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THE MECHANICAL BATHY THERMOGRAPH
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.

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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) contracts to the Woods Hole Oceanographic Institution. Columbus Iselin, Director of Woods Hole Oceanographic Institution, responsive to the Navy's need for information on water structure, was instrumental in furthering development of the BT to fulfill this requirement.

DEVELOPMENT OF THE BT

Spilhaus Bathythermograph

About 1937, Dr. A. F. Spilhaus, acting on a suggestion by Dr. C. -G. Rossby, improved a previous method of continuously measuring temperature with depth in the sea. An older device, called the "oceanograph," had been built by Rossby and Dr. Karl Lange.⁽⁷⁾ When lowered slowly into the sea, this instrument managed, by means of many linkages, to draw a graph of temperature against depth on a large, smoked brass foil (fig. 1). Spilhaus was also familiar with tiny meteorographs, instruments which preceded the radiosondes for measuring atmospheric changes. These two instruments may be considered the precursors of the mechanical bathythermograph.

Spilhaus had four major aims: a smaller, lighter design which would permit lowerings by a hand line from ships at rest or by the hydrographic winch at very slow ship speed; a rapid temperature response as the BT quickly passed through changing temperature regions; elimination of hysteresis in the pressure element; and an easily

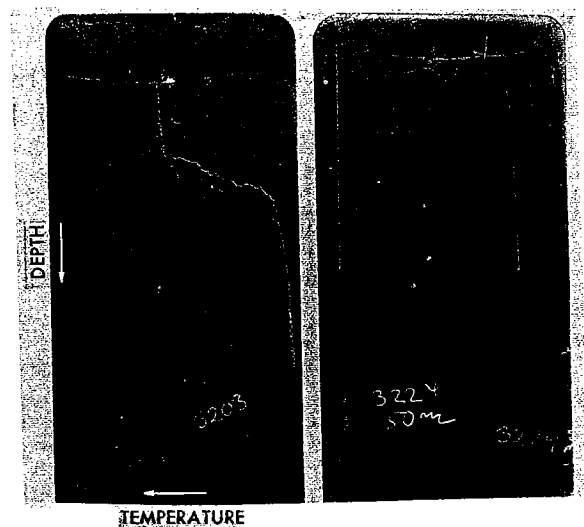


Figure 1. Oceanograph recording (after Rossby and Montgomery, 1934).

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 essentially unchanged. On this first model, he used a bimetallic strip, exposed to sea water, to move a stylus horizontally across the slide in accordance with temperature changes. Because the flow of water around the strip caused the stylus to vibrate, Spilhaus later substituted a Bourdon tube, shielded from the water flow, to which the stylus was attached.⁽⁸⁾ Connected to the Bourdon tube was a long, coiled tube filled with xylene (fig. 2). It responded to increasing temperature by increasing the internal pressure in the Bourdon. This caused the tube to "unwind" about a fixed axis, thus moving the stylus across the slide. It is noteworthy that linkages and pivots were avoided; only two elastically deformable elements were used.

In operation, the Spilhaus instrument was attached by a Nansen bottle clamp to the weighted, hydrographic winch wire. When maximum depth had been reached, a "messenger" could be sent down the wire to activate a "pen-lifter," a device designed to prevent the stylus from recording the uptrace (fig. 3).

Thus by 1940, a continuous record of temperature against depth, from the surface to 150 meters, could be taken in approximately 3 minutes from a ship underway and traveling at less than 7 knots. Furthermore, the records (slides) could be conveniently stacked and handled in small, slotted boxes. For analysis, Spilhaus projected the enlarged trace onto a frosted glass screen on which was superimposed a translucent calibration chart. The projector held the slide identically as in

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 paper.

