TELEMETRY OF PISTON PARAMETERS

BY

M. SLAFFER, B.SC., D.I.C., C.ENG., R.N.S.S.

This Paper reviews current methods employed to determine operating temperatures in the critical piston crown and ring belt areas. The development of the Admiralty Engineering Laboratory telemetry system is described in detail and it is claimed that temperatures up to 300 degrees C may be measured continuously with an accuracy of plus or minus 2½ per cent.

Introduction

The efficiency of any prime mover is dictated by two considerations: the mechanical efficiency of the system, and the thermal efficiency of the cycle. Improvements in thermal efficiency are related to higher working pressures and temperatures, both of which are limited by mechanical or thermal stresses dictated ultimately by the materials of construction. In this context it is of interest to note in FIG. 7 (Ref. 9), the increase in specific output of automotive power plants over the last 16 years.

In the case of the conventional piston engine, despite efforts made to limit excessive temperatures by water and oil cooling, the major controlling factor is generally associated with the piston and its rings, and in order to achieve maximum safe working conditions, a knowledge of the temperature and temperature gradients in the piston crown and in the ring belt area is essential. Several commercial methods of temperature measurement are available which include thermal paints, fusible plugs, hardness relaxation techniques, sampling systems and direct thermocouple measurements. All but the last fall short of the basic requirement for continuous temperature monitoring. The A.E.L. has developed a non-contact telemetry system for the continuous recording of temperature in these regions.

Current Procedure

An established technique for determining piston temperature distribution involves the use of small 'fusible' plugs that are inserted into the piston at selected sensing points. These plugs are available for a range of temperature bands within which they melt. They are examined after a test run and, by judicious reassemblies of plugs, further test runs and subsequent examinations, it is possible to arrive at a temperature distribution over the piston. A similar method, using 'hardness' plugs that are submitted to metallurgical examination after a test run, gives an indication of terminal temperatures reached over somewhat closer intervals than with fusible plugs. A third method of piston instrumentation involves sampling the parameter once per cycle by means of contacts fitted to the piston underskirt which make with corresponding contacts on the cylinder at bottom dead centre, thus connecting (say) thermocouples in the piston with external recording instrumentation (Ref. 1, 2). A fourth method, similar to the third in that it samples the information once per stroke at bottom dead centre, makes use of coupling coils instead of contacts, the coupling being effected by a high frequency carrier method. (Ref. 7).

None of the above four methods are, however, capable of providing continuous information so that parameter variations can be determined on a

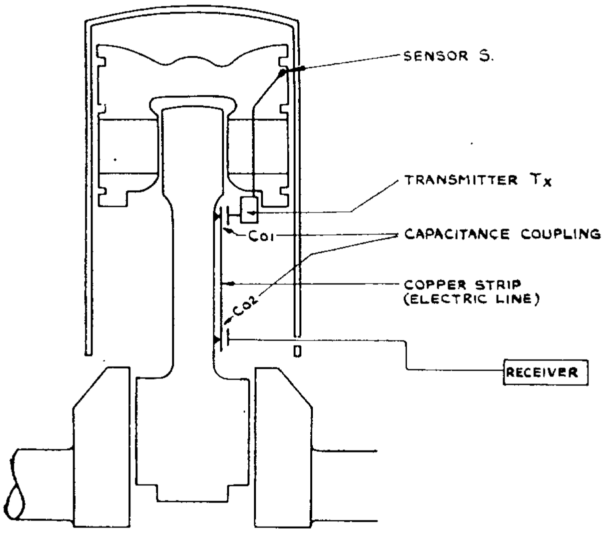

FIG. 1—BASIC ASSEMBLY

continuous time basis. Some success in this direction with reasonably reliable and interpretable results has been achieved by the use of flying or highly flexible leads or by the use of mechanical linkage systems, but always at the expense of modifications to the crank case (Refs. 3, 4, 5). This, however, is not always an acceptable feature for this kind of investigation, apart from its being tedious in application. Non-contact telemetering systems to give continuous information have also been publicised (Ref. 6) but, as far as the author is aware, the results have not been altogether successful.

Present System

The basic arrangement of the A.E.L. system consists of a temperature measuring sensor S (FIG. 1) in the form of a thermistor connected to a microminiaturised transmitter Tx, the latter being mounted on the skirt of the piston where the temperature does not exceed 100 degrees C. A thermistor consists of a piece of semi-conductor material, in our case the size of a pin head, with two lead out wires. Its resistance is sensitive to temperature and can change, typically, from 100,000 ohms to 100 ohms for a rise in its temperature from 50 degrees to 300 degrees C. The microminiature transmitter circuit is so arranged that when the thermistor resistance connected to it, changes from 100,000 ohms to 100 ohms then its signal frequency will shift uniformly from, typically, 2 MHz to 3 MHz. This change in frequency is noted in an outside receiver, Rx, so that we can observe a 1 MHz shift for a sensor change in temperature of 250 degrees C, i.e., we have a sensitivity in the measurement of 4 KHz per degree C.

