rates must be reduced for this purpose. Fry must be transferred from the trays to open tanks for feeding or release. Because alevins are commonly exposed to high water velocities and smooth substrate, fry from vertical tray incubators may not have the same capacity for rapid growth and high survival as fry from incubation systems designed to remove or reduce these environmental stresses. Deficiencies in quality of fry (see discussion under "Trough Incubators") can be minimized by keeping vertical tray incubators in darkness and by reducing the density of alevins if the substrate is rugose (either gravel or an artificial turf to simulate gravel).

Barrel Incubator

Barrel incubators are simple to construct and operate. They are made from devices (jars etc.) in which water flows vertically through a column of eggs. In past experiences with barrel incubators, the alevins have had problems with malformed yolks.

Incubation Channel

The recognition that pink, chum, and sockeye salmon fry from conventional trough and vertical tray incubators can be of poor quality has stimulated interest in the use of natural substrates for artificial propagation. Incubation channels are open channels or ponds which have a substrate prepared from graded rock. Water flow and other parameters are carefully controlled to optimize environmental conditions. Eggs are eyed in trough or tray incubators before they are transplanted to incubation channels. There are two types of incubation channels, which will be referred to as "upwelling" and "lateral flow."

Upwelling

In an upwelling channel, water is delivered into the substrate under pressure through diffusers. This type of channel looks like a shallow pond. The substrate is graded rock which can vary from 1/4 to 2 inches in diameter. The depth of the rock, i.e. the incubator matrix, can typically vary from 12 to 18 inches.

Stocking densities of 500 eyed eggs per square foot of surface area have yielded high survival to the fry stage. Water flow should probably be at least 1 cfs (450 gpm) per 1,000 square feet of surface area of substrate to ensure adequate circulation of water within the matrix. A deep matrix gravel incubator, which will be described shortly, essentially duplicates environmental conditions in an upwelling incubation channel but requires only about 20% as much water and 10% as much space for any given number of fry produced.

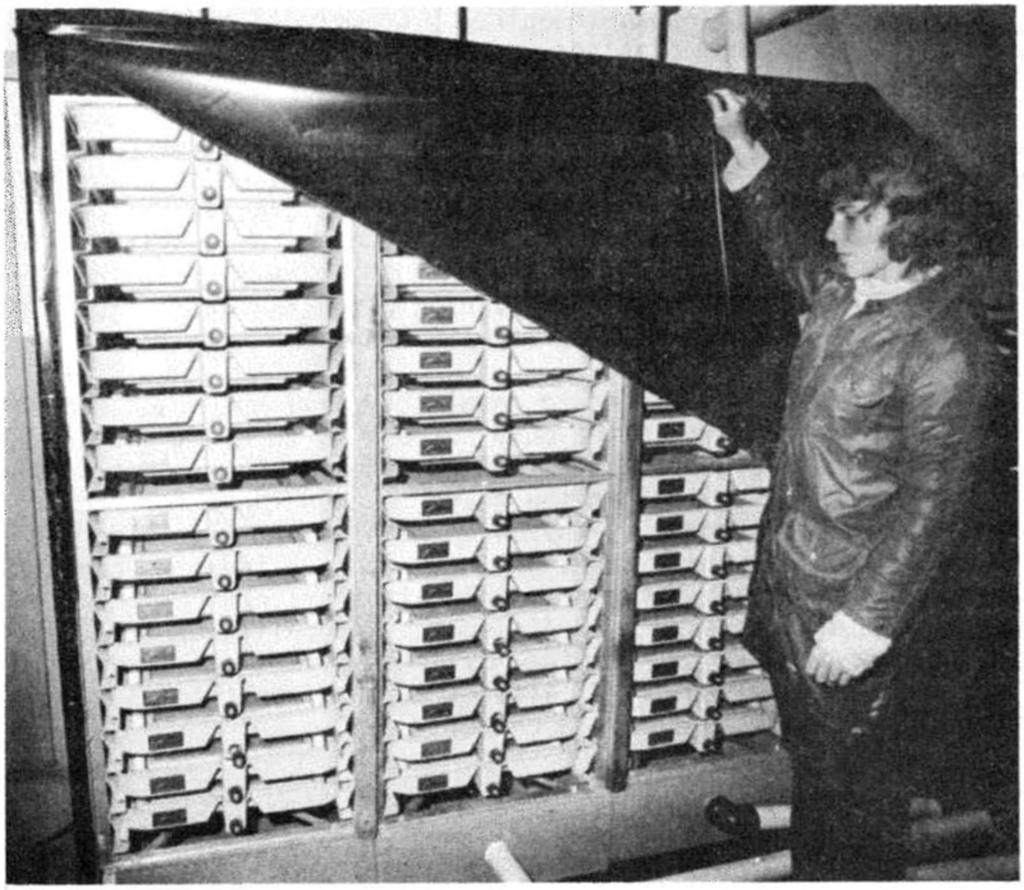

Figure 15.--Vertical tray incubators. Note the opaque plastic cover to exclude light.

Lateral Flow

Water in a lateral flow channel is introduced at the head of a shallow canal and flows laterally over a gravel matrix. The particle size typically varies from 1/4 to 4 inches in diameter and the depth of the matrix from a few inches to 18 inches.

Stocking densities of 500 eyed eggs per square foot of surface area have yielded high survival to the fry stage. Water flow should probably be at least 0.5 cfs (225 gpm) per linear foot of width of channel to ensure good interchange between surface and intragravel water. Thus, a 10-foot-wide channel should receive at least 5 cfs of water. Approximately 2,000 square feet of surface area is required to produce 1 million fry. An incubator that requires considerably less water and only 20% as much space to produce the same number of fry as a lateral flow channel will be described shortly. It is called a shallow matrix incubator.

Spawning Channel

A spawning channel (Figure 17) differs from a lateral flow incubation channel by the method of stocking. In a spawning channel, mature salmon are allowed to spawn naturally; in an incubation channel, eyed eggs are buried by hand in a rock matrix.

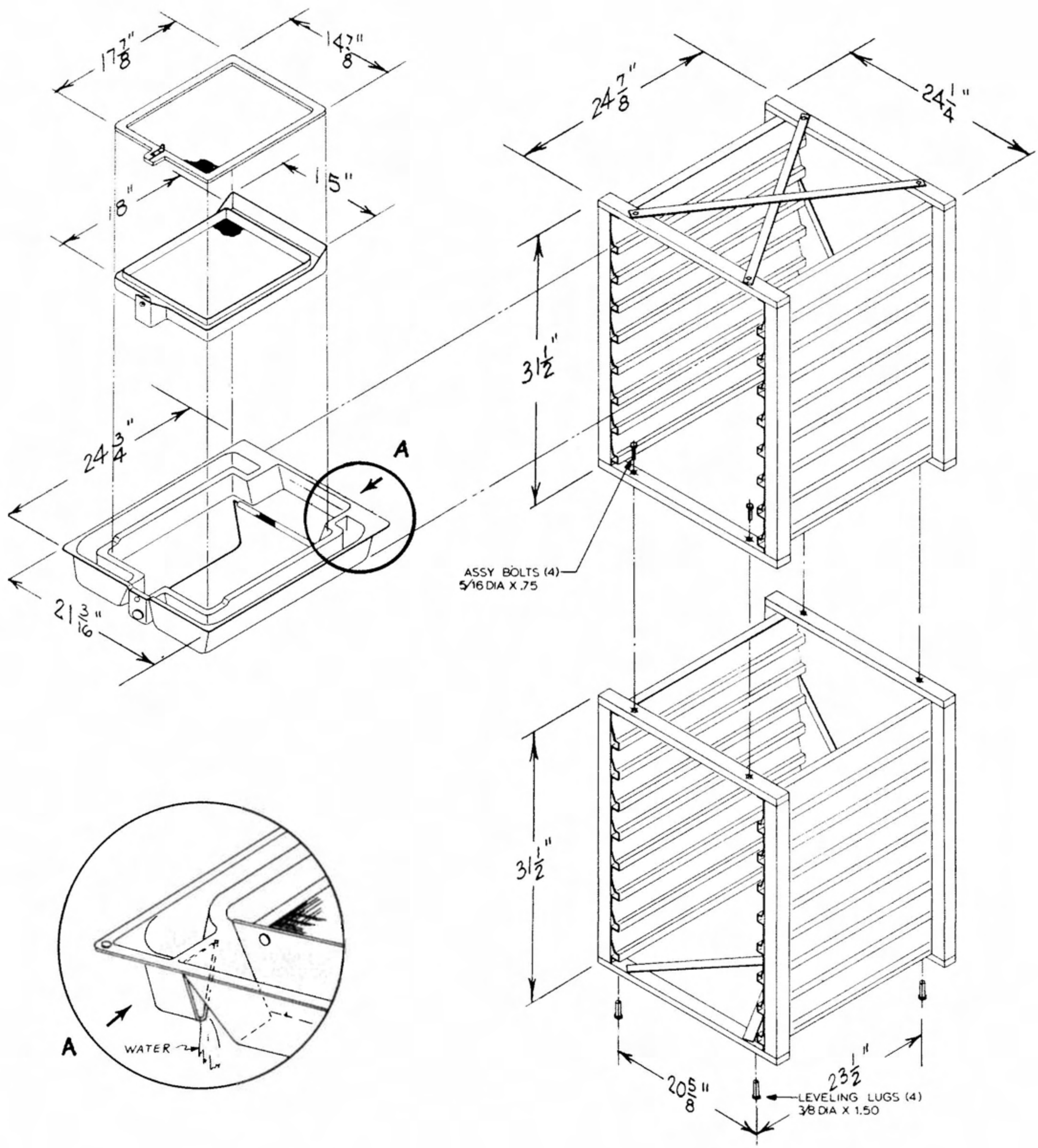

Figure 16.--Construction details of vertical tray incubators and detail of passage of water through a stack. (Drawing courtesy of Heath Techna Corp.)

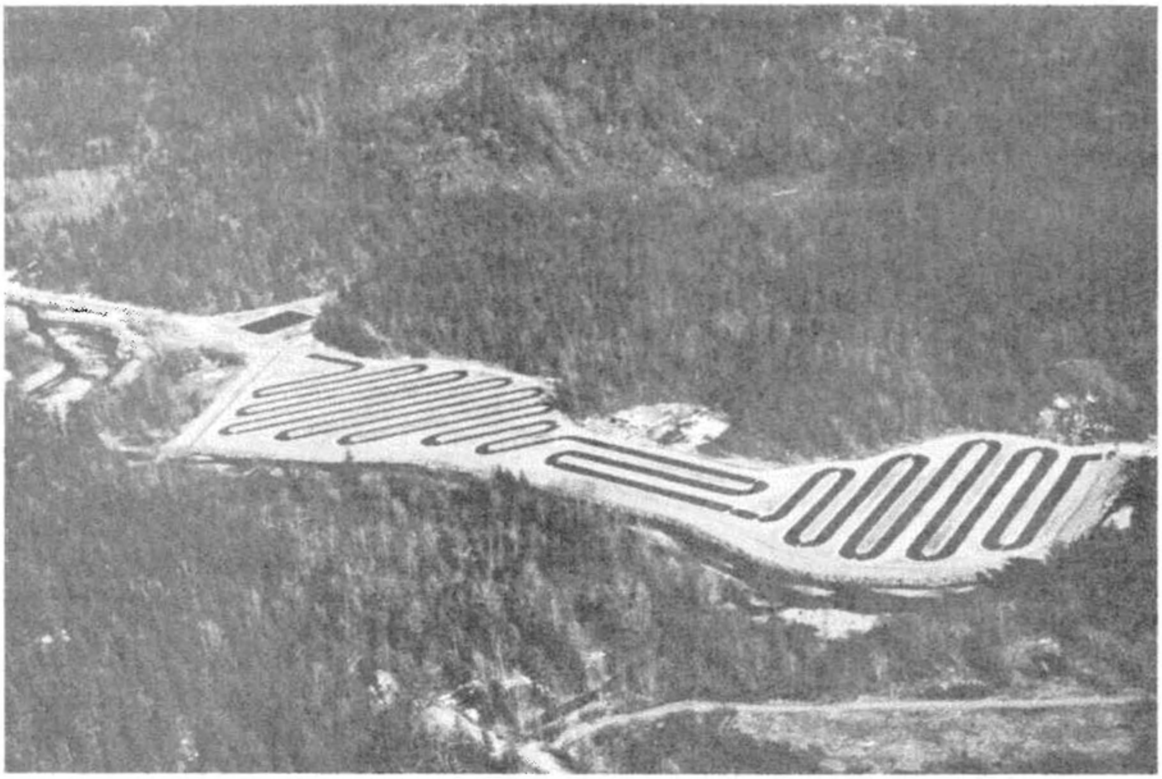

Figure 17.--Spawning channel for sockeye salmon on Weaver Creek in the Fraser River drainage, British Columbia. (Photo courtesy of International Pacific Salmon Fisheries Commission.)

The density of eggs in a spawning channel is controlled by the spawning behavior of salmon. The recommended densities for spawners are: pink salmon--one pair per 10 square feet, and sockeye or chum salmon--one pair per 20 square feet. Densities much in excess of those recommended lead to wastage of eggs through superimposition of redds. The final number of newly fertilized eggs recruited to a spawning channel will not be much in excess of 200 per square foot of surface area and may be considerably less than this number, even with optimum density of spawners. Thus, for any given number of fry produced, a spawning channel requires at least 2-1/2 times more surface area than a lateral flow incubation channel.

Water circulation within the gravel matrix of a spawning channel is determined largely by the rate of interchange between stream and intragravel water, as well as the hydraulic gradient of the channel. The direction and velocity of water flow within the matrix and interchange of water between the matrix and the surface water depend on permeability, depth, and longitudinal profile of the porous matrix. The points following are important to the design and operation of spawning channels.

Gradient needs to be 0.2 to 0.5% to facilitate flow of water through gravel and to generate interchange between surface and intragravel water.

Water depth should be a minimum 6 inches and the flow should be fast enough to avoid drying or freezing of the bed after spawning has occurred.

Water velocity should range between 1 and 3 fps in the surface water.

Gravel size should range from 1/2 to 6 inches in diameter to promote interchange and to ensure stability.

Construction of the bed should promote interchange by varying the depth of graded gravel of high porosity from 18 to 24 inches and by burying impermeable baffles.

Sediment should be controlled through the use of settling ponds or stream meanders to reduce the cost of maintaining clean gravel.

The control of water in a spawning channel is especially important. Transport of sediments into a channel, either in suspension or as bedload, increases maintenance and can lead to costly rehabilitation. Bypass channels for floodwaters and intake structures are required where channels are located on streams which experience more than minor fluctuations in flow.

A typical spawning channel is likely to require at least 1 cfs of water per linear foot of width during incubation of eggs and alevins. The volume of flow should be approximately doubled during the spawning period to provide adult fish with adequate water for excavation of redds. Spawning channels are not often suited for small streams or places where there is a scarcity of relatively level land that can be easily shaped with heavy machinery.

Spawning channels relieve most of the uncertainty about genetic responses of salmon to artificial propagation because the salmon spawn naturally. Other types of incubation systems require that salmon be spawned artificially, which raises questions about inbreeding and assortative mating. Genetic problems will be discussed in a later section.

Gravel Incubator

Gravel incubator hatchery systems are designed to provide a natural or simulated natural substrate for alevins. There are two basic configurations of gravel incubators, which are referred to as deep matrix and shallow matrix. Modification of these systems are under evaluation from Oregon to western Alaska.

The characteristics of deep and shallow matrix gravel incubator hatchery systems are as follows.

	Deep matrix	Shallow matrix
Stocked with:	Newly fertilized or eyed. eggs.	Newly fertilized eggs.
Eggs:	Buried within substrate.	On screen trays above substrate.
Alevins:	Buried within substrate.	On surface of substrate.
Fry emigration:	Voluntary.	Voluntary.
Water:	Upwells past eggs and alevins; 60-120 gpm/ million eggs.	Upwells past eggs; horizontal past alevins; 60-90 gpm/million eggs.
Filtration:	May be required.	Unnecessary.
Space:	100 square feet/million eggs.	400 square feet/million eggs.

Deep Matrix Incubator

This system operates best on filtered water because the water must upwell through a maxtrix of gravel and eggs. The water is introduced at the bottom and drained from the top. Water delivery can be calculated on the basis of 1 to 1-1/4 gpm per square foot of cross section of tank. For instance a tank with a cross-sectional area of 16 square feet must receive between 15 and 20 gpm to achieve desired water velocities. The dimensions and configurations (cubic, rectangular, or cylindrical) of a deep matrix system are optional within limits. A typical tank measures 4 by 4 by 4 feet.

A cubic tank with a total volume of 64 cubic feet contains about 50 cubic feet of matrix containing eggs and can safely be stocked with 150,000 pink salmon eggs (3,000 eggs per cubic foot of matrix). Stocking densities can be higher for sockeye salmon, which have smaller eggs, and lower for chum, coho, and chinook salmon, which have larger eggs. Increasing the depth of tanks in relation to cross-section area allows more efficient use of water. Fry appear to encounter little or no difficulty in passing upward through a 4-foot-deep bed of graded gravel. The gravel is graded to remove particles smaller than 3/4-inch diameter and larger than 1-1/4-inch. The water entering at the bottom passes through a manifold system consisting either of a grid of pipes or a false bottom with numerous holes for exit ports. To prevent passage of salmon alevins, the diameter of these holes must be no greater than 3/32 inch. A 3-inch depth of 1/8- to 1/4-inch diameter gravel over the top of the manifold acts as a pressure plate to achieve uniform water velocities in the cross-sectional area of the tank. Three-inch layers of 3/4- to 1-1/4-inch substrate are alternated with layers of eggs until the tank is filled to within about 10 inches of the top. The final layer of eggs is covered with about 6 inches of substrate to shield the eggs from light. A shallow depth of open water is left at the surface of the tank to enable emerging fry to swim to the outlet. A diagram of a typical deep matrix gravel incubator is shown in Figure 18.

The eggs must be resistant to shock from handling when tanks are stocked. Stocking can be done immediately after fertilization or after eggs have reached the eyed stage, but not during the so-called tender stage, which begins several hours after fertilization and ends when the eggs are eyed. Stocking with eggs that have been eyed in conventional incubators allows the hatchery operator to remove most of the dead eggs before the gravel incubator tanks are stocked. This minimizes the incidence of decomposing eggs in the gravel but requires substantial additional investment in conventional incubators which would be used only for raising eggs to the eyed stage. Dead eggs cannot be removed from deep matrix gravel incubators until after the fry have emerged. Gravel is removed and cleaned before tanks are restocked with eggs of a new brood. Figure 19 illustrates typical operations with deep matrix gravel incubators.

Shallow Matrix Incubator

The shallow matrix gravel incubator consists of a series of tanks arranged horizontally (Figure 20). Baffles direct water through an array of tanks, which can be constructed of wood, plastic, or fiberglass. Inlet and outlet tanks may also be added.

Newly fertilized eggs are placed on porous trays of nontoxic materials suspended in the water column (Figure 21). Eyed eggs could be used, but this would require additional incubators and negate the cost advantage of a single incubator. Four layers of egg trays are stacked vertically in each tank. The trays can be individual units measuring about 22 by 22 inches. A 48- by 48-inch tank contains 16 trays (4 per layer), and each tray receives eggs from an individual female salmon. Water upwells through the trays. Soon after the eggs hatch the alevins pass downward through the trays and repose on the surface of a 1-inch deep layer of 1/4- to 3/4-inch graded rock which is washed to remove silt before being placed in the tank. An opaque lid excludes light from the tank.