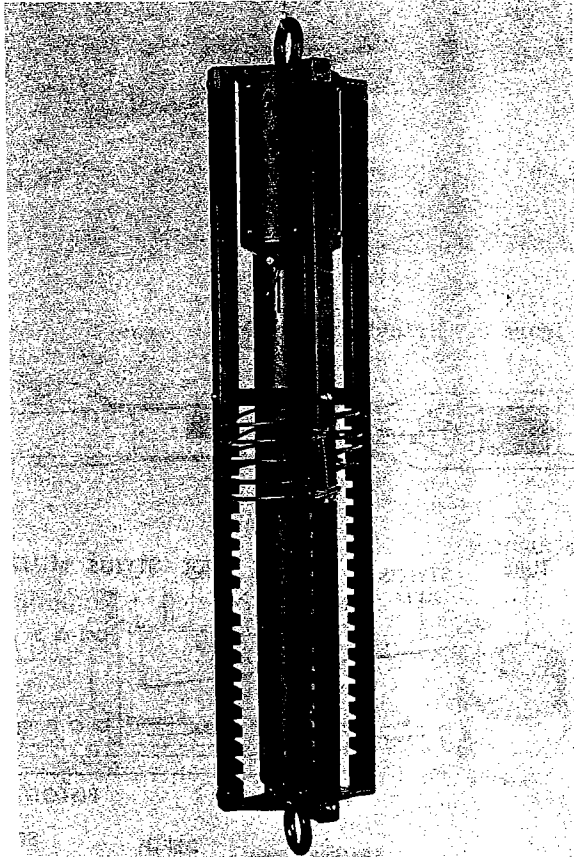


Figure 2. One model of original Spilhaus bathythermograph.

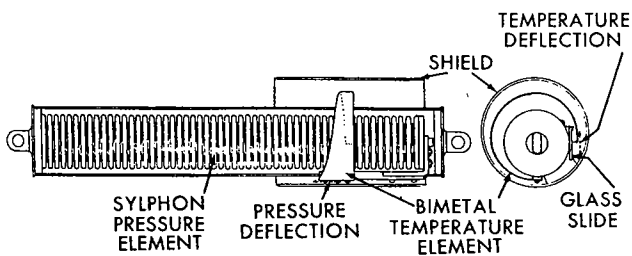


Figure 3. Design of Spilhaus bathythermograph (after Spilhaus, 1938).

The variations in temperature are shown with what was then startling clarity; these analog plots have not been improved upon in presenting summaries of temperature-depth conditions.

Spilhaus was encouraged to continue his developments by Dr. Henry Bigelow of Harvard University and Woods Hole Institution. Columbus Iselin quickly saw the application of the BT to the

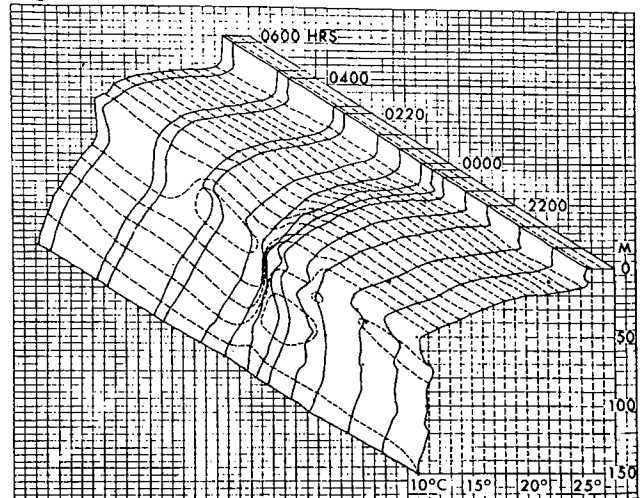


Figure 4. Temperature-depth-time structures as determined from bathythermograph traces (after Spilhaus, 1938).

sonar problem. Spilhaus, prior to being involved in meteorology during the war, participated in early (1938) antisubmarine warfare and BT tests aboard the research destroyer, USS SEMMES (DDG 18) out of New London. He also licensed the Submarine Signal Company of Boston to manufacture the instrument and a small number were constructed.⁽⁹⁾

Ewing Development

About 1940, Dr. W. Maurice Ewing, now director of the Lamont-Doherty Geological Observatory of Columbia University, together with assistance from Allyn C. Vine and Dr. J. Lamar Worzel, attacked the sonar problem under a National Defense Research Committee (OSRD) contract at Woods Hole Oceanographic Institution.* He and Iselin planned to equip merchant ships to take BT observations approximately every hour to assess the temporal and spatial temperature variability to important to the Navy. It was quickly apparent, however, that the Submarine Signal Company instrument was unsuitable. Furthermore, to meet the requirement of on-the-spot use at high military speeds, each of Spilhaus' original aims had to be modified. The instrument was packaged in streamlined form. Temperature-response time was reduced because use at a ship's speed of 15 knots required that sinking speed be increased; a special BT lightweight winch was introduced; and slide reading was done immediately on deck without benefit of projectors. Such a job would presently be called equipment (system) development, exactly the way the Navy then considered the BT-development of a component of sonar equipment, bought to equip ASW craft or to conduct surveys producing useful sonar information.