The transmitter is loop or capacity (C_{01}) coupled to a 'radio line' on the con-rod, whence the output is again similarly coupled to a fixed external receiver, the area of coupling remaining constant, in both cases, with relative movement of the con-rod. If the sensor readings of temperature change slowly, then they may be followed directly by manual tuning of the receiver or, if the Rx is in the form of an electronic counter, by noting the digital read out. If changes in the sensor parameter are fast and are to be followed, then the received signal frequency must be converted to an analogue and recorded.

The Transmitter

The requirement for small dimensions, considered together with the adverse conditions under which the transmitter would be operating, precluded the usually applied methods for attaining frequency stability, i.e., by the use of tuned circuits or crystals maintained at a constant temperature. Also the prospect of employing automatic frequency control in the receiver seemed full of uncertainties. Instead, a circuit was chosen that could meet what is, after all, the basic requirement, i.e., a large ratio of signal frequency sweep of the transmitter to its undesired frequency shift as caused by environmental temperature variations between ambient and 100 degrees C. Special care was, in any case, taken in the design to stabilize the transmitter, as far as possible, in its own right. The final circuit is shown in FIG. 2.

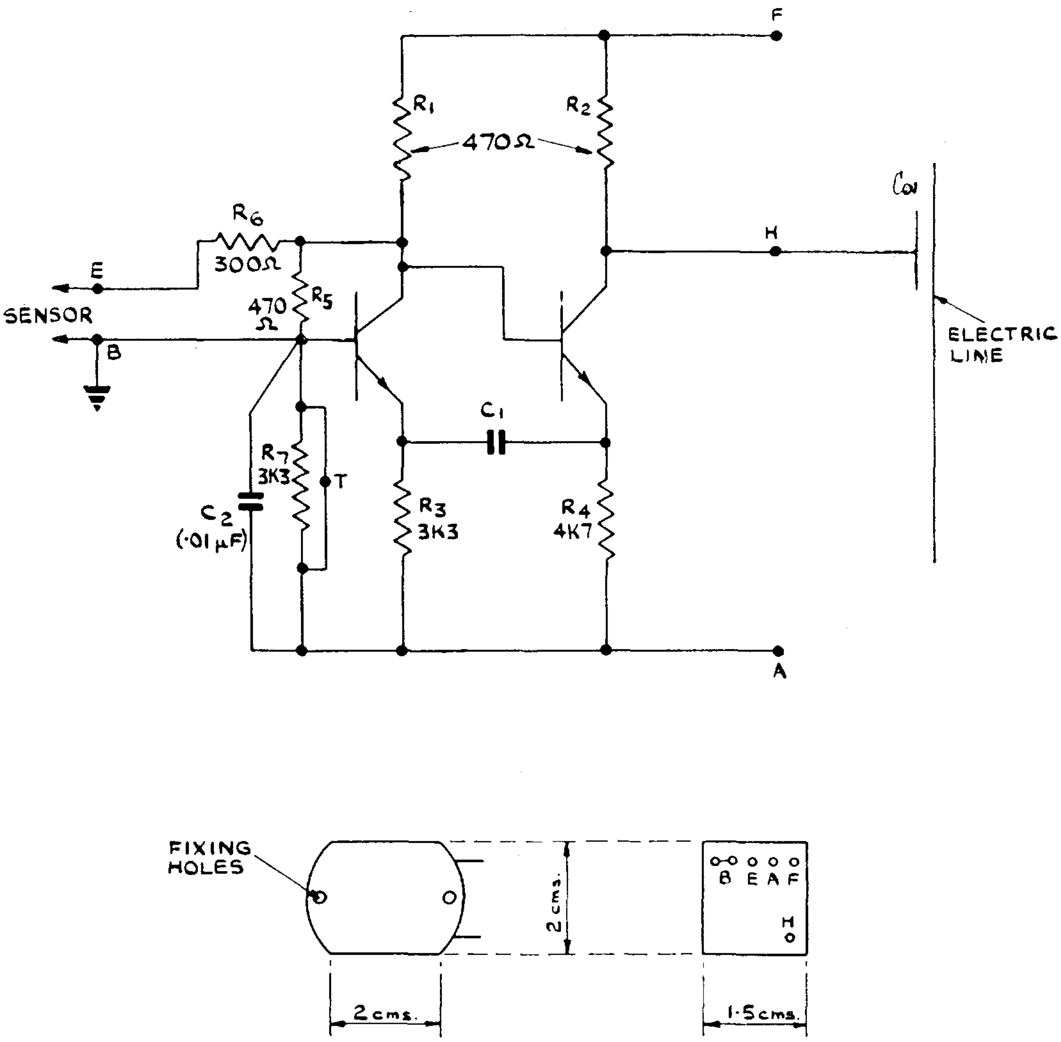

FIG. 2—TRANSMITTER (ONE CHANNEL) CIRCUIT DIAGRAM AND PHYSICAL DIMENSIONS

Two silicon transistors and micro-miniaturised low temperature co-efficient resistors (50 p.p.m.) are welded rather than soldered together in a switching type of RC circuit. Only one condenser with linear temperature characteristics is included in the frequency determining part of the RC circuit in order to ease the approach in the design for frequency/temperature stability. The circuit is essentially an emitter coupled multivibrator (Ref. 8) whose frequency 'f' is given approximately by

$$f \simeq \frac{1}{4} \frac{1}{CR_p}, \text{ where } R_p = \frac{R_1 R_5}{R_1 + R_5}; \text{ i.e., } R_1 \text{ and } R_5 \text{ in parallel (sensor disconnected)}$$

and where R_3 and R_4 are both large and assist in maintaining constant current generator action.