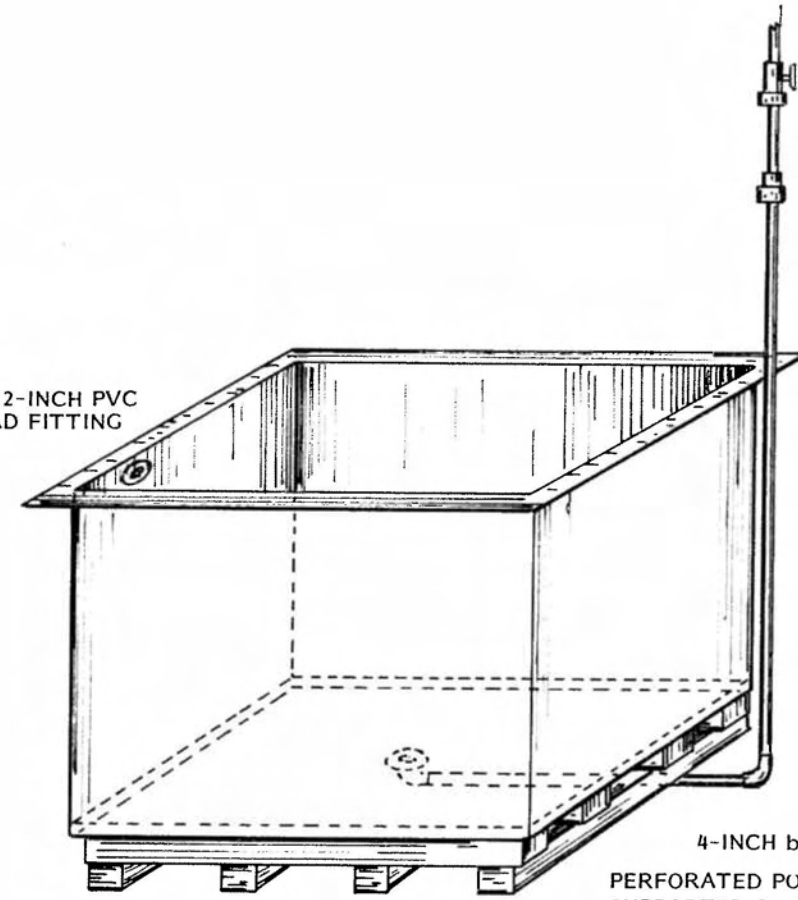

Figure 18.--Schematic diagram of a typical deep matrix gravel incubator.

The volume of water flow through a shallow matrix gravel incubator is calculated on the basis of 1-1/2 gpm per square foot of cross-section area of each tank in a series. Tank dimensions are optional, but a typical tank measuring 16 square feet would receive 24 gpm, which means that a typical array of eight hatchery tanks in series would operate on 24 gpm.

A small percentage of the artificially spawned female salmon have low fertility. The unfertilized eggs from these females settle and form a substrate where fungus and other biological growths spread and kill adjacent fertilized eggs. These infertile eggs can be isolated by placing eggs from only one female on each tray. It is convenient to remove dead eggs from egg trays at the time of eyeing. Alevins separate themselves from dead eggs by passing through the egg trays to the surface of the gravel substrate. Any dead eggs remaining are removed when the egg trays are taken from the tanks and stored.

Another reason for keeping eggs from individual females isolated from those from other females is to encourage random mating of hatchery stock. Proper operation of

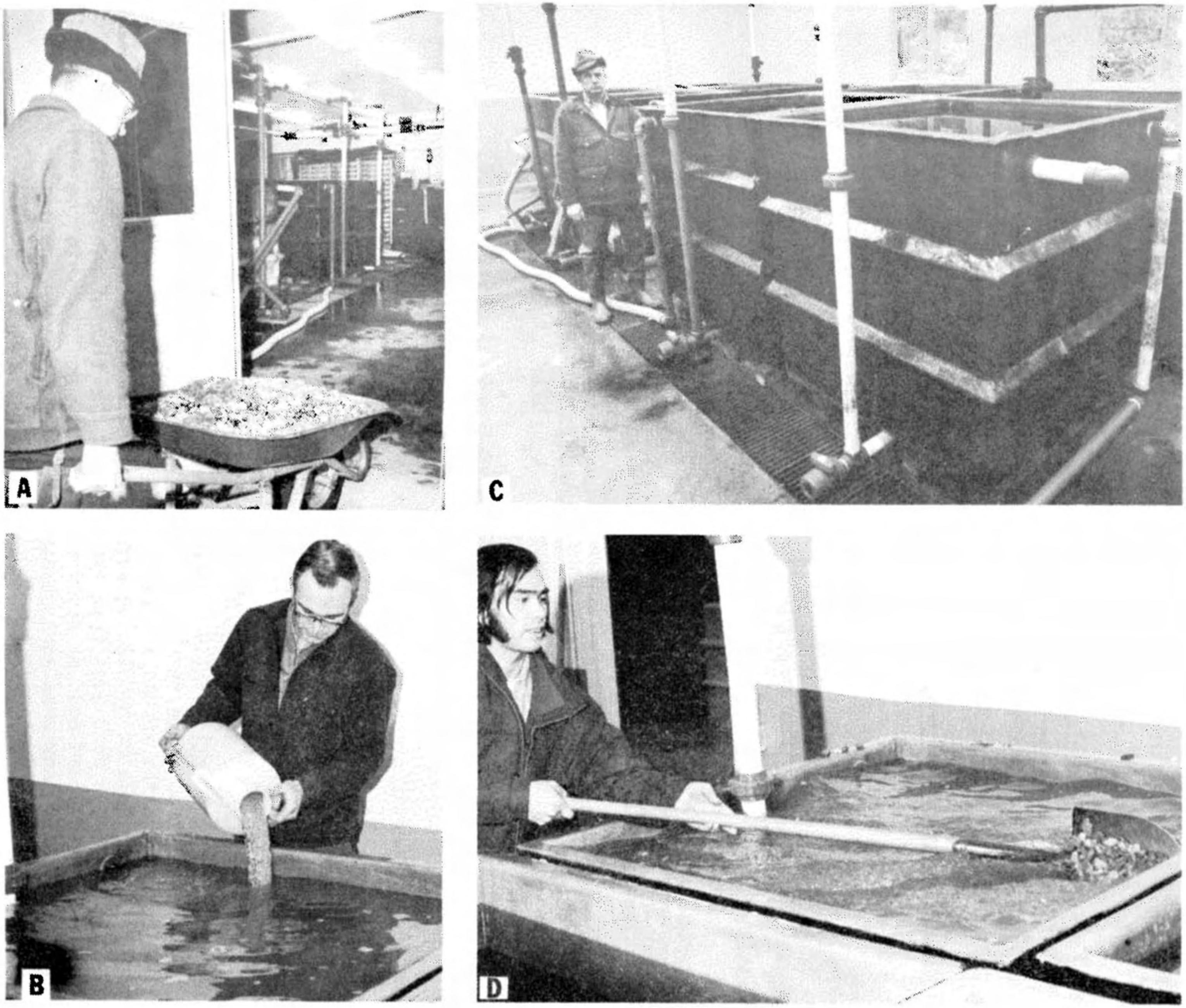

Figure 19.--Operations with deep matrix gravel incubator: (A) about 24 wheelbarrow loads of gravel are needed to load the incubator; (B) the eggs are divided into eight equal aliquots which are then poured directly into the incubator; (C) the completely loaded incubators require only a dependable supply of water to produce high quality fry; (D) a 3-inch layer of gravel is shoveled onto each successive aliquot of eggs.

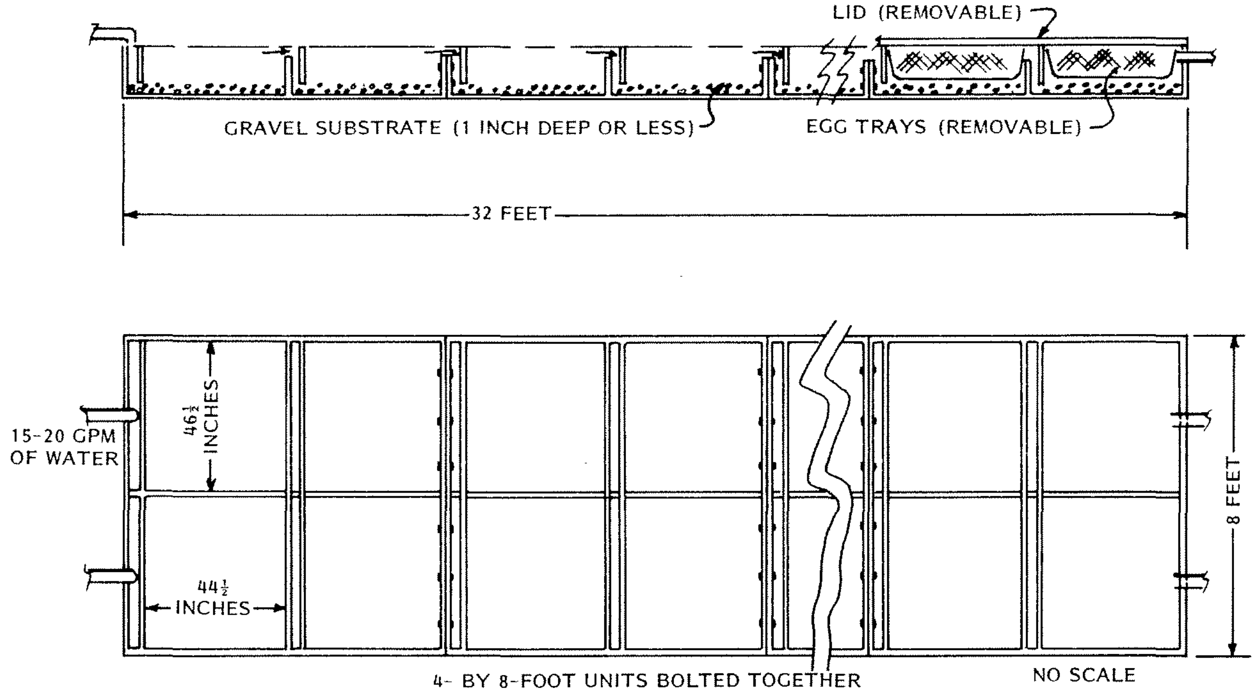

Figure 20.--Array of tanks making up a shallow matrix gravel incubator and cross section showing egg trays and gravel substrate.

the shallow matrix gravel incubator requires the pairing of individual males and females. If this pairing is done randomly, the chances of retaining genetic variability in the hatchery stock and avoiding inbreeding will be greatly improved. The importance of maintaining genetic variability in hatchery stocks will be discussed in a later section.

Stocking densities per unit volume of water flow in the shallow matrix gravel incubator compare favorably with other systems, including vertical tray incubators. For example, chum salmon, which average 2,500 eggs per female, would provide 40,000 eggs for each tank containing 16 trays, or 320,000 eggs per eight-tank array. The density of eggs on the trays would in this case be about five per square inch, which allows a loose single layer and avoids overcrowding of the eggs. Alevins are about four times more concentrated on the surface of gravel. Exclusion of light and contact with a natural substrate contribute to uniform density over the substrate and minimize activity of alevins. Because alevins pump water across their gills, water currents for the delivery of oxygen and the removal of metabolic wastes are not as critical for them as for embryos, which depend upon diffusion of gases across egg membranes. A heavy concentration of alevins on the bottom of a shallow matrix gravel incubator will not cause them to die, provided guidelines on the number of egg trays, stocking density, and water flow are adhered to.

Turf Incubator

Most recently (1974), work has started on the development of incubators which substitute artificial turf for gravel. Figure 22 shows salmon alevins on an artificial turf substrate, and Figure 23 shows a prototype turf incubator which is under development by the National Marine Fisheries Service at Auke Bay, Alaska. Even though turf incubators afford promise of greater compactness and more efficient use of floor space than gravel incubators, it is too early to compare them with

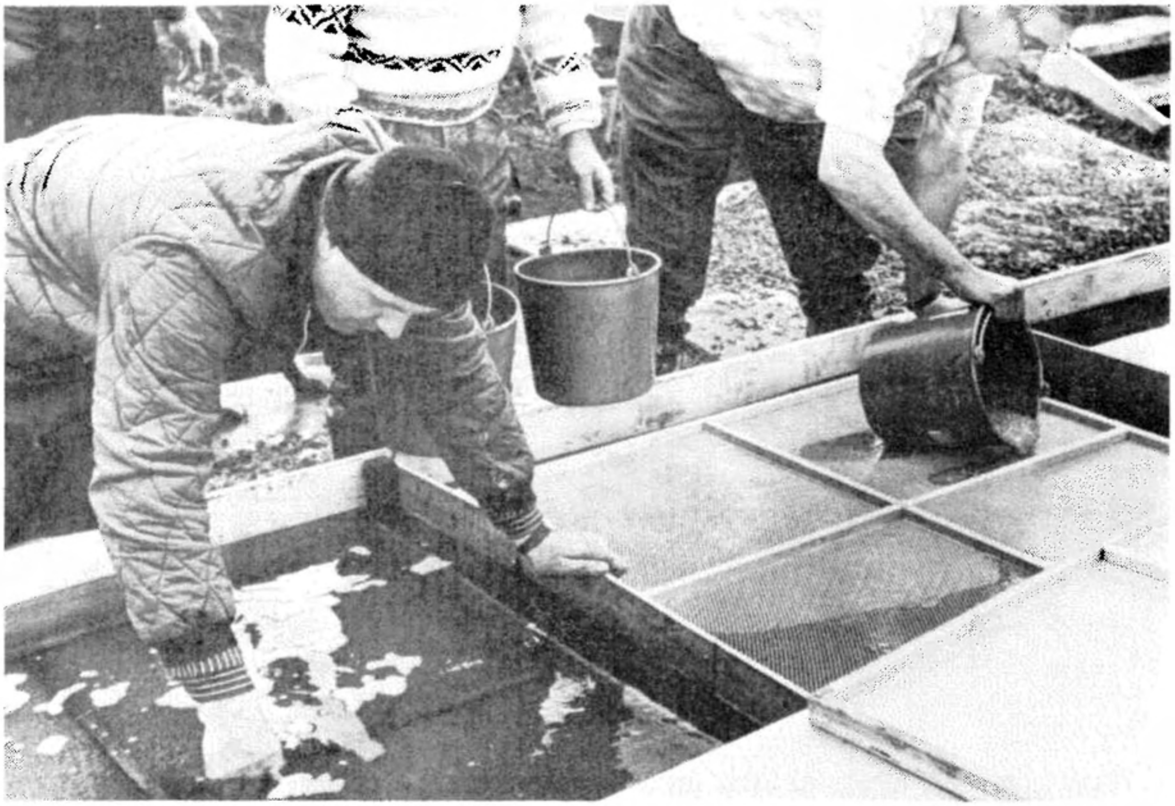

Figure 21.--Stocking a shallow matrix gravel incubator with chum salmon eggs.

other systems and to recommend their use in place of other systems.

SELECTION OF DONOR STOCK

Once a new hatchery stock becomes established, it will adapt rapidly to those parameters with the greatest influence on growth and survival, and the new self-perpetuating hatchery stock will soon become genetically discrete from its parental stock as well as other wild and hatchery stocks.

Precautions must be taken in selecting a donor stock to ensure that the hatchery stock will become self-perpetuating in the shortest possible time and will provide surplus of fish for harvest. The donor stock may be (1) a wild stock, (2) a hatchery stock, (3) an intraspecific hybrid of two wild stocks, (4) an intraspecific hybrid of two hatchery stocks, and (5) an intraspecific hybrid of a wild and a hatchery stock.

Hybrids can also be produced by crossing two species, with the exception of coho salmon. Such hybrids, called interspecific hybrids should not be allowed to reproduce, however. First-generation progeny of interspecific hybrids are uniform in appearance (phenotype), and hybrids of pink and chum salmon at least are fertile. However, second-generation progeny are highly variable in appearance and their phenotypes tend to intergrade between the two parental species. Interspecific hybrids should be held in captivity to avoid the danger of damaging genetic effects should they intermingle with wild stocks on spawning grounds.

Questions to be considered in the selection of a donor stock are:

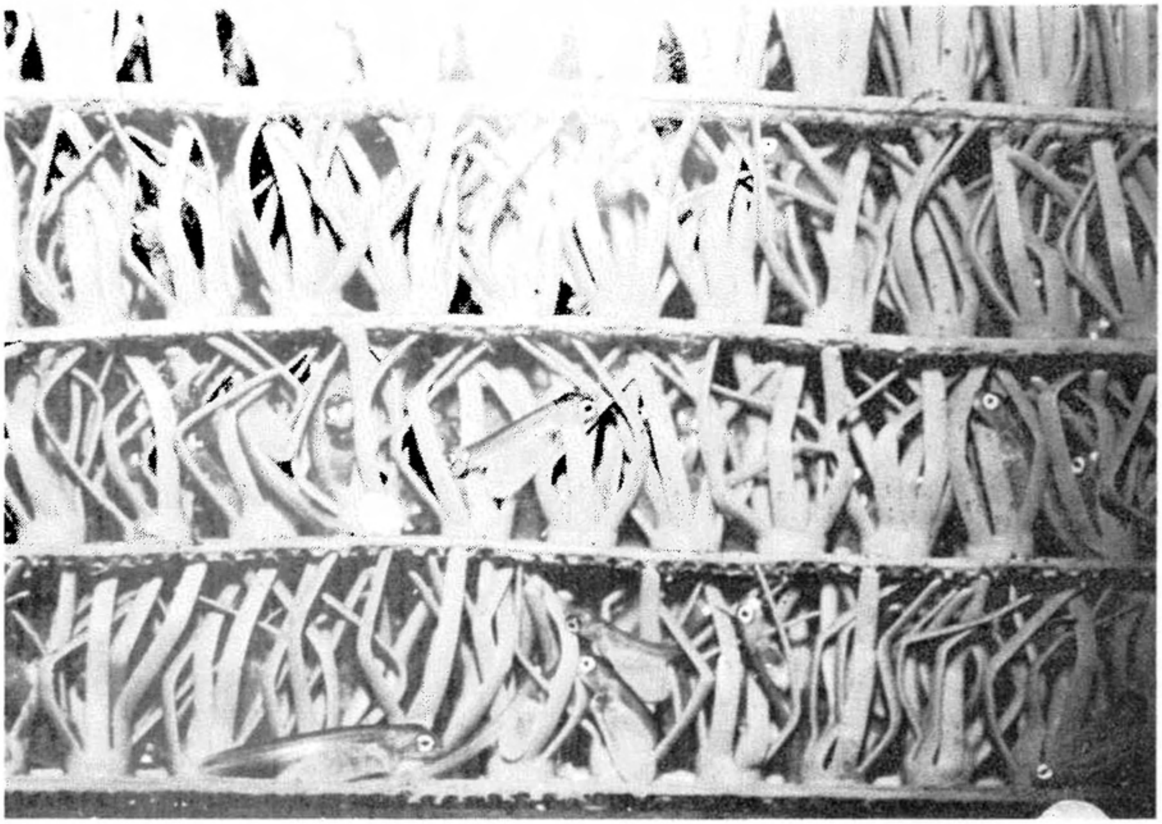

Figure 22.--Sockeye salmon alevins reposing on artificial turf substrate.

Is the donor species suited for the intended hatchery application(s)?

Does the donor stock come from a nearby location or an area with similar climatological and watershed features?

Does water in the donor stream or hatchery have a temperature regime similar to water in the recipient hatchery?

Will the timing of fry emergence coincide with a seasonal "bloom" of natural foods or are the fry to be fed artificially?

Is time of freshwater migration and is stage of maturity of adult fish of the donor stock suited for the recipient hatchery or hatchery stream?

