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THE MECHANICAL BATHYTHERMOGRAPH
AN HISTORICAL REVIEW

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ABSTRACT

Except for the mercury in glass stem thermometers, the bathythermograph (BT) has been the oceanographic instrument most often used to measure temperature in the ocean. Since its initial development in 1938 and including subsequent modifications, it has been used to acquire more than 1,300,000 continuous temperature-depth profiles in the upper layers of the sea. These data cover nearly every square mile of wide areas of the major oceans. The primary reason for rapid deployment of the BT and the voluminous acquisition of data was its use in antisubmarine warfare. The BT was designed to provide the depth of the near surface, generally mixed layer, and the underlying thermal gradients for a prediction of sonar range. A program was set up in World War II to train naval officers in the uses of the instrument and the data acquired. The data on glass slides were sent to Woods Hole Oceanographic Institution and the U.S. Navy Radio and Sound Laboratory for the preparation of sonar charts, which were printed by the U.S. Navy Hydrographic Office and issued to the fleet. These valuable data have been subsequently used in a variety of oceanographic studies. One conservative bibliography lists 700 reports concerned with BT data. Although other instruments such as the expendable BT, salinity-temperature-depth recorder (STD) and the thermistor chain are superseding the original mechanical BT, its use and the historical data that it has provided will still be with us for some time.

INTRODUCTION

The first version of the bathythermograph (BT) was invented by Dr. A. F. Spilhaus and reported in 1938.(1) In response to a wartime need for information useful to sonar, the instrument was improved and manufactured in quantity. Beginning with the prewar invention, a discussion is presented in this paper of the development and use of the BT: manufacture and testing; training program for observers; and collection, processing, and use of data. The paper also gives some highlights and accomplishments of what became one of the largest oceanographic surveys in history.

BACKGROUND

Previous Instruments

The term "mechanical bathythermograph," or "BT," is used to distinguish this instrument from the later electronic instrument known as the "expendable bathythermograph." Considering the extent of knowledge of temperature structure in the upper layers of the sea, measured by other instruments in use in 1937, BT development and use was a major breakthrough. At this time, the common way of measuring the temperature was to take a surface measurement with a mercury stem thermometer, and supplement it with spot measurements made with reversing thermometers attached to frames or water bottles. Measurements were made frequently at widely spaced depths of 10, 25, 50, etc. meters below the surface.

Particularly lacking was knowledge of the sharp temperature change occurring at the bottom of the so-called mixed layer, as well as the slight, gentle heating occurring at the very surface, above the isothermal layer. Even temperature inversions were questioned. With thermometers mounted several meters apart, it was only by coincidence that the predetermined depth coincided with the discontinuity layer.

Relation to Sonar

Sonar-range experiments conducted in the late 1930's by the Naval Research Laboratory at Piney Point(2) on the Potomac River did not agree with results from sonar equipment on Navy ships off Guantanamo Bay and San Diego. Among the difficulties at sea was the problem that the ranges were shorter in the afternoon than they were in the morning, a phenomenon which became known as "afternoon effect." This led to some interesting theories. The captain of the USS SEMMES, one of the experimental ships, thought that his sonar operators were dozing off because they had eaten too much lunch, and so for three months the poor boys suffered on salad lunches. Still the ranges were shorter in the afternoon than in the morning. It is now known that the afternoon effect was caused by a warming of the surface layers as the sun reached its zenith and advanced into the afternoon period.(3) The complicated distribution of temperature with depth, which actually exists, was simply not known in those early days and the BT was the instrument chosen to provide such information.

Work sponsored by NAVSHIPS SR 104 03 01.

The situation at Piney Point, where the ranges did not show a diurnal fluctuation in the afternoon, was caused by the sonar system and target operating in what is known as a sound channel. At sea, the downward refraction, the result of surface heating, caused the sound beam from the Navy ships to dive sharply and go beneath the target, except at very short range. Scientists and naval officers both at NRL on the East Coast and at Destroyer Division 19 on the West Coast had reasoned out what must be occurring. However, other oceanographic variables were also suspected of influencing sonar ranges.[4] LCDR (later RADM) Rawson Bennett, II, USN, played a critical role in identifying refraction as an important factor in World War II sonar operations.

As a result of the practical observations begun in 1930, based on weather and oceanographic phenomena in connection with sound transmission, a significant report by the Naval Research Laboratory[5] on "Transmission of Sound in Sea Water; Absorption and Reflection Coefficients and Temperature Gradients," was issued in 1935. The temperature gradients discussed in the report were sometimes indicated by thermometers hung outside the eyeport of a diving submarine.