From this it follows that the transmitter frequency can be conveniently controlled (by large amounts) by a varying thermistor resistance across R_5 or R_1.

A more accurate analysis would show that the frequency is to some extent dependent upon the supply voltage, the aerial loading and upon the transistor's temperature. Adequately stable frequencies can nevertheless be maintained for a particular sensor temperature throughout the temperature range of the transmitter environment by keeping the supply voltage constant, by ensuring that the aerial loading is fairly constant throughout the engine cycle and by

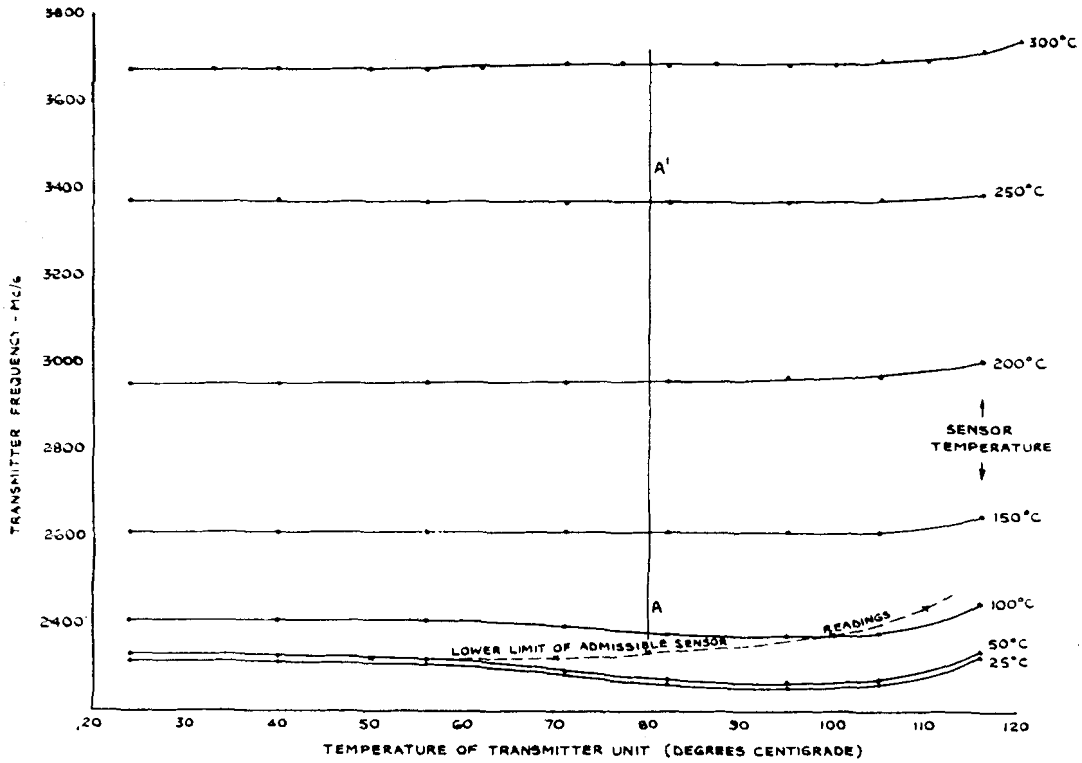

FIG. 3(*a*)—TRANSMITTER CHARACTERISTICS–FREQUENCIES FOR CONSTANT SENSOR TEMPERATURES UP TO 300 DEGREES C

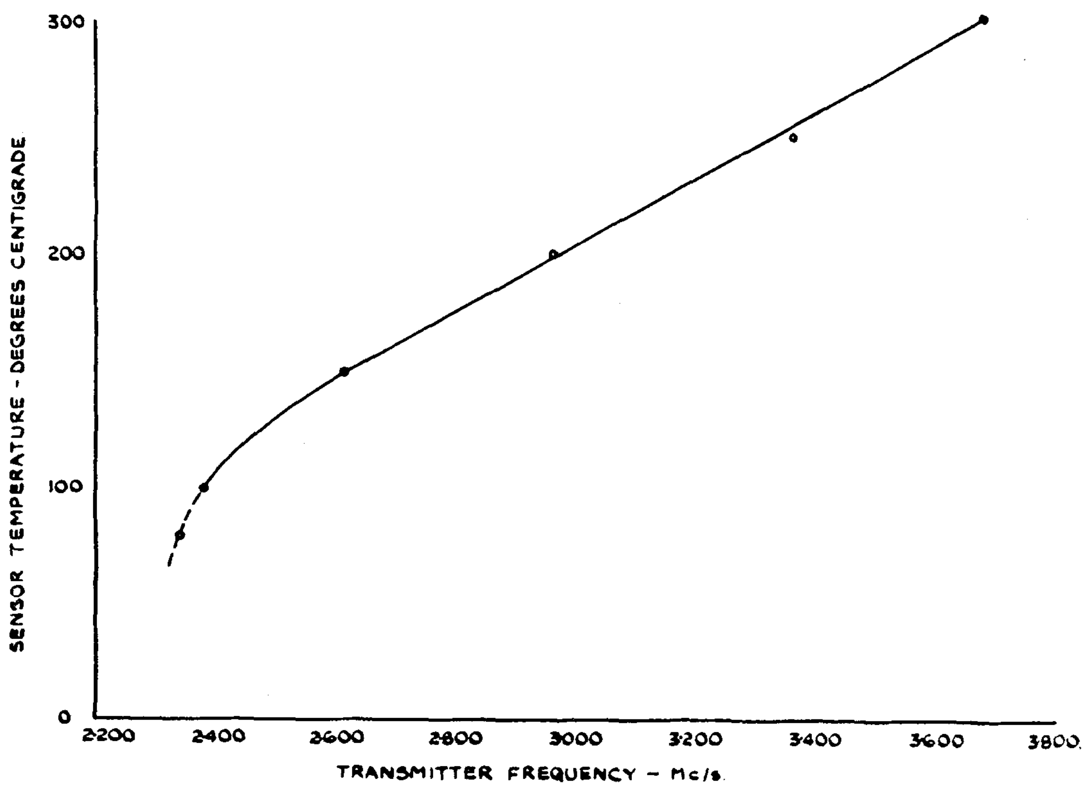

FIG. 3(*b*)—CALIBRATION—FREQUENCY AGAINST TEMPERATURE—TRANSPOSED FROM FIG. 3(*a*) balancing out the effect of the transistors' temperature variation with an auxiliary thermistor device, T, connected between base and emitter. This auxiliary thermistor is included in the completely encapsulated unit. FIG. 3 (*a*) shows transmitter frequency *versus* its environmental temperature plotted for a series of constant sensor temperatures. Ideally these lines would be horizontal. Temperature increments of the thermistor (sensor) environment are given, in terms of transmitter frequency, by interceptions on any vertical line. For example, the vertical line 'AA_1', transposed on to FIG. 3 (*b*), gives the calibration when the temperature of the transmitter is 80 degrees C; and there is no significant change in the calibration, for any other temperature value of the transmitter. The consumption per transmitter unit is 5v $\times$ 3mA.

Possible Displacement Sensor

For displacement measurements, preliminary work has shown that a tuned circuit shunted across R_5 or R_1 can control the transmitter frequency when its dynamic impedance is altered by proximity of metal to the inductance of the tuned circuit. The high frequency used for the transmitter permits the employment of a small value of inductance. In an actual experiment, a small probe consisting of an air cored coil of 50 