# Active element in submerged repeaters: first quarter century

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*Indexing terms:* *Repeaters, Submarine cables, Telecommunication equipment*

## Abstract

The review links the development of British submarine telephony during the last 25 years with the development and production of the active elements, thermionic valves and silicon planar transistors, in the submerged repeater amplifiers. These devices have played a major role in determining the performance, capacity and reliability of all submarine transmission systems. While concentrating on the work of the British Post Office Research Department the complementary role played by industry, and by Standard Telephones and Cables in particular, is recognised. British effort has been encouraged and stimulated throughout by the other major submarine development organisation, Bell Telephone Laboratories in the USA. The development in France of active devices for submarine systems has also been noteworthy. The work on oxide-cathode thermionic valves between 1950 and 1965 is mainly the history of a research and development effort aimed at improving the electrical reliability of the devices. Only in the latter part of the period was any major attempt made to improve valve performance and, consequently, the capacity of submarine systems. The use of systems incorporating valves extends from shallow-water cables around the UK to transatlantic and trans-Pacific cables which have completed a transmission link more than half-way round the world. The target of a 20-year system life, free from failures arising from the decay or collapse in the performance of the valves, has already been achieved for one of the early systems. One of the major links (CANTAT-1, between the UK and Canada) has now passed the 14th year of service satisfactorily. The era of silicon planar transistors, replacing the thermionic valves in submarine systems, started in 1961 and is still continuing. The twin targets of improving performance and reliability were equally stressed during the whole period from 1961 to date. The success in improving device performance is demonstrated by the capacity of the early transistorised systems, 640 (3kHz) circuits, almost double that achieved in the last valve system. Transistor performance has improved still further to provide 1840 circuits in the last transatlantic cable (CANTAT-2, laid in 1974) and later device developments will more than double this figure. The importance of this achievement rests, however, on the maintenance of ultrahigh reliability as an essential feature of performance improvement. An advanced technique for reliability assessment has enabled predictions of less than one active-element failure in a system life of 20 years to be made. It has only been possible to reach this level of reliability by careful design of the transistor and of the processes by which it is made, supplemented by a rigorous system of quality control imposed on materials, piece parts and assembly techniques. Experience of the first eight years of operational use on the sea bed is supporting the reliability predictions. For the future, it is believed that the foundations necessary to support the British effort in this important area of international communications have been well laid. Nevertheless, technical innovation is needed more than ever before to maintain a competitive position in the face of increasing overseas interest in the art of submarine telephony.

## 1 Introduction

Although the development of submarine telegraph cables has a history extending well over a hundred years, it was not until 1944 that the provision of carrier telephone circuits was attempted over a submarine cable incorporating a submerged repeater.[1] The key feature of this type of repeater is the amplifier using, at first, thermionic valves as the active elements and, later, transistors. The importance of the innovation lay in the promise it gave of high-capacity telephone cables over long sea routes, leading ultimately to transoceanic systems.

The history of the growth of submarine telephony from 1944 to the mid-1960s can be closely linked with the development of the oxide-cathode thermionic valve in performance and reliability. The even greater growth rate in the last eight years is, in turn, linked with the performance and reliability of the silicon planar transistor. During the whole of both periods, the UK has played a unique part in the development of these active elements and has maintained its position in the forefront of technological progress. This success has been due, in part, to the efforts made first by the Thermionic Group and, more recently, by the Transistor Development and Production Unit, both of the British Post Office Research Department at Dollis Hill. These efforts were supported throughout by parallel and complementary industrial teams at the STC Valve Division, Paignton, and at STC Semiconductors Ltd., Footscray (now ITT Semiconductors Ltd.), when transistorised repeaters were introduced.

In this review, the sequence of technological development in the British Post Office valve and transistor teams will be described and linked with the STC effort and also, more generally, with attempts to improve the overall efficiency of submarine telephony. The British effort has kept pace with parallel developments in the Bell Telephone Laboratories and in France with one important divergence. In the UK, silicon transistors replaced valves in 1965. In the USA, germanium devices were used first to replace valves in submarine systems and silicon transistors will not appear until 1976.

During the period of the review, some 26 years, two common threads of effort can be identified. The first of these remained in the forefront throughout, and arose from the fact that submerged repeaters lie on the sea bed for the operational life of the system. Consequently, it is essential for all components, and for the active element in particular, to have exceptional reliability. This thread is closely linked with the development of reliability-assessment techniques which can be used as short-term tests (not more than six months) to predict long-term behaviour. In this way some guarantee of device reliability can be provided as part of the overall system-reliability specification.

The second thread, which developed during the latter half of the 26-year period, is the effort to develop devices capable of amplification at ever-higher frequencies. In this way the capacity of the submarine cable, measured in the number of both-way speech channels per cable, has been increased thirtyfold during the quarter century, with a consequent reduction in the cost per channel mile, and further improvement is still possible. It was essential, however, that each improvement in frequency performance should be achieved without any loss in reliability. As operation at higher frequencies involves, for both valves and transistors, designs with smaller linear dimensions, and since in many respects the maintenance of reliability becomes harder as size diminishes, so the pursuit of the twin targets of performance and reliability has become progressively more difficult as the demand for higher-capacity cables has grown.

## 2 The early years (1944–50)

### 2.1 The development programme decision

The first submerged repeater, in 1944, was laid in a cable in the Irish Sea and this was followed by a further single repeater inserted in the Lowestoft-Borkum cable in 1946. A system was developed by STC and used in 1950 to provide 36 (4 kHz) both-way circuits in each of two submarine cables between the Netherlands and Denmark. A standard British Post Office submarine system was developed and laid between 1950 and 1951 when four repeaters produced by Siemens were inserted in each of two prewar cables linking Aldeburgh with Domburg in the Netherlands.[2] After insertion, each cable provided 60 (4 kHz) both-way telephone circuits. The repeaters

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incorporated an amplifier common to both directions of transmission together with the necessary directional filters. A d.c. method of power supply was used, with all the repeater h.t. circuits, and the valve heaters, in series with the cable centre conductor.

All these systems (except the STC) used a batch of commercial valves, made in 1942 and coded CV1065, as active elements in the repeater amplifier. The electrical performance of this valve type was quite conventional: $g_m$ (mutual conductance) = 6·8 mA/V at $I_a$ = 6 mA, $V_a = V_{g2}$ = 200 V, $C_{IN} + C_{OUT}$ = 15·3 pF and $C_{ag}$ = 0·005 pF

The stability of mutual conductance with time was, however, exceptionally good, showing a fall of only 22% during the first 33 000 h operation in the life-test laboratory. Similar batches of the same valve type made by the same manufacturers in 1943, and batches made by other manufacturers, showed inferior life characteristics. Some comparative curves are given in Fig. 1.

As soon as it was realised that the long-term stability of the 1942 batch was exceptional and not easily repeatable, either by the same or different manufacturers, an attempt was made to gather together all existing stocks of the 1942 production. Only 150 samples were collected, a total quite insufficient for any extended programme of submarine-system development.

It was therefore decided as early as 1946, that a development programme should be started in the British Post Office Research Department aimed first at elucidating the principal causes of valve deterioration, second, at the prediction of valve life from short-term tests and finally at exploiting these results in the design and production of submerged repeater valves.

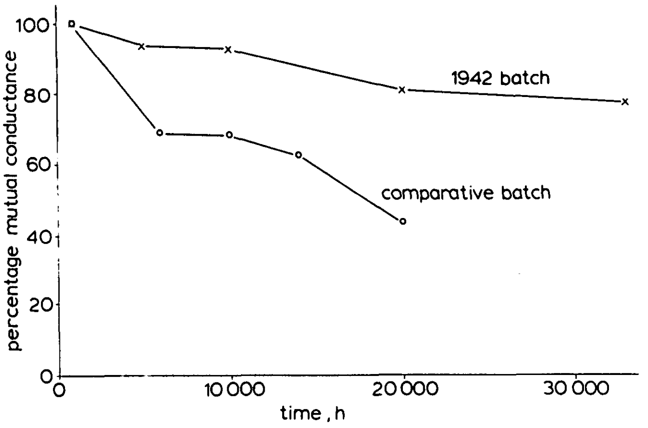


**Fig. 1**
*Comparative life-test characteristics of CV1065-type valves*

### 2.2 First valve design

To implement the development programme decision, it was considered essential to establish a small-scale valve-production unit. This unit would use, at first, standard valve designs to test the ideas, suggestions and theories which would arise in the course of the work. Although some success had been achieved with one batch of CV1065 valves, this was not due, it was thought, to any special virtue of the dimensional design of the electrode structure. In any case by the mid-1940s the CV1065 was being replaced in many applications by the CV138, a miniature valve on a B7G or 'button' base. Choice of the CV138 design as a first standard would make it possible to use electrode piece parts that could be easily available commercially and this advantage would eliminate the necessity of providing an in-house piece part construction facility.

The CV138 was one of the most successful general-purpose pentode valves ever designed with wide applications in telecommunications and the armed services. It had a smaller cathode and heater wattage than the CV1065, but otherwise had a similar performance. The lower heater rating was particularly advantageous in view of the overall voltage limitation of submarine systems. One major variation on the CV138 design was, however, incorporated into the British Post Office standard design. It was felt that the glass envelope and base should be changed from the miniature versions of the CV138 to the more conventional large-bulb glass-pinch, press-and-drop seal, top-cap control grid and octal base of the preceding generation of thermionic valves. The reason for this decision lay in the desire to reduce bulb temperature, for it was considered that a lower temperature in this part of the valve structure would probably favour the long-term stability of the major valve parameters. The drop seal was also felt to be more reliable than the button-base ring seal.

Until 1950, this standard design, coded 6P4, was used for most of the valves manufactured at Dollis Hill (a 6·3 V heater pentode of design mark 4). None of these valves were ever used in any submarine system as their mechanical design was not robust enough for operational use. Later versions of the design, the 6P7- and 6P10-type valves, were used in shallow-water submarine systems and the developments leading to these types will be described later. The typical electrical performance of the 6P4, 6P7 and 6P10 types at a nominal heater voltage was:

$$g_m = 6.4\,\text{mA/V}, \quad V_{g1} = -1{\cdot}8\,\text{V} \quad \text{at } I_a = 8\,\text{mA} \quad \text{and}$$
$$V_a = V_{g2} = 250\,\text{V}$$
$$C_{IN} + C_{OUT} = 12{\cdot}5\,\text{pF}, \quad C_{ag} = 0{\cdot}008\,\text{pF}$$

However, the 6P7 and 6P10 type valves had greater mechanical reliability than the 6P4. In particular, the diameter of one of the mica supports for the electrode structure was increased to allow metal 'snubbers' on this mica to meet the side walls of the glass bulb. This change gave a degree of lateral stability to the electrode structure which was not possible in the 6P4-type valve. The mechanical aspects of reliability in thermionic valves were being studied elsewhere at about this time,[3] in the attempt to produce 'trustworthy' or rugged valves which would give trouble-free service under conditions of vibration and shock. As a more mechanically stable and vibration-free environment than the sea bed would be difficult to find on earth, this aspect of reliability did not receive prime emphasis in the work at Dollis Hill. Nevertheless, submarine systems needed valves of good mechanical strength to survive handling during manufacture and validation, and the shocks of repeater laying. For these reaons, the problem of providing an adequate and reliable mechanical structure received continual attention as more efficient valve types were designed, developed and produced.

### 2.3 Cathode failure due to gas: the first problem

When the first submerged repeater was laid, the oxide-cathode thermionic valve had been in use for about 40 years. The adoption of improved pumping methods and gettering techniques had, by 1940, made possible the achievement of a vacuum in the valve which approached the level of measurability. It was still possible, however, that the low level of residual gas could adversely affect valve life. Consequently, the first efforts to improve electrical reliability, in terms of the stability of operating parameters, were directed towards the problem of gas attack on the oxide cathode.

The cathode consists of a granular matrix of barium and strontium oxides, about 0·06 mm thick, sprayed on a hollow metallic core which encloses the insulated heater. Its activity, or ability to emit electrons, is dependent on the amount of active barium in equilibrium with the bulk oxides of the matrix. The most important parameter showing change during life is the electron current flow through the core and matrix into the vacuum and then to the anode. In a well processed valve, operating at a temperature around 1000 K, the cathode will emit a saturated total emission current of the order of $2\,\text{A cm}^{-2}$. In the 6P4 type, as in other similar valves, only about 1% of this current is modulated by the signal applied to the control grid and is ultimately collected at the anode. The anode current is, in fact, space-charge-limited by an electron cloud at a potential minimum just off the surface of the cathode. This phenomenon contributes in no small measure to maintaining the stability of performance during life. Substantial changes in total emission can occur, but these cause much smaller changes in space-charge-limited performance due to electron reserves in the space-charge cloud.