Late in 1940, a committee of the National Academy of Sciences, chaired by Dr. E. H. Colpitts, investigated the Navy's antisubmarine effort.[6] One of their principal recommendations was for a study of oceanographic effects on submarine-detection equipment. A consequence of the committee's report was the awarding of one of the first Office of Scientific Research and Development (OSRD)

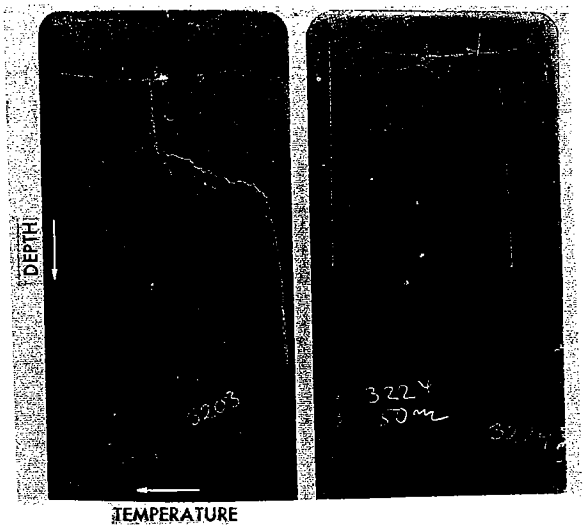
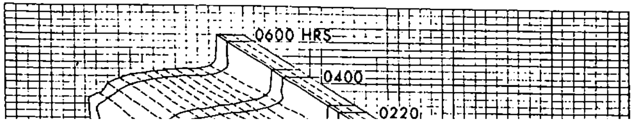


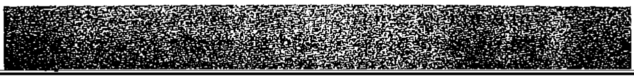
Figure 1. Oceanograph recording (after Rossby and Montgomery, 1934).

handled and evaluated record.[1] In accomplishing these aims, he developed a pressure element consisting of a sylphon bellows with an internal spring (similar to the capsule of an aneroid barometer). He mounted a small, smoked glass slide on the end of the bellows so that it moved vertically under the force of pressure. This feature has remained present BT instruments, and reference marks on the slide (such as required by the oceanograph were unnecessary. The ease with which comparison of data plots could be made is apparent in figure 4, an illustration from Spilhaus' first BT



Ewing, Vine, Worzel, and a gifted metal worker, Raymond Deysher, built the first 75 BT's in the Woods Hole Oceanographic Institution shops, incorporating the features of the modern instrument and handling equipment.[10]

for fast diving.



Two types of bathythermographs were initially manufactured: a deep range (0 to 450 ft.) and a shallow depth range (0 to 180 ft.). A deeper (0 to 900 ft.) depth range instrument was later added, requiring modification of the pressure element by use of a spring external to the sylphon bellows. The depth range is controlled by the size of the spring and sylphon bellows arrangement in the pressure element.(11) thru (16)

Temperature Element. The temperature element (figs. 9 and 10) consists of four parts: 45 to 50 feet of thin copper capillary tubing; a Bourdon tube; a case-compensating bimetallic coil carrying a stylus arm; and a pen lifter. The Bourdon tube is anchored to the body tube. Attached to the other end of the Bourdon tube, and free to move, is the bimetallic compensating coil carrying the stylus arm. The capillary tubing is fed into the Bourdon tube, and pressure of the xylene in the capillary is applied to the Bourdon tube. As water temperature warms the xylene in the capillary, internal pressure of the xylene increases, causing the Bourdon tube to unwind. This moves the stylus across the glass slide. The capillary tubing is wound on an hexagonal, tapered frame and extends beyond the body tube. The staggered winding insures maximum flow and contact with the water for maximum heat transfer.

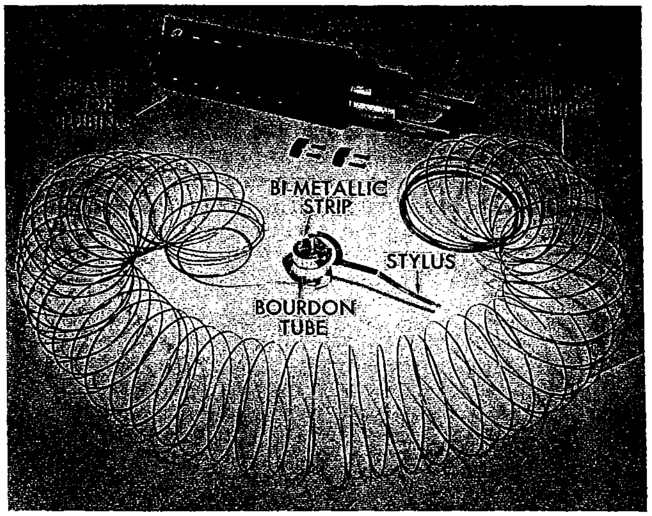


Figure 10. Thermal components.

The temperature range of the bathythermograph is from 30 to 90 °F. Temperature a few degrees below 30 °F will not harm the instrument, but temperature above 105 °F may result in a permanent set of the stylus or Bourdon tube.

The speed of response of the thermal unit should be such that when the temperature is varied from resistance to the longitudinal movement of the piston, caused by pressure on its outside face. With increasing water pressure (depth), the piston moves to compress the spring, and the slide holder moves longitudinally with the piston. A smoked glass slide carried in the holder thus moves longitudinally in response to pressure (depth) change, while the stylus swings crosswise in response to temperature change (fig. 12). The combined motion causes the stylus to scribe a continuous line on the smoked glass slide to give the well-known BT "trace."