* Letter of W. M. Ewing to CAPT John E. Long, USNR (Ret.), dated June 24, 1963. Lamont-Doherty Library.

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⁾

INSTRUMENT FEATURES

BT Assembly

The BT essentially consists of a thermal element, a pressure element, a body tube, a nosepiece, tail fins, and a body tube sleeve.⁽¹¹⁾ Its purpose is to make a graphic record of temperature against depth as the instrument is lowered or raised in the ocean (fig. 5).

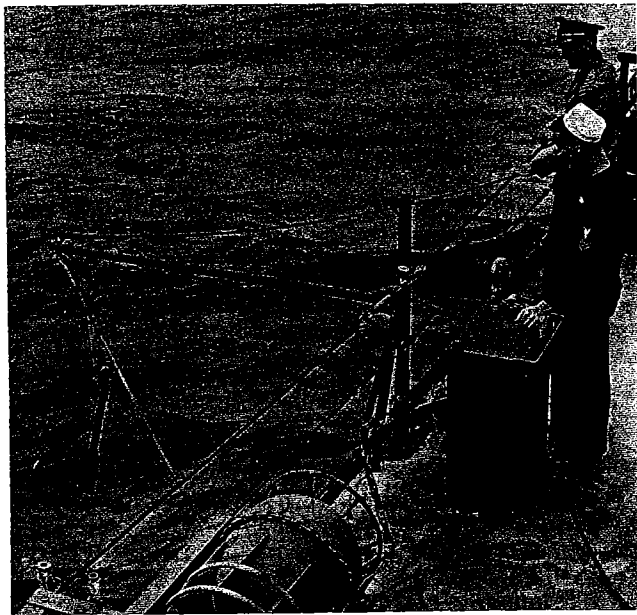


Figure 5. Lowering BT with original Navy BT winch with pipe boom.

Identities and contrasts of the present (Ewing) BT with the Spilhaus instrument are obvious (figs. 6 through 13). The smoked glass slide, slide-holder, syphon bellows and spring pressure assembly are essentially the same. The temperature-sensing, xylene-filled coil has been greatly lengthened, and is constructed of thin copper tubing, so wound as to assure maximum water circulation. Fins were added to the body tube, and a swivel to permit the wire to twist without spinning the BT.

An expanded view of the present mechanical bathy- is shown in figure 7. The cutaway version at the top of the figure shows the original streamlined features. The towing attachment and fins have been strengthened. The body tube housing is 2 inches in diameter and the overall length is 31-1/2 inches. It weighs approximately 21 pounds. The relative motions for temperature and depth are indicated in the lower part of the figure. The structural components are shown in figure 8, including a weighted nosepiece (or diving sleeve)

for fast diving.

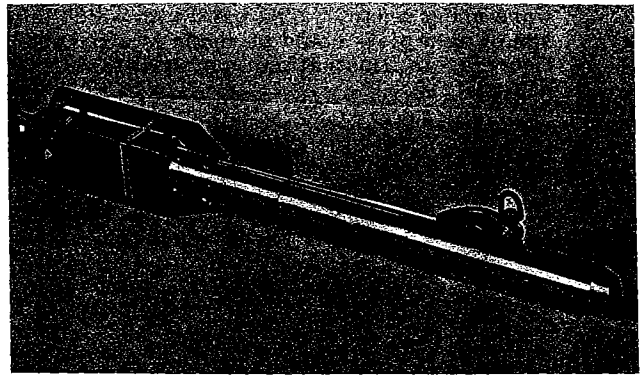


Figure 6. Bathythermograph.