microhenries tuned to the transmitter frequency by an auxiliary condenser, produced a frequency sweep of 150 kc/s for 0·015 inch movement when using a 3 mc/s carrier and an important additional test indicated that the presence or absence of oil in the gap had no effect on the frequency. The avoidance of an iron core in the coil will in some respects facilitate its design for use at high temperatures; but there seems to be no known alternative to the coil being wound with ceramic coated wire and encapsulated in some form of ceramic.

Block Schematics

A block schematic for single channel operation is shown in FIG. 4(*a*).

For multichannel operation, FIG. 4(*b*), a low pass filter acting as a separator is inserted between the output of each transmitter and the common radio line coupling, to prevent interference between transmitters. This reduces the output from each transmitter, but by this means interference is reduced to a sufficiently low enough level as to be of negligible significance. The signal strength can, if required, be more than retrieved with elimination of the high impedance coupling capacitance C_{01} by using the tinsel wire connection referred to later.

At the receiving end, channels are selected via appropriate filters and the signals converted to analogue values for direct recording.

Experimental Work and Results

Sensitivity

Two transmitters with ranges 1·8 to 2·7 mc/s and 2·8 to 3·7 mc/s have been built. The characteristics of an earlier unit tested on the bench, are shown in FIG. 3(*a*). The two transmitters have equally good characteristics but they are not reproduced here. A sensitivity of approximately 7 kc/s per degree centigrade is indicated for thermistor temperatures between 150 degrees and 300 degrees C, and an estimated overall measuring accuracy of $\pm\ 2\frac{1}{2}$ per cent is anticipated.

Intermodulation Interference

Apprehension that interchannel interference might nullify the system for general use was soon dispersed. Preliminary tests on the bench with both transmitters fitted on a piston, temporarily removed for the purpose from a Lister engine, showed that intermodulation interference between two adjacent