The generally accepted view, at this time, was that the life of the oxide-cathode valve was dependent on the cathode loading, i..e on the magnitude of the space-charge-limited cathode current density. A high density might, for example, decrease the emission of the cathode by electrolytic removal of active barium. A somewhat different approach was taken by the research department where early results emphasised the importance of the ionisation of residual gas produced by the electron-current flow outside the cathode. The ionised residual gas, it was felt, reduced the level of active barium in the cathode matrix and so reduced the electron emission from the cathode.

It was shown quite clearly[4] that a commercial pentode, with a relatively short life under normal connection, survived for a much longer period when connected as a diode using the control grid as collector. In a small batch of these valves, triode connected with 200V applied to the anode, screen and suppressor, the cathode current diminished to 30% of its initial value in 1500 h. In a similar batch, diode connected with 2 V on the control grid, the initial current of between 11 and 13 mA remained substantially constant for 6000 h when the experiment was terminated. The two conditions differ in that, as a triode, the residual gas is ionised and the cathode is subjected to high-energy-positive-ion impacts, whereas in the diode state the cathode only suffers the random impacts of neutral residual gas atoms. This effect is conveniently shown in a shorter time under total emisison conditions (i.e. at a lower cathode temperature) by assembling a diode and a triode in the same envelope using opposite sides of the same cathode (see Fig. 2). Here, the anode voltage was 250 V and that of the diode, 3 V.

This experiment not only directed attention to the importance of residual gas but also emphasised that it was the directed flow of gas ions to the cathode which constituted the real danger to valve life. These results were reinforced by an investigation into the voltage-dependent poisoning effects which are also found in the oxide-cathode valve.[5] Surface films on, for example, the control grid can be dissociated by electron bombardment above a threshold voltage, fixed by the heat of formation of the surface film. The products at decomposition of the film can adversely affect the cathode emission and the result can be seen as an abrupt discontinuity in a smoothly rising curve of cathode current against electrode voltage, as the threshold is passed (Fig. 3).

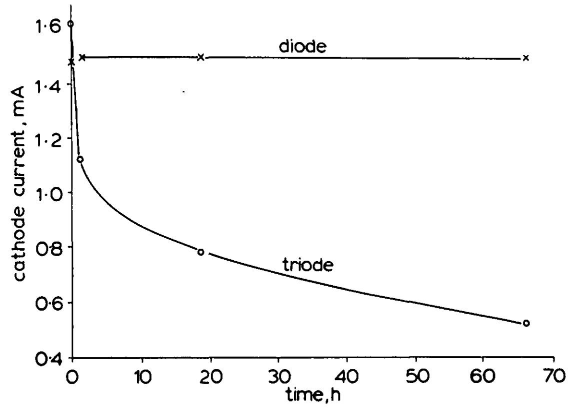


**Fig. 2**
*Demonstration of effect of ionised residual gas on cathode activity*

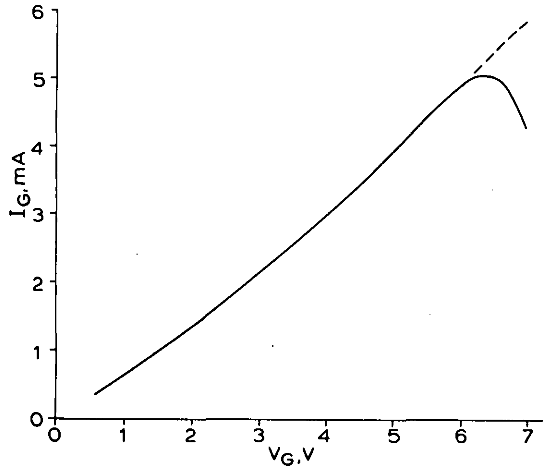


**Fig. 3**
*Effect of surface-film breakdown on cathode current*

As a result of these investigations, two important topics clearly required further attention: first, how could the potential danger to valve life be measured and secondly, how could it be diminished.

### 2.4 Measurement of gas attack

The first attempts to measure the potential danger of cathode deterioration due to gas attack was directed towards the measurement of the gas itself. Triode and pentode valves can be used as ionisation gauges to measure the residual gas pressure within their own envelopes. The positive-ion current mentioned in the previous Section divides between the cathode and the control grid and the proportion flowing to the latter is measured as the reverse grid current ($I_{rg}$). In the triode connection, with an anode current $I_a$, the gas pressure in the valve $p$, is expressed as a vacuum factor $k$ where

$$k = I_{rg}/I_a = cp \qquad (1)$$

and $c$ is a constant and a function of the valve geometry.[6]

It is of interest to examine the variation of $k$, and therefore of $p$, with time. Typical characteristics for CV138-type valves and 6P4-type valves are shown in Fig. 4. Both curves fall to a constant level of $k$ equal to $k_0$ in due course and $k_0$, defined as the residual vacuum factor, can be shown to be of the same order for all valves, irrespective of type, provided the anode voltage is the same. The integral $\int_0^\infty k dt$ is used as a 'gas' integral proportional to the amount of gas driven into the cathode. Hence, in Fig. 4, a much more severe gas attack is suffered by the CV138 than by the 6P4. On a larger-scale test a comparative study of two batches of a common valve type showed that the batch with the larger gas integral had a much shorter average life than the one with the smaller gas integral.

In spite of this facility of measuring the gas attack in terms of the gas integral, using the reverse grid current as a probe, there are difficulties. The nature of the gas is not identified. Two gases with the same gas integral could cause different degrees of damage to the cathode. To eliminate uncertainties due to this cause it is better to measure the degree of damage directly in terms of the change in cathode emission unmasked by the space-charge cloud of electrons. A measurement of total (or temperature-limited) emission is therefore needed.

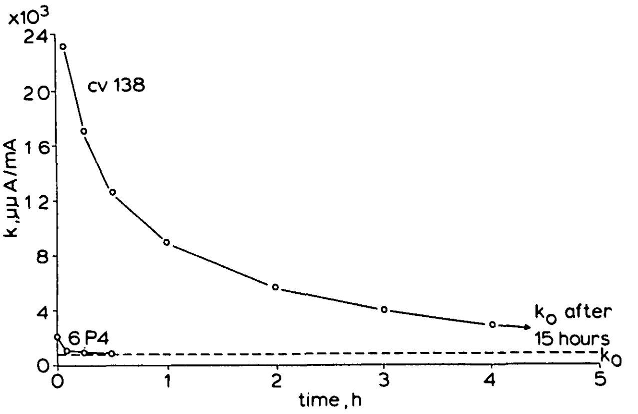


**Fig. 4**
*Gas integrals for batches of CV138-type and 6P4-type valves*

$V_a = V_{g_2} = 250\,V$

At normal operating temperatures for the cathode, to avoid excessive heat dissipation, total emission can only be measured by high-voltage pulse techniques. Such techniques would, however, disturb the system they were attempting to assess in an unacceptable way. As an example, the breakdown of films on the collecting electrode, or the temperature outgassing of components inside the valve envelope, might both contribute to the gas attack that the pulse measurement was attempting to quantify.

This difficulty is avoided by using d.c. measurement at low cathode temperatures and low collector voltages. The chosen measuring conditions incorporate electron collection at the control grid with a positive potential of 5 V applied, relative to cathode, and a heater voltage of 2 V (for a normal 6·3 V heater). With this heater voltage the cathode temperature is around 700 K. Under these circumstances, there is no film breakdown on the collector, no ionisation of residual gas, no excessive heat dissipation and no degassing of component parts. In addition, the low cathode temperature substantially freezes the ionic equilibrium within the cathode matrix in the state obtained at the normal temperature immediately before measurement. For these reasons, this method was chosen as the preferred technique for assessing the magnitude of gas attack on the cathode in the early years.[4]

There is some difficulty in extrapolating these low-temperature[7] emission measurements up to the normal operating temperature of around 1000K, but a good case can be made for the quantitative equivalence of proportional changes at low and normal temperatures. The curves in Fig. 5 show mean and typical total emission/time characteristics for CV1065- and 6P4-type valves. The peak value of the emission current was of the order of 1 or 2 mA in either case. The mutual conductance ($g_m$)/time characteristic of the CV1065 is also included in the same Figure and this shows the effect of the space-charge cloud in providing a reserve of emission. Despite a fall in emission at 3000 h to less than 20% of the peak value, the mutual conductance remains substantially constant, only to collapse when the emission falls below the 10% mark.

### 2.5 Reduction of gas attack

There are three basic processes which contribute towards improving the vacuum within the valve envelope, preprocessing of piece parts, pumping and ageing. The first of these involves treatment of the metal parts of the valve structure before assembly, in ways which reduce both the adsorbed and absorbed gas. Processes include washing, hydrogen stoving and vacuum outgassing. During these early years standard techniques were used.[6]

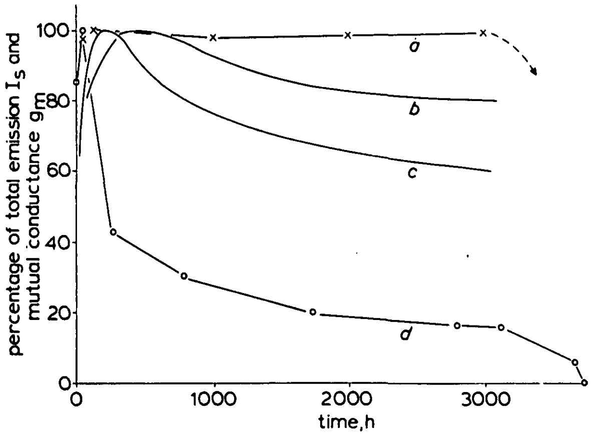


**Fig. 5**
*Mean and typical low temperature total emission/time characteristics and related space-charge limited life curve*

*a* $g_m$ life curve for typical CV 1065 (non-1942) type valve
*b* Typical 6P4-type emission characteristic
*c* Mean CV1065 (1942) emission characteristic
*d* Emission characteristic for valve *a*

The pumping process is divided into two parts, first external pumping using conventional pumps, an oil diffusion pump backed by a rotary pump, which, after several hours, reduces the pressure to $1{\cdot}10^{-6}$ mmHg. Secondly, internal pumping, using a getter fired just after sealing off the envelope, can be used to reduce the pressure still further. Work was done on gettering efficiency[8,9] and a barium-flash getter was chosen as being the most satisfactory at this stage of the development.

Finally, the third basic process is the 'ageing' of the valve where an attempt is made to associate all the residual gas with the getter. This gas may be spatial, adsorbed on the electrode structure, absorbed in piece-part components or even locked as a chemical-compound film on electrodes. Gas from all these locations must be moved, during ageing, to the getter and this is done by temperature outgassing by electron bombardment and by maintaining the gas at a high level of thermal energy to keep it moving until permanent getter absorption is achieved. During this sequence, the cathode is maintained at an abnormally high temperature (1250 K) to prevent it acting as an auxiliary getter and care is taken to avoid high pressure peaks throughout.

When all of these techniques were used to reduce the magnitude of gas attack, some very satisfactory emission/time characteristics were obtained for the 6P4-type sttucture. Confidence was gained, and the more robust version (see Section 2.2) of the 6P4 was designed and produced on a limited scale. This new valve was known as the 6P7-type; 18 were used in the 60 (4 kHz) circuit Dartmouth-Guernsey number 2 and 3 cables which were laid in 1952. There were three repeaters in each cable and the systems survived without faults for eight years, after which time the valves started to show failures in gain and noise.

The 6P7-type valve used the same electrode structure as the 6P4, i.e. that based on the CV138-type valve, and, in particular, used the standard nickel-cathode core. Its external dimensions and base were also the same as those of the 6P4. However, towards the end of the decade a new form of failure was identified and associated directly with the cathode core. This new hazard eliminated any hope of completely solving the long-term stability of electrical performance based solely on reducing the gas attack. It also terminated production of the 6P7-type valves after the completion of the Dartmouth-Guernsey exercise. The type was never used again. The new failure mechanism will be considered in the next Section where it will be shown that the solution of this aspect of the general problem required a new generation of thermionic valves.