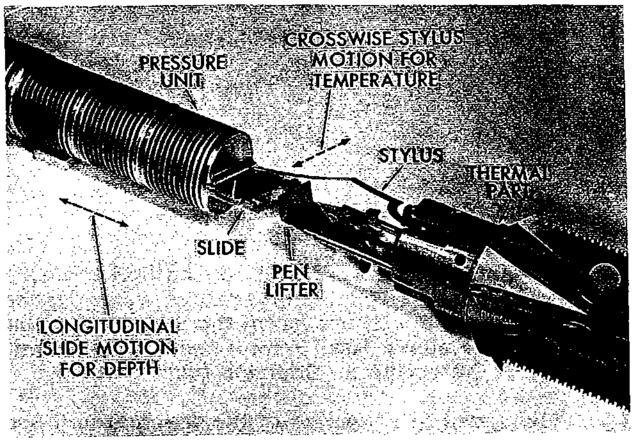


Figure 12. Pressure-temperature recording parts.

The calibrated steel spring is of such proportions that a pressure, corresponding to the maximum depth for which the BT is designed, will compress the bellows approximately 0.7 inch. The pressure unit is adjusted so that pressure hysteresis will not produce an indication of variance in excess of 2 percent of depth, that is; 2 feet per 100 ft. of depth.

Glass Slides. The glass slides are 1 x 1.75 inches and 0.033 inch thick, with one or two corners ground off for ease of insertion into the instrument and for orientation when placed on the grid (fig. 13). Failure to meet exact specifications sometimes gave trouble, especially when the thickness of the slide was not as specified and it would not fit into the holder. The slides were coated on [illegible] side with a carbon deposit, bound to the slide—by a thin coating of oil. The oil initially used was skunk oil, a name which caused amusing comment among the sailors.

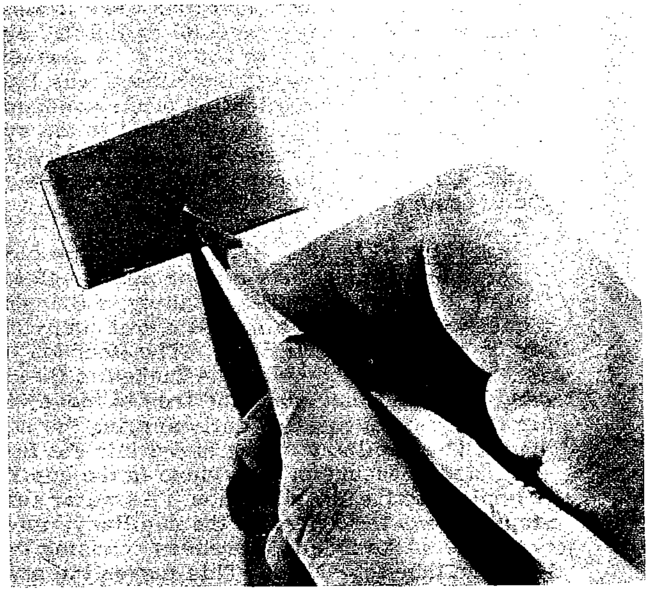


Figure 13. Glass slide.

An unexpected difficulty was encountered in obtaining a constant quality in the smoked slides. The Bristol Company developed a small automatic conveyor belt on which the oiled glass slides were carried over Bunsen-type gas burners for smoking. Opaqueness depended on composition of the oil and gas and the speed of advance of the chain. Temperature and humidity of the room were also critical factors. Although airconditioning helped in later manufacturing, continuous, full-time monitoring was necessary. After the war, "gold" coated slides, prepared by thinly sputtering a metallic mist onto the glass, were used by the Navy instead of the smoked slides. However, many scientists prefer the sharper trace afforded by the old friction-free surface of the oil-smoked slide.

Pen Lifter. In operation, the BT dives rapidly in free fall to maximum depth, then soars up near the surface when the winch brake is applied. As the cable is reeled in, the BT is hauled in near the surface, usually through the turbulent surface waves and wake of the ship. Turbulent water motion causes the BT to jitter and the stylus to flutter, obscuring the down trace and preventing an accurate reading of the record.

One successful means of reducing surface trace vibration is by use of a pen lifter (fig. 7). It is actuated by the pressure movement of the sylphon bellows and may or may not be used. It is so designed that when the BT comes back up to a certain depth below the surface where most of the vibration is occurring, the pen can be lifted as the BT is retrieved. The near-surface trace on the slide is thus not obscured.

Diving Devices. A heavy, detachable nose weight that allows deeper dives at high speeds, by permitting more rapid descent, is frequently attached to the BT (fig. 8). However, this sometimes causes the dive to be too fast for the stylus to follow the true temperature on the down trace, and a false gradient can result. Another device is a diving attachment placed well aft on the BT. The towing wire is led back from the swivel through the block and under a shear pin. Towing farther aft allows the BT to "plunge" more steeply. On retrieval, the pin shears at 60 pounds, shifting the towing point back to near the nose.

Care is thus required in interpreting the near-surface trace when the diving attachment causes the instrument to "plunge" at high ship speed.

