Several years ago we gave a very brief description of a thermostated water bath suitable for experimental work at temperatures below that of the ordinary room as well as above 20–25°C. It seems now desirable to provide a more detailed account of the construction of such units, including the results of experience since 1926. With attention to minor details of construction it is now possible to obtain, at temperatures down to 0°C., a precision of ± 0.001°C. Foote and Akerlof (1931) have described a somewhat similar unit, with best regulation to within 0.01°C.

The requirements to be met by efficient lower-temperature thermostats for our purposes are rather different from those necessitated by many ordinary problems in physical chemistry. It is required to maintain a temperature below that of the room for sometimes considerable intervals—several days or weeks; in other cases it may be necessary to alter the temperature to a new predetermined level, which will be held precisely, at intervals of an hour or so. Simplicity of construction is essential, with interchangeability of parts, when a number of installations are in use. The degree of precision attainable should be considerable. It is not infrequently supposed that since biological systems are intrinsically variable in their performance, quantitative measurements are significant only to a degree of exactness permitted by the statistical character of the intrinsic, organic variation. This conception is entirely erroneous. With utmost possible care directed to the reduction of variance due directly to external influences and to fluctuations in such influences, for example in the temperature, it becomes possible to investigate the intrinsic variance of performance as a property of a given biological system; this is done by considering the variance as a function of precisely adjustable magnitudes of independent
variables (Crozier, 1929). It is impossible to conduct analytical dis-
section of fluctuations in performance without the most rigidly attain-
able control of the extra-organic variables involved in a given ex-
periment.

Cooling Unit

For water baths of small volume, an immersible funnel-type cooling unit packed
with cracked ice has proved handy, efficient, and quite accurate (Stier, 1931).

Standard equipment, which may be used for short time or for long period operation,
is based upon the use of an SOs compressor, or of a compressor using some
analogous substance. The compressor used is usually of the piston type. 30-foot
coils of ½ inch copper tubing are fashioned for each thermostatic bath; these coils
are commonly 7-8 inches outside diameter, and the turns are spaced ½ inch apart
to permit good circulation of water. The expansion valve above water is attached
by a length of ½ inch copper tubing to the first turn, at the bottom of the coil.
(Rotary type compressors, factory-assembled and sealed, with the commercially
prepared coils permanently attached, have been used for certain installations; in
this case the shelves for making ice cubes are removed.) These units are used for
larger baths. The largest we have used with success contains 55 gallons.

When air incubators are to be used at temperatures below that of the room they
are most efficiently placed in cold rooms whose temperature is set about 5° below
the temperature wanted in the incubator. We have also used small commercial
electrical refrigerators, replacing the thermostat with our own thermoregulator and
relays. The cost is less than that of a laboratory incubator of similar size. The
precision of regulation is about ± 0.3°C., even without a circulating fan.

Fig. 1. Thermoregulator tube and carriage for suspension. One side of the U-
tube is closed by a stop-cock (5). It communicates with a suction tube (4), with a
cotton plug as air filter. The lead (4) makes contact through a sealed-in platinum
wire (6). The connecting wire (2) is held by a rubber cap (3). The other side of
the U-tube, bearing the capillary, is connected with the two other limbs by a solid
glass cross rod for support. The needle (18) for contact in the capillary is carried
on a fine screw (15) provided with a lock nut (16); the screw works in a brass
collar (17) which grips the upright tightly; it carries a binding post for the lead
wire (2).

The mercury-filled tube is carried in a brass stirrup (9) with a cross member (7);
the stirrup is of ½ inch angle-brass; where it makes contact with the glass, sponge
rubber buffers are inserted (8, 10). At its upper end the stirrup is borne by a
cross member to which the stirrup is bolted; the threaded ends of the bolt are
fitted with cotter pins. The cross member is supported by heavy rubber bands
(15) passing over rollers (12). There is a second cross piece (11) with a central
hole for attachment to a stand. In case of breaking one or both rubber bands,
through long use, a chain (14) prevents dropping of the thermoregulator to the
bottom of the tank.
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Heating Units

Three convenient methods are available for adding heat to the thermostatic tank: (1) current may be sent through the copper coils of the cooling unit (cf. e.g., Schmitt and Schmitt, 1932), employing a transformer; (2) show-case lamps, painted black, and ordinarily of 40 watts; (3) knife-type heaters, of 50 watts, for relay operation, or of 125 watts if used for higher temperatures.