Stocking marine nursery areas with hatchery fry is feasible only with pink and chum salmon. Other species must obtain their early growth in fresh water or in water of low salinity before juveniles can become adapted physiologically to live in water of high salinity. Thus, hatchery-raised coho, chinook, and sockeye fry must either be released into a freshwater or low-salinity estuarine nursery area, or they must be raised in captivity where salinity can be controlled for 3 to 12 months. When fry are released into natural nursery waters, there must be some basis to expect that the receiving waters afford sufficient food and space for them.

The ease with which a donor stock can be acclimated to a hatchery system will depend largely on ecological similarities between the recipient hatchery and the source of

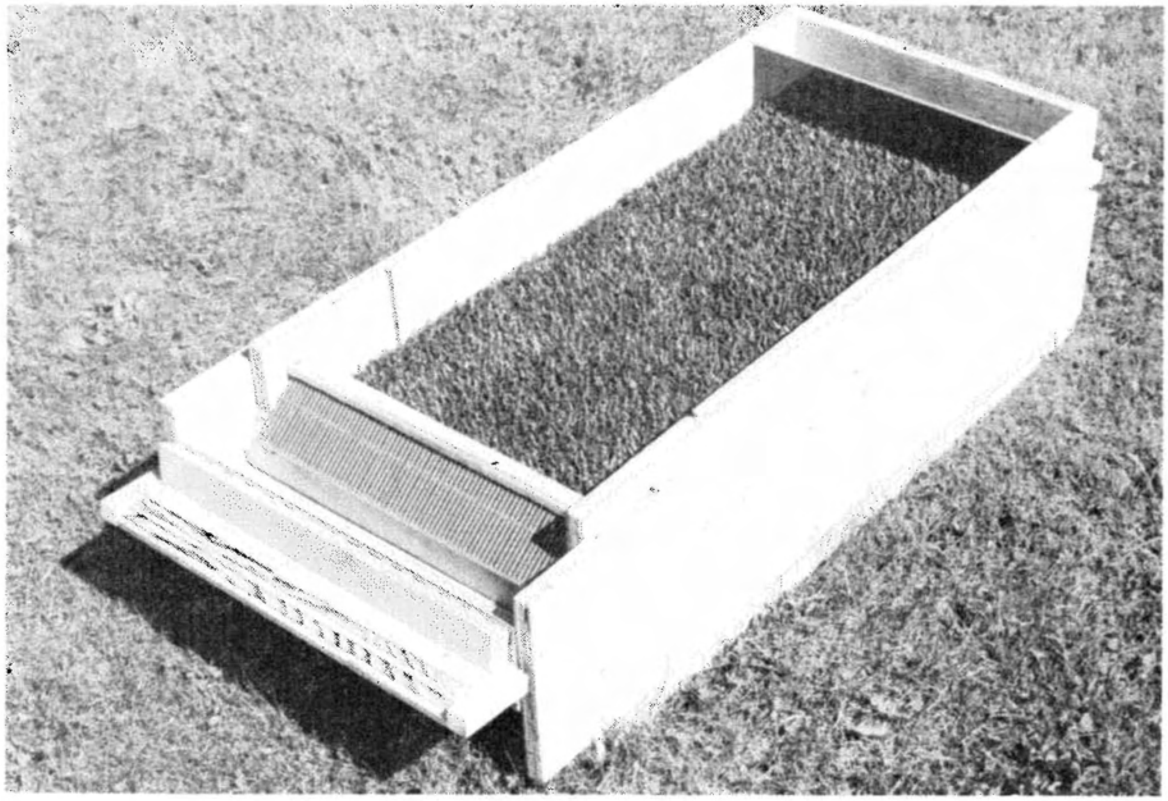

Figure 23.--Prototype turf incubator.

the donor stock. The donor stream or hatchery should be as close to the recipient hatchery as possible. The lowest risk of failure exists where the hatchery uses a stock which occurs naturally in the hatchery stream. Should the natural stock be too limited to serve as an egg source, the eggs of the donor stock can be hybridized by using males of the same species from the hatchery stream.

If fish native to the hatchery stream are unavailable, every effort should be made to match the temperature regime of the donor stream with that of the hatchery. Other precautions, such as short-term feeding in captivity, might be desirable in some instances to ensure that the time of release of juveniles coincides with the spring bloom of food organisms.

Proper selection of the donor stock could have an important bearing on rate of growth, age at maturity, and ocean survival of hatchery fish. Different genetic stocks within a species vary considerably in these and other attributes, including state of maturation when adults enter fresh water. There is considerable evidence that stocks respond readily to genetic selection. This can work to the detriment or advantage of the hatchery, depending on the circumstances.

CARE OF BROOD FISH

Reproduction in salmon is a seasonal phenomenon which is repeated on a precise schedule. Maturation is controlled by hormones released by the anterior pituitary gland in response to day length (photoperiod). Attainment of maturity does not always ensure successful reproduction. If environmental conditions are unsatisfactory while brood fish are held for maturation, egg fertility and embryonic development may be affected adversely. For example, warm water inhibits normal maturation and promotes the outbreak of certain diseases. Problems with maturation and disease should be anticipated if water temperature exceeds 56°F while adult fish are confined.

Holding and Handling Adults

Provided brood fish are nearly mature when trapped, they can be penned for a few days in flowing stream water or held in raceways. If it becomes necessary to hold them for longer periods, brood fish should be placed in large floating pens or in ponds where they have considerable freedom of movement and sufficient water exchange to avoid low levels of dissolved oxygen. Adult salmon have been held 20 days or longer in 10-foot-deep saltwater pens measuring 50 by 33 feet. Retaining salmon in salt water to full maturity has no detrimental effect on fertility. If it is not possible to provide large enclosures for adult fish, small enclosures should be covered and supplied with sufficient water flow to avoid stressing fish with low levels of dissolved oxygen.

Sockeye and chinook salmon are more likely to react unfavorably to confinement than the other species. When penned, adults of these species sometimes have a strong tendency to delay their maturation. Females frequently experience high prespawning mortality when penned, and eggs from fish reaching maturity sometimes have low fertility. Whenever possible, brood fish should be allowed to mature while at liberty and should be collected for spawning only after they have matured.

Females of all salmon species need to be checked periodically (daily in some cases) for ripeness. To facilitate handling, the fish should be crowded into a confined area by seining, by lifting a net enclosure, or by some other convenient herding technique. Workers should wear gloves made of wool or cotton fabric for grasping and holding fish. "Green" females are returned to the holding pen or pond along with surplus males. Ripe females are killed with a sharp blow to the head. An artery may be severed in the head or caudal region to drain blood which might otherwise mix with eggs and coagulate (Figure 24); coagulated blood can interfere with fertilization. It is not necessary to kill males for spawning. It is recommended that the number of males equal the number of females to allow a random pairing of adults.

Diseases

Organisms which cause disease are always present in fish and in most natural waters. Epidemics break out when unfavorable environmental factors (stressing agents) cause fish to lose their normal resistance to a disease. Water temperature is one stressing agent that allows infections to become pathogenic. Methods of treating specific diseases are changing continually with the introduction of new drugs and chemicals and with new applications of existing drugs and chemicals. For specific recommendations on methods of treating diseased fish, the hatcheryman should consult a qualified fish pathologist. However, the best way to handle disease is to avoid exposing fish to stressing factors which cause disease agents to become epidemic. Although several diseases are known to infect adult salmon, only six, which are considered most likely to cause significant prespawning mortality, are discussed here.

Columnaris

Infection from the bacterium *Chondrococcus columnaris* often kills prespawning adult salmon. Columnaris does not become epidemic unless water temperature exceeds 56°F. Even if fish infected with the disease survive to spawn, egg fertility and the percentage of normal embryos can be seriously reduced. Symptoms of columnaris typically include lesions on the gills or skin and musculature of infected fish. Gill lesions usually start at the periphery and extend toward the gill arch. Early lesions can occur under the scales and remain unnoticed until round necrotic areas 1 inch or more in diameter appear on the surface. Necrotic tissue on the gills and body is often yellow-orange. The edges of body lesions are often hemorrhagic and red. In advanced stages of infection, the skin becomes eroded and exposes underlying muscular tissue. It is common for lesions to become infected by fungus. Columnaris can be treated by injecting adult fish with sulfa drugs or by adding Diquat[6] to holding ponds. The most effective means of controlling columnaris is to maintain water temperature below 56°F.

Bacterial Gill Disease

Several species of bacteria appear to contribute to bacterial gill disease. Although the bacteria involved are not known for certain, at least three species of myxobacteria are involved. Diseased fish have large concentrations of bacteria on gill tissues and frequently the gills become eroded or "clubbed." Bacterial gill disease has been observed over a broad range of temperatures, but warm temperatures above 56°F are particularly conducive to epidemics. To avoid outbreaks of bacterial gill disease, fish should not be crowded. The disease can sometimes be relieved by reducing crowding of infected fish. Various antibacterial chemicals (including Roccal, Diquat, and Hyamine 1622[7]) are effective for treatment of this disease.

Figure 24.--Method of killing salmon for spawning. The caudal artery is severed soon after the fish is killed.

Furunculosis

Aeromonas salmonicida is the bacterium that causes furunculosis. This disease agent is waterborne and is active at temperatures as low as 35°F. Its optimum range for infection of salmon is above 56°F. The accumulation of decomposing organic matter stimulates mass reproduction of A. salmonicida. Furunculosis manifests itself

[6] Trade name for an herbicidal chemical.

[7] Roccal and Hyamine 1622 are trade names of quaternary ammonium germicides. Approval of the Food and Drug Administration may be required before germicides can legally be used.

internally or externally. In the internal form the hind gut is inflamed, and reddish fluid is discharged from the anus; in the external (muscular) form, purple, red, or iridescent blue abscesses develop and burst, leaving deep ulcers. The best ways to avoid furunculosis are to prevent overcrowding and to minimize handling of fish when water temperature is above 56°F. Adult salmon can be treated for furunculosis through injection of sulfa and antibiotic drugs.

Vibriosis

Vibrio anguillarum is the bacterium most commonly found in salmon infected with vibriosis. This bacterium is found in both low-salinity and full-strength seawater. It is most likely to become epidemic at water temperatures above 56°F, but deaths from vibriosis have been observed at much lower temperature. Fish infected with vibriosis have symptoms similar to fish infected with furunculosis--reddish lesions appear on the skin and in the musculature. Frequently there is hemmorrhaging in the eye and a discharge of blood from the abdominal opening. Outbreaks of vibriosis have not been documented in adult salmon, but the disease commonly becomes pathogenic where juveniles are confined in saltwater enclosures. Adults held in saltwater pens or concentrated in salt water off the mouths of hatchery streams should be watched closely for evidence of vibriosis should water temperature exceed 56°F. One possible way to control the disease would be to place brood fish in fresh water.

Fungus Infections

Although the fungus *Saprolegnia parasitica* is found most commonly, there are at least five other genera of fungi that infect fish in fresh water. Usually fungi occur as secondary infections of diseased or injured fish. Where adult salmon must be held in fresh water for prolonged periods to mature, the control of fungus can become important to avoid prespawning mortality. Salt water will prevent or greatly inhibit fungus infections.

CARE OF EGGS

With the protection that artificial propagation affords against stressing factors in natural spawning beds, 70 to 90% of the potential eggs in a salmon escapement can yield healthy fry. By contrast, in nature, only 5 to 20% of the eggs survive to become fry. The salmon rancher can take proper care of eggs if he has a good understanding of the environmental requirements and the physiological limitation of the eggs at every stage of development. In this section we discuss techniques that have evolved for handling eggs in relation to their biological characteristics. The salmon rancher can use these techniques or develop modifications to suit his own situation.

The time required between fertilization and hatching varies from 1-1/2 to 4 months, depending primarily on water temperature. At a given temperature, chinook and coho eggs will hatch sooner than pink, chum, and sockeye eggs. Cell division begins less than 12 hours after fertilization. Hatching is triggered by secretion of an enzyme from specialized glands which softens the egg shell and allows the alevin to emerge. The embryo remains sensitive to shock between the onset of cell division shortly after fertilization and the closure of the blastopore, which occurs just before pigmentation of the eyes. Eggs should not be handled before pigmentation of the eyes becomes evident.

The quality of eggs at the time of spawning has an important bearing on fertility and embryonic survival. It is essential, therefore, to use proper procedures in selecting brood fish and in handling eggs before and during fertilization. Once eggs have been fertilized, survival and development of embryos is determined largely by stressing factors during incubation. Optimum environmental factors combined with proper handling should in most instances ensure over 90% survival from egg fertilization to hatching.

Fecundity and Egg Size

The average number of eggs per female varies among species of salmon and among races within a species. Stocks spawning at northerly latitudes tend to have a higher fecundity than those at southerly latitudes. The average fecundities of stocks typically range from 3,000 to 5,500 eggs per female for chinook salmon, 2,800 to 4,200 for sockeye, 2,500 to 3,500 for coho, 2,100 to 3,500 for chum, and 1,400 to 2,300 for pink.

The size of fry at time of yolk absorption is determined by egg size (i.e. the amount of yolk available for metabolic functions, including growth). The diameters of eggs of the different species are as follows: chinook, coho, and chum salmon--0.27 to 0.36 inches, pink salmon--0.24 to 0.30 inches, and sockeye salmon--0.20 to 0.24 inches. Larger and older females usually produce larger eggs (and fry) than smaller and younger females.

Spawning Procedures

It is extremely important that females be spawned as soon as they become fully mature. Fertility will be low if females are green (not fully mature) or overripe. If spawned at the proper time, fertility of eggs should consistently exceed 95%. If fertility is much below 95% the procedures for selecting females for spawning should be carefully checked. This can be done by killing several females and examining the ovaries and eggs before continuing with further selections. Problems with selection of females can be anticipated if (1) eggs do not flow freely from the abdomen when the belly is slit, (2) color of eggs is not uniform, (3) some eggs appear to be more translucent than others, and (4) watery fluid is evident in the body cavity.

One clue which sometimes can be helpful in judging maturity is the ease with which loose eggs can be voided through the abdominal opening when gentle pressure is applied to the abdomen (Figure 25). However, this technique must be used with caution, because green females may void some loose eggs and fully mature females may hold their eggs. With experience, a hatcheryman learns to select ripe females by gently feeling the anterior abdominal area (Figure 25). When the eggs are loose in the body cavity, the abdomen has a characteristic texture. After cutting open the abdomen, gentle shaking should dislodge eggs from the ovaries. If the eggs are not easily shaken loose from the ovaries, the female is too green and the eggs should not be stocked in the hatchery.

Eggs can remain in the female's body cavity for an hour or longer after she is killed and bled, provided air temperatures are 50°F or cooler and the carcass is not exposed to direct sunlight. If air temperatures are warm or if carcasses are exposed to sunlight, eggs should be removed from females as quickly as possible. Eggs can be stored on ice for at least 3 days without seriously affecting fertility if they are protected against exposure to water while in storage. Natural fluid from the body cavity should be kept with the eggs during storage.

Males remain fertile for several days. After a male has been killed, sperm remaining in the body rapidly loses its fertility, but fresh sperm can be stored in sealed glass or plastic containers placed in iced coolers for up to 20 hours. Sperm-bearing milt is collected from the abdominal opening by applying pressure to the abdomen. Usually, the first stream of milt contains considerable urine and should be discarded. If milt is to be stored for periods of up to 20 hours, only males

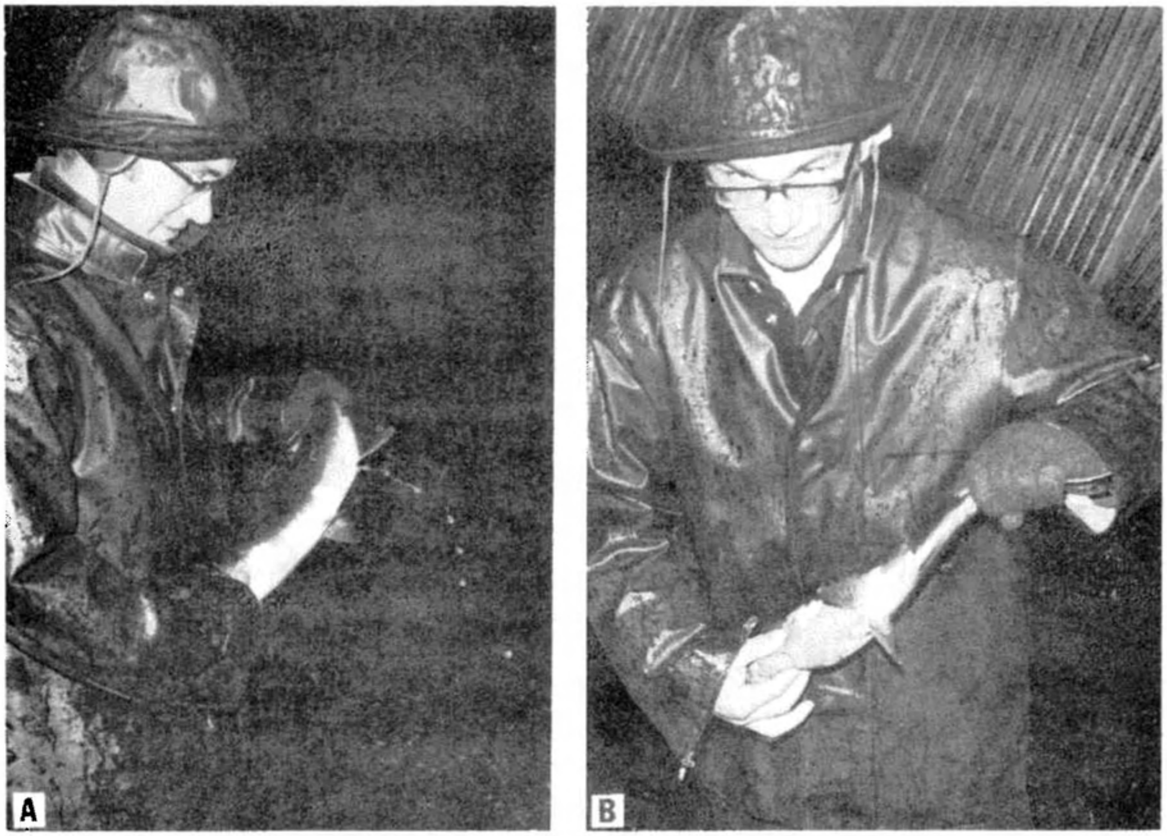

Figure 25.--Methods for checking female salmon for ripeness: (a) a few eggs are expelled to test for ripeness; (b) an experienced spawn taker can feel loose, ripe eggs through the abdominal wall to recognize females that are ready to spawn.

that appear to be healthy should be selected. Delayed fertilization of eggs is discussed later under the heading "Storage and Shipment of Unfertilized Eggs."

Spawning procedures can be modified without affecting fertility, but here are some helpful guidelines:

Make certain that surplus blood has been removed from females (see Figure 24).

Keep the females head lowered when carrying her so that the eggs will not fall out (Figure 26).

Dry the receptacle that receives the eggs before spawning, or place a disposable plastic liner in the egg receptacle (Figure 26).

Position the female over the receptacle before the belly is slit around the pelvic fin (Figure 27).

Shake loose eggs gently from the ovaries into the receptacle (Figure 27).

Add milt or store the eggs in a plastic bag or glass jar without milt (Figure 28).

Figure 26.--(A) When carrying a female salmon killed for spawning, keep her head lowered to avoid losing eggs; (B) plastic buckets make a convenient receptacle for spawning. Make certain that water is removed before a fish is spawned, or a clean, dry plastic liner can be inserted for collecting eggs.