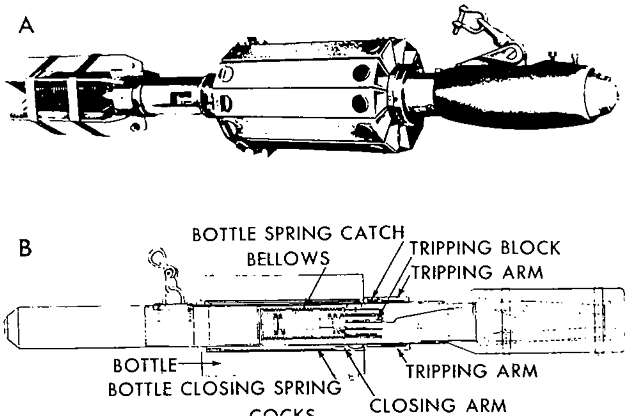
BT Accessories

BT Winch. The original Spilhaus bathythermograph was often attached to a hydrographic wire and lowered with a hydrographic winch. With the smaller device and thinner wire, a hand crank was

Sediment BT — Another BT modification was an

Sea Sampler. One limitation of the BT was that it measured only water temperature, and not related chemical properties. To improve its capabilities, Spilhaus added six small Nansen-type bottles and called it a sea sampler.(17) The sampling bottles surrounded a cylinder which contained a releasing block operated by a BT pressure element. This instrument was extensively used in 1940 with his original bathythermograph.

With the improved BT, Spilhaus and Miller(18) enhanced the sea sampler with 12 sampling bottles fitted closely around the body of the BT (fig. 19 A). Each bottle had its own tripping arm that was activated by the compression of the sylphon bellows and tripped at the appropriate position of the com-



were individually attached to the BT by a spring catch (fig. 19 C). Water samples could thus be collected at discrete, predetermined depth intervals, and at the same time a continuous temperature-depth BT trace could be obtained from a moving ship. It was also possible to collect a single sample of sea water by attaching a single water bottle called a "side saddle" to the BT. Increased tension on the towing wire at the maximum depth of lowering caused the towing pin to shear and activated valves to close the bottle (fig. 19 D).

A mouse trap type sediment sampler was attached to and used with the BT by A. R. Miller. Although

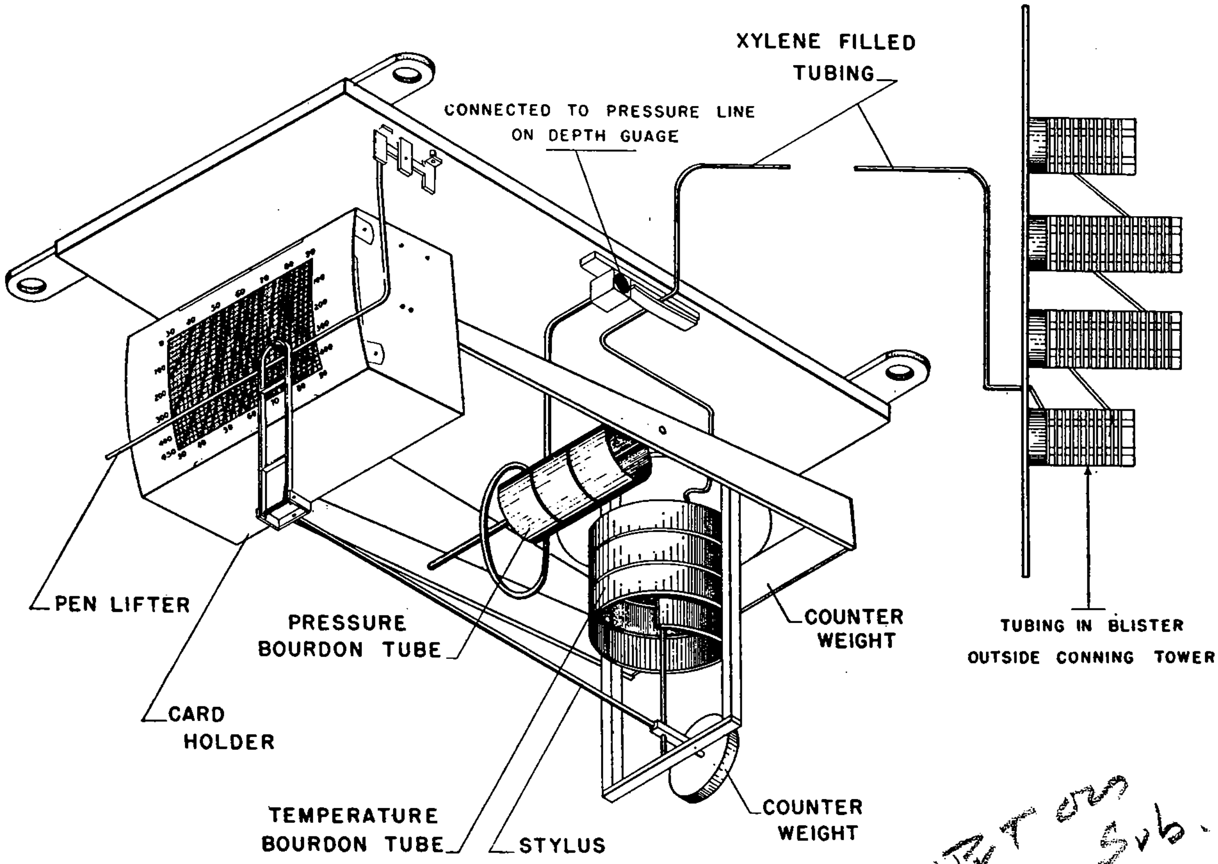


Figure 20. Diagram of submarine bathythermograph.