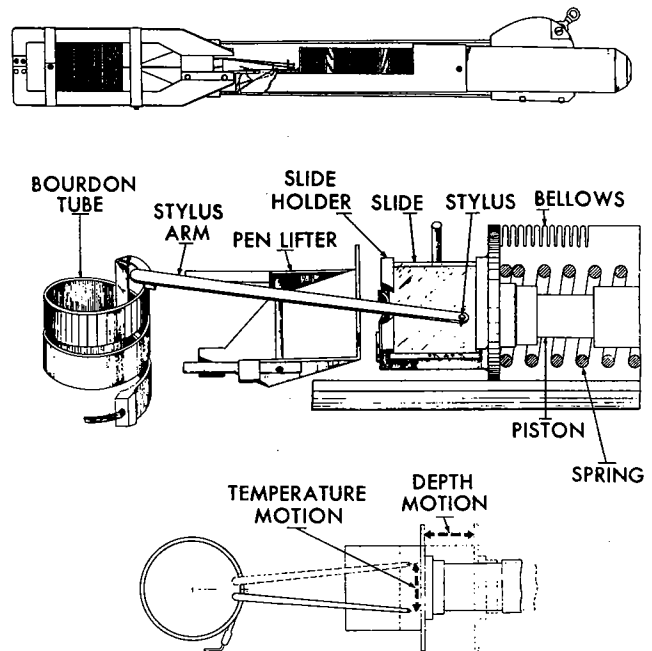
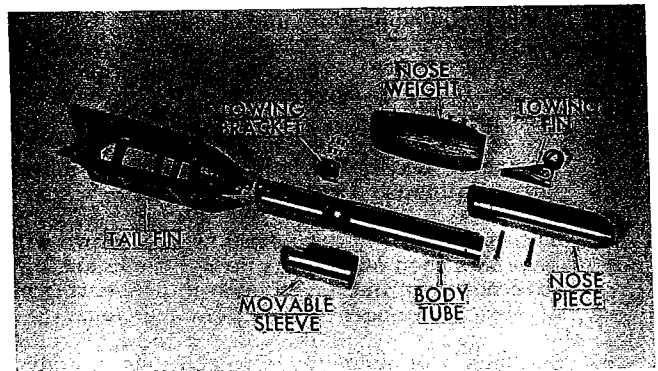


Figure 7. Cut-away of present bathythermograph.



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 sylinder bellows. The depth range is controlled by the size of the spring and sylinder 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.

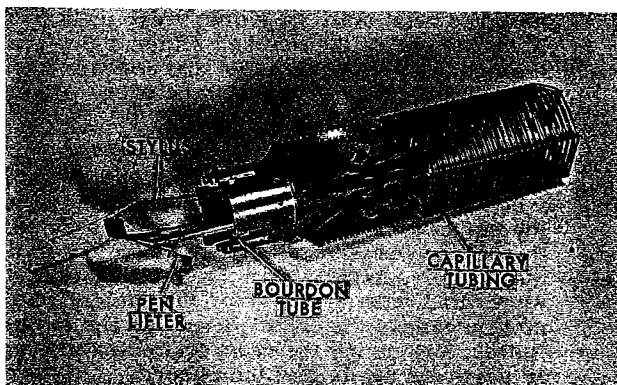


Figure 9. Temperature element assembly.

In contrast, there is only a slight flow of water around the Bourdon tube, bimetallic coil, and stylus within the free-flooding body tube. In the earliest models, it was found that the water inside the body tube and surrounding the Bourdon tube would cause a lag in the stylus (temperature) response because of a difference in temperature within the body tube with respect to temperature of the outside capillary tube. Waterscoops to increase circulation inside the body tube reduced the lag, but caused an unacceptable vibration of the stylus. The problem was satisfactorily solved early in 1941 by adding a reverse-wind, bimetallic coil between the free end of the Bourdon tube and the stylus. This addition provides the well-known Amthrop "case compensation"⁽¹⁰⁾ and the stylus position represents the average temperature of the xylene in the capillary tubing.