Storage and Shipment of Unfertilized Eggs

Ideally, the collection and fertilization of eggs is accomplished in the immediate vicinity of the incubators so that eggs do not have to be shipped. Situations may arise however, where it will be necessary to collect the eggs and milt at a remote stream and transport them to the incubators. In such instances special procedures should be used to preserve the viability of the eggs while minimizing weight and bulk of the shipment.

The fertilization of salmon eggs can be delayed for up to 20 hours if eggs and milt are kept cool and dry in separate containers shielded from direct light.[8] Cool means below 40°F but not frozen; the cooler the temperature, the longer the eggs and sperm retain their viability. Dry means free of contaminating water but in presence of body fluids. Plastic bags make convenient containers which can be shipped or stored with ice in styrofoam-insulated boxes (Figure 29). Care must be taken so that water from the melting ice does not reach the eggs or sperm. It is not necessary to include air or oxygen with the eggs; unfertilized eggs demand very little oxygen and they are less subject to sloshing and breakage if the containers are completely filled. Best results with stored milt have generally been reported where air was included in the receptacle containing milt.

[8] Eggs can be stored up to 3 days, but sperm should not be stored under these conditions for more than 20 hours.

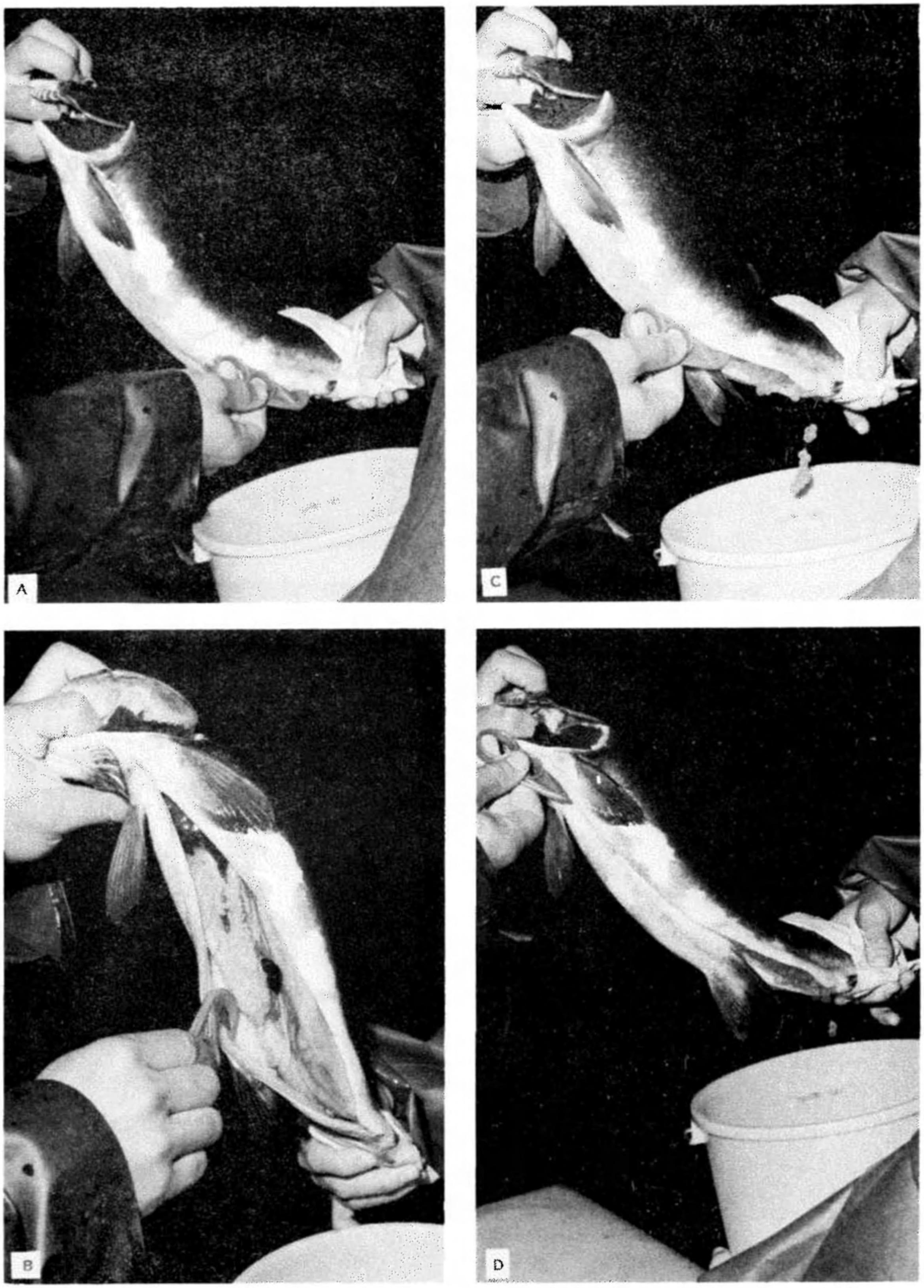

Figure 27.--(A) Slit the belly by inserting the knife in the abdominal vent and (B) cut above the pelvic fin, (C) make certain that eggs are shaken free of the ovaries and (D) into the receptacle.

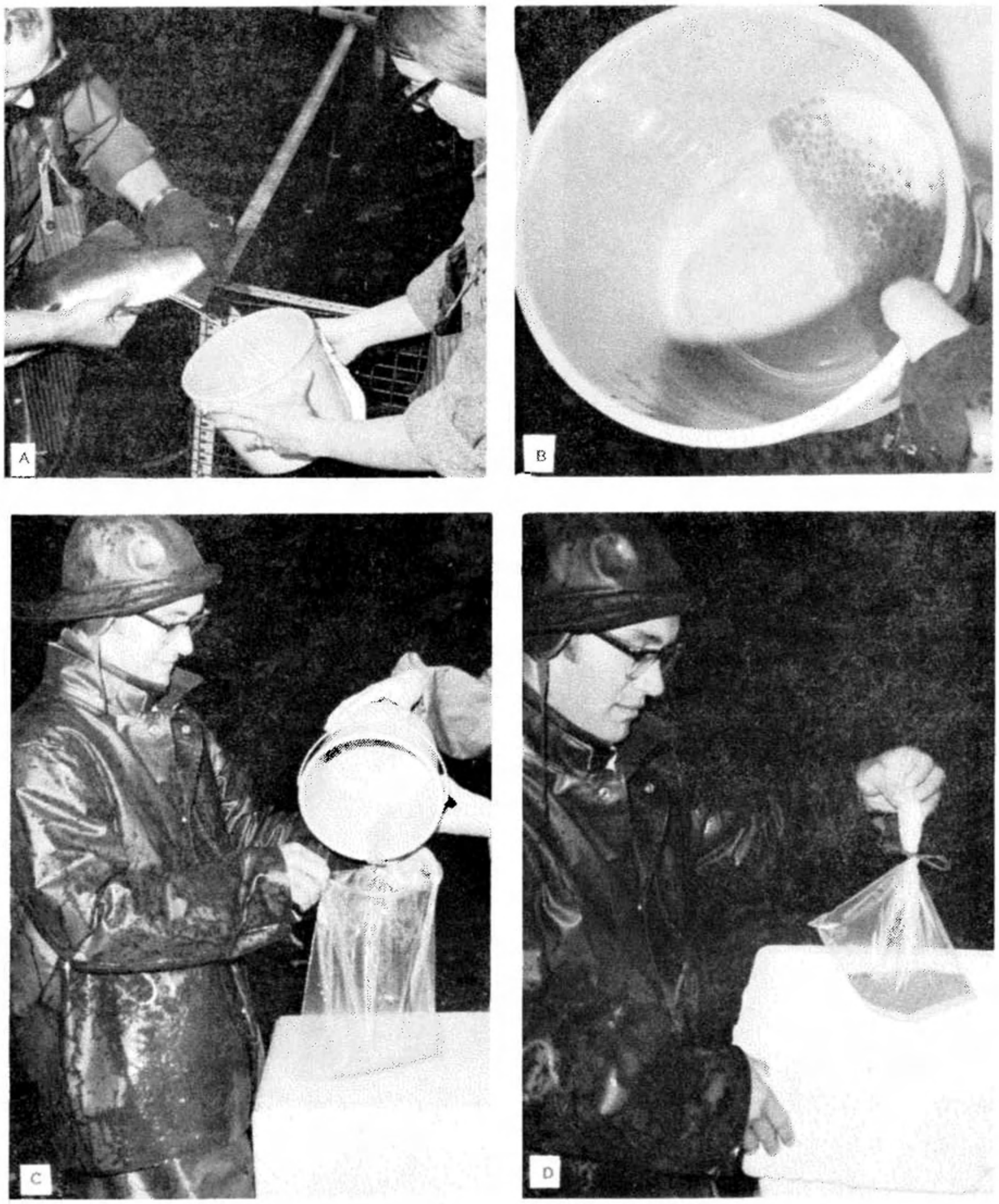

Figure 28.--(A) Milt is added to the newly spawned eggs; (B) when mixing milt with eggs, it is best to swirl the mixture and not risk breaking eggs by mixing with a hand; eggs can be (C) placed in a plastic bag and stored in a cooler for later (delayed) fertilization; (D) 60,000 eggs can be shipped in a sytrofoam container.

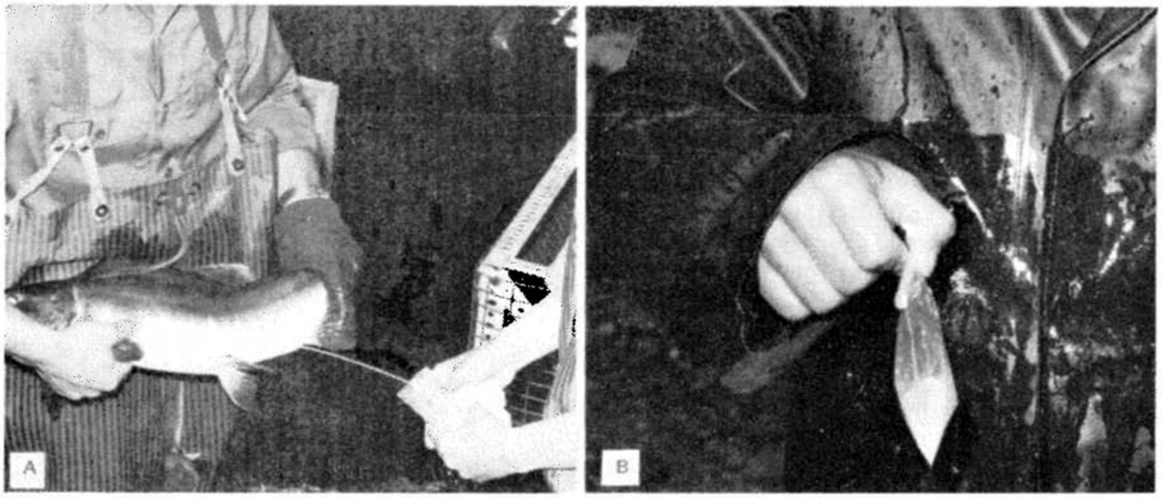

Figure 29.--(A) Milt is collected in a plastic bag with a large surface-to-air interface; (B) packets of milt can be stored and shipped in the same styrofoam container as the eggs.

Techniques for cryogenic preservation of sperm (i.e. frozen at very low temperatures) are being developed for salmonids. Since these techniques are experimental, they will not be discussed here.

Fertilization of Eggs

In natural spawning, milt and eggs are expelled at the same time. Sperm cells are activated by water and swim vigorously for a brief period until contact is made with an egg or until their limited energy reserves are exhausted. The egg is receptive to sperm for a brief period after contact with water. Embryonic development will proceed only if a viable sperm cell enters the fertile egg during this receptive period. The cloud of milt that surrounds the eggs contains many millions of sperm cells, and it is generally conceded that in nature, fertilization of more than 95% of the eggs is achieved.

To assure success with artificial fertilization, it is necessary to understand how the fertility of eggs and sperm declines with the passage of time in various environments. It is also essential to guard against the deleterious effects on fertility of contaminants. The relative "ripeness" of both the male and female salmon is still another factor that affects fertility.

The fertility of sperm, that is the ability to become active and impregnate eggs, begins to decline soon after milt is removed from the male salmon. The rate of decline in fertility is affected by temperature. At temperatures below 40°F (but not freezing) good quality sperm will fertilize 90% of the eggs after 20 hours of storage. For storage periods longer than 20 hours, the fertility of sperm drops rapidly. Fertility of eggs remains high, however, for at least 72 hours. Thus, for delayed fertilization, eggs should be collected first and milt last. The stored milt should be protected from light. Sperm cells are activated by contact with water, but once the vigorous swimming activity is triggered it persists for only 10 to 15 seconds.

Ripe eggs become receptive to impregnation by sperm on contact with water. The receptive period for individual eggs may persist for several minutes; but for practical purposes in achieving a high rate of fertilization, it is best to assume that some of the eggs lose their fertility after 30 seconds exposure to water.

Contaminants that commonly interfere with fertilization include broken eggs, slime, coagulated blood, and water. Broken eggs are especially harmful because the yolk from broken eggs coagulates on contact with water; the coagulated yolk and blood immobilize sperm and block openings in eggs (blastopore) where a sperm cell enters. Only three broken eggs in a container can significantly reduce fertilization of eggs in that container. Eggs are usually broken as a result of physical abuse of either the eggs or the females. Excessively vigorous attempts to strip all of the eggs from the females will invariably result in a few broken eggs, and a sharp blow or heavy pressure on the body of a female can rupture her eggs. Only one or two adult fish at a time should be brailed from a pen (Figure 30).

Broken eggs can also result from thé spawntaker's efforts to mix the eggs and milt. Once the milt is added to the eggs, mixing must be quick and thorough but not so vigorous that eggs are crushed and broken in the process. The egg receptacle should have a smooth surface such as enamel or plastic so that the eggs and milt can be swirled without breaking them. Stirring the eggs by hand is not necessary and often

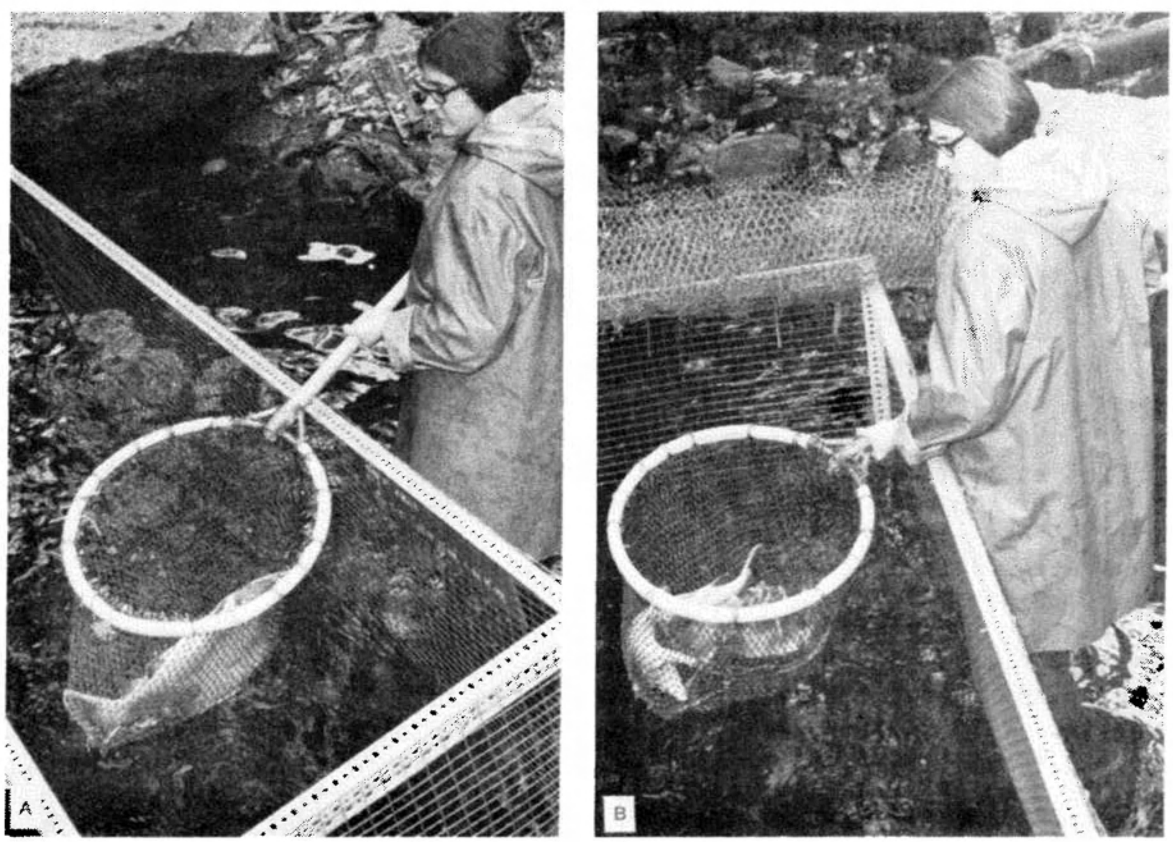

Figure 30.---(A) Proper and (B) improper practices in brailing adult salmon. Only one or two fish should be brailed at a time.

results in a few being broken. Excess slime and blood are kept out of the receptacle by wiping the female clean and by bleeding her before stripping eggs. In selecting fish for artificial spawning, the spawntaker selects only fish or gametes that are in the desired stage of "ripeness." The determination of ripeness is somewhat subjective, but the guidelines discussed in a previous section generally lead to a high rate of fertilization.

If eggs and milt are to be chilled and stored so that fertilization is delayed, they should be allowed to warm to above 42°F or to the temperature of the receiving water before fertilization is attempted. The milt should be mixed with water just before it is added to the eggs. Diluting milt with water at this stage of the process activates the sperm and increases the rate of fertilization. Dilutions should be at least 1:1 and not over 3:1 (water to milt).

Washing and Water Hardening Eggs

Immediately upon contact with water, salmon eggs begin to take up water. This condition persists for about 45 minutes, depending on temperature. The sticky property of the eggs at this stage is caused by the rapid movement of water into the eggs. The eggs are not harmed by gentle swirling of the container to separate them while washing away excess milt and foreign material such as feces, urine, slime, blood, and broken eggs. The washing should be done as soon as the eggs and milt have been thoroughly mixed. Fertilized eggs should be transferred immediately to the incubators and handled as gently as possible while being emptied from the receptacle in which they were fertilized. During the water-hardening process, the perivitelline fluid, which lies between the yolk and chorion, takes on water and causes the egg to increase its volume about 20%. The perivitelline space that forms at this time is the space in which the embryo will develop and grow. The chorion changes from its former fragile flaccid condition and becomes tough, and the egg is now resistant to further change in shape. The ovoid shape taken on during water hardening is retained until hatching.

Estimating Percent Fertilization

It is important to know what percentage of the eggs are fertilized. Unfertilized eggs provide a nutrient base for fungus which could spread and kill adjacent live eggs. Low rates of fertilization would be reason to suspect faulty egg-taking procedures which must be detected during spawning to allow timely corrections in technique. Experienced spawntakers expect to fertilize 95% or more of the eggs collected.

Percentage fertilization can be estimated by examining a sample of eggs during the first day or two after fertilization. The early cell divisions in salmon embryogenesis form large cells (blastomeres) which can readily be distinguished from the germinal disk of unfertilized eggs with low power magnification. To enhance the visibility of embryos, a sample of eggs is soaked in FAA or Carnoys' solution for several minutes. FAA solution is prepared by mixing 30 parts of acetic acid, 65 parts of formalin, and 1,000 parts of 50% ethyl alcohol. Carnoys' solution consists of 75 parts of 50% ethyl alcohol and 25 parts acetic acid mixed fresh each time it is used. The unfertilized germinal disk and the embryo of fertilized eggs turn opaque white in the preservative solutions and become visible through the translucent chorion without dissection or staining. A common procedure is to examine the eggs when the four-cell stage is reached. The rate of embryonic development will vary with temperature, species, and possibly with stock of salmon. The time required for pink salmon embryos to reach the four-cell stage is shown in Figure 31.