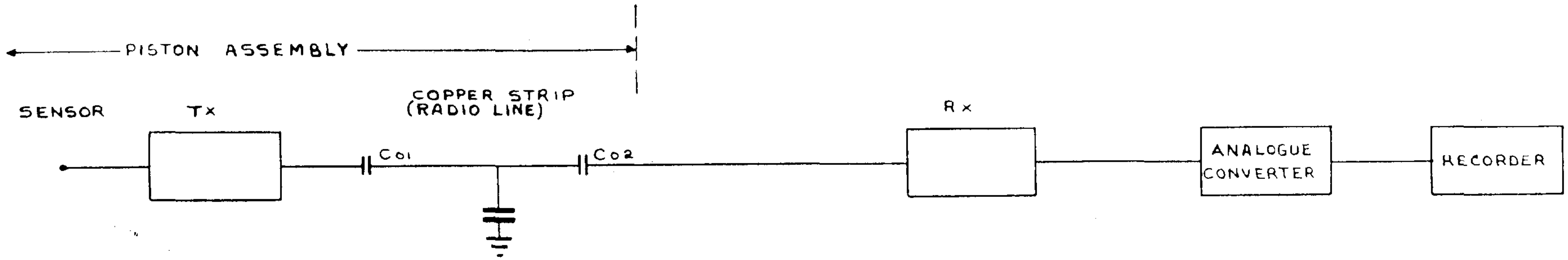

FIG. 4(*a*)—SINGLE CHANNEL

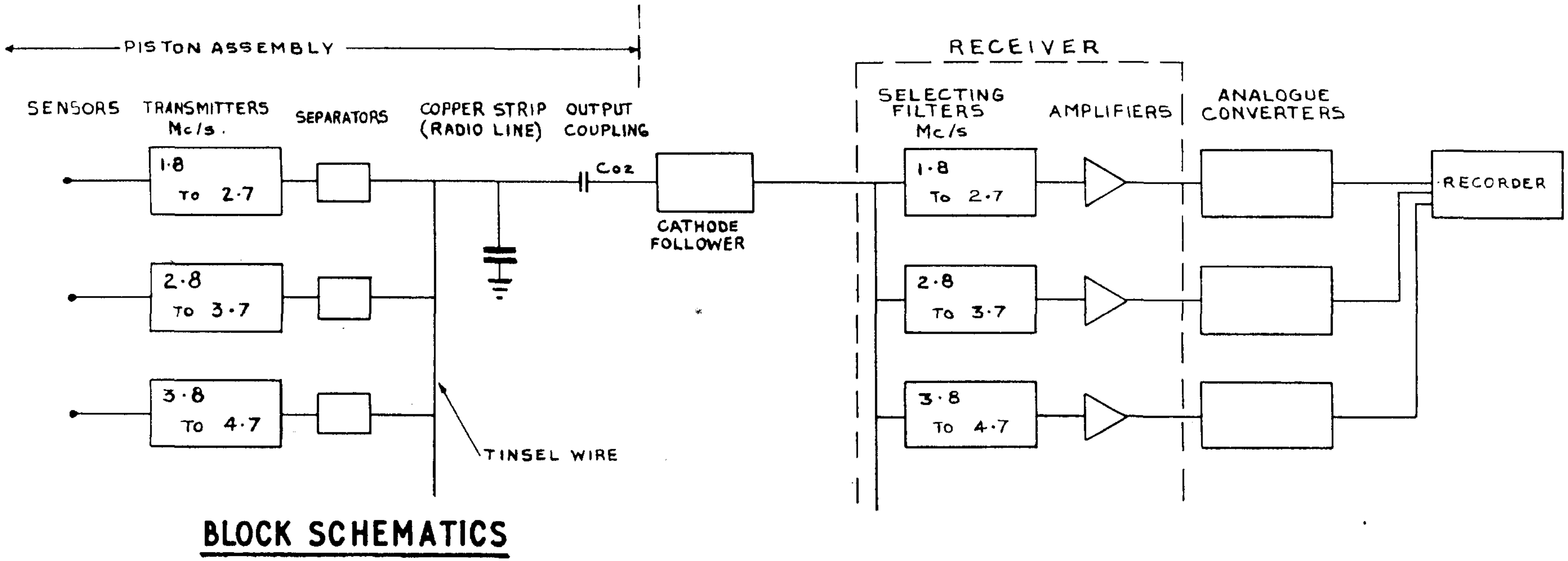

FIG. 4(*b*)—MULTI-CHANNEL

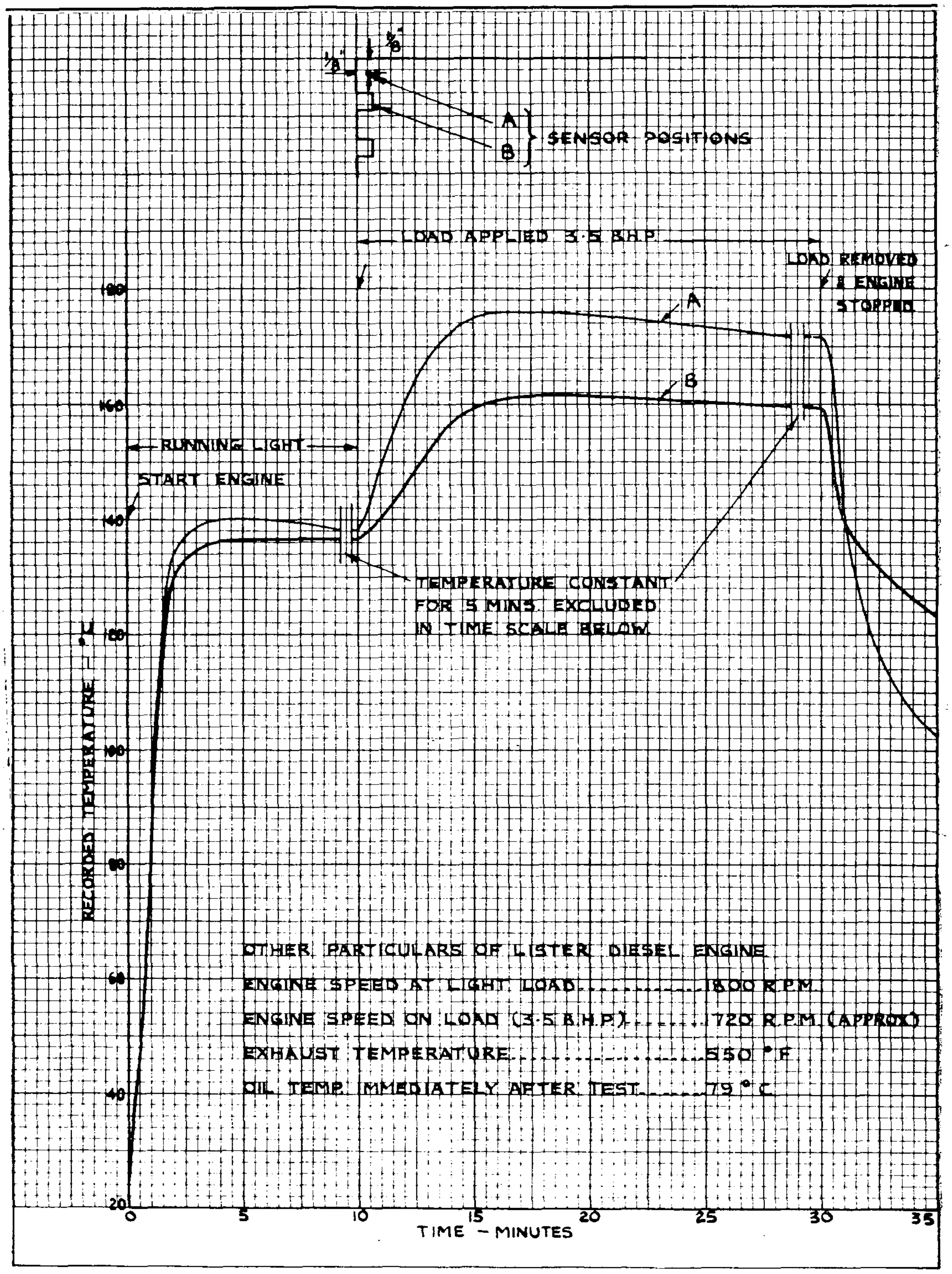

FIG. 5—TELEMETERED TEMPERATURES DURING ENGINE TRIALS UNDER START, LIGHT AND FULL LOAD CONDITIONS—SIMULTANEOUS OPERATION OF TWO CHANNELS

channels had been reduced to an insignificant value by the transmitter output filters and the receiver selecting filters.

When reassembled in the engine the transmitters were connected to temperature probes sited (*a*) near the perimeter of the crown and (*b*) just inside the upper groove base. The results for a half-hour run, which included start, light and full load conditions, are shown in FIG. 5. Separate runs for each channel confirmed the temperature rise times soon after starting and soon after