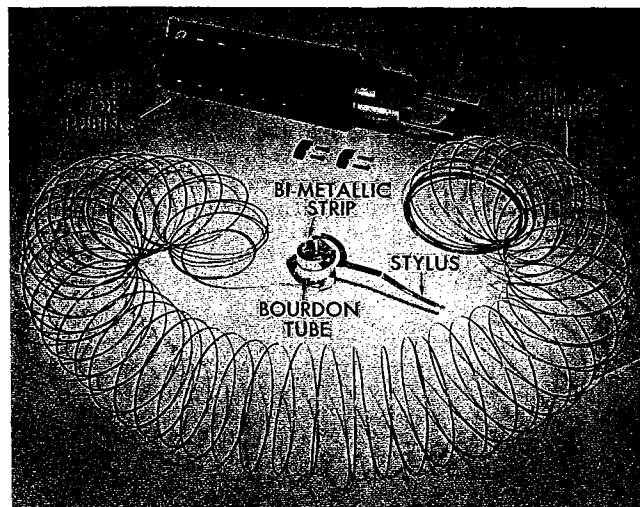
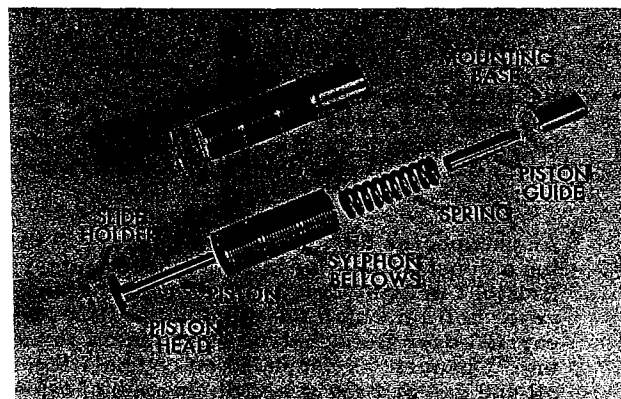


Figure 10. Thermal components.

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 85 to 35 °F, the stylus will move smoothly through at least two-thirds of the indicated range in less than 1 second. The instrument should be so constructed and adjusted that when it is subjected to a cycle of temperature changes and brought back to the starting point, the temperature hysteresis does not exceed 0.2 °F.

Pressure Unit. The pressure assembly including the piston, spring, sylinder bellows and slide holder have remained essentially unchanged from the Spilhaus instrument. The components are shown in figure 11. The soldered-joint, sylinder bellows keep water pressure off the spring, shaft, and inside face of the piston; however, they offer no



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."

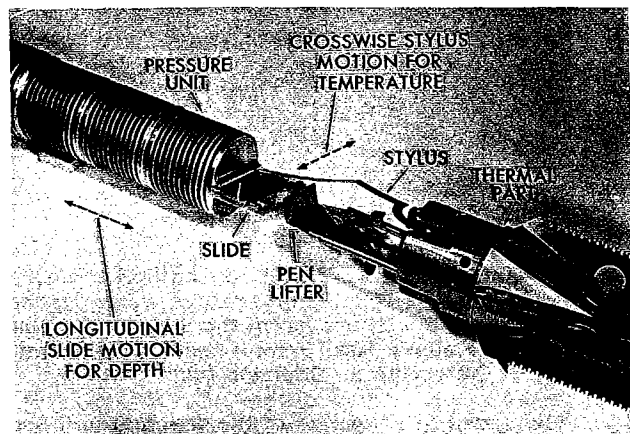


Figure 12. Pressure-temperature recording parts.

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 one 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.

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. Opacity 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



Figure 13. Glass slide.

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 siphon 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 tried. To paraphrase Ewing, "At first we modified a winch that had been used with a sounding machine lead and this was manually operated. The winch operator had to crank in a lot of wire under a fairly strong tension by hand, so we put motors on the first BT winches."

The early Navy BT winches were box shaped, with a drum on one side and control lever on another (fig. 5). With this model, it was difficult to keep the wire on the drum. Because winches were mounted on deck, they frequently took sea water inside, shorting out the motor. These early mechanisms were later replaced with a BT winch mounted on four legs to hold it off the deck. The drum and a larger motor were mounted in the center.

The standard instrument dives as nearly free fall as possible, dragging out wire as it sinks. At maximum depth, the winch brake is applied, and the BT is immediately brought up close to the surface and hauled in as previously described.

The free fall operation (as opposed to sending the instrument down on a weighted hydrographic cable) was an essential improvement by Ewing for the purpose of attaining depth at high ship speed. Design choices throughout the system were predicated on nearly free fall operation, and both friction and water drag were minimized wherever possible.