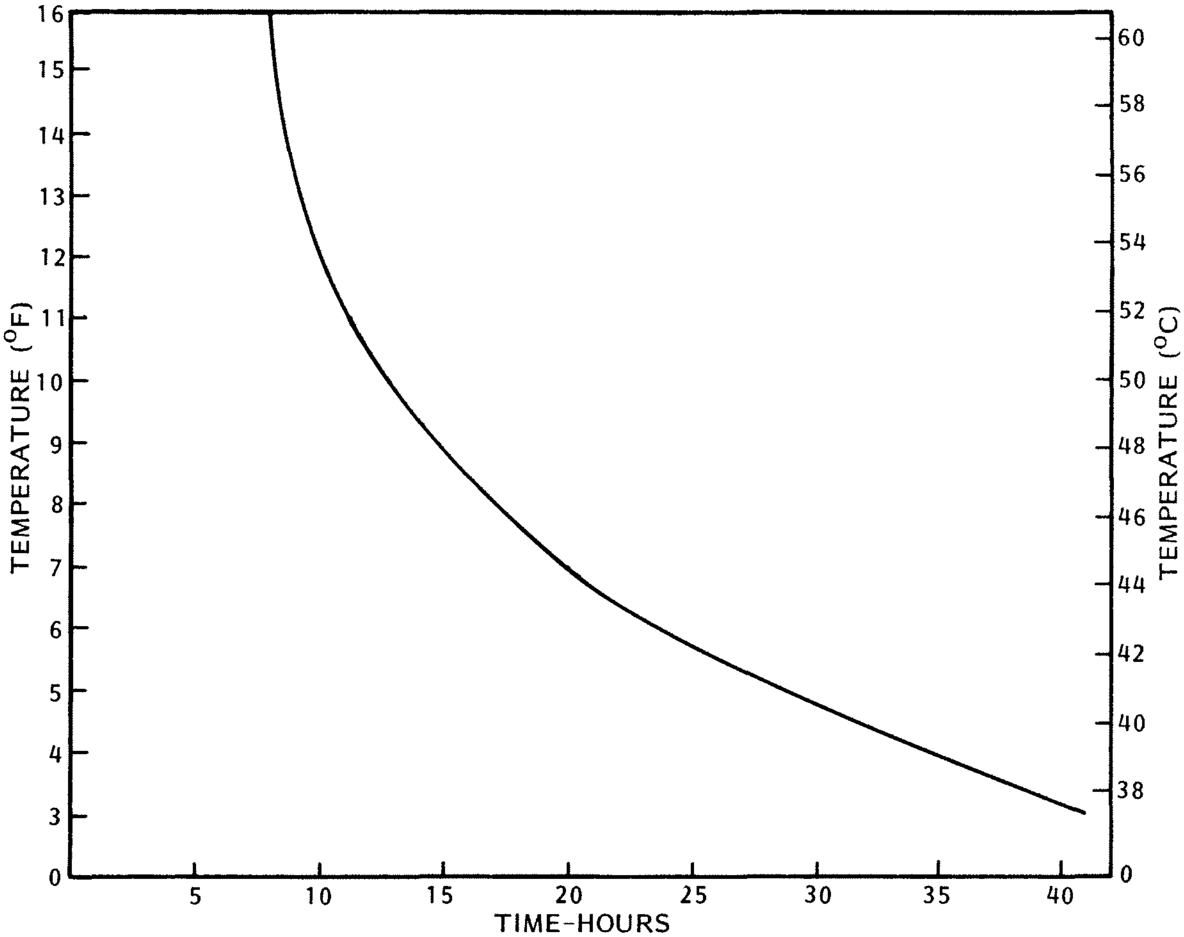

Figure 31.--The effect of temperature on time required for pink salmon embryos to progress from fertilization to the four-cell stage of development.

Environmental Requirements of Eggs

Salmon eggs and alevins are adapted to life in fresh water. The embryos are able to maintain a proper balance of internal salt and water while bathed in external environments ranging from fresh water to water with a salinity of 9 to 11‰ (seawater is 33 to 35‰). In many Alaska streams, pink and chum salmon spawn in intertidal streambeds which are periodically inundated by water with a salinity of 15 to 30‰. In these situations, survival of eggs depends on periodic flushing of the streambed by fresh water. Where eggs are exposed to high salinity for more than one-third of the incubation period, survival is reduced.

The water that bathes salmon eggs must be relatively free of suspended particles. Accumulations of sediment on the egg can interfere with respiration; accumulations in gravel can block movements of alevins and interfere with emergence of fry. The use of filters has been advocated to remove sediments where eggs are in deep matrix gravel incubators, but satisfactory results are possible without the use of filters if the water is reasonably clean. Shallow matrix gravel incubators and turf incubators are designed to operate without filtration. Settling ponds or lake sources can be used to protect incubators from heavy sediments. Collecting galleries of perforated pipes or large chambers are sometimes buried in the streambed to provide a cleaner source of water.

Salmon eggs require continuous flowing oxygenated water. The movement of water past the eggs is necessary not only to bring oxygen to the eggs but also to remove toxic metabolites such as ammonia gas and carbon dioxide. The rate at which an egg consumes oxygen and releases metabolic wastes gradually increases from the time of fertilization to absorption of the yolk in response to growth.

Eggs are easily killed by handling at certain stages of development. For practical purposes the tender stage of salmon eggs begins within a few hours after fertilization and ends when the pigmented eyes of embryos become visible (Figure 32). During the tender stage, eggs can be killed by merely jarring or vibrating the incubator. The hatchery operator should refrain from examining or handling eggs during the tender stage. By contrast, freshly fertilized and eyed eggs are not injured by the handling necessary for counting eggs and stocking incubators.

It is well known that salmon embryos can be injured by exposure to intense natural or artificial light. Light also stimulates premature swimming activity among alevins. Eggs should therefore be kept in shade or darkness during spawntaking, transporting, and stocking of incubators. Also, incubators should be constructed of opaque material or should be covered to exclude light; black polyethylene sheeting is a convenient cover for incubators.

Salmon usually spawn at temperatures of about 45° to 55°F. Incubation temperatures range downward from 55°F, and may drop to 32°F in winter. Salmon eggs and alevins can withstand temperatures as low as 32°F if they do not freeze and if they are past the stage of sensitivity to low temperatures. Laboratory experiments have shown that eggs exposed to temperatures below 40°F during early development (first 10 to 30 days, depending on water temperature) experience high mortality.

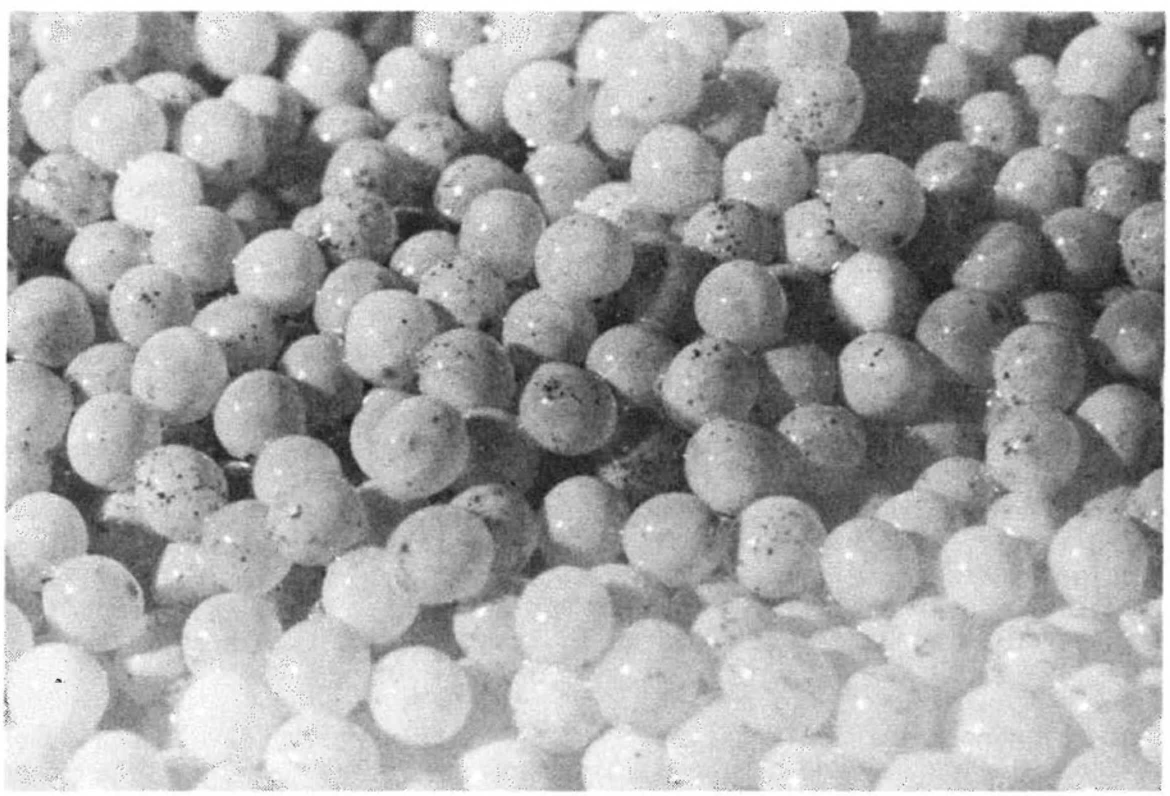

Figure 32.--Eyed eggs are not sensitive to shock from handling.

The incubation period from fertilization to emergence of fry varies inversely with temperature and is different for each species. The incubation period is also subject to genetic control within species so that salmon stocks are believed to be adapted to the specific seasonal temperature pattern of their home stream. Genetic control of the incubation period implies that salmon are adaptable to changes in seasonal temperature patterns if the changes are not too dramatic. For pink, chum, and sockeye salmon, it is important that the end of the incubation period coincide with the appearance of zooplankton blooms in the nursery estuary or lake. For salmon which are fed artificial foods, it may not be so important when the incubation period ends. But because of genetic adaptations to seasonal rhythms of temperature and photoperiod, deviations from the natural timing may introduce problems in migratory behavior, adaptation to salt water, and homing. Therefore, it is recommended that incubation temperatures in salmon aquaculture closely follow average seasonal temperature patterns experienced by the stock of fish being raised.

Natural predators or scavengers of salmon eggs include bears, gulls, sculpins, and certain aquatic insects. Egg losses to these predators and scavengers are virtually eliminated in hatcheries. Little is known of the role of invertebrate and lower life forms that inhabit natural spawning beds. Some of the stonefly nymphs are known to eat dead eggs, and certain species of stoneflies and caddisflies eat live eggs. Aquatic roundworms and flatworms eat dead eggs. Bacteria and fungi almost certainly aid in the decomposition and disappearance of dead eggs from streambeds. Because of the relatively high egg densities used in artificial culture, it is best to discourage activity of invertebrates and lower life forms.

Removal of Dead Eggs

In natural redds, dead salmon eggs can be found intermingled with live eggs. The dead eggs compete with the live eggs and alevins for oxygen and provide a nutrient base for the spread of fungus and other biological growths. It is advantageous in artificial incubation to remove dead eggs from incubators. This can be done when the eggs are at the eyed stage of development. At that time if the eggs are subjected to a physical shock or agitation the unfertilized ones will turn white and can easily be removed (Figure 33). In the shallow matrix gravel incubator, separation of alevins from dead eggs takes place automatically as alevins pass through the screen to the substrate. Nevertheless, removal of dead eggs at the eyed stage is recommended to minimize egg mortality from fungus growth.

Shipment of Eggs

Eggs can be shipped at four developmental stages: (1) as immature eggs in the ovary of the living female, (2) as mature unfertilized eggs, (3) as recently fertilized and water-hardened eggs, and (4) as eyed eggs. The methods that are most convenient and yield the best success are shipment of mature unfertilized eggs and eyed eggs.

Live immature females have been shipped successfully, but substantial problems are encountered in handling live salmon. In some instances adults have been released into a recipient stream or spawning channel to spawn naturally. In other instances they have been held in captivity to mature for artificial spawning. Large live tanks with circulating water are required to transport adult fish by water or by land.

Methods of shipping mature unfertilized eggs are fairly recent developments. Since fertilization will be delayed at the destination, special precautions should be taken to minimize time in transit, keep unfertilized eggs and sperm cool, and avoid contact of eggs with water before sperm is mixed with eggs. Storage and shipment

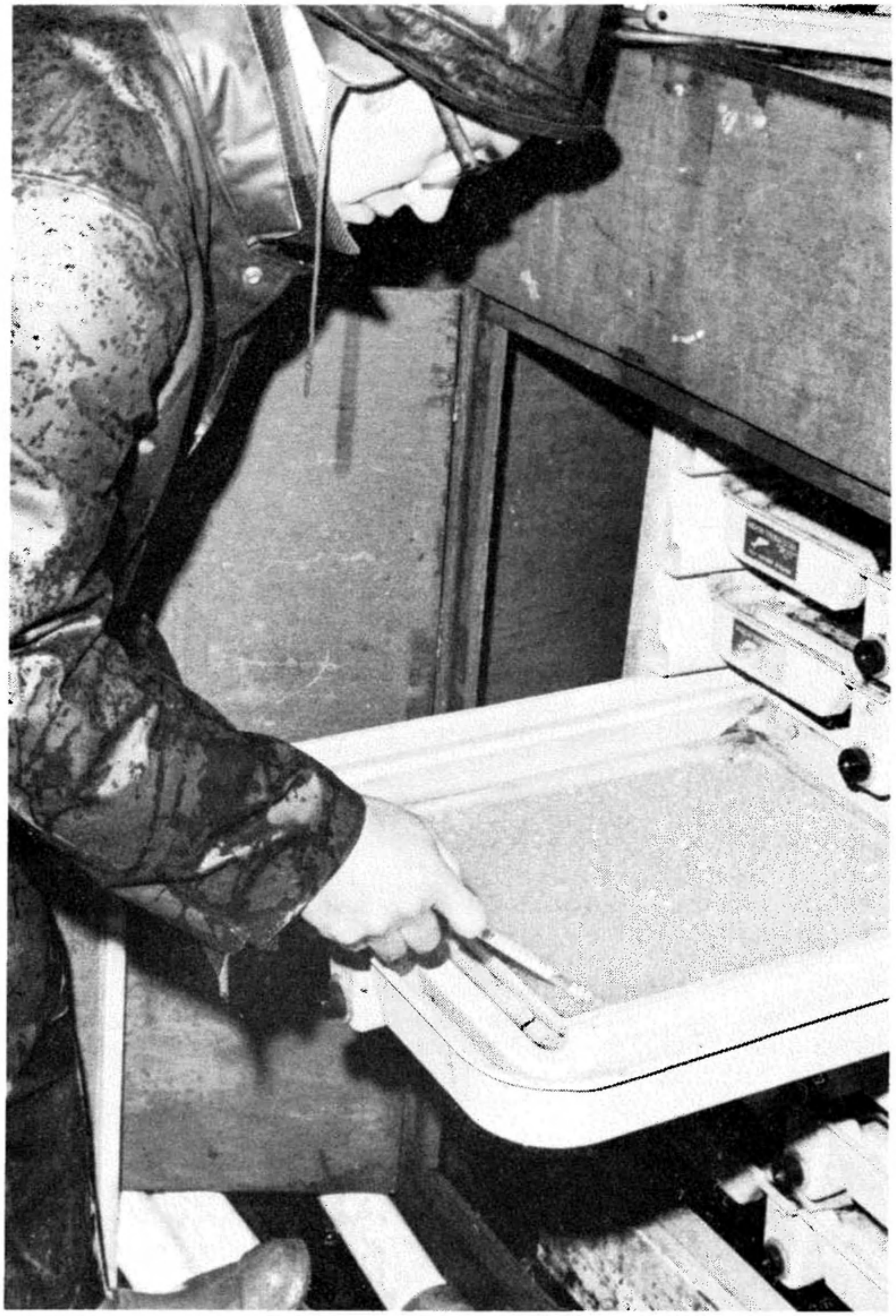

Figure 33.--Removing dead eggs from a tray incubator.

of unfertilized eggs and techniques of delayed fertilization have already been discussed in some detail.

Shipment of recently fertilized and water-hardened eggs is risky and requires special containers and very careful handling to avoid shocking the eggs. The eggs are gently placed in perforated trays stacked vertically in water-tight insulated containers. Ice is added to the top tray to provide moisture and to keep the container cool. Newly fertilized eggs should not be in transit for more than 12 hours. Eggs must be handled very gently, especially when they are transferred to hatchery incubators; cell division is already occurring and the sensitivity of eggs to shock can be very high.

The preferred time to ship eggs is after they have eyed because eyed eggs are very resistant to shock from handling. The major requirements are to keep them cool and moist. It is necessary to pack eyed eggs in moistened cloth or other absorbent non-toxic material. Air should be allowed to circulate freely among the eggs. If the air is too warm, ice can be packed over the eggs to maintain cool and moist conditions. Any delays in shipment can easily be accommodated when eyed eggs are shipped, provided hatching does not occur while the eggs are in transit.

Diseases

A small percentage of eggs will always retain a normal appearance except that no embryo develops. Such eggs are unfertilized and quickly turn opaque if shocked. It is common practice in hatcheries to handle eggs after embryos are well eyed in order to "shock" unfertilized eggs and remove them.

Certain bacterial and viral disease agents can be transmitted on the surface of eggs. Before eyed eggs are transferred, they should be disinfected with an organic iodine compound. More will be said about this later.

Fungus Infections

Fungus infections can become major problems. Dead eggs provide a nutrient base for fungus and other biological growths which, if prolific, can smother adjacent eggs. If fungus becomes a problem, dead eggs can be removed after the live eggs have eyed, but not before. Where hatcheries are located on estuaries, periodic pumping of salt water through incubators will inhibit growth of fungus. It has long been common practice to treat eggs in hatcheries with malachite green, but use of this chemical is not approved by the Food and Drug Administration. Formalin is also effective for control of fungus infections, and efforts are being made to obtain FDA approval for the use of formalin for this purpose.

White Spot Disease

Other disease conditions, such as "white spot disease" or "coagulated yolk" have been described for salmon eggs. Affected eggs have white areas where the yolk has coagulated. This condition may result from injury, but there may also be unknown pathogens involved.

Infectious Hematopoietic Necrosis (IHN)

A virus disease, commonly known as IHN, has been found to infect chinook and sockeye salmon. It is also found in rainbow trout. IHN is suspected to be transferred from adult to juvenile fish through the sex products. The disease does not appear to be active in eggs or alevins, but it becomes virulent in juveniles. If IHN is detected in a hatchery stock, newly fertilized or eyed eggs should be dipped in a solution of Wescodyne or Betadine[9] disinfectant containing 100 ppm of iodine buffered with sodium bicarbonate. Eggs should be exposed 15 minutes to the dip, and the disinfectant solution should be renewed if it turns yellow.

CARE OF ALEVINS

The alevin stage requires 2 to 4 months, depending on water temperature. Survival from hatching to absorption of the yolk may approach 100% in hatchery incubators, but stressing factors such as light, substrate, dissolved oxygen, and metabolic wastes have important effects on size, growth, and stamina of fry. An understanding of the behavioral and metabolic requirements of alevins is essential to ensure that incubation systems produce fry with a potential for rapid growth and high survival.