## 3 Thermionic valves for the first translantic telephone cable (1951–56)

### 3.1 Transoceanic telephone

At the same time as the events recorded in the previous section, similar work was in progress in the USA. Bell Telephone Laboratories had developed their first submarine system which was laid between Key West and Havana in 1950. For this project two cables were used, one 'go' and one 'return'. Unidirectional amplifiers were used in repeaters inserted in each cable. This design is in contrast with the British design where a single cable is used for both directions of transmission with one amplifier, and appropriate directional filters, in each repeater. The Bell amplifiers used thermionic valves with a mutual conductance (1 mA/V) much lower than that of the 6P7-type valve and, consequently, the available band width was smaller. Nevertheless, confidence on both sides of the Atlantic grew and negotiations between the British Post Office and the American Telephone and Telegraph Company concerning a transatlantic telephone cable were started in 1952. A target completion date of December 1956 was ultimately chosen for the opening of service between the USA and the UK. This background of a great new international venture greatly stimulated valve development in the British Post Office in the first half of the nineteen fifties.

### 3.2 New failure mechanism : interface resistance

During the latter half of the nineteen forties, it became well known that a resistive interface could develop between the cathode matrix and the supporting core of oxide-cathode thermionic valves. Conventional cores were made from nickel with a 0·05 to 0·10% impurity content of reducing agents, including silicon. The silicon reacts with the barium-strontium-oxide matrix in a manner suggested by the following chemical equations:

$$\mathrm{Si} + 2\mathrm{BaO} \longrightarrow \mathrm{SiO_2} + 2\mathrm{Ba}$$

$$\mathrm{SiO_2} + 2\mathrm{BaO} \longrightarrow \mathrm{Ba_2SiO_4} \qquad (2)$$

The final product, barium orthosilicate, forms a resistive interface layer between the matrix and the core which inserts a series resistance in the cathode circuit and reduces the mutual conductance of the valve at a given current according to the equation

$$g_m = \frac{g_{m_0}}{1 + g_{m_0} R}$$

where $R$ is the resistance of the interface and $g_{mp}, g_m$ are the values of mutual conductance before and after interface growth. The layer is only a few micrometres thick and consequently, under a.c. conditions, its own capacitance shunts the interface resistance. This property suggested a technique for measurement of the resistance[6] based on the measurement of valve gain at high and low frequencies with the resistance alternately shunted or not shunted by its own capacitance. Resistances between 0 and 50 Ω, on sample valves of type 6P4, were measured using this technique.

The growth and properties of interface layers were explored[10] and the effect of the layers on representative batches of valves was examined.[11] It was found that the thickness of the interface did not progressively increase with time as did the interface resistance. The latter increase was found to be due to an increase in the resistivity of the layer which corresponded to the deactivation of a semiconductor. Indeed, the linearity of the plot relating the interface resistance to the reciprocal of absolute temperature is characteristic of a semiconductor and the derived activation energy is similar to that associated with the barium-strontium-oxide matrix. Growth of the interface resistance is stimulated by higher heater voltages and by higher concentrations of silicon in the cathode core. In addition, growth is enhanced as the cathode current is diminished.

Work on commercial CV138-type valves showed that widely differing rates of deterioration of mutual conductance could be obtained in practice and some typical curves are shown in Fig. 6. As the growth of resistance is associated with deactivation of the physical layer, it was considered possible that the deactivating agent could be identified with the residual gas in the valve envelope. However, it was soon found that no improvement in pumping or processing could guarantee freedom from this failure mechanism and it seemed more profitable to move away from conventional cathode cores towards a new type which was entirely free from silicon.

### 3.3 Passive-cathode core

The growth of interface resistance had been identified with the presence of silicon as an impurity in the cathode core and a nickel core entirely free from silicon might be expected to provide an improved performance. However, as gas attack in general, and oxygen attack in particular, are hazards which thermionic cathodes must face, it might be even better to use a noble metal, which cannot be oxidised, for the cathode core material. Platinum was an obvious choice.

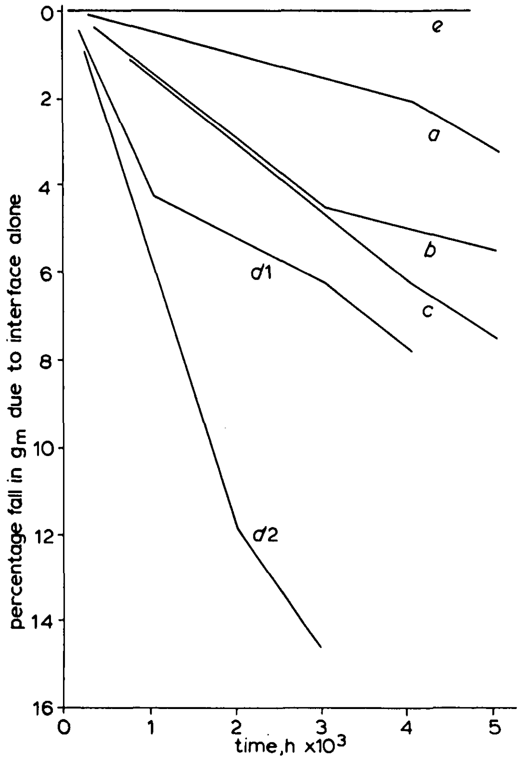


**Fig. 6**
*Fall in mutual conductance during life for typical batches of CV138-type valves, due to interface resistance growth alone*

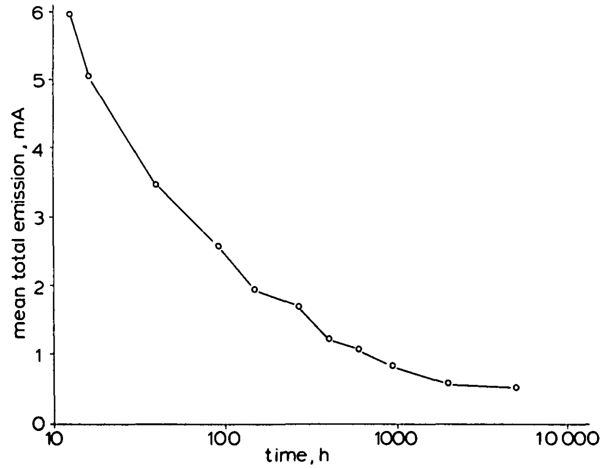


**Fig. 7**
*Oxide cathode on platinum core*

Fall in low temperature total emission under zero current load at normal cathode temperature

An investigation of the use of platinum and passive nickel (i.e. with an activity between $10^{-1}$ and $10^{-2}$ of that of conventional active nickel) was undertaken and a comparison with the standard active core made.[12] Much useful information on long-term emission performance was provided. The results, using a platinum core, were especially valuable as a simple model of cathode action and could be constructed without the complications introduced by the oxidising and reducing properties of the active nickel core. Throughout the work, the low temperature method for measuring total cathode emission was employed for most assessment needs (see Section 2·4 above).

It was discovered that, under zero current load and normal cathode temperature, an oxide cathode on a platinum core showed a progressive fall in low-temperature total emission from approximately 6mA to 0·5mA in the first 5000h of operation (Fig. 7). This decay could be due to a reduction in the level of active barium through the action of residual gas: it could also be due to loss of active barium by either evaporation or core solution. Strong experimental evidence was provided which indicated, first that the decay was substantially independent of gas evolution from components within the valve envelope and, secondly, that evaporation loss is not predominant in the first hundred hours of the decay. Core solution was thus isolated as the major factor responsible for early emission decay which, however, did not occur at cathode temperatures less than 800K and which was enhanced at temperatures greater than 1020K. This characteristic is due to barium mobility in the matrix and its very low values below 800K.

The action of oxygen on a platinum-core oxide cathode was significant. The space-charge-limited current of a diode was reduced to a level of some 8% of its original value by pure-oxygen poisoning. The oxygen atmosphere was then pumped away, the envelope sealed and the getters flashed. The cathode was then run at normal temperature under zero current load, but very little improvement was detected. A rapid and complete recovery in about 10min was, however, observed as soon as continuous cathode current was drawn (Fig. 8). Without the aid of cathode current, which is assumed to produce active barium by an electrolytic process, dispensation of barium from the cathode core will produce recovery in a much longer period; about 1000h instead of 10min.

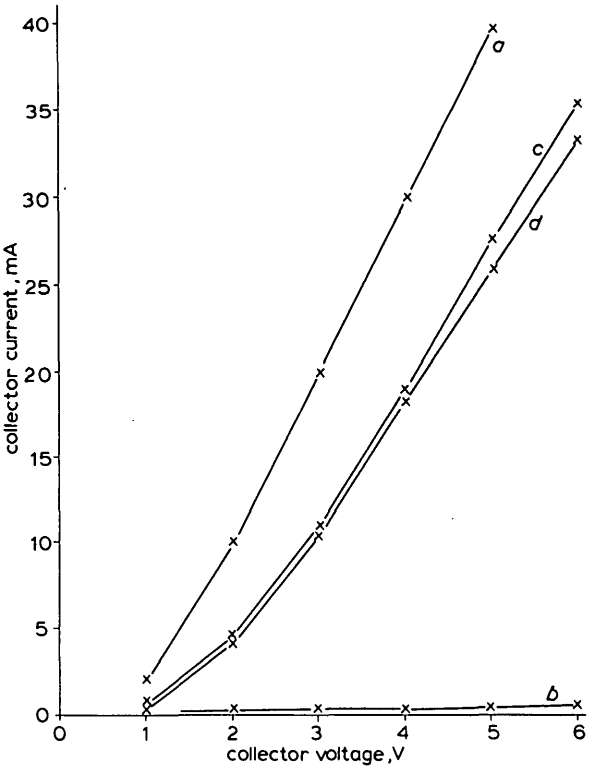


**Fig. 8**
*Voltage/current characteristics before oxygen attack and after attempt at recovery*

*a* Nickel before attack
*b* Nickel after attempted recovery
*c* Platinum before attack
*d* Platinum after recovery treatment

When a passive nickel core is used, only a very slight core solution of barium takes place; an absorption rate 10 000 times slower than for platinum is measured. Even more important, an oxygen attack on an oxide cathode on a passive nickel core produced an irreversible collapse of the diode voltage/current characteristic (Fig. 8). This was shown to be due to powerful oxidation of the nickel core and a consequent nickel-oxide interface layer.

The passive nickel core only differs from the conventional active nickel core in that the latter possesses strong reducing agents, in the magnesium and silicon impurities, which are capable of reacting with the matrix to provide active barium and of reducing any nickel oxide produced by oxygen attack. The unfortunate byproduct of the silicon activation sequence, the orthosilicate interface layer, has already been mentioned in the previous section.

The major conclusion, at this stage, is that the oxide cathode with a platinum core does not suffer from interface resistance growth and can recover from a serious oxygen attack under the action of cathode current flow. The electrolytic reactivation process, which is supported by the experimental evidence, suggests that the reserves of active barium represented by the bulk of the oxide-cathode matrix are sufficient to give a valve life in excess of 20 years with two provisos. The first is that the oxygen, evolved as an electrolytic byproduct, is prevented from returning to the cathode and the second is that residual gas generators within the envelope must be eliminated.

### 3.4 First deep-water valve

The advantages of a platinum core in providing immunity from interface resistance growth were so decisive that a redesign of the 6P7-type valve was undertaken for shallow-water systems. This new type, coded 6P10, had the same electrical characteristics as the 6P7 but used a platinum core. It was used in twelve submerged repeaters on the Holyhead-Dublin and Lowestoft-Hague routes laid in 1953 and 1954. These 36 valves were the last high-voltage valves (with $V_a = V_{g_2} = 250V$) used in British Post Office systems and more than half are still in service after more than 20 years operational life.

The diversion of attention to transoceanic systems made it essential to design a valve for operation at a lower h.t. voltage to meet the severe overall voltage limitation imposed by power feeding from the terminals. Consequently, soon after the 6P7 redesign, the 6P10 was, in its turn, modified by adjusting the position of the screen grid closer to the control grid to allow operation at 60 V instead of 150 V. For the output stage, however, it was still necessary to use an anode voltage of 80 V to provide the required output power. This new valve design was known as the 6P12 type.[13]

The proximity of the screen grid to the control grid did not introduce any hazard arising from internal short circuits and complete freedom from this form of fault was proved over the whole period of valve production at Dollis Hill. (The special problem of heater-cathode insulation will be dealt with later.)