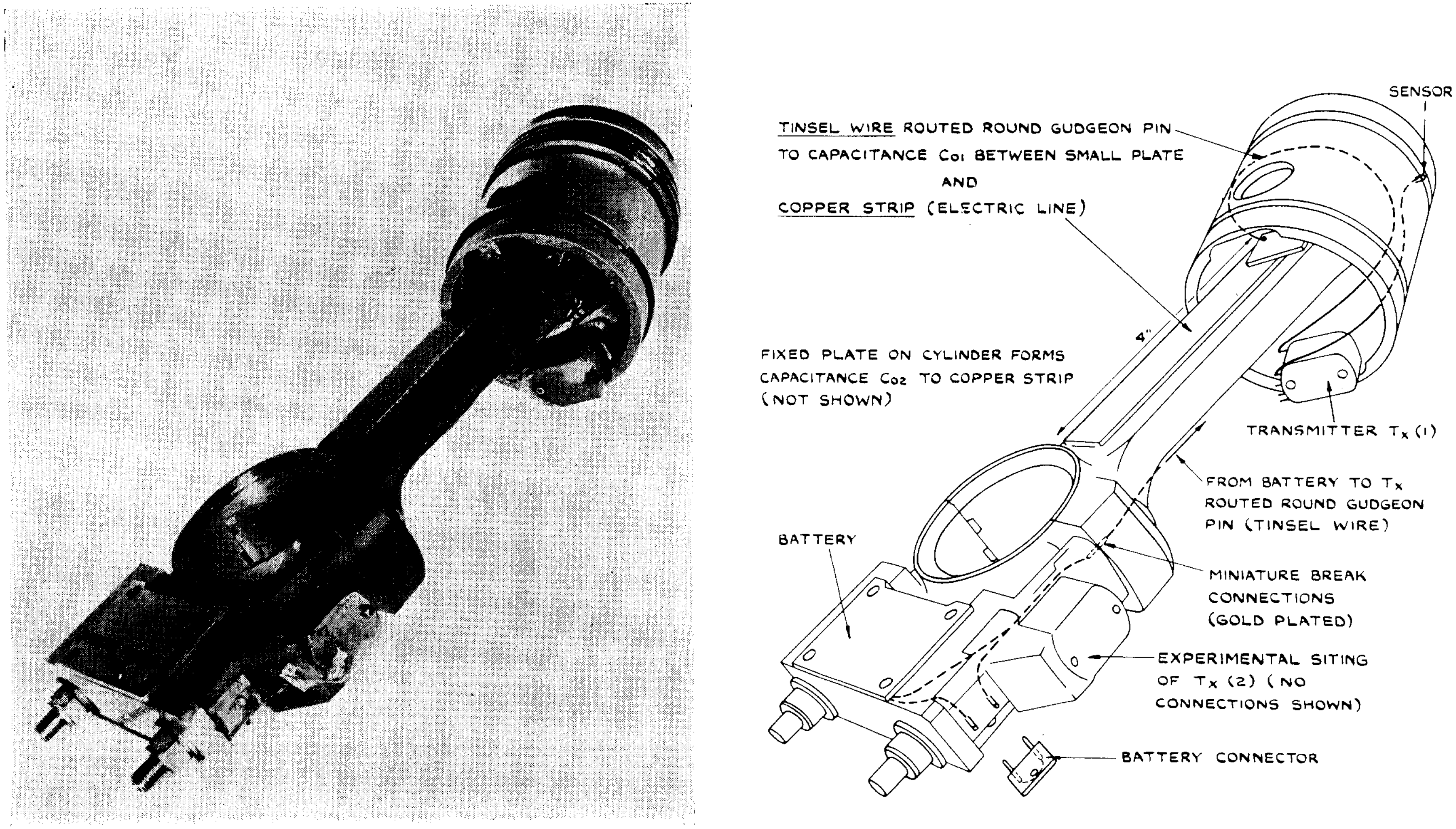

FIG. 6—LAYOUT OF SINGLE CHANNEL TRANSMITTER SYSTEM

applying the load: but the droop of a few degrees during the following ten minutes was not evident. Nevertheless the results confirm that no untoward phenomena arise during running conditions. The differences are believed to be due to slightly different running conditions and thermal distributions in the engine and in the transmitter units themselves. Regarding the latter, small monolithic designs of stable transmitters may shortly become available so that transient temperature differential between internal components of the transmitter, that occur during a rapidly changing heat condition, will not have a significant effect on the frequency measurement.

Mechanical Strength, Signal Stability and Battery Capacity

The transmitter units fitted in the Lister engine, withstood the forces encountered under light and full load conditions estimated, from stroke and rpm considerations, at $\pm$ 200g. One of the transmitters was, in fact, finally fitted on the base of the con-rod where it also experienced an impact force during every engine cycle, when plunging into the sump of hot oil.

In the original design it was intended that the transmitting part of each consist channel of a 'throwaway' probe complete in itself, i.e., containing the sensor, the transmitter and its own small battery. It was soon established that techniques at elevated temperatures were not, and still are not sufficiently well known to warrant this forward step. Instead it was decided to fit one transmitter on the piston underskirt, one on the con-rod, and the batteries for both in a housing fitted to the con-rod base. This would demonstrate possible optional sitings for these components.

The problem of flexible connections between components on the piston and their counterparts on the con-rod was solved by the use of copper tinsel wire insulated with PTFE tubing—always routed round the gudgeon pin. The PTFE tubing was anchored to frame near the ends where the tinsel wire emerged. This proved highly successful; and, to demonstrate the durability of the tinsel wire, some of the leads were duplicated, routed round the gudgeon pin, connected in series, and the engine operated for a period of five hours without the necessity for lead or component replacement.

During this test one of the transmitters was kept under close observation for stability. The frequency did not change by more than 5 kc/s, i.e., 1 degree C.

The power supply consisted of a battery of four Type RM625 Mallory cells connected in series. The maker's characteristics indicate an operating time of 60 hours for one channel, 30 hours for two channels and *pro rata* for more channels.

Further Development

It is intended to develop the system to enable eight parameters to be observed simultaneously. The only type of sensor that can be visualized at present for detecting movement in oil atmospheres and under high temperature conditions is a small, multilayer coil embedded in ceramic. The choice of high frequencies in the present system permits the use of a small value of inductance and without an iron core, the limiting value of a cored inductance being the curie point of the metal used.

Although the present design of transmitter unit is quite small, it is reckoned that a smaller one, produced by integrated circuit techniques, would have much reduced thermal delays between its constituent components thus leading to an improvement in transient measuring accuracy.