Size of Alevins and Fry

Stressing factors such as temperature and dissolved oxygen sometimes influence the stage of development when hatching occurs. Alevins hatching prematurely in response to stressing factors are often much smaller than those not subjected to such stressing factors, but they have a higher percentage of yolk material. At time of yolk absorption, an alevin hatching prematurely will often recoup some, but not all, of the growth delayed during embryonic development. Efficiency of yolk conversion is therefore usually lower for alevins which hatch prematurely than for those which do not.

The total wet weight of yolk and tissue changes very little from completion of water hardening of a newly fertilized egg to completion of yolk absorption by the fry. Dry weight, on the other hand, declines 30 to 60% over the period of development. The difference between wet and dry weight reflects the consumption of protein, fat, and carbohydrate from the yolk to maintain vital processes, and the replacement of these nutrients with water.

Where environmental conditions are optimal, as much as 70% of yolk material may contribute to growth and as low as 30 percent may be used to maintain vital functions. Where environmental conditions are less than optimal, as low as 40% of yolk material may contribute to growth and as high as 60% to maintenance. At least six factors influence efficiency of yolk conversion and size of fry: (1) rugosity of substrate, (2) water temperature, (3) water current, (4) light, (5) dissolved gases, and (6) waste metabolites. Thus, a poor hatchery environment for alevins can contribute substantially to low efficiency of yolk conversion to body tissue and result in undersized fry.

Environmental Requirements of Alevins

The effect of environment on the efficiency with which yolk is transformed to body tissue is very important because larger fry can be expected to have a higher capacity for growth and survival than smaller fry. The percentage gross efficiency of yolk utilization can be calculated by

$$\frac{\text{Dry weight after yolk absorption}}{\text{Dry weight of fertilized egg}} \times 100$$

As already stated, growth efficiency typically varies between 40 and 70%, depending on stressing factors.

[9] Wescodyne and Betadine are trade names of iodophor disinfectants.

Stressing factors that occur during the alevin stage can induce anatomical and functional disabilities and deficiencies in salmon fry which possibly are more important to growth and survival than efficiency of yolk utilization. Foremost among these are yolk-sac malformation, deformation of the gut, translocation of the liver, and fat dystrophy. The relative importance of these factors to growth and survival remains to be clarified, but it is apparent that hatchery incubators must satisfy the environmental and behavioral requirements of alevins if they are to produce large fry free of anatomical and functional disabilities and nutritional deficiencies.

Substrate

The importance to alevins of a gravel substrate or an artificial substrate simulating gravel cannot be overemphasized despite the widespread use of smooth substrates in hatchery incubators. The presence of a rough substrate appears to be especially critical for pink, chum, and sockeye salmon. Various studies with these three species have shown that fry from gravel substrates are seldom abnormal. A gravel substrate also minimizes premature swimming, and the resulting fry are much larger and have greater stamina than fry from a smooth substrate.

Temperature

Warming of water stimulates alevins to become more active and to increase the amount of energy required for maintenance of body functions. Hence, gross conversion of yolk to body tissue decreases as temperature increases. Heightened activity of alevins in warmer water also contributes to a higher incidence of yolk-sac malformation in hatchery incubators with smooth substrates. The recommended optimum temperature regime is the normal temperature regime of the home stream.

Current

The flow of turbulent water through incubators containing alevins should be avoided in order to minimize activity. The current must be sufficient, however, to ensure delivery of oxygenated water to alevins and to remove metabolic wastes.

Light

Exposure of alevins to light stimulates swimming activity and results in a decrease in gross efficiency of yolk utilization and increased incidence of yolk-sac malformation. Fry from alevins exposed to light are much smaller than fry from alevins held in darkness. It is essential, therefore, to shield incubators from light.

Dissolved Oxygen

Reduction of dissolved oxygen below 6 mg/liter should be avoided in hatchery incubators so that alevins will not be subjected to pronounced oxygen stress. It is always preferable, however, to maintain dissolved oxygen levels to as near the saturation value as practicable.

Handling Alevins

Handling stimulates activity in alevins and is a stressing factor that should be avoided whenever possible. Gravel and turf incubators are designed to keep the handling of alevins to a minimum and to allow volitional emigration of fry. Fry can easily be collected as they emigrate from incubators.

Diseases

There are few, if any, effective means of treating diseased alevins. Therefore, the avoidance of conditions that favor the outbreak of disease becomes particularly important for alevins. Every precaution must be taken to avoid exposing alevins to stressing factors in the hatchery environment.

Yolk-Sac Malformation

Several diseases have been described for salmon alevins which involve rupturing of the yolk sac, coagulation of yolk material, and formation of scar tissue on the yolk sac (Figure 34). Diseases with these symptoms include coagulated yolk disease, hydrocoele embryonalis, white spot disease, and cold-water disease. Only in cold-water disease has a pathogenic agent been isolated and described. In this case the myxo-bacterium *Cytophaga psychrophila* was found, but it might have occurred as a secondary infection.

In alevins afflicted with yolk-sac malformation the development of organs and absorption of the yolk are delayed; the liver is abnormal; and acute fat dystrophy may occur. Afflicted alevins often survive to the fry stage, but food assimilation and growth is poor and delayed mortality is high. Yolk-sac malformation can be prevented in most instances by providing alevins a rugose substrate and by excluding light from incubators.

Costia

A protozoan parasite (*Costia* sp.) can infect alevins as well as older fish, although infections are not common in the alevin stage. *Costia* has no identifiable visual symptom. Transferring infected fry to salt water does not inhibit *Costia*, and the disease, carried from the alevin stage, can become epidemic among fry in both salt water and fresh water. Alevins can be treated for *Costia* by adding 1 part formalin to 6,000 parts water flowing through incubators (provided the Food and Drug Administration approves the use of formalin in fish husbandry).

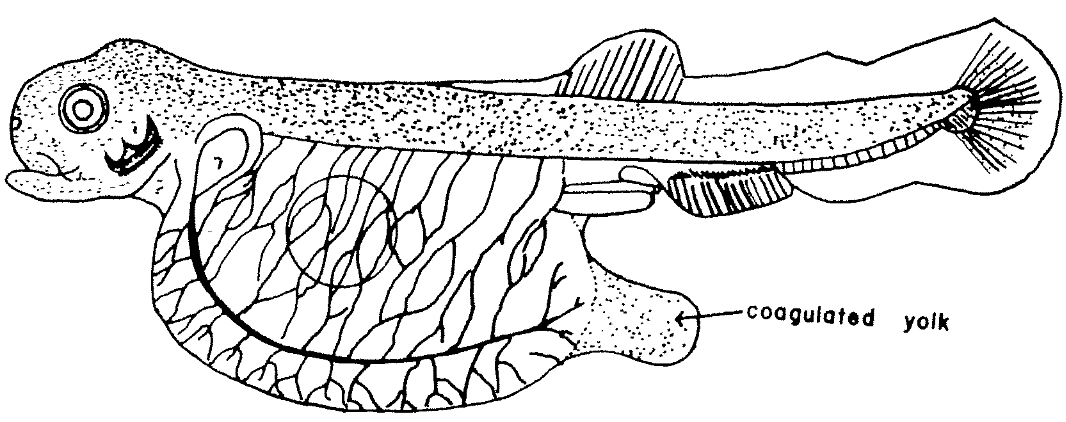

Figure 34.--Salmon alevin exhibiting yolk-sac malformation (from Emadi, 1973).

Trichodina

Another protozoan parasite observed on salmon alevins is *Trichodina* sp. In alevins heavily infected with *Trichodina* a light blue slime forms over the surface of their bodies. Exposure to salt water kills *Trichodina*.

Gas Bubble Disease

Alevins are intolerant to supersaturation of gases dissolved in water. Nitrogen, the principal element in the atmosphere, is the gas that usually causes problems. Damaging gas bubbles can be expected to form in alevins when nitrogen exceeds 103% of its saturation value.

Three precautions will guard against supersaturation of dissolved gases in the hatchery water supply: (1) Prevent air from entering the intake side of a pump delivering water to hatchery incubators; (2) prevent air from entering the intake of a gravity waterline delivering water to hatchery incubators; and (3) avoid use of well or spring water which has not been thoroughly checked for supersaturation of gases.

CARE OF FRY

The emergence of wild fry from natural spawning beds is timed to coincide with the seasonal (spring) bloom of food organisms in nursery waters. The period of release of unfed hatchery fry should coincide, therefore, with the emigration of fry from natural populations. If fry are fed in captivity, the time of release could still be important to survival. Furthermore, the conditions under which fry are held in captivity will to a large extent determine their capacity for survival. There are a number of useful references which can be consulted for additional information on practices commonly employed to raise salmonid juveniles. Two of the more recent ones, which are listed in "Selected References," are Bardach, Ryther, and McLarney (1972) and Halver (1972).

Holding and Handling Fry

Conventional hatchery systems require manual removal of fry from incubators, whereas gravel and turf incubator hatcheries and spawning channels are designed for voluntary emergence and emigration of fry. In the latter systems, when fry emerge (usually during darkness), they can be trapped and transferred to feedlots or allowed to enter a natural nursery area without being handled.

Should pink or chum fry emerge from incubators before their yolk is fully absorbed (i.e. as "unbuttoned" fry), they should be retained in fresh or low-salinity ($\leq 11^{o}/oo$) water until external yolk material is no longer visible. Premature migration of unbuttoned fry into salt water is not recommended, because in many cases these fry will experience acute dehydration and die.

Fry raised in captivity can be held in ponds, raceways, or floating pens (Figure 35). They should be fed a proper diet[10] before they completely absorb their yolk material to avoid loss of body condition through starvation. Hourly feedings during daylight are necessary to ensure that fry get off to a good start. The density of fry should not exceed 3/4 lb of fish per cubic foot of water. Small fish are more sensitive to overcrowding than large fish. The minimum rate of water exchange depends largely

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[10] Suitable diets are commercially available.

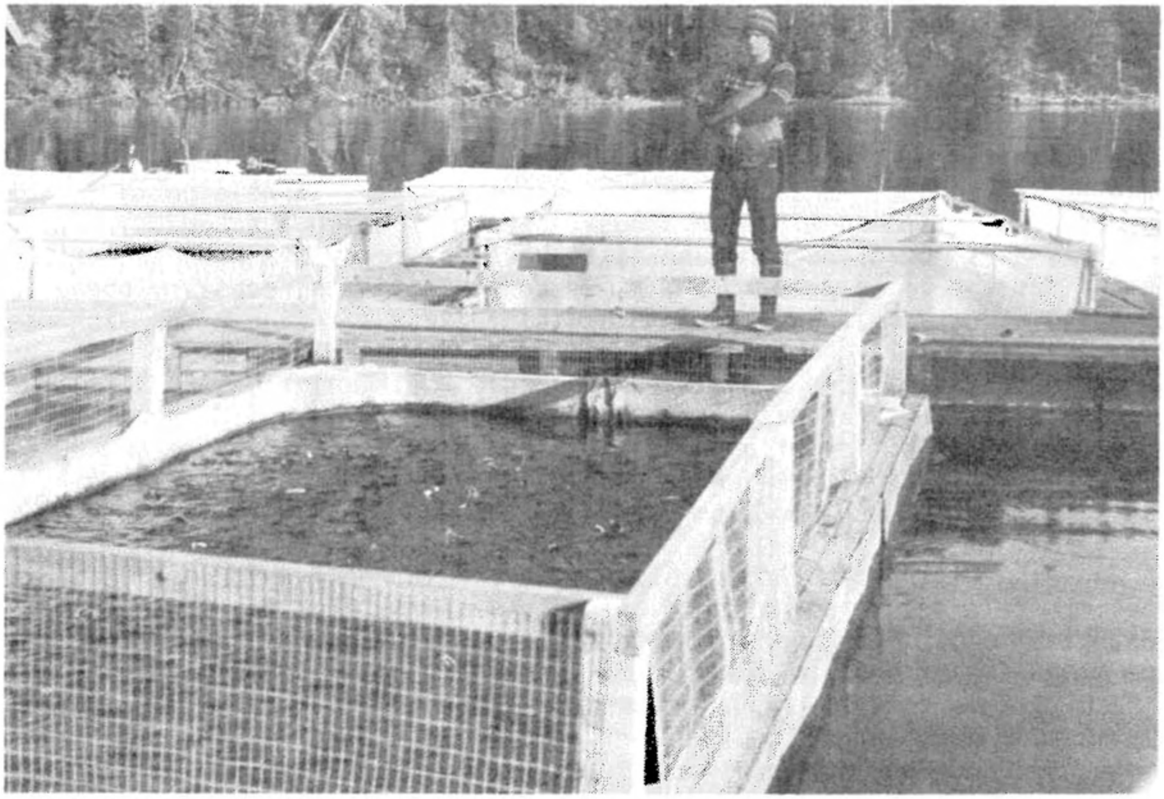

Figure 35.--Floating pens are used to raise salmon in lakes and estuaries.

on water temperature; 1 gpm of water saturated with dissolved oxygen can supply about 15 lb of fry at 45°F and about 8 lb at 50°F.

The carrying capacity of each hatchery should be determined from information on oxygen consumption rates of fry and oxygen levels of incoming and discharge water. With this information, the hatchery operator can use the equation given earlier in this manual to calculate the pounds of fish that can be raised per gallon per minute of water flow. For example, it has been determined experimentally that chum fry consume 0.8 lb of oxygen per 100 lb of fry per day at a water temperature of 50°F. If the dissolved oxygen content of water entering a raceway should be 10 mg/liter and if a minimum concentration of 5 mg/liter (assuming no re-aeration) is to be maintained, we calculate the weight of fry per gallon per minute (W) by the equation

$$W = \frac{1.2\ (C - C_{min})}{O_2} = \frac{1.2\ (10-5)}{0.8} = 7.5 \text{ lb fry/gpm}$$

The oxygen consumption per pound of salmon raised decreases as the fish grow.[11] The amount of oxygen consumed per day by 100 pounds of newly emerged coho fry that have attained a weight of 1,000 per pound is as follows for three temperature levels:

0.55 lb O_2 at 45°F
0.75 lb O_2 at 50°F
0.90 lb O_2 at 55°F

[11] See Liao (1971) in "Selected References." This paper presents equations and graphs for determining oxygen consumption rates of juvenile salmon.

When these same fish attain a weight of 100 per pound, the amount of oxygen consumed at the same temperature levels is about:

0.35 lb O_2 at 45°F
0.50 lb O_2 at 50°F
0.60 lb O_2 at 55°F

A buildup of waste food, fecal matter, and other detritus in holding tanks, raceways, or pens must be avoided to minimize stressing factors which are conducive to outbreaks of disease. Dead and moribund fish should be removed and burned or buried. Handling of fry should be held to a minimum consistent with necessary operation of the hatchery. Nets should be placed in a disinfectant solution after each use.

Healthy fry receiving a proper diet should double their weight every 3 to 6 weeks, depending on water temperature. Temperatures between 50° and 55°F are ideal for rapid growth and inhibition of diseases. Salmon grow slightly faster at 60°F than at 55°F, but chronic problems with stressing factors and diseases frequently become acute at temperatures much above 55°F.

At some Japanese chum salmon hatcheries, fry are held and fed for 4 to 6 weeks before they are released to emigrate to sea. This allows chum fry to double or triple their size from about 1,200 per pound to 400 to 600 per pound. The larger fry are released at a time of peak food availability and are better able to escape predation, with a resultant increase in marine survival. However, if chum salmon juveniles are raised to a size much larger than 400 per pound, the adults return at a smaller size and younger age and have a much reduced market value.

Experience with artificial propagation of pink salmon has been limited in North America, and the release of unfed fry from spawning channels and gravel incubators appears to afford the greatest promise of success at present. Large numbers of pink salmon are raised in Japanese and Russian hatcheries, but it is unclear from the literature if many of these fish are held and fed for short periods, as are chum salmon fry.

It is common practice for chinook salmon hatcheries near the coast to hold and raise fry for 12 to 15 weeks before the young fish are released to emigrate to sea. During this period, the fry increase their size about tenfold to attain a weight of about 90 to 100 per pound. Certain genetic stocks of chinook salmon successfully adapt to salt water at this size.

Coho salmon must be raised to a larger size than chinook salmon before they can successfully adapt to salt water. The usual practice with coho is to feed juveniles for 1 year and raise them to a size of 15 to 40 per pound before releasing them.

Experiments suggest that sockeye salmon adapt to salt water as readily as chinook salmon. Most experience with sockeye salmon has been on stocking nursery lakes with fry from spawning channels, although some sockeye are raised in Columbia River hatcheries 1 year and released.

Environmental Requirements of Fry

Salmon fry will grow over a temperature range of 40° to 60°F; in terms of general overall vigor and growth, the most satisfactory temperature range is 50° to 55°F. At temperatures below 50°F, growth is slow, but above 55°F the danger from outbreaks of disease is compounded. Temperatures above 65°F place fish under severe temperature stress, and mortality from high temperature can be expected above 70°F.

Fry should not be subjected to concentrations of dissolved oxygen much below 6 mg/liter. The carrying capacity of water for fry is determined in part by oxygen saturation values, which are affected by temperature, salinity, and altitude. Temperature also controls activity and metabolic requirements of fish. For example, fresh water fully saturated with oxygen at sea level will support 15 lb of newly emerged salmon fry per gallon per minute at 45°F but only 4 or 5 lb at 60°F. Thus, the weight of fry stocked in tanks must be reduced or the flow increased as water warms. Fry should not be stocked in excess of 3/4 lb per cubic foot of water even if the rate of water exchange in gallons per minute will support more than this poundage per cubic foot.

Accumulation of metabolic wastes must be avoided in hatchery water. Even a sublethal buildup of ammonia gas is recognized as a serious stressing factor. Waste metabolites represent a more serious threat to health of fish where water is recirculated or is passed through rearing ponds in series than where water is not recirculated. Possible toxicity from ammonia must be watched carefully where waters have a pH value of 8.0 or above.

Pink and chum salmon survive direct transfer as fry from fresh water to full-strength seawater provided they have absorbed their yolk. The other three species must grow in fresh water or water of low salinity (≦11°/oo) for 1 to 12 months before they can survive and grow in water of high salinity.

Juvenile salmon undergo a period of physiological adjustment when they first enter the sea in order to regulate water and salts in body fluids and tissues. This adaptive phase may last 1 or 2 days and is characterized by a depression of activity and dehydration of body tissues. Early exposure to water of low salinity can stimulate the physiological adaptation to seawater of salmon species which typically remain in fresh water for several months as juveniles.

Feeding and Nutrition

Fish nutrition is a technical field demanding continuing research and development for the formulation of improved diets which are economical to produce, store, and feed. Fry should be fed at least once per hour during daylight, but the frequency of feeding can be reduced gradually as the fish grow. Automatic feeders are desirable because they provide frequent or continuous feeding. The recommended daily ration is determined by a number of factors, including protein content of food, water temperature, fish size, and desired growth rate. Manufacturers of prepared diets commonly provide guidelines on feeding rates for their diets. Overfeeding should be avoided to prevent the accumulation of uneaten food which can pollute the water and to minimize the cost of supplying food.

Salmon require high protein foods balanced with essential fats, vitamins, and minerals. Raw fish carcasses are no longer fed to juveniles because certain diseases can be transmitted from carcasses to the young fish. Fish carcasses and offal are now sterilized before being processed into moist or dry foods. Moist foods must be stored at below freezing temperatures; otherwise fats oxidize and vitamins deteriorate.

Energy for growth (anabolism) is supplied by protein, but energy for other metabolic functions (catabolism) can be supplied by fat and carbohydrate in addition to protein. About 70% of the energy in natural foods of salmon is protein and most of the remainder is fat. However, salmon can be raised on artificial diets supplying as low as 50% total energy as protein and most of the remainder as fat. High carbohydrate levels should be avoided in salmon diets to avoid the accumulation of glycogen in the liver.

