NEW TECHNIQUES IN BATHYTHERMOGRAPH SYSTEMS

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This paper discusses the present state of art in Bathythermograph systems and highlights their relative merits and demerits with particular reference to their applications in field operation.

A thermograph, literally meaning a heat writer, is basically a temperature recording instrument. The prefix 'bathy' means 'deep'. A bathythermograph, is, therefore an instrument that registers the temperature at various depths of sea. Classical methods and techniques used for measuring the prevailing temperatures in the oceans, possess many limitations. They are grossly inadequate to meet the present demands of collection of data accurately and expeditiously. Efforts were therefore directed towards solving the basic problems of conventional methods and consequently new techniques with high reliability and operational simplicity required by the user have been evolved using the concepts of modern electronics.

This paper discusses the various avenues of approach that led to the present state of art in bathythermograph systems and highlights the economic aspects relating to their high speed operation for maximum saving of expensive ship time, lightweight and small size for reasons of logistics, principally that of stowage encountered in ships and low operational costs.

CLASSICAL METHODS

The classical methods of measuring temperatures at various depths in the sea, make use of the reversing thermometer (which is still the standard instrument for precision readings) and the mechanical bathythermograph (MBT) which is less accurate and is only used to a depth of 275 metres. The merit of the latter, however, is that it gives a continuous plot of temperature versus depth and is faster since the vessel does not have to stop as it does when reversing thermometers are used.

Reversing Thermometer

The reversing thermometer was first introduced by Nagretti and Zambra of London in 1878. About the year 1900, Richter in collaboration with Nansen[1], developed the reversing thermometer with an accuracy of $\pm 0\cdot01$°C. An unprotected reversing thermometer in conjunction with a protected thermometer shown in Fig. 1 serves as a tool for thermometric depth determinations. A wire rope, carrying at intervals, five or six sampling 'Nansen' bottles, each fitted with a pair of reversing thermometer is lowered in the sea from a still ship. As the bottle is inverted to trap water sample, the thermometer is inverted. As a result of their construction, the mercury thread breaks at the point of constriction and mercury runs into the other end of the capillary to record the temperature *in situ* at the depth of reversal. The hydrostatic pressure compresses the glass tube of the unprotected thermometer and causes it to indicate a higher temperature than the protected one. The difference in readings of the thermometers is a measure of pressure *i.e.* depth. In this way, it is possible to get water samples and temperatures at any desired depth and in considerable numbers through a vertical column[2].

Mechanical Bathythermograph (*MBT*)

Mechanical bathythermograph was originally conceived and developed by Dr. Athelstan F. Spilhaus[3] in 1938. The mechanism for recording data with a mechanical bathythermograph is not complicated. Temperature is measured by a thermometer which is composed of about 25 metres of Xylene-filled coiled tubing with a pivoting Bourdon tube. The end of the tube is fixed with a pointer which marks the trace of temperature on a smoked slide. Depth is determined by a small bellows that reacts to pressure. Fig. 2 illustrates two different versions of the present day MBTs.