Thermoregulator

When it is desired to change the temperature at frequent intervals, as often as once every hour, an open-end U-type thermoregulator is used, filled with redistilled mercury. The capacity of the standard regulator is 3.7 pounds of mercury. The capillary in which contact is made is 0.025 inch bore. A stop-cock at one end of the U, with a slight enlargement above it, permits easy changing of the volume of mercury in the regulator proper. A diagram of this regulator, which includes ideas derived from a number of sources, is given in Fig. 1. Chattering at the relays is largely eliminated by a special spring suspension supporting the regulator. This is quite important when the regulator is used to start a ½ h.p. motor in the compressor unit, since the starting load is heavy. Contact with the mercury is made by a No. 28 platinum wire sharpened to a point. Tungsten is also satisfactory, but the “sensitivity” of constantan seems to vary a good deal.

When it is desired to maintain constant temperatures for long periods, weeks or months, single tube thermoregulators filled at the top with inert gas and completely sealed are preferable. The difficulty of precisely setting these regulators prohibits rapid work with them.

Stirring Motor

A satisfactory stirring motor for use in a thermostatically controlled bath must have the following characteristics: (1) variable speed, adjusted by rheostat or step transformers; (2) no “radio interference;” (3) it should have grease-packed ball bearings, reducing servicing; (4) it should be silent in operation, since the observer’s head must frequently be close to it; (5) it must be capable of running continuously for at least a year; (6) low cost.

These specifications are effectively met by a condenser type motor of 1/20 to 1/15 h.p. Both end bells are ventilated, and Bakelite insulation is provided on the wiring in the motor. The shaft of the motor extends 2 inches beyond the motor housing. A brass coupling with lock screws unites the shaft to a bronze propeller 1½ inches in diameter. The propeller blades throw water downward, but the rotation can be reversed. The housing of the motor is arranged for vertical or horizontal mounting. The lower end bell has 3 lugs cast upon it, so that the motor may be hung from a wall bracket, or from the ceiling. Or the motor may be mounted upon a horizontal support resting on “live” rubber. A “C” clamp sup-
port may be attached to the side of the motor through bolt holes provided in the motor casing, and permits attachment to the side of the tank or to a table near the tank.

Motor-driven propellers do not always give the most effective stirring for some purposes. To produce a uniform top-to-bottom movement of the liquid in the bath, water may be drawn from the top by a centrifugal pump which returns the water to a horizontal brass pipe, on the floor of the tank, with apertures along its length. This method of agitation is desirable for long thermostat tanks, particularly if they carry a projecting shoulder at one side.

Relays

The weakest link in any system of thermostatic control of tanks is always to be found in the relays. We have persistently endeavored to keep the relay device as uncomplicated as possible. The general purpose and aim have been to reduce the operating current of the relay to the smallest possible, thus reducing oxidation at the mercury surface of the regulator. We have used many more complicated schemes than the one here to be outlined, including amplification devices (Beaver and Beaver, 1923; Roberts, 1925; and others), and Thyratron valves (cf. Schmitt and Schmitt, 1932).

We have used with good success secondary relays of the latch type (operating on 110 volts A.C.) actuated by a primary relay (operating on 1 ma. at 6 volts D.C.) in series with the thermoregulator. The oxidation at the mercury surface in the capillary of the thermoregulator is practically negligible with such a low operating current for the primary relay. Since the latch type of relay gives greater pressure at its contacts and is more positive and powerful in its action, "sticking" of the contacts (often a serious difficulty when a ½ h.p. motor is to be started with an 8 ampere starting load) is eliminated. Sticking of relay contacts can also be avoided by using gas-filled mercury switches, or vacuum contacts which are actuated by the armature of the relay. Under laboratory conditions where a large number of relays are employed we have found these glass-enclosed switches to be too fragile for general use.

A cheaper relay which is also serviceable is easily made from an ordinary 20 ohm telegraph relay, single pole, double throw type, operating on 6 volts. If used directly, very considerable arcing is apparent at the mercury surface in the capillary of the thermoregulator. This is entirely obviated by connecting an additional coil of 20 ohms resistance in series with the coil of the relay; when the thermoregulator circuit is made, the thermoregulator mercury short-circuits the additional coil. Large silver contacts, 1 inch in diameter, insulated from each other, replace the standard fixed contacts supplied by the manufacturer. The armature carries a solid, double-faced carbon contact. For dependability over long periods of time, it is advisable to use a secondary power relay of the double pole, single throw type operating on 110 volts A.C. for starting the motor of the compressor. This combination can be purchased for about five dollars.
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Control Cabinet

A sheet metal box with removable cover and hinged back has been developed as a standard control unit (see Fig. 2). It contains the relay mechanism, the rheostat controlling the speed of the stirring motor, and on the front face a 10 gang ordinary commercial receptacle set carrying permanent connections to the units in the control cabinet. One has then only to plug into the front panel with standard plugs, in order to secure the proper interconnections. In ordinary laboratory operation this is important as avoiding short circuits, as disconnected cords are always "dead." Switches controlling a.c. and d.c. lines which enter the control cabinet are provided with suitable pilot lamps and separate fuses, the latter precaution preventing raids upon wall panels.