BT on Sub.
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management responsibility for the Bristol Company contract. Allyn C. Vine was consultant and liaison with Woods Hole. The Bureau of Ships drew up specifications, determined accuracy tolerances and let contracts for production in quantity. Submarine Signal Company assembled the first batch of commercial instruments, an order which paid patent requirements. The major quantity came from the Bristol Company, Waterbury, Connecticut, where they were in full production by 1942. Although common commercial practice in temperature devices called for only 3 percent of full scale in recording accuracy, the BT required precision to ± 0.1 °F at the surface and repeatability of about ± 2 feet in depth. Many original Bristol instruments came close to these specifications. Mass production and wartime changes in metal quality later required some leeway in tolerances. In fact, to produce the great numbers of bathythermographs required, accuracy tolerance below depths of approximately 380 feet had to be reduced. Thus, some of the deeper records are really spread over a greater depth than the slide would indicate.

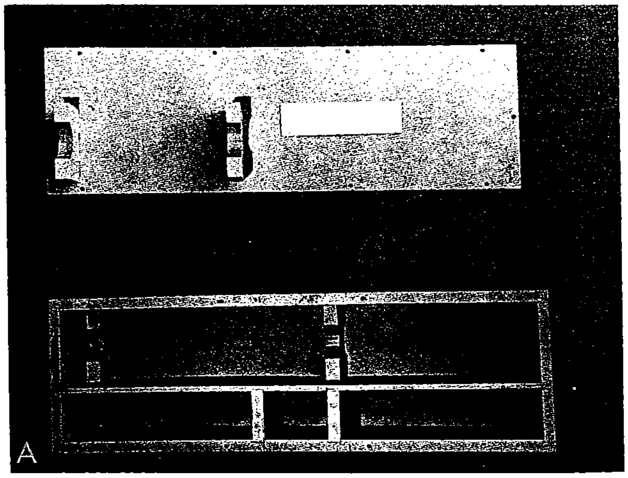
At the Navy Electronics Laboratory both old and new models of BT's were tested for reliability and evaluated for conformity to BUSHIPS' specifications.(19) thru (24) The Bureau of Ships also made a statistical check of production BT performance in 1952.(25)

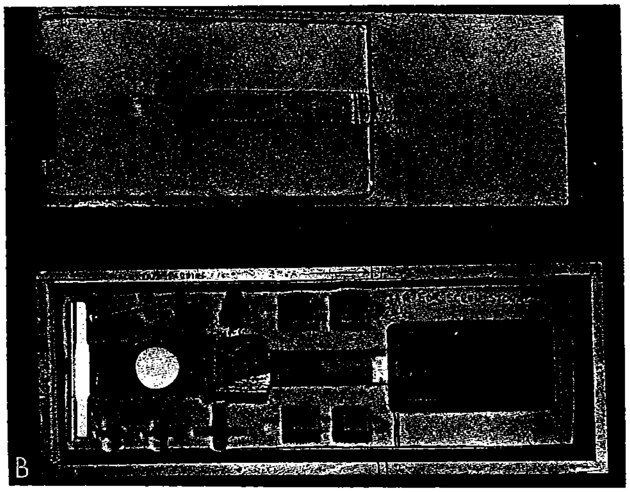
Wartime shipments were made in narrow wooden boxes (fig. 21 A). One BT with swivel and nosepiece, viewer grid, extra grid, and a number of smoked slides were in the box. Other small containers included a can of clear lacquer, lacquer thinner, tweezers, a small Fahrenheit stem thermometer, and an instruction book. Because rough handling caused some of the BT's to become out of adjustment, packing boxes were later made of metal, or lined with molded styrofoam, for maximum instrument protection (figs. 21, B, C).

CALIBRATION

Background

The standard or Navy bathythermograph was a tool for sonar. It was developed as an indicator of temperature gradients, that is, the relative changes in temperature with depth, versus the original concept of completely accurate and repeatable measurements of temperature variation. Relative gradient was needed by the sonar people; all other considerations were minimized. Actual characteristics of each Bourdon tube were so delicate and the elastic movement so individual, that a special grid had to be made to interpret the complicated



