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Abstract.—Laboratory simulation of water temperature regimes that occur in subarctic rivers through winter necessitates the ability to maintain near-freezing conditions. A heat-exchanging apparatus is described that provided a convenient means of simulating the range of temperatures (0.5–12°C) that incubating eggs of salmon (*Oncorhynchus* spp.) typically experience in south-central Alaskan watersheds. The system was reliable, easily maintained precise temperatures at our coldest test levels, and was used over several years with few mechanical complications.

Temperature control is an important aspect of laboratory experimental design in fishery research. For example, investigators often wish to compare fish behavior and growth in thermal regimes that differ from those experienced by fish in nature. Thus, experimental temperature regimes must be established and precisely controlled if valid comparisons are to result. Efficient chilling of water is a special consideration for studies conducted in subarctic areas, where natural stream temperatures can approach near-freezing during winter.

Several chilling and heating systems have been designed (Colby and Brooke 1970; McCormick and Syrett 1970; Scott 1972; Zirges and Curtis 1975; Robinson et al. 1978; Jensen 1980), and devices to regulate and monitor water temperature have been described (Syrett and Dawson 1972;

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Chavin 1973; Wurtsbaugh and Davis 1976; Lemke and Dawson 1979). However, none of the reported methods met our requirements to simulate, with a precision of ±0.1°C, the August–April stream temperatures recorded by thermographs in a south-central Alaskan river. We needed to chill more than 8 L of 3.4°C well water to 0.5°C per minute to simulate the winter conditions and to elevate temperatures at other times of the year in accordance with thermograph readings. These criteria were required to compare the incubation rates of eggs and alevins of salmon (*Oncorhynchus* spp.) in natural stream temperatures with incubation in those river temperatures predicted to result from hydroelectric development.

We built a simple heat exchanger to accomplish our objectives. Well water was pumped into insulated 470-L circular tanks that were supported by tables about 1.2 m above the floor. The tanks served as water baths for temperature regulation (range, 0.5–12.0°C). About 2.1 L of water/min flowed from each bath into insulated Heath incubators (Figure 1). A small quantity of excess water (<0.2 L/min) drained from an overflow pipe in each water bath. Each incubator was modified to receive separate flows in each of the first (top) and fifth trays, and water drained from the fourth and eighth trays. This modification allowed us to incubate eggs of two species of salmon at a given temperature regime. Five-hundred-watt immersion heaters (model EPC-55, Evans Products, Seattle), installed through the sides of the water baths, were used at times of the year when incubation temperatures 3.5°C or higher were required. The heaters were controlled by an electronic relay (model K-2149-00, Cole-Parmer, Chicago) activated by a thermoregulator (model K-2149-71, Cole-Parmer) placed in the first and fifth tray of each incubator. A magnetic switch in the thermoregulator was set to the desired temperature and opened or closed depending on the temperature of water entering the incubator.

Because our incubation study included the winter months, water chilling was our primary concern. In the chilling mode, the electronic relay and thermoregulator controlled a heat-exchanger unit composed of three 746-W water chillers (model DI-100, Frigid Units, Toledo, Ohio) in a 364-L bath of 38% ethylene glycol connected to cooling coils. Solution temperature of the glycol bath was maintained between −10 and −5°C. Immersion pumps (21 W; model K-07142-02, Cole-Parmer) circulated chilled glycol through Tygon tubing (9 mm inside diameter [ID]) into a water bath where the tubing connected two 6.1-m polyurethane-coated copper tubes (8 mm ID). The tubes were bent into coils about 40 cm in diameter. Glycol was circulated through the cooling coils and returned from the water bath to the glycol bath through the Tygon tubing. The immersion pumps in each glycol bath were regulated by the electronic relay and thermoregulator. Two additional immersion pumps were affixed to the bottom of each water bath and operated continuously to circulate water past the cooling coils.

Four water baths were chilled by one heat-exchanger unit. All water baths contained two pairs of cooling coils, with one glycol-circulating pump per pair of coils. This quantity and configuration of copper tubing was sufficient to maintain an experimental temperature regime of 0.5°C during winter.