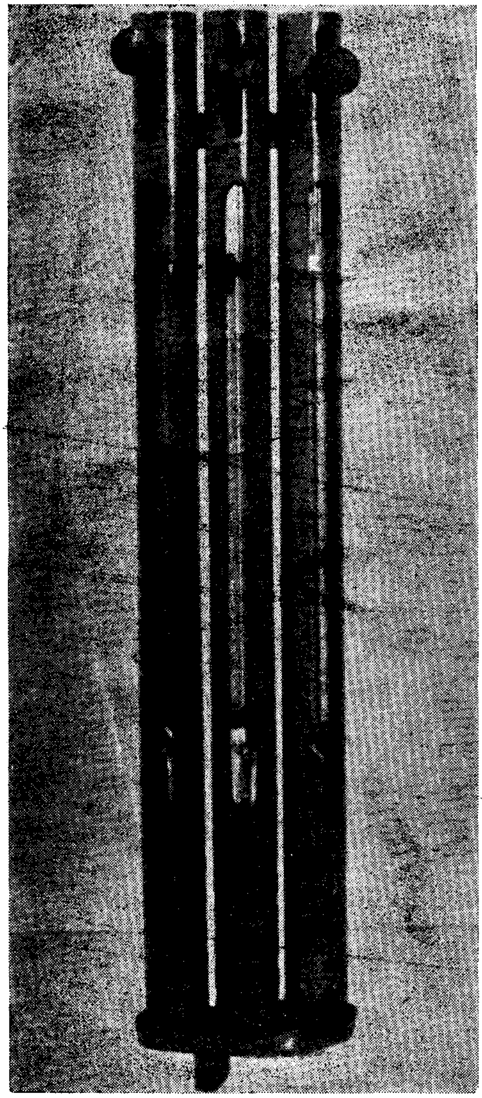

Fig. 1—Assembly of an unprotected and a pair of protected reversing thermometers (The use of two protected thermometers is an additional facility for rechecking the temperature measurements).

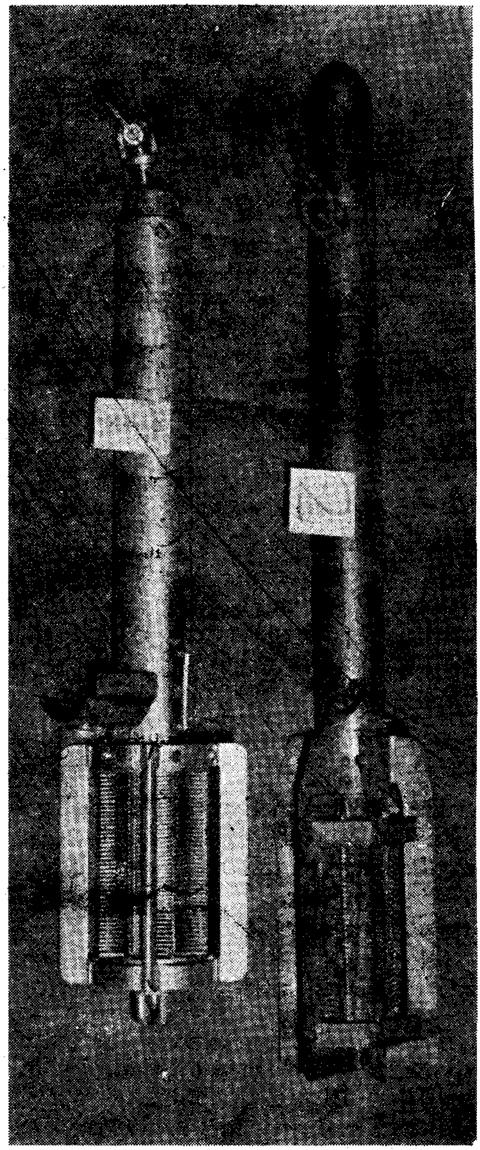

Fig. 2—Two different versions of mechanical bathythermographs (Mark 1—USSR and Mark 2—UK).

The mechanical bathythermograph though used over quarter of a century, possessed many limitations[4,5]. Due to their structural limitations, they cannot be used beyond depths of 275 metres and cannot be operated at ship's speed exceeding 15 knots. The use of MBTs is also limited due to sea state, as in heavy weather, it is not safe to have personnel operate the winch on the open deck of the ship.

New Techniques Explored

As a result of the limitations on the classical methods, new techniques have been explored to obtain water temperatures reliably and rapidly from ships underway with low operational costs and logistics. The requirement of rapid collection of data suggests the use of some type of telemetry system. Attempts have therefore been made to employ towed sensor cable and such techniques as underwater radio, optical, acoustic and hard wire telemetry for the proposed system.

Towed Sensor Cable Systems

Towed sensor probes—The towed sensor probe designed by Fox comprises a small probe of size 40 cm by 10 cm diameter housing a potentiometer type Bourdon tube as a pressure sensing element and a thermistor as a temperature sensing element[6]. The system employs a single core thin cable. The two sensors form arms of two separate Wein bridges, whose operating frequencies are selected, sampled by a control unit and recorded on a printer in sequence. The probe operates over a temperature range of 10—20°C with a resolution of 0·01°C and a depth range of 0—1000 metres with a resolution of 1 metre.