At the time of the 6P12 design, the Bell organisation in the USA had a greater experience than the British Post Office in deep-water systems. It will have been noted from the earlier Sections of this review that all the British experience had been in shallow waters. For this reason the division of responsibility, in relation to repeaters and valves, for the first translantic telephone cable was arranged so that Bell designs were used for the long link between Oban and Newfoundland and British designs for the short link between Newfoundland and Nova Scotia.

To provide a proving trial for the British link, a new submarine cable was laid between Aberdeen and Bergen in 1954. This system incorporated new concepts in repeater and amplifier design and also made use of the new 6P12-type valve. The repeaters, seven in all, were designed to withstand the deepest ocean pressure. In conformity with shallow-water practice, the amplifier and directional filters handled both-way traffic. The new development was the use of two three-stage amplifiers in parallel between common input and output transformers with a single feedback network. This arrangement allows a failure in one amplifier path, including any valve failure, except a fault on the control grid of the input valve or on the anode of the output valve, without appreciably altering the overall gain. The overload point is, however, reduced by about 5dB by failure in one amplifier and there is an increase in distortion (12dB for second harmonics).

From the point of view of valve reliability assurance, the new arrangement has the substantial advantage that the catastrophic failure of any one valve (with the exceptions noted above) would not cause a system failure. Indeed, although the Aberdeen-Bergen cable is still working satisfactorily with the original vlaves, some 21 years after the laying operation, there was a period in its early life when the failure of one amplifier was suspected. The overall traffic performance was unaffected.

The success of this North Sea system gave confidence that the British section of the transatlantic cable would also succeed in meeting all specification requirements and, amongst other decisions taken, plans were made to use 6P12-type valves in the amplifiers of the British section of TAT 1 (the code name given to the overall system between Canada and Scotland).

### 3.5 Characteristics and selection techniques for the 6P12-type valve

A photograph of the 6P12-type valve is shown in Fig. 9 where it will be seen that the external structure and base are the same as those described earlier for the 6P4, 6P7 and 6P10 types. The main electrical characteristics of the 6P12 are given in Table 1. These characteristics are not those which apply at the time the valves are produced, but are appropriate after the proving-in life test (at least 4000 h) and immediately before acceptance for insertion in the repeater amplifier.

**Table 1**
ELECTRICAL CHARACTERISTICS OF THE 6P12-TYPE VALVE

| | |
|---|---|
| (i) Test condition | $V_h = 5{\cdot}5$ V<br>$V_a = 90$ V $V_{g_2} = 60$ V<br>$I_a = 6$ mA |
| Mutual conductance $g_m$, mA/V | = 6·0 (min) |
| Working point $V_{g1}$, V | = −1·6 to −2·6 |
| Reverse grid current $I_{g1}$, $\mu$A | = 0·1 (max) |
| Screen current $I_{g_2}$, mA | = 1·35 to 1·90 |
| Anode impedance $r_a$, k$\Omega$ | = 300 (min) |
| (ii) Test condition | Valve cold, no voltages applied |
| Input capacitance $C_{IN}$, pF | = 9·5 (max) |
| Output capacitance $C_{OUT}$, pF | = 9·5 (max) |
| Anode-control grid capacitance $C_{ag}$, pF | = 0·03 (max) |
| (iii) Test conditions | $W_h = 500$ mW<br>$W_{g1} = 5{\cdot}0$ V |
| Total emission $I_{g1}$, mA | = 0·2 (min) |

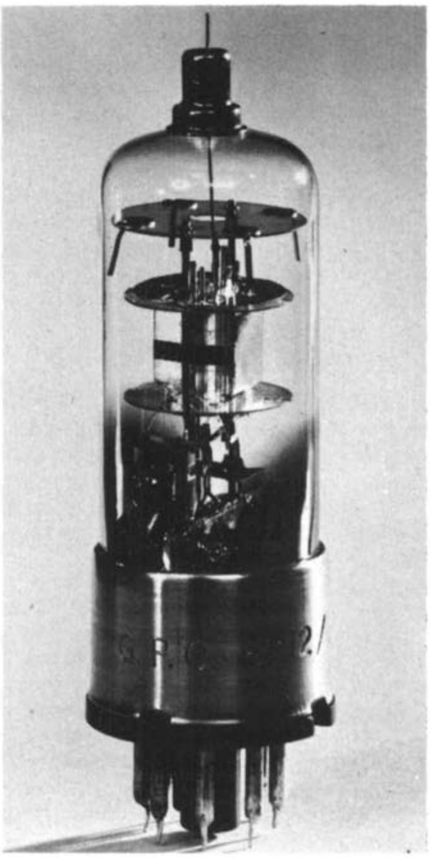


**Fig. 9**
*The 6P12-type valve*

The reliability of the new valve type was, however, as important as the electrical performance. The general life behaviour of any valve type can best be assessed by running a production batch of valves over a substantial period under operational conditions and by extrapolating to the future on the basis of experience and a well understood model of cathode action. Before this could be done for the 6P12-type, one important operational parameter remained to be settled: the heater voltage. It was known that, over a range of heater voltage from 4·0 to 6·0 V, there was only a marginal change in amplifier performance at zero time. It was also realized, however, that the change in performance with time would depend on the heater voltage, which would in turn determine the cathode operating temperature.

A series of life tests were, therefore, initiated to guide the choice of a suitable heater voltage and five batches of 6P12-type valves were placed on tests at $V_a = 90$ V, $V_{g_2} = 60$ V, $I_a = 6$ mA and $V_h = 4{\cdot}0$, 4·5, 5·5, and 6·0 V, respectively. The results were conclusive. At $V_h = 6{\cdot}0$ V, after 3000 h, excessive negative grid current developed and at values of $V_h$ lower than 5·5 V the trends in mutual conductance and working point were unsatisfactory. The best results on all parameters were recorded at $V_h$ = 5·5 V and this value was chosen for system use. At the time of the first TAT system, three year life tests on a batch of 92 6P12-type valves at this heater voltage had been completed and the results gave grounds for optimism (Fig. 10).

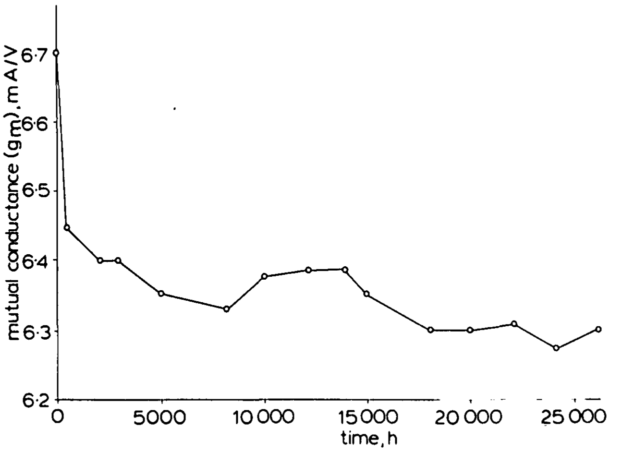


**Fig. 10**
*Behaviour of a batch of 92 6P12-type valves over a period of three years*

$V_a$ = 90 V, $V_{g_2}$ = 60 V, $I_a$ = 6 mA, $V_h$ = 5·5 V

The work on platinum cores reviewed earlier had provided a firm base on which extrapolation of life-test results could be attempted with some confidence. In addition, at about this time, further work was done[7] on the relationship between cathode emission, cathode resistance and mutual conductance in therminonic valves. Enough success was achieved to permit the conclusion that the trend in mutual conductance with life for 6P-type valves, which were not subject to interface resistance growth, could be explained by measured changes in total emission and cathode bulk resistance. Nevertheless, great reliance was placed on the safety introduced by having parallel amplifiers. In this connection a system for shunting the heaters was developed which served two functions, first, to trim the heater wattage to within acceptable tolerances of the chosen norm (corresponding to a heater voltage of 5·5 V for the average heater-coil resistance) and, secondly, to provide an electrical path for the heaters of the alternative amplifier should any heater become open circuit.

A very comprehensive test procedure was used to assess the performance and reliability of individual valves and to select those needed for the system. The valves were required to pass a production specification at the time of manufacture and, if successful, were placed on operational test on life test racks under static conditions appropriate to that stage of the amplifier in which they would be used. This test continued for at least 4000 h and the stability of the main electrical parameters was monitored throughout. Only those showing satisfactory trends were accepted as potentially suitable for use. Three other tests were then applied at the end of this life test. First, all valves were required to pass a conventional acceptance specification which included, among others, all the characteristics noted in Table 1. (The clauses in Table 1 are appropriate to the output stage of the amplifier. Different limits and test conditions apply to valves intended for the first two stages). Secondly, every valve was tested in a functional circuit simulating the stage of the amplifier in which it would, if satisfactory, be used. Here, additionally, measurements of noise and harmonic generation were made and compared with a functional specification. Thirdly, every valve was subjected to a detailed visual inspection where some 80 constructional features were checked. Final acceptance for system use was subject to successful completion of all these tests.

There are 16 repeaters in the Newfoundland-Nova Scotia link of TAT-1 and the system was brought into service in 1956 with a capacity of 60 (4 kHz) speech channels. The 96 valves have been fault free after almost 20 years of operational life on the sea bed.

### 3.6 Other contemporary developments

The thermionic valves of type 175 HQ,[13] used by Bell in the longer section of TAT-1, had been tried in the system laid between Key West and Havana in 1950. At the outset of TAT-1, therefore, this valve type had accumlated three times the operational experience of the 6P12 type in the Aberdeen-Bergen system. Indeed, work on a transatlantic valve had started in the Bell Telephone Laboratories as early as 1933. The longer fault-free operation in service and the more extensive life-test experience were two of the factors leading to the choice of the Bell system for the longer section.

The lower slope of the 175 HQ had the advantage of minimising any effect of increasing interface resistance. Although the nickel cathode used in the 175 HQ-type valve was not entirely free from silicon, tests showed that the trend of mutual conductance with life was quite acceptable for a predicted operational life in excess of 20 years. In addition, the confidence gained in the period between 1933 and 1952 enabled Bell to dispense with the need for parallel amplifiers.

In 1957 a French submarine system was laid between Marseilles and Algiers using an indirectly heated pentode valve (type PTT 301)[13a] with a slope of about 3·2 mA/V. A nickel-tungsten cathode was used, thus minimising or avoiding interface growth (see Section 4.6), but, like the Bell system, there was no provision for parallel amplifiers.

## 4 Commonwealth system : a new valve design for deep water (1956–64)

### 4.1 Problems yet to be solved

Although valve development had, by 1956, produced the 6P12-type valve, which could be used with some confidence in submarine systems, there were still problems which remained to be solved. These were:

(*a*) the growth of anode-control grid capacitance
(*b*) the growth of intermittent noise
(*c*) the failure of heater-cathode insulation
(*d*) the part played by anode activation
(*e*) yields and quality control

The solution of these problems involved considerable difficulties, but led, in the end, to further changes in design and a new valve type. The development of this new type will be outlined in this section. It proved to be the most important valve ever designed for submarine use and probably had the most widespread application of any valve in submarine telephony. There was one subsequent design, which will be mentioned later, but this was only used in a single, albeit very long, cable.

### 4.2 Growth of anode-control grid capacitance

Although the most important valve-failure mode is the decline in the level of cathode emission, there are others. One of the most important of these is the growth of anode-control grid capacitance ($C_{ag}$). The importance derives from the consequent increasing internal feedback within the valve and its effect on the circuit performance. Values of $C_{ag}$ as high as 0·2 pF are sometimes recorded on operational test, compared with the specification limit of 0·02 pF maximum at start of life, and growth is still detected in some cases after 16 000 h operational life. Circuit performance considerations required a full investigation and suggestions for improvement.[14]

The growth in capacitance was usually attributed to the presence of thin films on the valve insulators (the micas) produced by cathode evaporation. The first indication that this might not be the whole answer arose when a large-scale investigation of life-test results on 6P12-type valves was made. It was found that 45% of a batch of 600 valves operating under output stage conditions ($V_a$ = 90 V, $V_{g_2}$ = 60 V and $I_a$ = 6 mA) showed $C_{ag}$ values greater than 0·05 pF after 3000 h. Measurements on 500 valves operating under input-stage conditions ($V_a$ = 40 V, $V_{g_2}$ = 60 V, $I_a$ = 4 mA) showed no $C_{ag}$ values greater than 0·02 pF. The heater voltage was the same for both batches.