Tanks

The thermostated tanks are made of sheet copper throughout. If this is not done, electrolytic corrosion results in connection with the copper coils of the cooling unit. All apparatus dipping into the tank must be of brass, or heavily copper-coated. The wall of the copper tank is double, an outer shell of sheet copper being provided, which is coated with Bakelite or clear lacquer to prevent tarnish. The 1/4 inch space between the tank and the outer shell is filled with thin sheets of cork, which give very effective insulation; the sheet form of the cork gives additional air spaces. The edge of the tank is of angle-iron, copper-covered, for attachment of clamps (see Fig. 2).

For purposes of observation plate glass windows (1/4 inch thick) are inserted at various positions on the sides, or in the bottom. Such windows may be made water-tight by one of a number of devices. The most effective consists in mounting the plate glass in a copper frame, using a mixture of white lead with the best grade of varnish; the copper frame is then soldered to the wall of the tank. Emptying tanks is facilitated by 1 inch cocks built into the bottom.

For use with Warburg manometers, and for certain other purposes, a shoulder may be provided on the long side of the thermostated tank; the floor of this projecting shoulder is made of plate glass (Fig. 3).

The Operation of the Thermostat to Obtain Precision ± 0.001°C.

The best thermoregulation is of course obtained with adjustment of the gas pressure in the compressor so as to give the shortest cycle of operation of the cooling unit. Morgulis and Beber (1927) used an SO2 compressor operated continuously in conjunction with heating lamps acting intermittently through a thermoregulator; the precision of regulation was only 0.1°C. We have used the same general method and have obtained a precision as great as ± 0.002°C. in the neighborhood of room temperature. The labor of adjustment
FIG. 2. A standardized thermostatic bath, showing mountings of tank, cooling unit, stirring motor, and thermoregulator, as well as control box.
FIG. 3. A standardized thermostatic tank with shoulder at one side, for use with manometer vessels. This particular unit is cooled by a commercial rotary type compressor with the customary coils permanently attached (see text).
of action of the compressor, and of the heating elements, is altogether too great, with this method, particularly when the temperature is to be newly adjusted at frequent intervals.

During one cycle of the cooling unit, with intermittent operation, the following changes are detectable: Immediately after the compressor starts to work, the temperature of the well-stirred bath rises. The rise may be as much as 0.006°C., and depends upon the setting of the expansion valve in the cooling coil and upon the length of the preceding cycles. During the activity of the compressor the temperature of the bath gradually falls. When the compressor is stopped by the interruption of the thermoregulator switch, the temperature of the bath continues to fall; the magnitude of the fall, and its duration, depend upon the setting of the expansion valve and the working time of the compressor; the excess fall in temperature may be as great as 0.008°C. Part of this fluctuation is due to lag in action of the thermoregulator. Attempt has been made (Fig. 1) to adjust suitably the relations of volume of mercury to surface exposed.

A short cycle of operation in the bath has been attained, with corresponding increase in precision, by three refinements. (1) The lag is reduced by placing the thermoregulator beside the cooling coil. (2) A 50 watt knife heater is located near the thermoregulator, and so connected that the heater is in operation when the cooler is stopped. The relay is of single pole, double throw type, making one circuit when the relay is energized, making the other circuit when the relay is not activated. (3) The setting of the expansion valve on the cooling coil is so adjusted by trial that there is a minimum of additional cooling after the compressor motor has been stopped by the action of the regulator.

Under these conditions a precision of ± 0.001°C. is obtainable in a tank holding 20 or 30 gallons of water, even when no cover is used. Tests are made with a Beckman thermometer tapped continuously.

We wish to record our obligation to Mr. E. A. Gibbs and Mr. A. B. Small, of the Engineering force of Harvard University, for their kind assistance in connection with the development of these installations.
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SUMMARY

Details are given concerning the construction and operation of relatively simple thermostats which permit maintaining precise temperatures down to 0°C. (with water), or temperatures above that of the ordinary room, and in which the temperature may be quickly altered at short intervals to new levels.

CITATIONS

Crozier, W. J., in Foundations of experimental psychology, Worcester, Clark University Press, 1929, Chap. II.
Stier, T. J. B., Science, 1931, 73, 288.