Conclusions

A system of telemetering information continuously from piston engines using frequency modulation of carriers in the band 1 to 10 mc/s and occupying

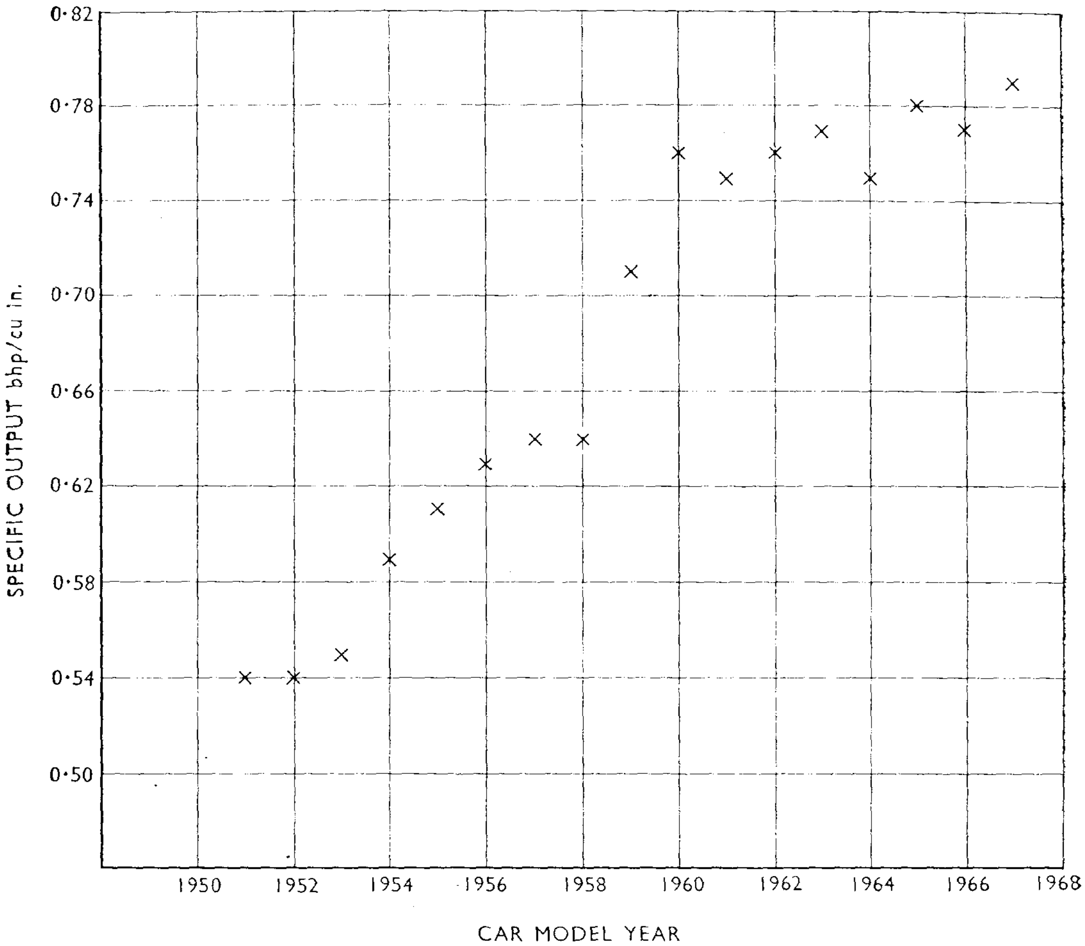

FIG. 7—AVERAGE MAXIMUM BHP/CU IN. FOR BRITISH PASSENGER CARS (MODEL YEARS 1951–1967)

1 mc/s per channel has been described and proved for two channels as regards temperature measurement. Outstanding items of which details are given in the text are:

(*a*) A micro-miniaturized transmitter, adequately stable in frequency in its own right throughout the working temperature range, 20 to 100 degrees C, and capable of being directly modulated by a thermistor sensor up to 300 degrees C or more to give an estimated temperature measuring accuracy of $\pm 2\frac{1}{2}$ per cent.

(*b*) A constant load, non-contact arrangement for sending signals from the transmitter unit via the con-rod to an external receiver.

(*c*) An optional flexible lead system consisting of tinsel wire in PTFE tubing for connecting components on the piston to those on the con-rod.

References:

[1] Goschel, K. H., Ouhne, H. P., and Stonbrenner, H. 'Piston Temperature Measurements on a high-speed, high-powered Diesel Engine', M.T.Z., 22, July 1961, p. 282 (in German).

[2] Kazachkov, R. V., 'Measurement of the piston temperature of high-speed internal combustion engines', Izmaritel 'maya Takhnika (Measurement Techniques), No. 5, May 1960, p. 25 (in Russian).

[3] Steinbrenner, H. 'Measurements to determine the piston ring flutter in high speed reciprocating engines', M.T.Z., 22, July 1961, p.261 (in German).

[4] Fearon, W., 'Effect of oil cushioning on piston operation', British Rail Symposium on Cavitation, Nov. 1965, Paper 3.

[5] STRAUCH, H., 'Subminiature inductive transducers with high carrier frequencies', International Telemetering Conference, Washington, 1965.

[6] Westbrook, M. H., 'A telemetering system for piston engine research', International Telemetering Conference, London, 1963.

[7] Essers, E., Essers, U., and Heyer, G., 'Concerning the Measurement of Piston Temperatures' M.T.Z., June 1966, p. 260, and September 1966, p. 355 (in German).

[8] Bowes, R. C., 'A new linear delay circuit based on an emitter coupled multivibrator', Proc. I.E.E., Vol. 106, Part B, Suppl. No. 16, 1959.

[9] Unpublished B.P. Research report.