The suspicion that anode temperature was important (350° C in the output stage compared with 250° C in the input stage) was confirmed when it was shown that cooling fins attached to the anode checked the increase in $C_{ag}$ but did not completely prevent it. As a result of this work, attention was directed to the impurity of the nickel anodes. After exhaustive tests it was shown that an increase in the anode carbon content within the range 0·009–0·041% was the only change which could be correlated with increasing $C_{ag}$ growth. Hydrogen firing of the anodes was found to reduce the carbon content to less than 0·004% and also to eliminate $C_{ag}$ growth completely in early life (up to 3000 h). On the other hand, there was found to be no correlation between cathode temperature, in the range $V_h$ = 4·0 – 6·0 V, and increasing $C_{ag}$.

Some attention was now given to locating the films which could cause an increase in $C_{ag}$. It was demonstrated by the triple-band method[15] that films were deposited, during valve life, on the inside of the glass envelope. It could therefore be assumed that similar films would be formed on the mica insulators. Both types of film cause an increase in $C_{ag}$ value, but, whereas that due to the envelope film may be cancelled by earthing the outside of the valve envelope, that due to the mica film cannot. Films deliberately deposited on the micas did, however, exactly simulate the growth of $C_{ag}$ found in operational life. A search was made for these films on the micas of valves which had grown substancial $C_{ag}$ values and, after thinning the micas, the films were eventually detected visually. Chemical analysis showed that the films contained carbon. It was therefore concluded that the anode plays an important part in providing the carbon which is the major cause of $C_{ag}$ growth.

Two techniques were adopted to avoid the growth of $C_{ag}$ in future designs. First, a change to very pure anode material was made, i.e. a tungsten/nickel alloy (L2) was chosen with a very low carbon content (less than 0·02%). Secondly, arrangements were made to shield vital areas of the mica insulators from direct evaporation. In these ways a substantial cure for the growth of anode-control grid capacitance was achieved.

### 4.3 Growth of intermittent noise

During 1955–56, it became clear that the improvements effected by reducing the residual gas level in submarine repeater valves could give rise to another problem, the development of intermittent noise.[16] When measured in the frequency range 20–1000 kHz, in terms of the equivalent grid resistance, the noise level, in the form of short duration pulses or 'spikes', was found in some cases to approach 100 000 Ω (in contrast with a normal value below 1000 Ω).

This problem was investigated for both commercial and submarine repeater-type valves and the first result confirmed that the excessive noise levels were not present in new valves but appeared intermittently as the valves aged. Selective applications of potential to various electrodes in turn, indicated that the noise depended primarily on the anode voltage, to a lesser extent on the cathode temperature and very little on the other parameters. The 'spike' noise increased as the anode voltage was increased above 100 V but was never detected at 60 V or lower potentials.

The noise persisted with the cathode disconnected, suggesting a prime cause which was independent of the main electron stream but associated with leakage paths between anode and some earth point (e.g. the suppressor grid) in the valve. The development of leakage paths was thought to be associated with the sublimation of metals, barium or magnesium, from the cathode to form conducting films on the micas supporting the electrode structure. At the same time any oxidising residual gas produced in the valve could destroy the conducting film. The leakage might have been worse if particular care had been taken to eliminate residual gas (e.g. in submarine valves) but in any case would depend on a balance between sublimated metal and the evolution of residual gas. The noise itself was, however, not related to the magnitude of the leakage current but more to its instability.

Experiments on rearranging the electrode structure confirmed that the noise did originate in leakage paths across the mica and it was consequently indentified by the initials l.a.m. (leakage across mica). The use of platinum in place of an active nickel cathode core reduced the rate of noise growth by a factor of 10 owing to the higher level of reducing agents (e.g. magnesium) in the latter core. An effective cure, as in the case of capacitance growth, resulted from the provision of shields on the micas which prevented metals collecting there and forming unstable metallic paths between critical electrodes.

### 4.4 Failure of heater-cathode insulation

The heater of an indirectly heated thermionic valve consists of a fine tungsten wire, usually formed into a spiral, covered with a thin layer of sintered alumina. So insulated, the heater is inserted in the sleeve of the cathode.

Evidence was accumulated that, if a potential is applied between heater and cathode during operation, then there is a danger of insulation breakdown. The danger is greatest when the heater is positive to the cathode and the breakdown, when it occurs, is sudden.

In amplifiers using 6P12-type valves, the heaters were fed in series with the h.t. supply and were arranged to be negative to the cathode; this arrangement is the least dangerous. The circuit design is, however, expensive in overall repeater voltage and is not practicable for a transoceanic crossing. A more economic arrangement is to use the voltage drop across the heater chain as the amplifier h.t. supply. Such a circuit would, however, place all the heaters positive to the cathodes and give the greatest danger of breakdown. Some way of avoiding this danger was essential if a British crossing was to be attempted and research effort was concentrated on this problem.[17]

In the first place, some information was sought on the influence of varying conditions on the incidence of failure. An automatic testing technique was evolved which, under prescribed conditions, recorded the time taken to the first breakdown of heater-cathode insulation. It was found that, for a batch of valves, these times fell reasonably well into an exponential distribution with a constant failure rate and that the batch average life could be taken as the time constant of the distribution.

Tests undertaken at different heater temperatures showed a linear relation between the logarithm of batch average life and the reciprocal of heater temperature (Fig. 11). In particular, it was shown that, at a heater temperature of 1700 K, and with the heaters 36 V positive to the cathode, the average life was 50 h. With the heaters negative by 36 V, but all other conditions unchanged, the average life was 6340 h, a life improvement by a factor of more than 100 times.

No evidence of any change in average life was obtained using different metals for the cathode core nor was any marked effect noted due to change in heater coating composition. Visual examination of breakdown sites showed an intense stain on the heater coating surrounded by a grey area.

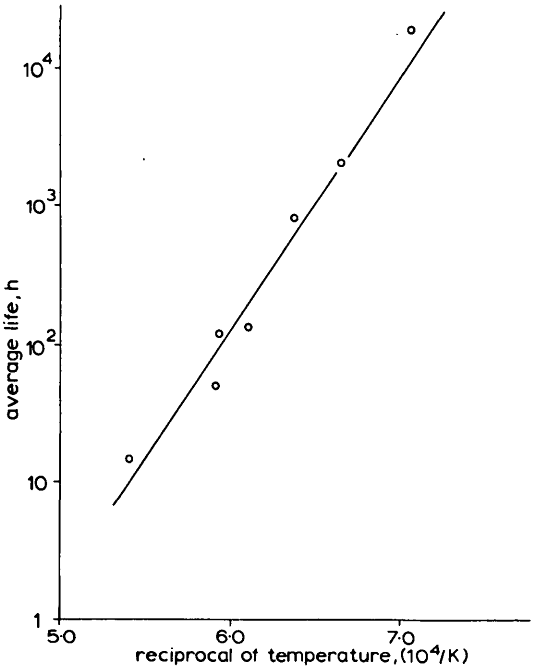


**Fig. 11**
*Relation between average batch life and temperature for the heater-cathode insulation failure mode*

Further tests were undertaken using a simplified structure, a commercial recrystallised alumina tube, cut to take a conventional 2-watt tungsten spiral heater (straight and uncoated), and having its exterior surface wound round with a tungsten or platinum wire as a second electrode. Using this structure, with the central heater positive to the outer spiral, breakdown sites were observed on the exterior of the alumina tube similar to those on actual heater-cathode assemblies. The same directional breakdown properties were also obtained. Tungsten from the heater could always be detected in the stained portions of the tube. The amount of tungsten transferred from the hot positive electrode was found to be strongly dependent on the passage of current between cathode (or outer electrode in the simplified structure) and the hot electrode (or heater).

The phenomenon can be explained by assuming that positive tungsten ions are produced at the heater by electron bombardment and then move towards the cathode at a rate dependent on the rate of positive-ion production, which in its turn, is dependent on current magnitude and on the temperature of the positive electrode. On this basis the breakdown can be avoided if the initial process, i.e. the bombardment of the heater with electrons, is prevented by the interposition of a pore-free layer of alumina.

For all valve designs after the 6P12 type, the normal coiled and sprayed heater was placed in a heater sleeve of nonporous alumina and this structure inserted in the usual metallic cathode sleeve. No cases of heater-cathode breakdown have been detected in valves using this innovation, even though the heaters have been run at voltage which are positive to cathode for many years.

### 4.5 Part played by anode activation

Platinum core 6P12-type valves had now been used successfully in the Aberdeen-Bergen and TAT-1 systems. In a third system, however, the Bournemouth-Jersey, serious deterioration in gain was noticed shortly after the cable was laid in 1958. The problem was unprecendented and immediate action became necessary to identify the cause of failure, to take corrective action on the faulty system and to prevent recurrence in future systems.

Tests were conducted at the repeater terminals and some of the most revealing results were obtained when the line current was changed. This alteration in system conditions immediately affected the heater current and, therefore, the cathode temperature of all the valves in the system. The changes in gain and other system parameters resulting from the line current changes suggested that the cause of system deterioration could probably be attributed to changes in valve performance. This view was reinforced when specimens of 6P12-type valves, made at the same time as those in the Bournemouth-Jersey, were identified on operational test on the life-test racks at both Dollis Hill and Paignton. These specimens showed failure characteristics quite untypical of earlier valves. The falls in mutual conductance and total emission were much increased in comparison with values that had come to be regarded as standard for satisfactory performance. An investigation of this aberrant behaviour was started at once.

One component came immediately under suspicion. All the stock of anode nickel used for earlier systems had been exhausted and a new stock had been opened at Dollis Hill. The start of the new stock coincided with the new failure mode. Chemical analysis of the new nickel showed that the only difference between the old and new stocks was that the latter had a much higher carbon content.

This clue also linked with STC experience where the anode nickel had been 'passivated' by removal of the carbon in a wet hydrogen furnace. It seemed, therefore, that an acceptable level of cathode activity in platinum-core 6P12-type valves (compare with the growth of $C_{ag}$) was critically dependent on the carbon content of the anode nickel. Too much or too little caused a greatly inferior performance.

Confirmatory tests were started at Dollis Hill on batches of valves with different anode carbon contents and the results are shown in Fig. 12. It is clear from this curve and other batch tests that only when the carbon content is controlled between 0·005% and 0·015%can rates of fall of mutual conductance be reduced to acceptable levels. Wet hydrogen stoving, which reduces the level to around 0·001%, or an increased content above 0·02% are equally dangerous.

The suggestion, here, is that the electrolytic activation of an oxide cathode on a passive-cathode sleeve, described in Section 3·3 above, is inadequate to maintain cathode activity at the level needed for valve operation. If there are no activating agents in the cathode sleeve then they must be available elsewhere in the valve, for example as carbon in the anode[17a]. On the other hand, too high a carbon content may reduce oxides present on the anode surface to yield carbon dioxide which impairs the cathode activity. This discovery had a major effect on the design of the new deep-water valve.

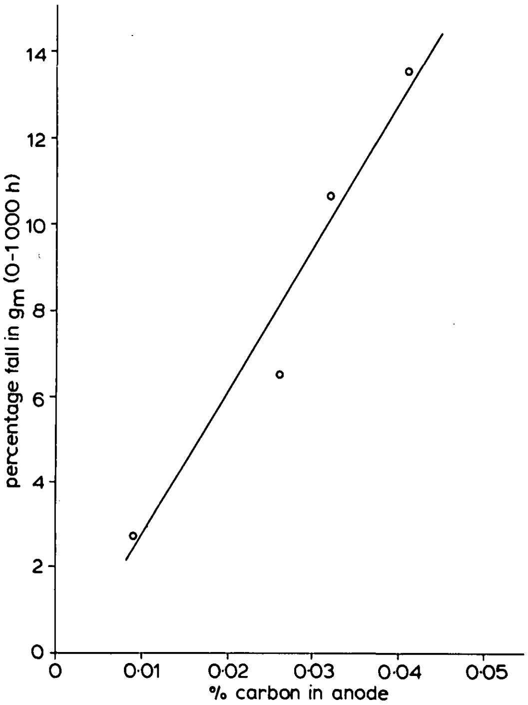


**Fig. 12**
*Relation between the fall in mutual conductance and the anode carbon content*

Experience of oxide cathodes on passive cathode sleeves in the British Post Office had already led to the belief that irreversible damage to the cathode is rarely, if ever, encountered. In the case of the valves in the Bournemouth-Jersey system, it was felt that the equilibrium level of cathode activity was too low for successful valve operation and that this was due to the fact that the residual gas level in the valve was too high to be coped with by electrolytic activation alone, and there was no carbon available from the anodes which had been passivated. Under these circumstances, it was felt that the best chance of recovery was to raise the rate of desorption of gas from the cathode, in the hope that the intrinsic activation alone would then give an adequate level of cathode activity. It was therefore decided to raise the line current by 13 mA, which would increase the heater voltage to 6·1 V from the original 5·7 V. This change proved beneficial at the start but, over a period of 18 months, did not achieve the required degree of stability. A further increase of 7 mA in line current was then made, raising the heater voltage to 6·3 V (Fig. 13). On this ocassion, stability was achieved about 8 months after increase. The system had been restored to satisfactory operation and the resilience of passive-core valves demonstrated.