A new tool for temperature-conductivity-depth measurements was developed by National Research Council, Canada with emphasis on the economic aspects of marine surveys, high speed operation and light-weight[7]. The system employs d.c. signal transmission and utilizes a copper resistance thermometer, a four electrode conductivity cell and a diaphram strain gauge pressure transducer. A seven-conductor armoured well logging cable is used to tow the probe. The probes can be towed up to a ship's speed of 14 knots with 2-3 m/sec vertical casts up to 1000 metres. More recently emphasis has been shifted to reduction of analysis time and to increasing utilization times of National Research Council systems. The development of *Batfish* a towed bathythermograph (fish) is a modification of this system intended mainly to sample the upper layers of the ocean more repidly and more thoroughly[8].

Some of the problems encountered in the acquisition of data in the oceans with temperature-salinity-depth probes have been discussed by Sankey[9].

Towed sensor chains—The problem of rapid acquisition of temperature/depth data was solved to some extent by the development of a towed cable with a chain of temperature sensors (thermistors) fixed at different depths and a depth sensor attached to the last sensor[10]. The design was similar in principle to the operation of the contouring temperature recorder system[11]. The thermistors are electronically scanned in sequence from top to the bottom of the chain in a time interval adjustable from 2 to 20 seconds. The temperature data from thermistors are plotted as a continuous record of the vertical distribution of isotherms. As the ship proceeds along its course, the system makes a vertical and horizontal temperature profile of the water in the range —2° to +32°C. However, the need for a multicore cable of about 100 conductors in the system has resulted in bulky and expensive fairings and deck handling equipments.

An improved version of the towed sensor chain system uses a single core cable, resulting in reduced size and cost[12]. The chain is towed from the ship at speeds up to 10 knots. About 15 sensors are inserted in a single core cable and a depth measuring unit is attached to the deepest sensor. The device is lowered from a ship for a number of given depths down to 600 metres using a special winch.

Radio Telemetry

In consideration of the economy of ship's time, techniques employing underwater radio telemetry were attempted for telemetering the temperature/depth data of sea to a surface vessel or aircraft. However, as the radio waves suffer a high attenuation in sea water throughout its spectrum, it became very difficult to develop a device with adequate power to transmit useful energy over the required distances[13].

Optical Telemetry

As in the case of radio waves, the effect of absorption and scattering of light waves was extremely predominent in sea. Excessive turbidity in the sea also posed severe problems in optical underwater telemetry.

Acoustic Telemetry

The principal advantage of acoustic telemetry system is its relatively smaller attenuation of acoustic waves in sea water compared to electromagnetic waves. But the sea is far from the ideal medium for sound propagation[13]. The stratification of the sea water due to the vertical velocity gradient of sound in the sea causes the transmitted 'beam' to be refracted[14]. These problems become especially acute when a significant horizontal range is involved.

The sea link multichannel system shown in Fig. 3 is an instrument that transmits information acoustically on four undersea parameters to a towing hydrophone[15]. The system provides real time information on underwater data while lowering, raising or towing is taking pace. Two of the underwater telemeter's four channels are used to give it the built-in capacity to sense and transmit its own depth and water temperature data. The telemeter can either be lowered from the ship or released with recoverable type acoustic release transponders to provide additional capability of recovery of the telemeter upon receipt of a proper acoustic coded command from the surface ship.

In the systems incorporating towing hydrophones, the interference of the noise generated by high speed ships, remained serious and posed severe problems in noise limited operations[16]. As a solution to this problem, acoustic cum radio telemetry was exploited by Castelliz in developing a successful model of air droppable acoustic bathythermograph[17]. An expendable bathythermograph slug (probe) about 15 inches long and three inches in diameter, comprising of a temperature sensor, water activated batteries, electronic units and an acoustic transmitter is dropped from a hovering aircraft. A sonobuoy dropped from the same aircraft in the vicinity of the slug is used as a relay station. The slug on impact at the sea surface sinks freely in water and transmits temperature data acoustically to the sonobuoy hydrophone. The sonobuoy in turn radio telemeters the information to the parent aircraft. Depth is obtained from the elapsed time and known sink rate of the expendable slug. A modification of this system is an Air Expendable Bathythermograph (AXBT) buoy[18] which incorporates the temperature sensing probe. When the buoy hits the water on drop from an aircraft, the temperature probe attached to a spool of wire drops from the body of the buoy and descends to a depth of about 300 metres. As the probe descends, the buoy relays temperature to the aircraft. In about five minutes the transmission is complete and the buoy eventually fills with water and sinks.