The amount of food fed to a given poundage of fish depends largely on the caloric content of the food. Highly concentrated artificial diets can have up to four times the number of calories available for energy per pound of food as natural foods, and feeding rates must be adjusted to the caloric content of food. Fry averaging 1,000 or more per pound require about twice the number of calories per day per pound of fish as fish averaging 30 per pound. An increase in water temperature from 35° to 55°F doubles the number of calories required to take full advantage of the increased growth potential of fish at the warmer temperature. For example, newly emerged fry fed a moist pellet diet might require 4 lb of a certain formulation of food per day per 100 lb of fish at 35°F and 8 lb per day at 55°F. As fingerlings weighing 100 per pound, their daily food requirement would decline to about three-fourths of these levels. As smolts weighing 30 per pound their daily food requirement would be about one-half that of fry. Descriptions of formulations of artificial diets are given in the book "Fish Nutrition" (see Halver (1972) in "Selected References").

Salmon are very susceptible to nutritional deficiency. Most nutritional diseases have been overcome by including vitamin supplements in diets and by ensuring that the sources of energy in diets consist of 50% or more protein, largely animal protein. At least 14 vitamins are known to be essential for growth and development of salmon. Also, salmon are unable to synthesize nine essential amino acids, which must occur in their diet. The total protein requirement of salmon is two to three times higher than for most farm animals.

The high cost of animal protein in diets has encouraged the inclusion of larger amounts of fats as sources of energy for catabolism. Moderately soft fats can be digested by salmon but hard fats cannot. Care must be taken to ensure that fats do not contain toxins which can induce tumors in the liver or other organs. Oxidization of lipid components of fish foods while in storage can cause serious nutritional problems and in some cases can make food toxic to salmon. Nutritional requirements of salmon for fatty acids are not well understood, but it is suspected that certain fatty acids are essential for the formation of fertile eggs. There is also evidence that linolenic-type fatty acids are essential for normal growth and development, but much work remains to be done to clarify the role of fatty acids in salmon nutrition.

Diseases

It is better to avoid the problems than to have to treat fish for diseases. Certain precautions should be taken to minimize disease:

Stock enclosures with healthy fry.

Maintain an adequate flow of water of suitable temperature, high levels of dissolved oxygen, and low levels of metabolic wastes.

Avoid overcrowding.

Minimize handling.

Provide a balanced healthful diet on a frequent feeding schedule.

Maintain high standards of sanitation.

Egg incubators and various types of enclosures where fish are raised should be thoroughly cleaned and disinfected with a quarternary ammonium compound (Hyamine 1622,

might be carried externally. Many states require certification that eggs and juvenile fish are disease free before they can be transplanted. The certification usually applies to certain virus and sporozoan diseases especially difficult to control and not to common bacterial and parasitic infections.

Release of Juveniles

It is generally advisable to release juvenile salmon from hatcheries and feedlots at the same time that wild fry migrate from streams and lakes. Deviations from this practice have sometimes produced satisfactory results, but not always. For example, feeding of chum salmon for about 6 weeks in Japanese hatcheries produced increased marine survival, but a longer period of feeding did not. The use of heated water to accelerate the freshwater growth of coho and chinook salmon so that juveniles can migrate to sea in their first spring has produced some encouraging results, but this work is experimental.

The following times of release of juvenile salmon from hatcheries and feedlots appear to be appropriate for the Pacific Northwest and Alaska:

Species	Pacific Northwest	Alaska
Pink	March, April, May	April, May, June
Chum	March, April, May	April, May, June
Coho	April, May	May, June
Chinook	April, May, June	May, June, July
Sockeye	April, May	May, June

Juvenile salmon should emigrate from hatcheries and feedlots at night to encourage dispersion and to minimize the possibility of attracting predators to the outlet from the hatchery or feedlot. At time of release, juvenile salmon will generally be in the following size ranges: pink, 1,500 to 1,800 per pound; chum, 500 to 1,500 per pound; sockeye, 30 to 100 per pound; chinook, 20 to 100 per pound; and coho, 15 to 30 per pound.

GENETIC PROBLEMS

Man is just beginning to appreciate the significant role of genetics in determining the survival of a population of salmon. When salmon are bred artificially, certain potentially unfavorable genetic responses must be recognized and avoided if possible. There are also potentially favorable genetic responses which can work to the advantage of the salmon rancher.

Precise homing of salmon spawners to ancestral spawning grounds is necessary to ensure that each spawning population adapts genetically to particular environmental experiences. Some stocks spawn in early summer and others in late autumn. Some migrate long distances from the ocean and others short distances. Some spawn in swift streams and others in quiet lakes. These are but a few examples of adaptation through genetic selection.

When salmon are removed from their natural environment, spawned artificially, and raised in the controlled environment of the hatchery, they become exposed to new sets of environmental experiences. The hatchery environment minimizes many of the stresses which greatly reduce egg-to-fry survival in nature, but the hatchery can impose other stresses (e.g., crowding, premature exposure to light, smooth substrate, and disease)which are not experienced by wild fish to the same degree. Thus, hatchery stocks must adapt to new environmental experiences if they are to survive, and the processes of genetic selection must proceed fairly rapidly to permit adaptation to the hatchery environment.

Inbreeding and Assortative Mating

Inbreeding occurs when mates selected from a population of hatchery brood fish are more closely related than they would be if they had been chosen at random from the population. The extent to which a particular fish has been inbred is determined by the proportion of genes that its parents had in common. Inbreeding leads to increased incidence of phenotypes (i.e. visible characters) which are recessive and seldom occur in wild stocks. An albino salmon is one example of a fish with a recessive phenotype. Such fish are typically less fit to survive than fish which do not have recessive phenotypes. This explains why animals with recessive phenotypes tend to occur infrequently in populations where mating is random.

Assortative mating, which occurs when fish are selected for mating on the basis of their similar appearance, implies that mates have similar phenotypes without necessarily sharing a common ancestry. As a practical matter, when animals have a similar appearance the chances of their having a similar genotype also increases. Assortative mating will, therefore, increase the incidence of recessive phenotypes but not as rapidly or to the same extent as inbreeding.

To reduce the risk of trending toward a high incidence of recessive phenotypes in hatchery stocks, assortative mating is not recommended for hatcheries involved in ocean ranching. Until our knowledge of fish genetics becomes more complete, random mating appears to be the safest practice from a genetic standpoint.

Random Mating

By random mating, the matings occur without consideration of definable characteristics (size, age, color, shape, etc.) of the brood fish. Hence, the probability of choosing particular genotypes for mates is equal to the relative frequency of particular genotypes in the population, and risk of genetic drift toward recessive phenotypes is minimized.

Because there is a strong human tendency to base a selection of brood fish on their appearance, assortative mating is difficult to avoid without devising some scheme which avoids personal judgment. One method of selecting brood fish for random mating is to place unfertilized eggs from individual females in separate but identical unmarked containers (Figure 36). Unspawned males should be chosen at random and separated from the rest of the unspawned males. The sperm from two or more males is then used to fertilize the eggs from one female. Another method, which ensures even better randomization of matings, is to select several females (say five) and several males. Unfertilized eggs from the five females are first mixed together and then divided into five aliquots in separate containers. Two or more males are used to fertilize each aliquot. This procedure simulates fertilization of eggs in nature, where females deposit their eggs in clusters of several hundred eggs each in separate pits. Males typically leave a female as soon as a cluster of eggs is fertilized and search for another female who is about to spawn. This polygamous behavior ensures the maintenance of genetic variability in a stock of salmon, and any hatchery mating procedure which simulates polygamous spawning behavior is to be recommended at this time.

The number of males used in any mating program can under most circumstances be less than the number of females. A conservative recommendation would be for the number of randomly selected males held as brood stock to represent about 20% of the total number of males and females held as brood stock. Where very large numbers of brood

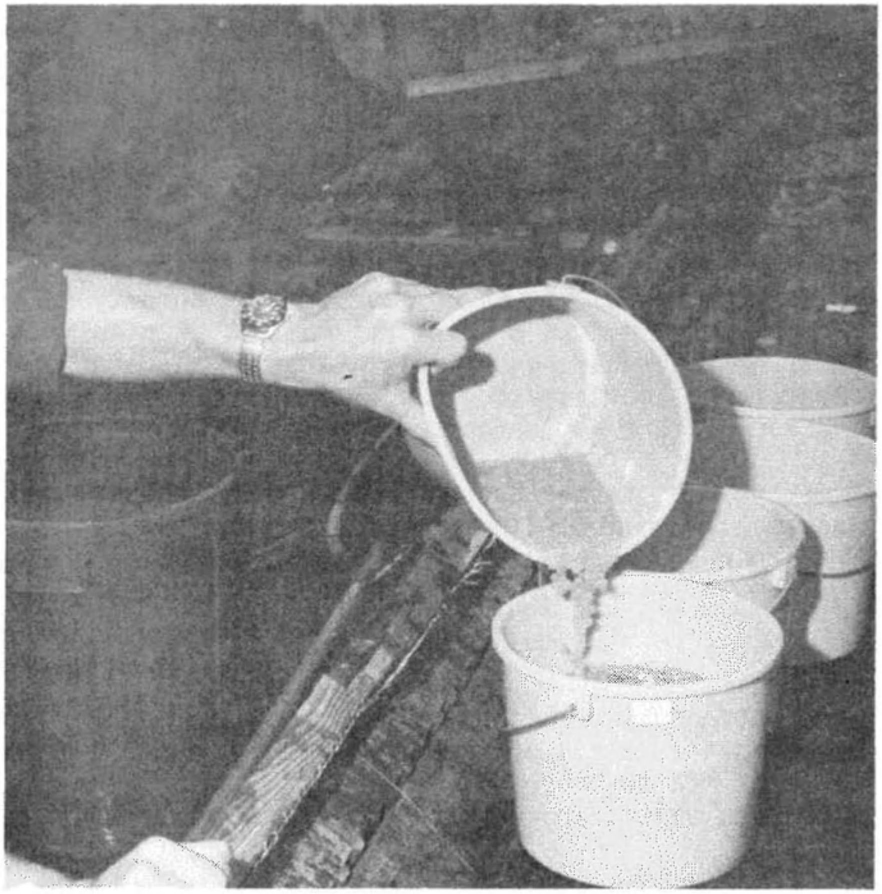

Figure 36.--One method of avoiding assortative mating is to place eggs from individual females in separate unmarked containers and to use a different male to fertilize eggs in each container.

fish are involved, say more than 1,000, the percentage of males might be reduced to about 10%. Each male would be spawned on at least four separate occasions and would be mated with four to nine females. Unless the hatchery stock consists of small numbers of fish, this procedure of using relatively few males picked at random should avoid inbreeding and afford two significant advantages to the salmon rancher:

More surplus fish (males) become available for harvesting.

There is a reduced requirement for facilities to hold brood fish.

Fertilized eggs from all portions of a run should under most circumstances be represented in the hatchery. It is not a good practice to fill the hatchery with eggs from one portion of a run. Rather, eggs should be placed in the hatchery in proportion to the percentage of the total run comprising early, middle, and late portions.

We recommend transplantation only in cases where there is a chronic shortage of brood fish in the hatchery stream. The presence of a small natural run in the hatchery stream will provide an opportunity to hybridize eggs transplanted from a donor stream with sperm from males from the recipient (hatchery) stream. We recommend that this be done to provide a contribution of genetic material from the hatchery stream to the gene pool of the newly created hatchery stock. There is evidence from preliminary studies that hybridization will increase the chances of a transplanted hatchery run to become established.

Natural Selection

Every hatchery and wild stock undergoes a continuous process of selection with or without random mating. Selection occurs when a particular genotype produces a different number of mature progeny than another genotype. Differences in mating, fertility, and survival lead to selection.

Selection is the genetic response to differences in total fitness for survival among individual fish in a population. Usually fish with traits intermediate between extremes of any attribute found in the population have the highest overall fitness. For example, in a population of chum salmon comprising predominantly 4-year-old fish (3- and 5-year-old fish are common and 2- and 6-year-old fish are rare) selection will strongly favor the 4-year-old age group. The same tendency will hold for any definable trait which is in part genetically determined. Selection should lead to continued improved fitness in any new hatchery stock until the stock becomes adapted to the new environmental experiences imposed by the hatchery.

Selective Breeding

Selective breeding is artificial selection as opposed to natural selection. It involves assortative mating with a resulting loss of genetic variability in the population. There are risks from selective breeding associated with loss of adaptive flexibility in the population because of decreased genetic variability. There are also potential benefits, and genetic selection for particular traits is widely practiced in animal and plant breeding to improve stocks. However, selective breeding of salmon for ocean ranching should probably be limited to experimental hatcheries. Such hatcheries should be operated under the direction of qualified geneticists until we gain more knowledge about the role of genetic variability in fitness of stocks.

Maintaining Genetic Variability

Variability in the genetic makeup of a population of salmon is favored by mutation, natural selection favoring heterozygotes, heterogeneous environment, and straying. Because the hatchery environment tends to be uniform, natural selection favoring heterozygotes and heterogeneous environment might be expected to play a diminished role in maintenance of genetic variability. The salmon rancher can help to maintain a variable gene pool in his hatchery stock by practicing random mating, but this in itself may not prevent unfavorable genetic drift toward fish with recessive phenotypes. The judicious introduction of gametes from another stock is one means to maintain genetic variability. Scientific studies have not been undertaken on the genetic consequences of introducing outside stocks. Therefore, an outside stock needs to be chosen with care to ensure that it is as well adapted to a similar spectrum of environmental experiences as the hatchery stock in question, or deleterious gene recombinations may reduce the fitness of the hatchery stock and homing behavior. Furthermore, any introductions should probably be done on a modest scale, say no more than 10% of the total brood stock if possible.

The problem of maintaining normal genetic variability of wild stocks inhabiting a stream where a hatchery is sited merits consideration. Straying of a hatchery stock and the resulting intermingling of hatchery and wild fish on spawning grounds could endanger wild stocks. This is because uncontrolled mating of hatchery and wild fish can dilute the wild gene pool with a hatchery gene pool. The resulting hybrid progeny could have a reduced fitness for survival in the natural environment, thus contributing to decreased productivity of natural spawning and nursery areas.

Care should be exercised in the selection of sites for hatcheries to minimize the dilution of wild gene pools with hatchery gene pools. Preference should be given to hatchery sites which provide limited opportunity for wild and hatchery fish to intermingle on natural spawning grounds. Perhaps certain watersheds should be zoned for hatcheries and others for maintenance of wild stocks.

Hybridization between Species

Even though interspecific salmon hybrids occur infrequently in nature, pink, chum, chinook, and sockeye salmon can be hybridized through artificial spawning. Coho do not hybridize successfully with other Pacific salmon.

Hybrids tend to be intermediate in appearance between the parental species. There may be some advantage in growing hybrid salmon in feedlots for market, but the hybrids should not be released for ocean ranching because of the risk of genetic "contamination" of wild stocks from hybrids straying onto natural spawning grounds.

ECONOMIC PERSPECTIVE

A paucity of good economic data makes it difficult for investment planners to predict the profitability of salmon ranching. Demonstration hatcheries began to phase into production on the Pacific Coast of North America in the early 1970's and the outlook for profitability is likely to remain mostly a matter for speculation until the late 1970's or early 1980's.

Pink and chum salmon are especially attractive for ocean ranching because the fry can be released into marine waters as soon as they are ready to emerge from the incubators. Juvenile sockeye, coho, and chinook salmon, however, must be raised in fresh water (or water of low salinity) for a few months at least before the juveniles can be released into marine waters. Feedlots will be required for these species except where natural freshwater lakes, ponds, or streams can be stocked with unfed fry. Figure 37 illustrates processes for ocean ranching of Pacific salmon.

Revenues will be determined by the (1) amount of seed stock available to start production, (2) rate of return of hatchery fish for proprietary harvest, and (3) value of hatchery fish harvested in a proprietary fishery. Usually, only modest numbers of eggs can be made available by state fishery agencies to stock private hatcheries, and most salmon ranchers will require at least two cycles of production to realize their maximum returns of adults from the ocean. Thus, at least 4 years are required to generate significant income with pink salmon and 6 to 10 years with other species. For example, a pink salmon incubation system designed for 50 million eggs might be stocked with 5 million eggs in each of the first 2 years. Such a system would require 6 years to achieve full production if the following assumptions held true: (1) egg-to-fry survival is 80%; (2) fry-to-adult survival is 1% (after natural plus fishing mortality); (3) sex ratio of adults is equal; and (4) average fecundity is 2,000 eggs per female. The expected number of pink salmon fry and adults that would return to such a hypothetical incubation system is as follows:

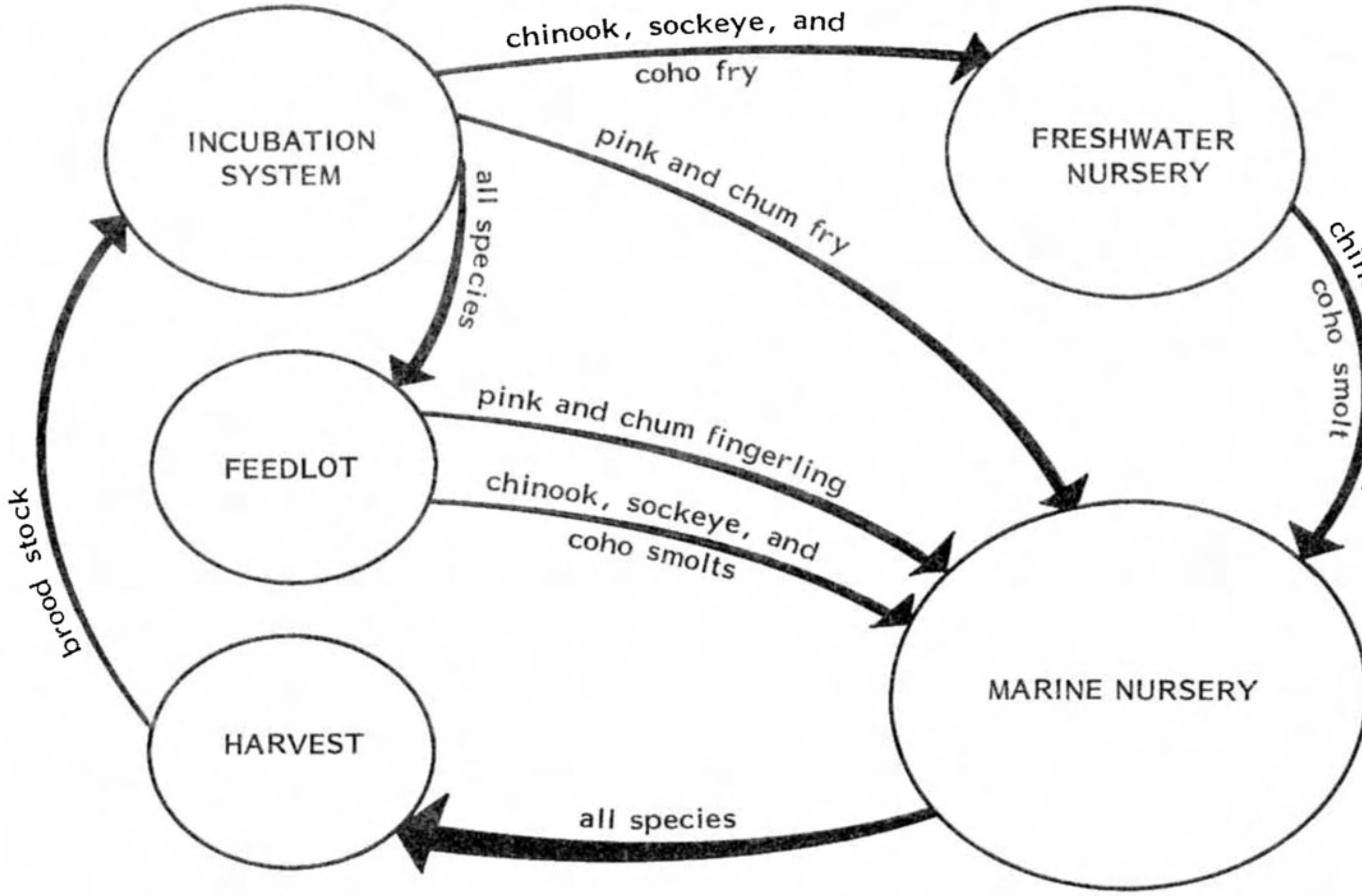

Figure 37.--Processes of ocean ranching of five species of Pacific salmon.