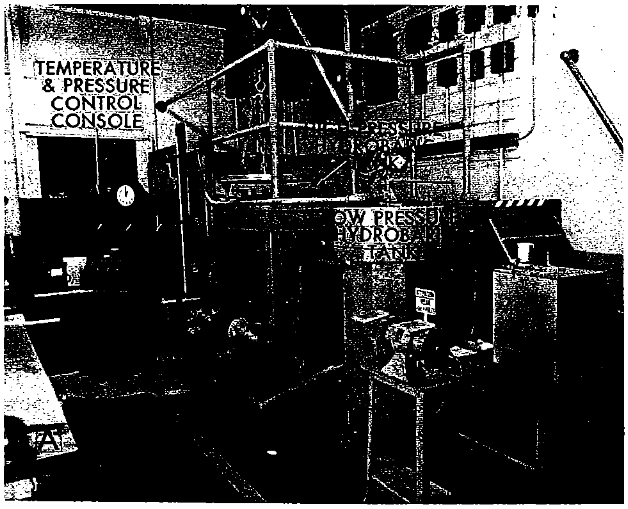


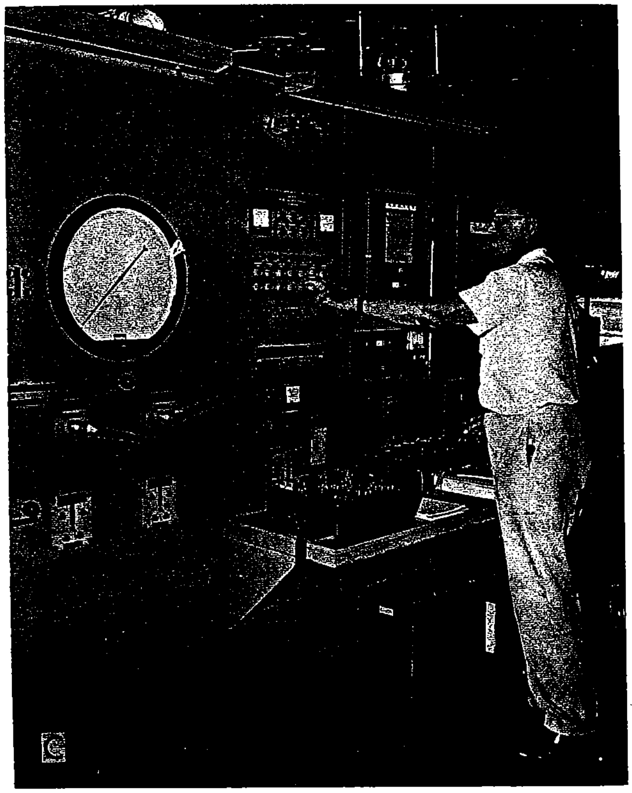
movement of the stylus. Calibration was an instrument-by-instrument process: one grid or one bathythermogram could not be superimposed over another. For comparison of traces made by separate BT's, each had to be plotted on a standard scale. Although an annoyance, this feature was accepted to keep the instrument "simple," while still obtaining essential sonar information. This concept of a useful tool versus a precise instrument was demonstrated by the fact that during early development grids were calibrated to 80 °F. To make the BT useful for sonar application in the 84 °F water off Florida, it was only necessary to use pliers to bend the stylus arm so the stylus still registered on the glass slide and did not run off scale. Of course, the resulting shift in scales prevented a measure of the true temperature, but the trace, nevertheless, was a useful indication of the temperature gradient - the relative temperature change with depth, the information needed for the military problem.

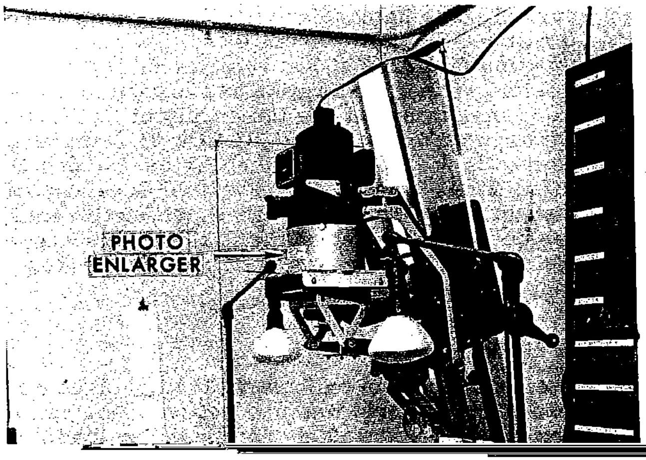
Two grids for each instrument were supplied by the manufacturer, but the instrument often incurred some damage and needed repair and recalibration. The Navy established three primary calibration facilities at San Francisco, Honolulu, and Boston. Other calibration and testing facilities were maintained at the University of California Division of War Research (UCDWR) (later known as the Navy Electronics Laboratory) in San Diego (figs. 22 A, B) and at Woods Hole Oceanographic Institution. More recently a calibration facility has been established at the National Oceanographic Instrumentation Center (NOIC) in Washington (fig. 22 C).