### 4.6 Yields and quality control

Finally, there remained the problem of yield. Although some very beneficial results had been obtained when the change was made from an active nickel to a platinum core, there had been penalties. The platinum cathode core valves were not easy to activate and were not strong mechanically. Shrinkage in production, after the stringent mechanical and electrical tests, could reach 60%, a barely acceptable yield.

At about the same time as work was started on platinum core valves, an experimental programme, using tungsten-nickel as an alternative core material, was initiated. The function of the tungsten was to provide the activator needed to generate active barium and to prevent growth of a nickel-oxide interface layer. The results of this investigation showed that, over a period of 40 000 h of life test, the trend of mutual conductance for valves with tungsten-nickel cores is in no way inferior to the trend for platinum cores. No interface growth was detected.

The tungsten-nickel alloy is stronger mechanically than platinum and cathodes using tungsten-nickel cores are easier to activate. The shrinkage rate was reduced from 60% to 30% when the new cores were used in production; this gave a much more acceptable yield. For these reasons, coupled with the complications arising in the case of platinum cores due to its dependence on a controlled level of anode carbon, it was decided to adopt tungsten nickel for both the cathode and the anode in the new design for a deep-water valve. The L2 alloy was chosen (see Section 4.2) as the appropriate material to use.

In more general terms, the yield and reliability of the valves were considerably improved by a system of quality control which had been evolved during the 1950s. This system was based on visual inspection and dimensional checks of the piece parts from which the valves were made, and on very comprehensive process specifications applied to all the piece parts. In all more than 50 process specifications were invoked to control the treatment of as many piece parts before assembly, with special emphasis on degreasing, outgassing and the exclusion of dust particles. To prevent recontamination by dust the piece parts were stored in dust-free containers and valve assembly was undertaken in a small clean room specially built for the purpose. In later years, this clean room was extended and improved to accommodate the winding of the close-spaced grids of the final valve designed for submarine use (see Section 5.2).

The subject of quality control cannot be left without special mention of the cathode which was formed by spraying a suspension of coprecipitated barium-strontium carbonates in amyl acetate containing a methacrylate binder. The formulation of this spraying paste was strictly controlled, as was the spraying process, to give cathodes of the specified density and thickness. The technological difficulties associated with the spraying process were considerable and were the subject of an investigation which led to the design and development of a new cathode-spraying machine which was a considerable advance on previous models.[17b]

### 4.7 New valve design: the 10P-type valve

The way was now open to design a new valve for use in deep-water systems. The new design[18] could take advantage of all the experience gained in the solution of the problems outlined in Sections

4.2 to 4.6. Unlike its predecessors, the new design was not based on an existing commercial model but was planned specifically for use in submarine telephony. Even so, the emphasis, as with the earlier valves, was still on reliability and compatibility with the overall system voltage limitations. There was no great pressure to increase the system capacity. Indeed, the concept of a cable between the United Kingdom and Canada (later to be extended across the Pacific to New Zealand, Australia and the Far East) did not, at this time (1958–60) demand more than a modest increase from the original 60 to 80 speech channels.

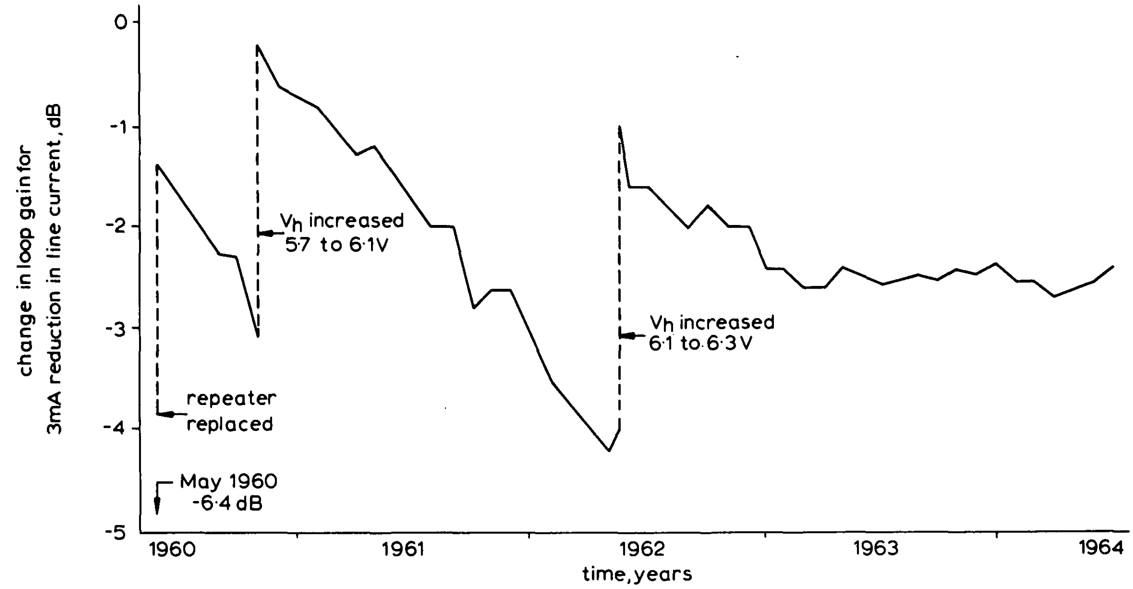


**Fig. 13**
*Decay and recovery characteristics for the Bournemouth–Jersey submarine system*

Later, as the cable reached towards its Far Eastern terminals, there was a demand for more circuits, rising to 160 (3 kHz) circuits between Guam and Australia. However, the need to economise still further on overall system voltage remained important and, to this end, the use of the alumina heater sleeve permitted the heater chain to be arranged in parallel rather than in series with the h.t. supply. A standard 10 V, 300 mA heater coil was chosen and, with six valves per repeater, the voltage drop across the heater chain is 60 V, a value not inconvenient for a screen voltage of 70 V.

The following symbolic equation was used as a guide to design:

$$\begin{bmatrix}\text{potential of}\\ \text{screen}\\ \text{grid}\end{bmatrix} + \begin{bmatrix}\dfrac{1}{\text{mechanical}}\\ \text{quality}\end{bmatrix} = \begin{bmatrix}\text{mutual}\\ \text{conductance}\end{bmatrix} + \begin{bmatrix}\text{magnitude}\\ \text{of}\\ \text{working point}\end{bmatrix} + \begin{bmatrix}\text{steady}\\ \text{anodic}\\ \text{current}\end{bmatrix} \quad (4)$$

The use of $V_{g_2}$ = 70 V allows acceptable values of the parameters summed on the right-hand side when the mechanical quality (proportional to the size of the interelectrode gaps and to the grid-wire diameters) is chosen for adequate reliability.

The compromise of attempting to meet both input and output needs in one model was no longer necessary and the 10P2-and 10P1-type valves were therefore designed, respectively. The two types are structurally very similar, only differing markedly in their control-grid and suppressor-grid dimensions. The external structure, as can be seen from Fig. 14, is very similar to that of the 6P12-type valve.

The new valves were first given a trial in a shallow-water system in the North Sea (the Anglo-Swedish cable) which was laid in 1960. They found their first major use in the British transatlantic cable linking the UK and Canada (CANTAT-1). This cable was subsequently extended by the Commonwealth Pacific cable (COMPAC) from Sydney to Vancouver via Auckland, Suva and Oahu, and by the South East Asia Commonwealth cable (SEACOM) from Singapore to Cairns in Austraila via Jesselton, Hongkong, Guam and New Guinea.

The whole project, CANTAT, COMPAC and SEACOM used 10P-type valves, 4692 in 782 working repeaters in some 20 000 miles of submarine cable. The provision of the valves was a joint project shared by the Thermionics Group at Dollis Hill and the STC unit at Paignton on a 50/50 basis. The first section (CANTAT-1) was laid in 1961 and the last, linking Guam and New Guinea, in 1966. From 1960, when the trial system was laid, to the present date, although there have been three repeater failures where thermionic valves have been suspected as the cause, investigation in each case has failed to substantiate the early suspicion. The most important of these cases is considered in more detail in the next Section.

### 4.8 Life stability of the new valves

The decision to use $V_h$ = 10·2 V or 10·3 V for the 10P-type valve was based on earlier work on the 6P12 type (Section 3.5) as the change from platinum to tungsten-nickel for the cathode sleeve did not in itself suggest that any change in cathode temperature should be made. However, from a preliminary study of life-test results at 8000 h, it became clear that with $V_h$ = 10·2 V, some 8% of the valves tested were showing leakage paths to the suppressor grid in the range 10–100 MΩ. It was felt in consequence that, although protection had

**Table 2**
ELECTRICAL CHARACTERISTICS OF 10P-TYPE VALVE

| | 10P1-type valve | | 10P2-type | |
|---|---|---|---|---|
| (i) Test condition | $V_h$ = 10·2 V<br>$V_a$ = $V_{g2}$ = 70 V<br>$I_a$ = 10 mA | | $V_h$ = 10·3 V<br>$V_a$ = 40 V $V_{g2}$ = 50 V<br>$I_a$ = 3 mA | |
| | Min | Max | Min | Max |
| Mutual conductance, mA/V | 6·3 | 7·4 | 5·4 | 6·7 |
| Working point, V | −2·8 | −4·2 | −1·1 | −2·1 |
| Reverse grid current, μA | - | 0·1 | - | 0·1 |
| Screen current mA | 1·8 | 2·7 | 0·55 | 0·85 |
| Anode impedance, kΩ | 150·0 | | 250·0 | |
| Input capacitance, pF | 10·8 | 12·7 | 12·9 | 15·1 |
| (ii) Test condition | valve cold, no voltages applied | | valve cold, no voltages applied | |
| Output capacitance, pF | 6·2· | 7·2 | 6·8 | 7·6 |
| Anode-grid capacitance, pF | 0·020 | 0·032 | 0·015 | 0·025 |

been provided against the growth of anode leakage as a possible cause of noise (Section 4.3), there was some risk that the mica shields would not give unlimited protection against sublimation products from the cathode or the anode. Accordingly, it was decided to re-evaluate the choice of cathode temperature.

It was first of all demonstrated that changes in heater voltage, over the range 8·5 – 10·8 V, had little effect on the long-term trends in mutual conductance and working point. The relative effect on leakage growth of changes in cathode temperature was then estimated using the triple-band method referred to earlier. This technique gave rise to an estimate that, whereas trouble might be expected for an average valve after 125 000 hours at a heater voltage of 10·2 V, at 9·7 V the same condition would not occur until 280 000 hours. The decision was therefore taken in 1964 to reduce the nominal heater voltage to 9·7 V as a safety precaution. As, by that time, many systems had been laid with valves operating at the higher value of heater voltage, the decision involved not only a change for planned new systems but also a change in line current (from 432 mA to 415 mA) for systems already on the sea bed.