Hardwire Telemetry

Hardwire telemetry has been successfully employed in developing bathythermograph systems with expendable sensors. Arthur D. Little has evaluated and assessed the utility of expendable bathythermograph systems for tactical field uses (ASW Sonar Technology Report No. SF 101-03-21, Dept. of Navy, USA—1966).

The main advantages of expendable systems are :

(*a*) Operation from a vessel at high speeds

(*b*) Availability of data for rapid processing

(*c*) Deployment of sensors under any weather conditions

(*d*) Possibility of operation by untrained personnel

(*e*) Launching without a winch

(*f*) Low operational costs and logistics

Experimental data when correlated with the theoretical predictions on the depth accuracy of expendable oceanographic instruments have established that with careful design the maximum total depth error could be within $\pm 2 \cdot 8\%$ of actual depth[19].

Expendable Bathythermograph (XBT) Systems

A laboratory model of the early expendable bathythermograph system[20, 21] developed by the Marine Physical Laboratory of the Scripps Institute of Oceanography comprises of an expendable radio telemetering buoy and the associated ship board apparatus. The expendable part is contained in a telemetering buoy which is launched from a fast moving ship or aircraft. After impact at the sea surface, a diving weight containing the thermistor is released from the buoy. Changes in thermistor voltage due to changes in sea temperature are amplified and transferred to the buoy via a miniature single conductor cable. The buoy in turn transmits the data via radio telemetry to the receiving ship or aircraft. This laboratory model has served to demonstrate the combined attributes of simplicity, accuracy and low cost obtainable with the expendable system.

Frequency modulated transmission technique was employed by the Marine Division of the Bissett Berman Corporation in the design of a new XBT system[22]. The system consists of a deck unit, a launcher, a deck spool and an expendable unit containing the underwater wire spool and temperature sensor. The deck unit housed in a small cabinet, provides d.c. power to the underwater unit, accepts the frequency modulated signal and records temperature versus depth on a strip chart recorder. The frequency modulation technique employed allows the use of a miniature single core cable and has the advantage of being relatively insensitive to wire insulation break down, electrical noise and supply voltage variations.

The General Motors Defence Research Laboratory model of XBT system[23] generally known as BTX (Bathythermometer-Expendable) sensor system consists of a hydrodynamical bomb shaped underwater unit, a launcher and a recorder. The BTX sensor is a weighted body containing a thermistor and a bale of wire in the rear, a shipboard container with telemetering wire and a submerged drogue. A launch stand conducts the telemetering wire from the sensor to the in-board recording system. Since the sensor unit contains no electronics or power supply gears, the cost of the expendable part was relatively low.

A versatile, simple to operate expendable bathythermograph was designed by the Sippican Corporation in collaboration with Plessey. The system is comprised of an expendable unit package, a ship board launcher and a strip chart recorder[24,25] (Fig. 4). The probe consists of a ballistically shaped, spin stabilised housing containing a calibrated thermistor connected to a spool of fine wire. The wire is connected to a second spool of wire within the probe canister. When the probe is launched, the wire from both spools is free to unwind, permitting free fall conditions for the probe. Since the rate of descent of the probe is known, depth is obtained directly from the time axis of the chart and the temperature changes of the water are traced on the horizontal scale of the ship board recorder. In this way, accurate temperature depth profiles are continuously recorded without interfering with the operation of the surface vessel. The system requires only 90 seconds for a BT sounding to a depth of 450 metres.