Procedure

The initial step in calibrating the BT or composing a new viewing grid was production of the calibration slide. This was accomplished by loading several BT's with blank slides and submerging them in a hydrostatic tank in which both the pressure and temperature could be accurately controlled (fig. 22 D). Temperature was regulated by


TEMPERATURE & PRESSURE CONTROL CONSOLE
HIGH PRESSURE HYDROBARIC TANK
LOW PRESSURE HYDROBARIC TANK

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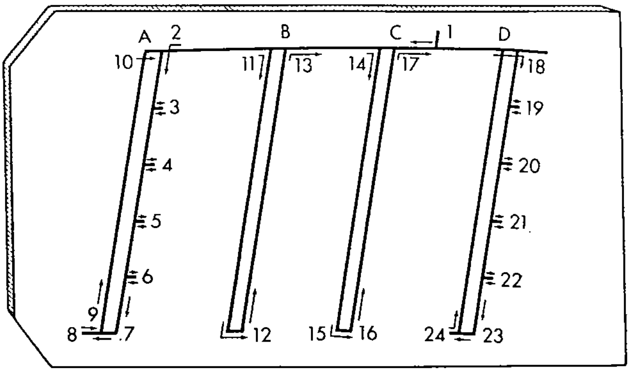

Figure 23. Schematic of BT calibration grid. Isothermal lines are labeled A - D, and pressure (depth) lines are 2 - 7 and 18 - 23.

Holding the temperature roughly constant, the pressure is increased to a chosen depth at (3). Holding the pressure constant, a short line is drawn by increasing the temperature. The tank is allowed to cool by the amount of the small increase; pressure is then increased to (4). The procedure is repeated to a chosen high pressure limit at (7) where the temperature is allowed to cool by approximately 2° to (8). Pressure is then carefully increased again to (9). At (9) the pressure is slowly and smoothly reduced to zero, drawing the first isoline at (A). The temperature is increased approximately 10° to (11); the pressure is increased to the previously chosen high pressure; and a little heat is applied to raise the temperature to (12). Pressure is then slowly and smoothly reduced, drawing isoline (B) from (12) to (13). The process continues as shown, with six depth marks made between (18) and (23), and the final isoline (D) being drawn from (24) to the surface.

Viewing Grid.

The viewing grid was made by adapting an adjustable temperature-depth grid to the calibration slide. The calibration slide was placed in a photo enlarger and projected on a white back mat, producing an enlarged image (fig. 22 B). Temperature graduations (vertical lines) were provided by means of an overlay device composed of adjustable, evenly spaced, parallel wires. This wire-strung pantograph looked somewhat like a harp. Spacing between the wires was adjusted until thermal lines on the calibration slide coincided with corresponding temperature graduations on the "harp" (fig. 24). Depth lines were provided by a series of back mats consisting of a selected set of curved (arc) lines with various curvatures and spacings, a card being chosen so the depth lines coincided with the depth steps on the calibration slide. Suitable depth and temperature scales were placed in position on the sides and top of the mat, and the BT identification and date of calibration were in the lower left-hand corner.

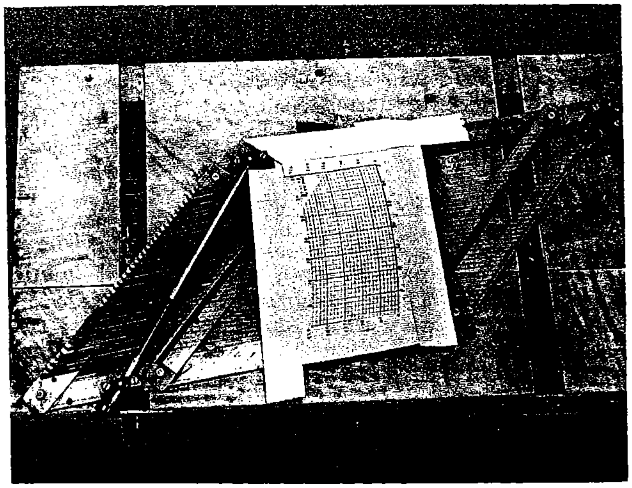

Figure 24. "Harp" and back mat used to make temperature and depth lines on BT grid.

The calibration slide was removed from the slide holder in the enlarger, and replaced with a glass photographic plate of the same dimensions. The plate was now exposed, removed from the holder, and developed, producing a photographic negative of the grid. From this negative, positive grids were made on clear glass slides of the same size. The positive grids were next dipped in lacquer for preservation, and then cemented in an adjustable slide holder. The calibration slide was placed in the metal slide holder, and the stops were adjusted so the depth and temperature lines of the positive grid coincided with those of the calibration grid. In later versions, set screws were added to make the final adjustment (fig. 25). This mounting frame was attached to a magnifying lens, called a viewer, for immediate reading of a slide by the sonar officer (fig. 26 H). Two positive grids were made for each BT. The calibration slide and negative grid were filed for future reference. Each

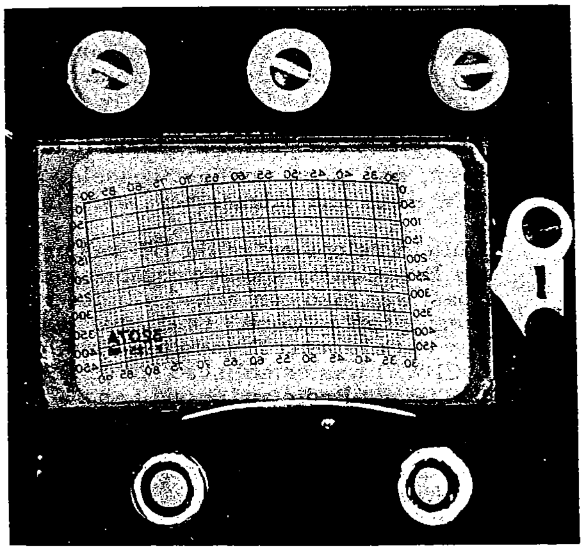

Figure 25. Printed side of BT grid in holder.

time a BT was repaired and recalibrated, the letter following the serial number was changed to the following letter of the alphabet for indication of which grid applied to a particular BT at a particular time.