Preformed, seven-stranded, stainless steel, airplane-target towing wire $3/32$ "-diameter, afforded the essentials of strength, relatively small diameter, and seminoncorrosive properties (fig. 14). The small wire diameter reduced drag in the water, and a later nylon coating helped prevent kinking. Friction was reduced through use of a ball-bearing drum spindle on the winch, and a free-running pulley with no fairleads. The cable was guided onto the drum manually without using a built-in level winder. The result was that reliable records to depths of 450 feet could be taken in 2 to 3 minutes, on a ship cruising at 15 knots.

"Power on," "power off," and "brake on," "brake off" operations had to be nearly instantaneous. Initially used was a split-pulley, V-belt drive and a brake-drum control, all linked to one lever. Although modified for higher power and ruggedness, the modern BT winch includes the same necessary features for obtaining near-friction free fall under operating conditions. Booms also improved from a single wooden spar, to steel pipe, to a gate type (fig. 16). Some ships, however, used improvised davits (fig. 15).

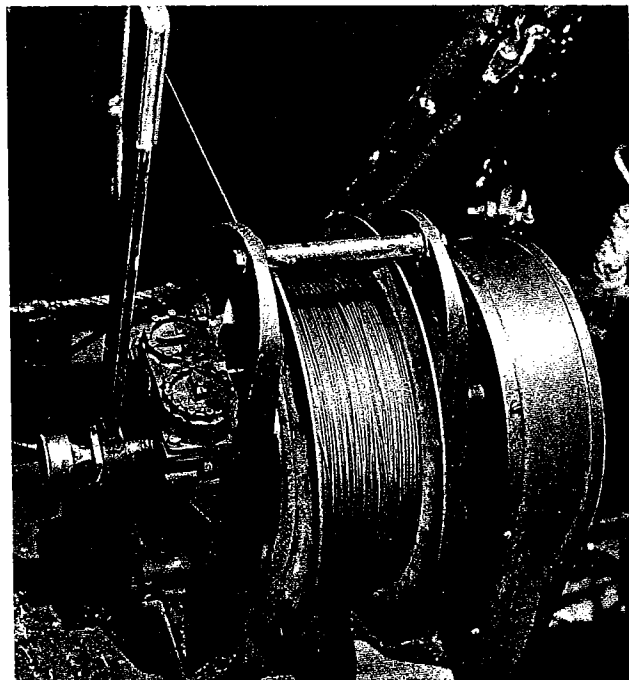


Figure 14. Drum, wire and counter on BT winch.

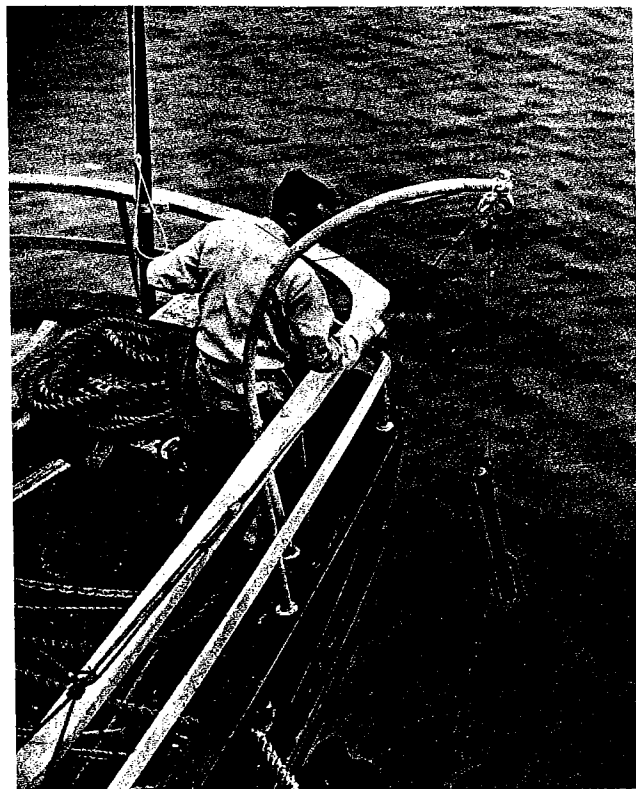


Figure 15. BT davit on R/V E.W. Scripps