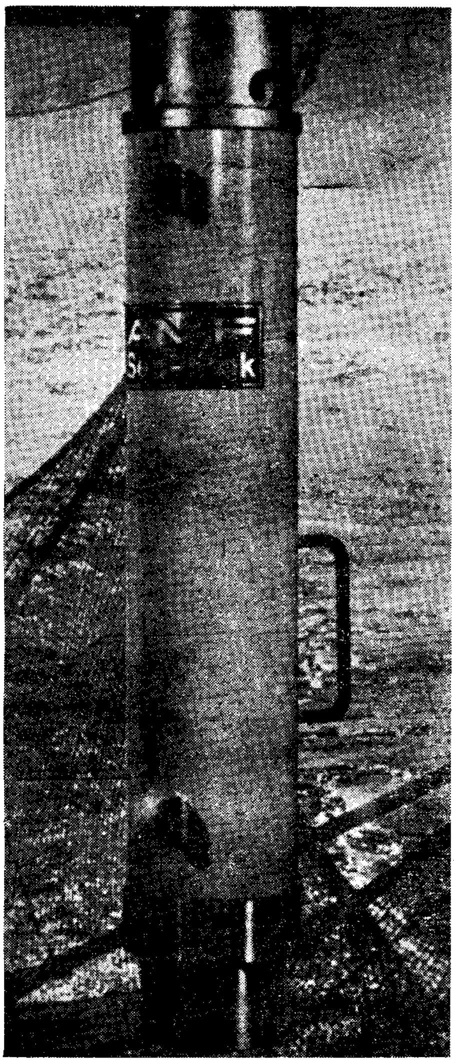

Fig. 3—Sea link multichannel acoustic telemeter.

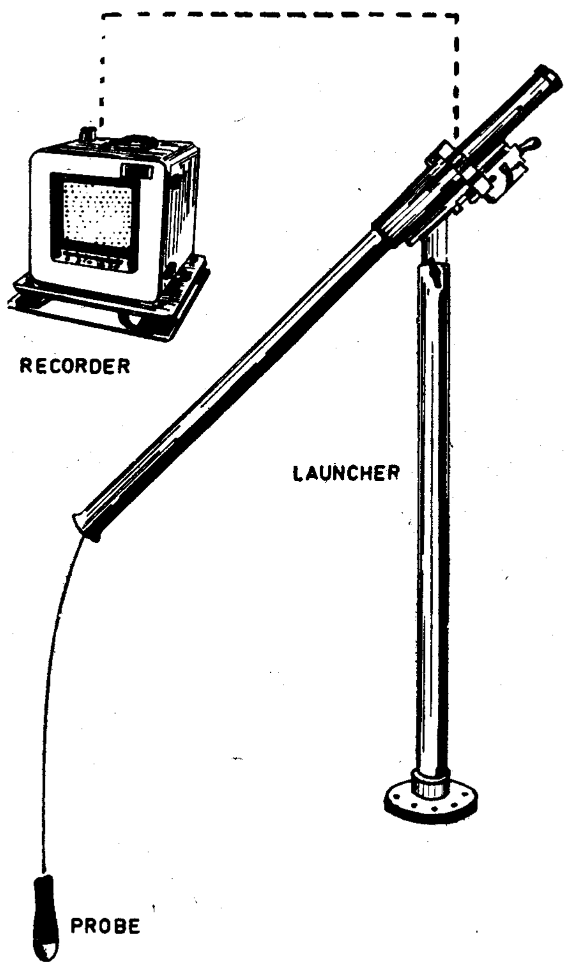

Fig. 4—Expendable bathythermograph system (Sippican-Plessey).

GENERAL DISCUSSION

Comparison of critical characteristics, salient features and performance costs of the various techniques successfully developed for bathythermograph systems are summarised in the Tables 1—4. It can be seen that expendable bathythermograph system possess the features of rapid measurement of data, low cost consistent with good reliability and successful operation at ships' speed up to 30 knots. These features of the XBT system, have made it more suitable for fleet tactical use. In recent years, improvements have been made in the XBT system to provide increased accuracy of both the temperature and depth measurements[26]. The depth range, even at speeds of 30 knots for XBT, has been increased from 275 metres to 450 metres. Laboratory models of XBT have been made for operation to depths of 1800 metres. XBT probes with some minor modifications have been adopted successfully to obtain measurements of thermal microstructure with a resolution of better than[27] 0·002°C.

Though the successful development of XBT systems have solved the basic problems of obtaining temperature depth data encountered in tactical field operations, still there is vast scope for development of systems in which the sensor probes could be recovered after every series of operation as in the case of undulating recoverable modules[28], a field still open for further studies and exploitation.

CONCLUSION

The selection of a bathythermograph system depends mainly upon the special applications. In applications where field operational time is less important as in oceanographic research surveys, the reversing thermometer or mechanical bathythermograph may be extensively used. The towed chain systems is an advantageous system for the study of thermal stratification aspects or isotherms. In operations, where time is more important as in naval operations, expendable bathythermograph is preferable.