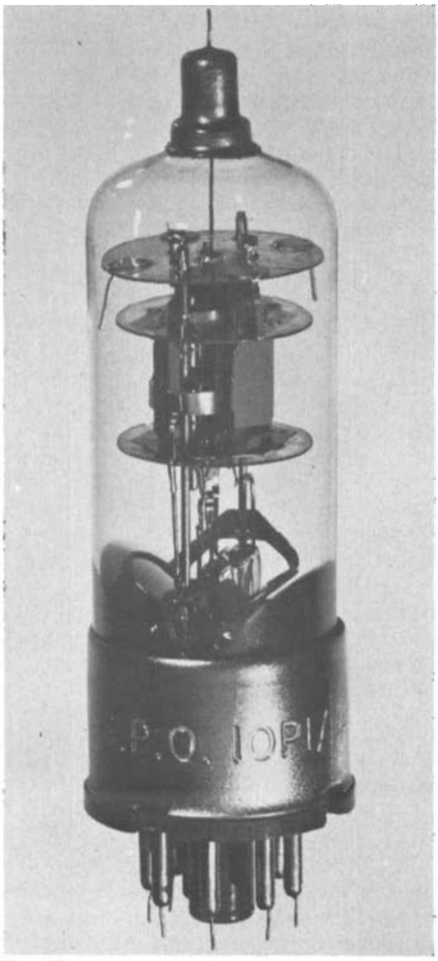


**Fig. 14**
*10P-type valve*

It should be emphasised that the above change was made on the assumption that anode leakage, which is fairly well predictable and understandable, will lead, in the long run, to noise at a level which could cause system failure. If the assumption was wrong then it must also be stressed that no other cause of system failure based on leakage has ever been detected. An opportunity to test the need for the change arose in 1973.

In that year an unacceptably high level of noise was reported in the Sydney-Auckland section of the COMPAC system. The faulty repeater was recovered and the amplifier was investigated. First measurements suggested that the input stage 10P2-type valve of the A amplifier was responsible for the high level of noise, which could be induced by tapping the suspect valve. After several tests, however, the fault condition disappeared and at this stage the valves were removed from the amplifier for laboratory examination.

It was immediately suspected that the noise had been due to the l.a.m. phenomenon outlined earlier, despite the fact that l.a.m. noise had never been detected at anode voltages lower than 60 V (and the 10P2-type valve operated with $V_a = 40$ V). However, the change from a platinum to a tungsten-nickel cathode might have caused higher sublimation rates. It was therefore decided to undertake an investigation in some depth on 10P2-type valves. Samples, 81 in all, were chosen from long-term tests after periods of operation ranging from 85 000 h to 103 000 h at values of heater voltage ranging from 8·5 to 10·8 V. To these were added the four 10P2 valves from the Sydney-Auckland repeater, four others from a recovered SEACOM repeater and three from a repeater recovered from the Anglo-Swedish system, all with operational lives ranging from 44 000 to 116 000 h.

The tests carried out included measurements of noise (in terms of the equivalent grid resistor) under normal operating conditions and of anode leakage and excess noise (l.a.m.) at normal and elevated potentials. The results were noteworthy:

(*a*) Not one of the 92 valves tested showed noise greater than the specified limit ($R_{eq} = 1000\,\Omega$ max.)
(*b*) Not one valve showed excess (l.a.m.) noise at $V_a = 70$ V
(*c*) Some l.a.m. noise was detected at voltages of 170 V and higher on a few valves and there was, in these cases, some correlation with an unstable anode leakage
(*d*) A high noise level was detected at low potentials in two cases but in each case the source was isolated to a point adjacent to but outside the valve, to a choke and a valve base adapter, respectively.

As no excess noise, under normal conditions, was detected on any valve, the possibility of the noise in the faulty repeater arising at a

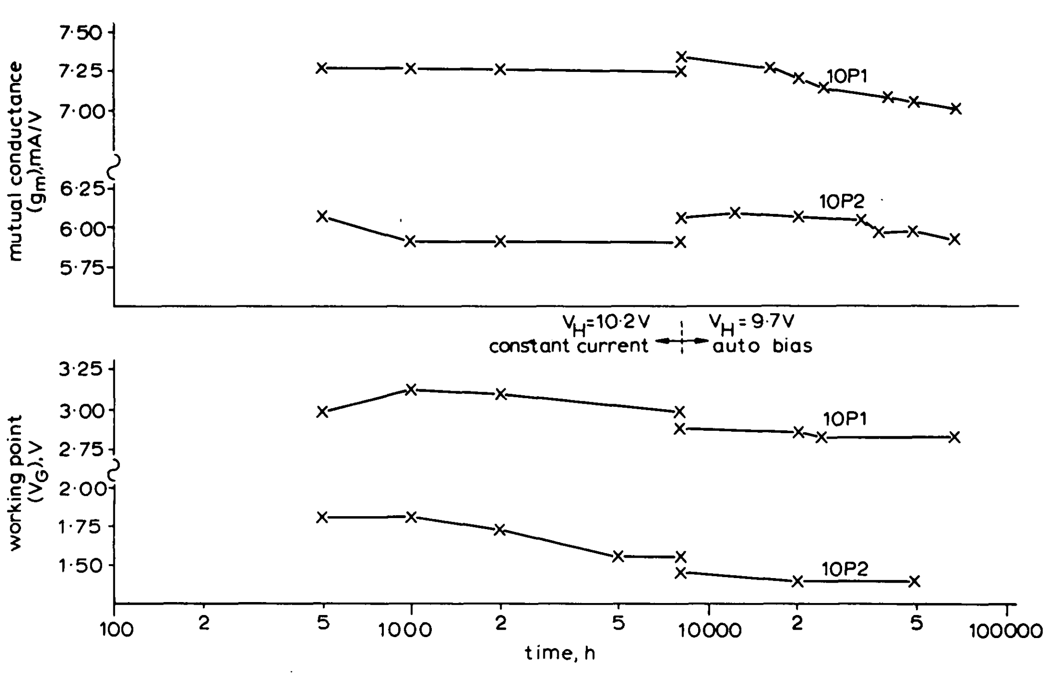


**Fig. 15**
*Typical life-test curves for batches of 10P1 and 10P2-type valves*

point near the input valve cannot be discounted. The results of this investigation have been given in some detail because a single case of proven excess noise could indicate the start of an endemic fault pattern which would have serious consequences for the whole Commonwealth System. However, the original prediction of a cure derived from the use of mica shields (see Section 4.3) and supported by a low operating potential appears to have been sustained, at least for operational lives of up to 15 years.

Typical life-test curves, based on a sample of 30 valves each, show trends of mutual conductance and working point over a period of almost 70 000 hours, which includes a change of heater voltage for the reasons explained earlier (Fig. 15). It is clear from these curves that the rate of fall of mutual conductance with time has been diminishing over the last seven years of the test. It should be noted that much depends on the accuracy of the $g_m$ measurement in these life tests and an accurate technique[19] was developed at an early stage and used throughout most of the submarine-valve life-test work.

A contributory cause to this satisfactory performance was the continuing effort to reduce the level of gas attack on the cathode during the 1950s. The major sources of gas in the valve are absorbed in the components and tungsten nickel and mica are the materials chiefly involved. Techniques for degassing were developed[20, 22] and applied in production.

Some confidence may be derived from the trend in $g_m$ that the system life is likely to exceed 20 years on the basis of a fall in $g_m$ as the main failure mode. During the last seven years of the life test the total emission has fallen by 50% and this is in accord with the minimal fall in $g_m$.[7]

There are other systems, apart from those mentioned, which use the 10P-type valve and a total of more than 6000 are on the sea bed in many oceans and seas. The operational performance of all these is, so far, supporting the results of the life tests and adding to confidence in a life span of more than 20 years.

### 4.9 American and French developments

Following the trouble-free experience with the 175HQ-type valve, Bell Telephone Laboratories started development work on a new valve type in 1955. The performance of the new design (type 455 A/F) was much improved on the earlier version with a mutual conductance of 6 mA/V and a screen potential of 45 V.[22a] Interface resistance growth was minimised through use of a Ni/W/Mg cathode and a frame grid structure was adopted as a feature of the new design (see Section 5.2). An alumina block was used to insulate the heater from the cathode for the reasons explained earlier (Section 4.4). Parallel amplifiers were introduced, for the first time in an American system, to give increased reliability. This valve type was used in TAT-3, a transatlantic system, linking the USA directly to the UK, which was laid in 1963. The system provided 128 (3 kHz) channels.

Later, the French also developed a successor to the valve type PTT 301 with an improved electrical performance. The new type, coded PTT 400,[22b] had a slope of 6·1 mA/V, made use of a frame-grid construction (screen potential 48·5 volts), used a Ni/W cathode and special heater/cathode insulation. This valve type was used in several transmediterranean systems in the later 1960s and provided 128 (3 kHz) channels.

## 5 Final valve design (1962–68)

### 5.1 Development of performance

So far, in this review, it is clear that almost the whole of the research and development effort has been concentrated on the improvement of the reliability of the active devices. Work on the second thread of development, the pursuit of a higher frequency of operation to increase the system circuit capacity, has been minimal. However, in the early 1960s evidence grew that systems of higher capacity than the 160 (3 kHz) circuits of the final sections of SEACOM would be needed. There was a possible need for a new repeater with a higher circuit capacity for use on a future transatlantic system and this would require a new valve design. Such a repeater would need an amplifier with increased bandwidth, which would involve closer repeater spacing and an even lower h.t. supply voltage. The consequent valve structure had, therefore, to provide improved frequency performance at lower electrode potentials.

The most direct link between a figure of merit $M$, for the valve and the necessary increased bandwidth for the amplifier is provided by the following expression:

$$M = \frac{Kg_m}{2\pi C} \qquad (5)$$

Here, the right-hand side is proportional to the gain-bandwidth product of the amplifier. Thus, to improve amplifier perfromance, $g_m$ should be increased and the total earth capacitance $C$ associated with the valve should be reduced. However, $M$ is not independent of amplifier design factors and, consequently, an alternative basis for valve design comparison was developed[23] from the approximate equation

$$G = g_m R_L = \frac{g_m}{I_a}(V - V_a) \qquad (6)$$

where

$G$ = voltage amplication, $R_L$ = anode load and $V$ = supply voltage

If $V$ is fixed, $g_m/I_a$ should be high and $V_a$ low. The ratio $g_m/I_a$ can therefore be used both as an approach to design and a method of comparison of performance achieved.

Two approaches were made to the design of a new valve, one by the British Post Office and one by STC. Both will be described but only the STC design was ever used in an operational system. No other country designed and used a submarine valve with a performance comparable to these two British types.

### 5.2 British Post Office double grid

To design a multi-electrode valve for high mutual conductance[23, 24, 24a] the cathode-control grid spacing must be small. When the supply voltage also needs to be low the screen grid must be brought close to the control grid. The advantage of such close spacings is only fully realised when the diameter and pitch of the grid wires are also reduced to decrease the variable-mu effect. When fine wires (10 μm), wound with tight pitch (~ 60 μm), are used, a grid supported by its own grid posts is no longer practicable. A frame grid structure is needed in which the two posts, on which the grid is wound, are kept at the correct spacing by a metal framework at each end. This framework, however, makes it impossible to assemble two such grids, one over the other, to give as small an interelectrode spacing as the fine wire would permit. It was in the solution of this problem that the British Post Office and STC followed two different courses.

In the British Post Office design the control grid was wound first on near conventional grid support posts. The twin-frame cross straps supporting these posts at either end were extended beyond the posts. The posts themselves were cut away slightly in the region overlaid with the grid wires. A pair of ground sapphire posts was then located in the slots provided by the extension of the four cross-straps, two at each end of the control grid posts. Owing to the cut-away section of the control grid posts, there was no contact between the sapphire posts and the control grid wire. The screen grid was then wound over the sapphire posts, which have a slightly larger diameter than the control grid posts, entrapping a soft metal tape for metallic connection. The double grid was then, as a single unit, assembled over the cathode in the usual way (Fig. 16).

In winding the grids, care must be taken in adjusting the wire tension to take account of the subsequent rise in temperature under operational conditions and of the bending of the support rods during winding.

Three forms of valve were designed during the development phase, one, a pentode (8P1) and two tetrodes (8T1 and 8T3). In all these valves the double grid permitted the control grid/screen grid spacing to be reduced between 80 and 90 μm. This close spacing allowed a reduction in the supply voltage to 50 V for the first two designs, when used as output valves, and to 30 V when used as voltage amplifiers. In addition, there was a threefold increase in mutual conductance when compared with the 10P-type valve. For the 8T3-type valve some mutual conductance was sacrificed to permit operation in the range 15–25 V.

The slope of the 8P1- and 8T1-type valves is around 23 mA/V at an anode current of 15 mA, thus providing a $g_m/I_a$ ratio at 45 V some three times that for the 10P type at 70 V. The 8T3 type at 20 V provides a $g_m/I_a$ ratio 50% higher than for the 10P1 type. If figures of merit are compared then (with $K = 1$ in eqn. 5) the value of $M$ is 112 MHz for the 8T1- and 8P1-type valves, compared with 60 MHz for the 10P1 type.