Water and glycol lines were insulated with foam rubber pipe wrapping (Rubitex). Incubators and the tops of the water and glycol baths were enclosed with 4-cm-thick closed-cell Styrofoam. All baths were insulated with urethane foam about 5 cm thick. Heat produced from the chiller motors was reduced by installing ventilators in laboratory windows. Room temperatures averaged 16°C during most of the study. Heat-exchanger efficiency would have increased if cooler room temperatures had been maintained.

Temperatures were monitored with platinum thermocouple probes (0.1°C resolution, ±0.3°C precision; model PR-11-2-100, Omega Engineering, Stamford, Connecticut) placed in each incubator. The probes used resistance temperature detection (RTD) sensors. Permanent records were kept with a temperature data logger (model DL-2020, Electronic Control Design, Milwaukie, Oregon), which could receive input from up to 10 probes. The data logger consisted of a scanning digital monitor (0.1°C resolution) and printer that provided an hourly temperature record of each input channel. This record was used to sum the accumulated temperature units for the incubation study.

The temperature monitoring system (data logger and thermocouple probes) was tested and calibrated as a unit by Omega Engineering before the study. During the study, a hand-held digital (RTD) thermometer (0.1°C resolution, ±0.3°C precision; model 450-APT) with a platinum probe (model 459) from Omega Engineering was used to verify the precision of our monitoring system. The thermometer was initially calibrated and certified (National Bureau of Standards) by the manufac-

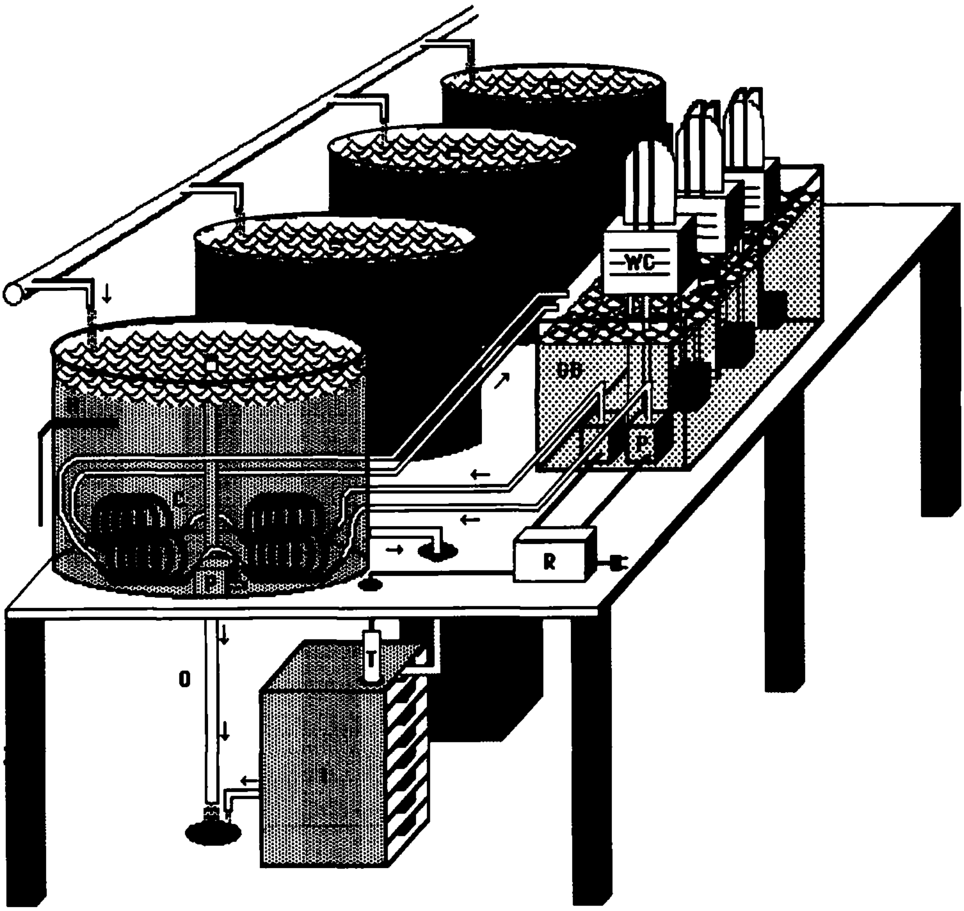

FIGURE 1.—Diagram of the temperature-regulating apparatus for simulating water temperature regimes in subarctic rivers (thermoregulator and water-flow input to tray 5 of the incubator are not shown). Symbols: C, cooling coils; GB, glycol bath; H, immersion heater; I, incubator; O, overflow pipe; P, pump; R, relay; T, thermoregulator; WC, water chillers.

turer. An additional level of quality control was implemented to insure against the possibility that the monitoring system and hand-held thermometer would fail or deviate simultaneously. The readouts of the thermometer and each thermocouple probe were verified against a known standard (ice bath).