TABLE 1

PERFORMANCE SPECIFICATIONS OF ACOUSTIC TELEMETRY BATHYTHERMOGRAPH SYSTEMS

Features		Sea Link	Air Droppable
Information channels	(No.)	4	1
Depth Range	(m)	0 to 1000	0 to 300
Depth Accuracy	(%)	±1	±2
Temperature Range	(°C)	0 to +30	—1 to +20
Temperature Accuracy	(°C)	±0·2	±1
Transducer Frequency	(kHz)	12·0	5·5
Transducer Beam Width	(Degrees)	55	360
BT Diameter	(cm)	12·7	7·5
BT length	(cm)	75	38
Battery life	(Minutes)	4800	6
Weight	(kg)		
(*i*) In Air		29	1·36
(*ii*) In Water		21·32	0·8

TABLE 2

PERFORMANCE CHARACTERISTICS OF VARIOUS EXPENDABLE BATHYTHERMOGRAPH SYSTEMS

Characteristics		Manufacturer			
		Scripps Institution of Oceanography	Bissett Berman Corporation	General Motors	Sippican-Plessey
Depth Range	(m)	0—300	0—450	0—1600	0—450*
Depth Accuracy	(%)	±1	±2	±2	±2
Temperature Range	(°C)	5 to 15	—2 to +35	—10 to +50	—2 to +35
Temperature Accuracy	(°C)	±0·1	±0·2	±0·2	±0·2
Time constant of temperature sensor	(sec)	0·1	0·15	0·1	0·15
Probe Sink Rate	(m/sec)	3	7	7·5	6
Probe Weight (approx)	(kg)	4·5	1	1	0·75

*Research models are now available for depths up to 1800 metres.

TABLE 3

COMPARATIVE STATEMENT OF PERFORMANCE, COST AND UTILISATION BETWEEN MECHANICAL (U. K.) AND EXPENDABLE (SIPPICAN-PLESSEY) BATHYTHERMOGRAPH SYSTEMS

Characteristics		Mechanical	Expendable
Depth Capability	(m)	275	450
Depth Accuracy	(%)	6—8	±2
Depth Resolution	(m)	4·5—9	1
System Response Time	(sec)	5	0·15
Temperature Range	(°C)	—2 to +32·6	—2 to +35
Temperature Accuracy	(°C)	±0·2	±0·2
Temperature Resolution	(°C)	±0·2	±0·1
Ship's speed	(Knots)	15	30
Recording Time	(Minutes)	5	1·5
Fuel Costs	($)	85	None
Total cost for BT Launch	($)	25	19
Time for which personnel required on deck	(Minutes)	10	0·5
Exposure		(*i*) Separation of ship from task force (*ii*) Increased vulnerability of ship to enemy	No incremental exposure to enemy
Validity of data		Thermal profile of previous task force	Thermal profile of current task force
Helicopter Launch		Not readily launched from helicopter	Adaptable to helicopter launch

TABLE 4

BRIEF SUMMARY OF ADVANTAGES AND DISADVANTAGES OF VARIOUS BATHYTHERMOGRAPH SYSTEMS

Sl. No.	Type of Bathythermograph	Advantages	Disadvantages
1.	Reversing Thermometer	High reliability and accuracy	Large time constant. Readings not in a convenient form for data processing. Slow rate of data acquisition from still ships.
2.	Mechanical	Graphic record of temperature/depth data. Operation from ships underway up to 15 knots.	Limitations of depth and sea state. Inability to hold calibration.
3.	Towed Cable	Availability of temperature profiles for a number of fixed depths. Study of thermal stratification of oceans.	Underwater unit bulky and expensive. Maximum towing speed 14 knots.
4.	Sea Link	Record of real time information on underwater data. Rapid rate of acquisition and operation at high ship speeds.	Interference of ships noise. Relatively high cost.
5.	Air Droppable	Economic operation of aircraft as compared with conventional ship operation. Fast operation even in high sea states.	High cost of expendable units.
6.	Expendable	Instantaneous record and immediate readout. Greater depth and temperature accuracy. Operation at high ship speeds and in any sea state. Low maintenance, time and cost.	Effect on depth accuracy by the *in situ* effects and launching conditions.

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