Year	Millions of fry (80% of eggs)	Thousands of adults (1% of fry)
0	0	0
1	4	0
2	4	40
3	32	40
4	32	320
5	40	320
6	40	400

Note that in the hypothetical system eggs are placed in incubators in year n; fry are produced in year n + 1; and adults return in year n + 2.

Costs of salmon ranching will be determined by numerous variables: (1) consultants' fees; (2) site acquisition; (3) site preparation; (4) construction of water delivery, incubation, feedlot, trapping, ripening, and spawning facilities; (5) purchase and/or manufacture and storage of fish food; (6) security; (7) waste water treatment; (8) warehousing; (9) processing; (10) transportation; (11) purchase of seed stock; (12) labor to operate facilities; (13) business and technical management; and (14) administrative overhead.

Because the variables that determine costs are numerous and complex, it is difficult to develop guidelines on expected costs which would apply in every situation. However, there are a number of steps to follow in establishing a salmon farming business:

Select the proposed site with the aid of professionals (biologist, hydrologist, and engineer).

Prepare a detailed and critical analysis of economic feasibility, including specifications on components and production goals by species.

Prepare a proposal for review by regulatory agencies for issuance of required permits and licenses.

Identify donor stock and make arrangements to acquire eggs.

Purchase or obtain leases to site of proposed salmon farm.

Prepare site for construction and installation of components.

Construct and test water delivery system.

Construct and test egg incubation system.

Construct and test enclosures for feedlot rearing system.

Construct essential support facilities (fish food storage, housing, warehousing, trapping, processing, etc.)

Acquire eggs for initial stocking of incubators (usually for 2 to 6 years, depending on species and other factors).

Costs attributable to the above steps are charged to "investment." Once the salmon farm begins to operate, there are recurring annual "variable" and "fixed" costs. Variable costs include salaries, fish food, maintenance, fuel, transportation, etc. Fixed costs include interest on investment, depreciation, insurance, etc.

Even though the principal incentive of a salmon rancher may be the production of salmon for proprietary harvest, the rancher is also likely to contribute substantial numbers of fish to common property commercial and recreational fisheries. Rates of exploitation in common property fisheries will vary by location, species, and year, as will mortality from natural factors. It becomes difficult, therefore, to project future production from a salmon ranch with a high degree of precision. It is believed, nevertheless, that a hypothetical example will help to clarify the economic outlook of salmon ranching.

For our hypothetical example, we will release unfed hatchery pink salmon fry to intermingle with wild fry. Egg-to-fry survival of our hatchery fish is assumed to be 80% as opposed to 10% for wild fish. Survival in the ocean from natural mortality factors is assumed to be 3% for hatchery and wild fish. Finally the common property fishery is to be regulated to allow replacement of wild spawners. With these stated assumptions, we can construct schedules of survival and production per pair of spawners for a hypothetical wild stock and a hatchery stock of pink salmon (see top of page 73).

For each pair of spawners, our hypothetical hatchery stock yields a surplus of 14 fish after satisfying requirements for two brood fish and contributing 32 fish to the common property fishery. The value of the 14 surplus fish plus any value in the two spawned carcasses will generate the revenue required to satisfy costs of investment and operation and for profit.

If we assume a value of $1.20 for each surplus pink salmon and 30 cents for each spawned carcass, one pair of brood fish will generate $17.40 of gross income. This is about $11 in revenue per 1,000 fry released.

Wild stock	Hatchery stock
2 spawners	2 spawners
2,000 eggs	2,000 eggs
200 fry	1,600 fry
6 adults	48 adults
4 adults for fishery	32 adults for fishery
2 spawners + 0 surplus	2 spawners + 14 surplus

Is this enough income to realize a fair profit? There are insufficient economic data to answer this question; but if current projections prove to be correct, costs in large production hatcheries (20 million or more fry annually) are likely to range between $5 and $10 per thousand fry.

If the owners of a hatchery also enjoy revenue from fish caught by the common property fishery, the economics of the hatchery stock assumes a much brighter outlook. In our hypothetical example, one thousand hatchery fry contributed 21 salmon to the common property fishery in addition to two spawners and nine surplus fish. The value of these 21 fish appearing in the catch would be 21 fish X $1.20/fish = $25.20 to fishermen. This added value to the catch could become a substantial inducement for salmon fishermen and processors to engage in ocean ranching of salmon, even if the hatchery required a modest subsidy.

LEGAL PERSPECTIVE

In 1900, Federal regulations required any person or corporation harvesting salmon in Alaska to establish a hatchery to produce sockeye salmon fry. Because this regulation was difficult to enforce, Congress provided a tax incentive in 1906 for voluntary operation of private hatcheries in conjunction with salmon canning in Alaska; and for several years canneries artificially propagated hundreds of millions of sockeye salmon fry for a tax advantage. Little attention was given to the environmental requirements of salmon, and substantial numbers of sockeye fry were dumped into streams flowing into saltwater estuaries where the fry had little or no chance to survive.

Early private hatcheries in Alaska and elsewhere on the Pacific Coast of North America failed, and most private hatcheries had disappeared from the scene by 1930. A body of state laws and agency regulations arose which effectively prohibited private hatcheries, and state and federal agencies emerged as the sole practitioners of salmon husbandry.

The coastwide prohibition against exclusive rights to salmon was broken in 1968, when California passed legislation to allow a private salmon hatchery to release juvenile salmon. In 1971, Oregon followed the example of California. The 1971 Oregon law limited private hatcheries to the propagation of chum salmon, but the 1973 Oregon Legislature liberalized this law to include coho and chinook salmon as well. The 1971 Washington legislature passed a law which allowed salmon farmers to grow pan-size salmon in feedlots.

The Alaska Constitution originally prohibited an exclusive right or special privilege of fishery in the natural waters of the State. This prohibition was removed from the Constitution in 1972 to allow the development of aquaculture in Alaska and the establishment of limited entry to fisheries. A private hatchery law was subsequently approved by the 1974 Alaska Legislature. The Alaska law requires that private salmon hatcheries be operated as nonprofit corporations. Income from surplus hatchery fish can be used for operating costs, including debt retirement and expansion of facilities. Any "profits" are to be expended on fishery research, salmon rehabilitation, or other fishery activities--all in cooperation with the State of Alaska. The Alaska law is designed to keep the profit incentive for private hatcheries with traditional harvesting and processing segments of the Alaska salmon industry.

Salmon from private hatcheries are public property while at sea and are harvested in common property recreational and commercial fisheries along with wild fish and fish from public hatcheries. Private hatcheries engaging in ocean ranching derive their income from the sale of adult salmon that escape the common property fisheries. The rates of exploitation by common property fisheries on hatchery fish can vary from near zero to 90%. The extent of variation depends on the species of salmon, the location of the hatchery, and the management policies for protection of intermingled wild fish against overexploitation. In Alaska the private hatchery law requires the State to manage common property fisheries to conserve wild stocks. Thus, a higher percentage of fish would return to a hatchery when wild stocks were weak and fishing was severely restricted than when wild stocks were strong and fishing was intensive.

Only California requires that salmon from private hatcheries be marked to ensure positive identification of fish returning to a hatchery stream. Oregon and Alaska are more flexible in permitting proprietary harvest of adult salmon returning to hatchery streams without positive determination of hatchery origin. The State of Oregon, for instance, has developed an agreement with at least one private hatchery to release a specified number of adults for natural spawning in a stream inhabited by both hatchery and wild fish.

Transplantation of eggs and juvenile salmon is rigidly controlled by state fishery agencies. Periodic examination of hatchery fish by a qualified pathologist is mandatory. Oregon and Alaska regulations require operators to reimburse the state for inspections of private hatcheries. Eggs for private hatcheries are typically purchased from state fishery agencies. In some instances state and federal agencies have provided contracts or grants to private salmon farms to grow salmon for experimental purposes or to release juveniles for common property recreational and commercial fisheries.

Numerous local, state, and federal regulations apply to salmon aquaculture. The number and kinds of permits and licenses vary, depending on location and type of salmon husbandry proposed. Nevertheless, each prospective salmon rancher must take into consideration the following items.

Zoning laws.--Some local and state governments are beginning to zone estuaries and other coastal waters for aquaculture. Zoning laws also apply to various support facilities which might be required for storage, processing, and transportation.

Leases for use of public waters.--Coastal tidelands and waters and freshwater streams and lakes are frequently publicly owned.

Water rights.-- Even though a salmon hatchery is a nonconsumptive user of water, a state water right may be required.

Salmon aquaculture permit.--This permit is issued by a state to authorize a salmon farm.

Aquaculture license.--An annual license may be required to operate a salmon farming business.

Fish handling license.--An annual license may be required to sell salmon.

Permit for seed stock.--Introduction of eggs into a hatchery usually requires a permit from the appropriate state fishery agency.

Health certificate for seed stock.--It may be necessary to have a pathologist certify that salmon eggs and juveniles are disease free before they are transplanted or released.

Permit for catching fish.--A permit may be required for locating and operating trapping or other facilities for harvesting salmon returning from the ocean.

Public access.--Depending on state laws and riparian rights, public access may have to be provided where public waters are leased for aquaculture.

Obstructions to navigation.--Structures placed in or on navigable waters may require permits from the U.S. Corps of Engineers and/or the U.S. Coast Guard.

Food and drug regulations.--The treatment of fish with chemicals added to the water or to the feed may be subject to state and federal regulations.

Sanitation certificate.--Where fish are harvested and/or processed, local or state sanitation certificates of inspection may be required.

Permit for waste discharge.--The Federal Water Pollution Control Act Amendments of 1972 require that certain aquaculture facilities obtain a National Pollution Discharge Elimination System Permit. Facilities which produce less than 20,000 pounds of aquatic animals per year are exempt from this requirement. Certain ocean ranching systems, especially those raising pink and chum salmon fry, may qualify for an exemption because of the relatively small poundage of fry produced even though the numbers may be large. A statement of exemption should be filed with the appropriate state pollution control agency.

Performance bond.--A bond may be required to ensure restitution of damages to publicly owned fish runs by private hatchery operations.

Environmental impact statement.--Construction and operation of hatcheries on public lands may require an environmental impact statement. Statements are more likely to be a requirement in Alaska than elsewhere because of substantial land ownership by the Federal Government.

At least 4 months and sometimes a year or longer should be allowed for acquisition of necessary permits, licenses, certificates, and bonds. State fishery agencies and university extension services should be consulted to obtain advice on how best to proceed with administrative approval for a salmon ranching enterprise. State guidelines on policies and procedures for operating salmon aquaculture facilities can be obtained by writing to California Department of Fish and Game, Oregon Fish Commission, Washington Department of Fisheries, or Alaska Department of Fish and Game.

SOURCES OF INFORMATION

The literature on ecology, management, and artificial propagation of salmon is extensive. Approximately 400 published reports plus numerous additional sources of unpublished information were reviewed for the preparation of this manual. Several selected references are listed on pages that follow to introduce the reader to the literature.

To obtain current information on technical developments in salmon ranching, one should contact local university marine advisory or extension services; the nearest Sea Grant College; and the Regional Office of the National Marine Fisheries Service. Private consultant biologists, hydrologists, and engineers are developing expertise in salmon ranching and offer their services for a fee.

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GLOSSARY

Alevin - larval salmon from the time of hatching to absorption of the yolk.

Aliquot - an equal part.

Amino acid - principal constituent of protein.

Ammonia gas - common metabolic byproduct which occurs as a gas, NH_3.

Ammonia nitrogen - used here to mean ammonia gas (NH_3), ammonia (NH_4), or ammonia hydroxide (NH_4OH).

Anabolism - constructive metabolic processes in living organisms: tissue building and growth.

Aquaculture - culture or husbandry of aquatic organisms.

Assortative mating - sexual reproduction in which the pairing of male and female is not random but involves a tendency for males of a particular type to breed with females of a particular type.

Atmospheric oxygen - molecular oxygen (O_2) which occurs in the atmosphere.

Bed load - soil, rocks, and other debris rolled along the bottom of a stream by moving water.

Blastomere - cell formed during primary division of an egg.

Blastopore - channel leading into a cavity in the egg where fertilization takes place and early cell division begins.

Brood fish - adult fish retained for spawning.

Caloric content - heat or energy content of a substance.

Carbohydrate - sugars and related compounds.

Carcinogenic - cancer causing.

Catabolism - the destructive metabolic processes in living organisms, opposite of anabolism.

Chorion - outer shell of the egg.

Cm/hr - centimeters per hour (1 cm = 2.54 in).

Conditioned response - behavior which is the result of experience or training.

Cryogenic - of or pertaining to cold, very cold.

Donor stock - brood fish contributing gametes (sperm and/or ova) for transplantation.

Egg - the matured female germ cell, ovum.

Embolism - blockage of a (blood) vessel.

Embryo - organism in early stages of development, especially before hatching from the egg when it is dependent upon its own yolk supply for nutrition.

Embryogenesis - process by which an embryo is formed.

Enzyme - catalyst produced by living organisms and acting on one or more specific substrates.

Estuary - water mass where fresh water and seawater mix.

Eyed egg - the stage where pigmentation of the eyes of the embryo becomes visible through the egg shell.

Fat - any mixture of fatty acids and glycerides stored in plants and animals.

Fat dystrophy - inadequate fat or imbalance of fats.

Fatty acid - acid present in lipids, varying in carbon content from C_2 to C_{34}.

Fecundity - egg content of a female spawner, fertility.

Fitness - relative ability of an organism to survive and transmit its genes to the next generation.

Free carbon dioxide - molecules of carbon dioxide commonly found in the atmosphere, CO_2.

Fry - juvenile salmon at the time of yolk absorption and the initiation of active feeding.

Gametes - sexual cells which conjugate and form a fertilized ovum.

Gene - hereditary unit that occupies a fixed chromosomal locus, which through transcription has a specific effect upon phenotype, and which can mutate to various forms.

Gene pool - the total genetic information possessed by the reproductive members of a population of sexually reproducing organisms.

Genotype - the genetic constitution of an organism, as distinguished from its physical appearance or phenotype.

Germinal disc - the disclike area of an egg yolk on which segmentation first appears.

Gill arch - part of visceral skeleton in region of gills.

Glycogen - animal starch, a carbohydrate storage product of plants and animals.

Gpm - gallons per minute.

Heterozygosity - condition of having one or more pairs of dissimilar genes.

Heterozygote - organism that has alternative forms of a gene and therefore does not breed true.

Homing - behavior which leads mature salmon to return to their stream or lake of origin for spawning.

Hybrid - progeny resulting from a cross between parents that are genetically unlike.

Hydraulic gradient - the slope of the water surface under condition of uniform flow, slope of the energy grade line.

Hydrogen sulfide - a gaseous product of organic decomposition, H_2S.

Imprinting - the imposition of a stable behavior pattern in a young animal by exposure, during a particular period in its development, to one of a restricted set of stimuli.

Inbreeding - breeding through a succession of parents belonging to the same stock or very nearly related.

Incubation period - period from fertilization of the egg until beginning of active feeding by fry.

Incubator - device for artificial rearing of salmon from fertilization of the egg to release or emigration of fry.

Instinct - inherited and adapted system of coordination within the nervous system, which when activated finds expression in behavior culminating in a fixed action pattern.

Interchange - exchange of water between water column overlying a substrate and water occupying interstitial spaces in the substrate.

Interspecific hybrid - progeny from cross breeding two stocks of different species.

Intragravel water - water occupying interstitial space within a gravel (spawning) bed.

Intraspecific hybrid - progeny from cross breeding two stocks of the same species.

Matrix - substrate occupied by eggs and/or alevins.

Metabolism - vital processes involved in the release of body energy, the building and repair of body tissue, and the excretion of waste materials; combination of anabolism and catabolism.

Mg - milligram, or 1/1,000 of a gram.

Mg per liter - one milligram of a substance dissolved in one liter of water or other solute.

Milt - sperm-bearing fluid.

Moribund - in a dying state, near death.

Mutation - process by which a gene undergoes a structural change.

Myxobacteria - slime bacteria, some of which cause serious fish diseases.

Necrotic - dead cells or tissue.

Nitrogenous wastes - metabolic byproducts or wastes containing nitrogen; examples are ammonia gas and urea.

Ocean ranching - type of aquaculture which involves the release of juvenile aquatic animals into marine waters to grow on natural foods to harvestable size.

Oxidation - to combine with oxygen.

Parts per million (ppm) - one part of a substance by weight contained in one million parts of a solution.

Pathogen - any disease-producing organism.

Perivitelline fluid - fluid lying between the yolk and outer shell (chorion) of an egg.

Perivitelline space - area between yolk and chorion of an egg where embryonic growth occurs.

Permeability - property or condition of a substrate that relates to passage of water through it.

pH - measure of acidity or alkalinity of a solution, or the concentration of H or OH ions ranging from 0 to 14; values above 7 are alkaline, below 7 are acid.

Phenotype - observable properties of an organism, produced by the genotype in conjunction with the environment.

Photoperiod - duration of daily exposure to light.

Pigmentation - disposition of coloring matter in an organ or tissue.

Polygamy - condition of having more than one mate.

Porosity - fraction of volume of a substrate not occupied by solid particles.

Protein - nitrogenous compound of cell protoplasm; a complex substance characteristic of living matter and consisting of aggregates of amino acids.

Recessive - character possessed by one parent which in a hybrid is masked by the corresponding alternative or dominant character derived from the other parent.

Redd - area of stream or lake bottom excavated by a female salmon during spawning.

Rugose - full of wrinkles.

Sediment - settleable solids which form deposits.

Selective breeding - selection of mates in a breeding program to produce offspring possessing certain defined characteristics.

Smolt - juvenile salmon at the time of physiological adaptation to life in the marine environment.

Solubility in water - capacity of water to contain a dissolved substance.

Spent - spawned out.

Sperm - male sex cell.

Sporozoan disease - group of infectious diseases caused by protozoa that form microscopic spores.

Stock - group of salmon that share a common environment and gene pool.

Stressing factor - any factor which adversely influences the capability of a fish to perform normal functions.

Superimposition - repeated digging of the same location by two or more females preparing redds.

Supersaturation - where concentration of a substance dissolved in water exceeds solubility at the prevailing temperature and normal atmospheric pressure; usually occurs when ambient pressure exceeds normal atmospheric pressure.

Suspended particles - solids retained in suspension in the water column.

Tender stage - period of early development during which the embryo is highly sensitive to shock, from a few hours after fertilization to the time pigmentation of the eyes becomes evident.

Toxin - poison derived from a plant or animal.

Ulcer - a superficial sore discharging puss.

Upwelling - water passing upward.

Vitamin - any of a group of constituents of food, of which small quantities are essential for normal nutrition.

Water hardening - process where an egg absorbs water which accumulates in the perivitelline space.

Yolk-sac malformation - misshapen yolk, often with scar tissue.

Zooplankton - animal plankton, small animals with weak locomotory power.

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