The temperature control and monitoring system described here operated for several years with few mechanical or design complications. Icing of the cooling coils in the water baths when water temperatures were maintained at 0.5°C did not result in a loss of control of water-bath temperature. A postproject experiment (Figure 2) established the relationship between the length of coiled, polyurethane-coated copper tubing, the flow rate (L/min) of chilled water, and the resulting effect on water temperature. Increased efficiency in the heat-exchanger coils might be gained by experimenting with the power of the circulating pumps and the diameter of the heat-exchange coil material. Copper tubing was chosen as the coil material because of its high conductivity. It was coated with polyurethane to prevent copper ions from entering the water baths.

Certain risks and limitations accompanied the use of this apparatus. Circulating glycol through heat-exchanger coils poses the potential for toxic leaks into the water bath if tubing clamps are not secure. However, use of glycol was necessary because the Frigid Unit water chillers could not operate at temperatures below 1.0°C without ice for-

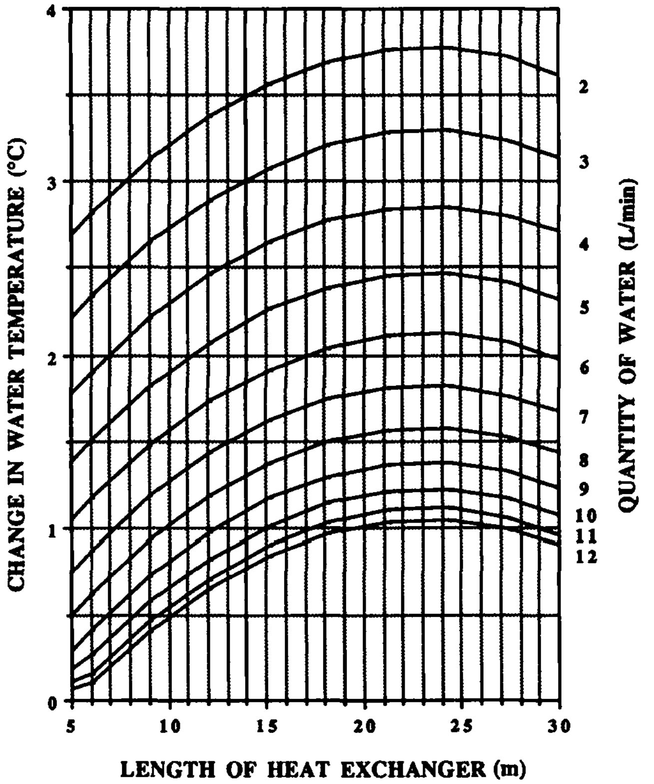

FIGURE 2.—Quantity of polyurethane-coated copper tubing (8 mm inside diameter) required to chill 10°C water a desired amount at a specific flow rate. Ethylene glycol was circulated at 1 L/min through the tubing and room temperature averaged 17°C during the tests that generated these data.

mation impeding the unit's water pump. The 746-W chiller lost most of its chilling capacity as ice formation continued. Another limitation of the water chiller was that it was not feasible to refine the precision of its thermostat beyond ±2.5°C to regulate a shorter on–off cycle. Frequent cycles (required for ±0.1°C temperature regulation) would shorten the working life of a 746-W compressor (D. McCloughan, Frigid Units, personal communication). In contrast, the 21-W immersion pumps were regulated by electronic relays and thermoregulators to ±0.1°C, and operated without breakdown throughout the incubation study. This system proved to be reliable. It provided precise temperature control in two incubation studies, and it allowed us to simulate and maintain the water temperatures that typically occur in subarctic rivers during winter.

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