TRAINING PROGRAMS

Introduction of new oceanographic equipments in the Navy necessitated development of training programs. These programs included the use of submarine, as well as surface vessel BT's. Much of this work was done through a liaison officer, then CDR Roger Revelle, on duty at both the Bureau of Ships and the Navy Hydrographic Office, with assistance from CDR Marston Sargent and LCDR Mary Sears. Before Pearl Harbor the first 10 of an eventual 30 naval officers were sent to Woods Hole for training (see Appendix A). Under the direction of Ewing, Iselin, and the Woods Hole staff, these ensigns were taken to sea, taught to make lowerings and read slides, and given the rudiments of sonar propagation as it is affected by refraction.

Immediately after Pearl Harbor and formal entrance into World War II, the ensigns were assigned to the Atlantic or Pacific Fleet to introduce a new concept, based on the temperature structure in the sea, in antisubmarine warfare. They were initially given one winch, one spare roll of wire, one bathythermograph, a box of slides, a can of clear lacquer to preserve the slides, and instruction materials. After the first few lowerings under operating conditions, frequently using wooden booms and wire that frayed, the first fleet bathythermographs virtually disappeared; however the officers, whenever possible, continued the work for which they had been trained and equipped. They made fine combat records; one was awarded the Navy Cross for heroism and several were war casualties.

As the war shifted to the Pacific, the Fleet Maintenance Office of the Service Force, Pacific Fleet, set up an installation and training unit at Pearl Harbor under Lt (later CDR) B. K. Couper, who coordinated activities of the Pacific military BT specialists. The officers were given new equipment, and many auxiliary vessels, in addition to ASW ships and submarines, were instrumented.

While development of the BT was progressing on the East Coast, another organization on the West Coast was also concerned with the BT and related oceanographic work. On 1 July 1940, the University of California Division of War Research (UCDWR) was established on the grounds of the U.S. Navy Radio and Sound Laboratory at San Diego, California. The oceanographic section of UCDWR was composed of a group from the Scripps Institution of Oceanography, originally headed by Dr. H. U. Sverdrup, followed by Dr. R. H. Fleming, and later by Dr. E. C. LaFond when the laboratory became NEL. Its primary purpose was naval oceanographic research. One of the divisions at UCDWR was concerned with the training problems involved in introducing new oceanographic equipments into the Navy.

The civilian training programs on both coasts were very effective, and men with a wide range of talents were recruited. Talent was used wherever found. Even biologists and astronomers were trained and became instructors, teaching others to install bathythermograph winches, take observations, read slides, and apply the information to sonar ranges.

TRAINING MANUALS

Instruction materials, which presented Naval and sonar procedures, as well as the new oceanographic concepts were expertly prepared at UCDWR. One of the first editions of the BT Range Prediction Manual was largely written by the well-known astronomer, Dr. Lyman Spitzer. (He also coordinated inter-laboratory programs.) Although serious in nature, comic strip art and cartooning were deliberately employed to catch attention and stress important points.

One manual was concerned with handling of the bathythermograph.(26) The proper procedures in making a BT lowering are shown in figure 26, parts A through H. Surface temperature, for instance, was obtained by dipping a bucket into the water (fig. 26 D), and then quickly measuring its temperature with a stem thermometer. Measurements were normally estimated to ± 0.1 °F by this method. On high-speed military ships, the temperature of the water in the main condenser intake was used, usually with a considerable reduction in accuracy. The recorded surface temperature was the primary independent field check that could be made on a BT's performance.

Despite the hazards of operating the BT (fig. 27, parts A through D), difficult lowerings were made on time and records were kept. Danger points were also described in the manufacturer's instruction book; among the instructions were warnings not to: "lower the BT while the ship is expected to turn;" "lower unless the water is deep enough;" "leave in a temperature greater than 105 °F;" "bump, drop, or jar."(26)(27) However, loss of BT's was still high. Their deployment offered innumerable opportunities for making mistakes: putting the slide in upside down; failing to pull back the sleeve; lowering too deep, and so forth. Despite reporting of the intended BT lowering to the bridge the message was not always received, and the ship would turn, causing the wire to foul the propeller. Probably the greatest hazard was a swinging BT after it left the water. A familiar saying was: "sight, surface, oh that son of a gun," or words to that effect, as the instrument swung in circles around the boom. The BT can make hundreds of successful lowerings with excellent results, but it is still a delicate instrument which can be easily damaged (fig. 28).

One of the most interesting instruction booklets, the "Manual for Bathythermograph Pilot Instructors"(28) presented a whole spectrum of antisubmarine warfare subjects. Not only did it give the technique and uses of BT's, but also such useful knowledge as how to tell the difference in rank between an ensign and a captain. Another manual