### 5.3 STC version: the 5A/190 G type

The same problem of arranging a frame grid structure with very close interelectrode spacing was faced by the STC team at Paignton but was solved in another way.[25] The Paignton approach was to wind the control grid and screen grids separately, and to devise a new method of assembly while retaining the essential frame supports at each end of the grid posts. Their solution was to construct the control grid with the conventional twin straps at one end and with a single end bar at the other. This end bar, narrower in width than the grid-post diameter, permitted the screen grid to be assembled over the control-grid structure from the single-bar end (Fig. 17).

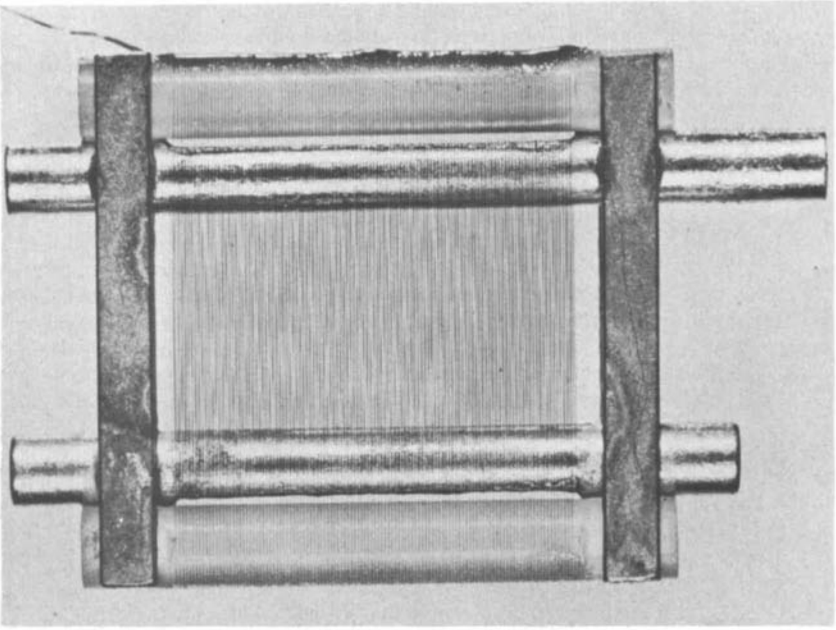


**Fig. 16**
*Post Office double grid*

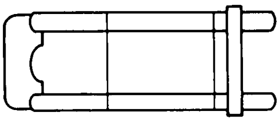


**Fig. 17**
*STC single end bar control grid*

The same principles were used in the design of the 5A/190G-type valve as were used for the Post British Office 8P- and 8T-type valves, with very similar results. The grid- wire diameter was the same (10 $\mu$m) and the control grid/screen grid spacing of the same order (100 $\mu$m). With similar supply voltages and anode currents, the mutual conductance was almost identical and so, in consequence, were the values of the ratio $g_m/I_a$ and the figure of merit $M$.

One of the dangers resulting from the use of fine grid wires is the increased effect of an electrical surge on the valve if the cable is cut (for example by a trawler). Some surge protection is provided by gas filled tubes but the valve must be able to withstand the short peak discharge before the gas tube fires. In the worst condition 200 V might be applied for 5 ms. Tests to destruction of the 5A/190G-type valves showed that this level of overload could be accepted by the valve without damage resulting.

One other design feature is worthy of note. After an extensive study, it was decided that suppression of secondary electrons from the anode should be achieved by a potential minimum defined by beam plates rather than by a suppressor grid. The tetrode structure developed had a more uniform potential minimum yielding a sharp knee for the $I_a/V_a$ characteristic, occurring at a low value of $V_a$, and an acceptably high anode impedance. These features improved the output power and harmonic distortion. An even further improvement was obtained by roughening the anode surface. This caused electrons to be trapped more easily at the anode, giving additional control which was effective against laterally moving electron. A 20% decrease in knee voltage and a similar increase in anode impedance was the result in one case. The rough surface was created by a layer of high-purity nickel powder sintered to the surface. The well tried tungsten-nickel alloy used for the 10P-type valve was also used for the cathode, anode, beam plates and shields of the 5A/190G-type valve. All these parts were, however, made by a new photo-etching process rather than by the earlier stamping technique. This improvement reduced the danger of free metal particles within the envelope, an increasing hazard with the exceptionally close grid spacing now being used.

The main characteristics of the 5A/190G-type are given in Table 3.

**Table 3**
ELECTRICAL CHARACTERISTICS OF THE 5A/190G-TYPE VALVE

| Test condition | $V_h$ = 7·4 V<br>$V_{g2}$ = 45 V | $V_a$ = 50 V<br>$I_a$ = 15 mA |
|---|---|---|
| | Mean | |
| Mutual conductance, mA/V | 22·5 | |
| Working point, V | −1·6 | |
| Screen current, mA | 15·0 | |
| Anode impedance, kΩ | 45·0 | |
| Test condition | $V_h$ = 7·4 V<br>$V_{g2}$ = 35 V | $V_a$ = 30 V<br>$I_a$ = 12 mA |
| | Mean | |
| Mutual conductance, mA/V | 21·0 | |
| Working point, V | −1·5 | |
| Screen current, mA | 2·65 | |
| Anode impedance, kΩ | 33·0 | |
| Hot input capacitance, 28·5 pF | | |
| Hot output capacitance, 5·0 pF | | |
| Anode-grid capacitance, 0·03 pF | | |

### 5.4 Lisbon-South Africa system

When the decision was taken to provide a long submarine telephone system between Lisbon and South Africa via the Canary Islands, the Cape Verde Islands and Ascension Island the contract was awarded to STC. The development of the new repeater mentioned in Section 5.1 was completed by the company and its design based on the use of the 5A/190G-type valve.

The route mileage was almost 6800 m and included 624 repeaters at about 11 mile spacing (on the deep-water sections). The system provides 360 (3 kHz) speech channels. With two parallel amplifiers in each repeater, the number of valves required was over 3700, a total not far short of the number required for the whole Commonwealth system. Provision of these valves, to keep pace with the repeater production programme, was one of the most exacting tasks ever faced by the production teams, The major burden (75%) was borne by the STC unit at Paignton but some 900 were supplied by the British Post Office using the STC design. The cable was laid in 1968.

The behaviour of mutual conductance for a batch of 5A/190-type valves is shown in Fig. 18. The average change in $g_m$ after 20 000 h is about 0·045% per 1000 h, a figure very similar to the trend recorded for the 10P-type valves over a similar period. On the basis of these and other tests it is expected that these high slope valves will give the same satisfactory service over a 20-year period as was predicted for the earlier valve types used in submarine systems.

## 6 Transition (1951–60)

### 6.1 New active device

At about the same time as thermionic valves were being developed for use in shallow-water submarine systems, an event occurred in the USA which was to have profound effects on telecommunications in general and submarine systems in particular. The transistor effect in semiconductors was discovered in 1948 by Bardeen, Brattain and Shockley at the Bell Telephone Laboratories. It was immediately realised that in some respects the transistor was superior to the thermionic valve and, consequently, in 1951 a Transistor Group was formed at Dollis Hill to study this new active device.

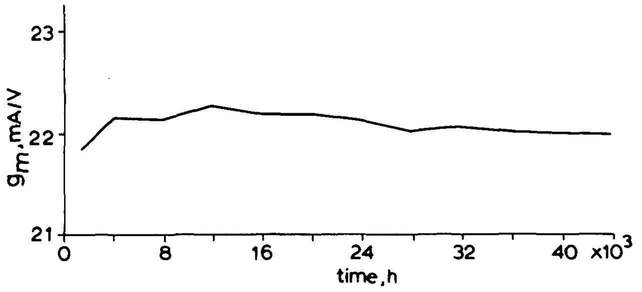


**Fig. 18**
*5A/190G-type life characteristic*

The first objectives of the team were to understand the transistor phenomena and to attain competence in judging manufacturers' claims for devices which could be used in British Post Office systems. To meet these objectives, skill was required both in measuring techniques and in appreciation of the technological processes necessary for manufacture. The first transistors were manufactured from germanium crystals with two metal point contacts on the top surface of the crystal (the emitter and collector electrodes) and an ohmic contact to the opposite crystal face (the base). These devices were superseded after a short time by the alloy-junction-type transistor and the changeover within the British Post Office was supported by practical experience gained in small-scale manufacture of point-contact transistors.

The junction devices were made from thin crystal slices of *n*-type germanium with alloyed indium dots on opposite faces of the slice, forming emitter and collector electrodes of *p*-type germanium. The base electrode was formed from the original *n*-type material. The more highly developed theory behind the junction device, as compared with the point contact, gave promise of better control of manufacturing processes to produce transistors to the specifications demanded by the users. In addition, certain salient features of the junction transistors, notably noise and power-handling capability, showed a marked improvement on the earlier technology.

Once again, practical experience in production of the new type of transistor clearly demonstrated the importance of process control in attaining stability and reliability in subsequent life. Attention was therefore directed towards the development of a life-testing programme which would reveal areas of weak technology and, hopefully, suggest where improvements were most needed. This plan was implemented in the mid 1950s at the time when it was becoming clear that thermionic valves could be made to a standard of reliability which would support a transoceanic cable halfway round the world. There was, however, already an opinion among device development engineers that transistors would be basically more reliable than valves and even at this early stage, despite the progress in valve reliability, it was felt that a transition from valve to transistor for use as the active element in submerged repeaters was eventually inevitable.

### 6.2 Early reliability investigations

The technique used for valve life testing has already been described and the many possible causes for valve failure have been outlined. It was not possible to accelerate the decay of performance of valves in any quantifiable manner so that accurate information on potential reliability could be obtained. The main reason for this lack of success was due to the many failure modes and the inability to analyse their individual effects when using temperature as an accelerating factor. Even a modest increase in cathode temperature introduces, for example, increased leakage, increased degassing of piece parts, increased matrix evaporation, increased rejection by the cathode of gas impurities, etc.; a very complex situation which defied analysis.

Transistors, on the other hand, operate at temperatures very much lower than those used for piece-part processing and, consequently, temperature acceleration of the ageing process may introduce a more limited range of physical changes than for thermionic valves. It was thought very possible that failure would be related to the diffusion of impurities on or into the semiconductor and that this process could be accelerated by temperature. The hypothesis was tested in the first major accelerated ageing experiment which was carried out on germanium *p-n-p* alloy-type transistors.[26]

These devices, hermetically encapsulated, were selected as far as possible from a continuous commercial production run and attempts were made by the manufacturer to maintain production conditions which were as uniform as possible throughout. The most important temperature in relation to ageing acceleration was considered to be $T_J$, the collector junction temperature, but two other factors could have a significant influence, first the temperature gradient between junction and external mount $(T_J - T_M)$ and secondly the potential gradient within the device, $V_{CB}$. Consequently, a functional life equation was proposed of the form

$$L = F[V_{CB}, (T_J - T_M)] \exp(KT_J^{-1} + e) \qquad (7)$$

where $K$ = contant, $e$ = random variable with zero mean and $L$ = life

To examine this equation the following operating values were chosen: $T_J = 60, 70, 80, 90, 100^\circ$ C; $T_J - T_M = 10, 20^\circ$ C; $V_{CB} = -1, -4, -20$ V 30 batches, each of 20 transistors, were tested to cover this range. It was found from this experiment that, although failure could occur due to the degradation of several performance parameters, the transistors usually failed first because of an unacceptable increase of collector-base leakage current ($I_{CBO}$). It was also found that there was some correlation between this form of deterioration and an increase during life of the noise figure $N$ measured at 1 kHz. The life of these devices was found to be approximately halved for each 6 deg C rise in the region of 80° C and a median life of more than $10^6$ h could be predicted at junction temperatures below 50° C.

In a later assessment of this project[27] it was suggested that the median life $L$, based on the criterion of an increasing $I_{CBO}$, could be represented approximately by the simpler equation

$$L = A \exp \frac{B}{T_J} \qquad (8)$$

where $A$ and $B$ are constants, and an experimental plot based on this equation is shown in Fig. 19 line *a* for failure due to rising $I_{CBO}$. Failure due to degradation of other parameters could lead to other lines e.g. *b* and *c*. It can therefore be appreciated that, unless it is certain that the failure mode represented by *a* is the only mode, it would be unsound to extrapolate the line *a* from the experimental temperature range down to normal operating temperatures.

In this early work on the assessment of transistor life it is not possible to identify a single dominant failure mode but the techniques developed formed the fondation for many subsequent reliability investigations.

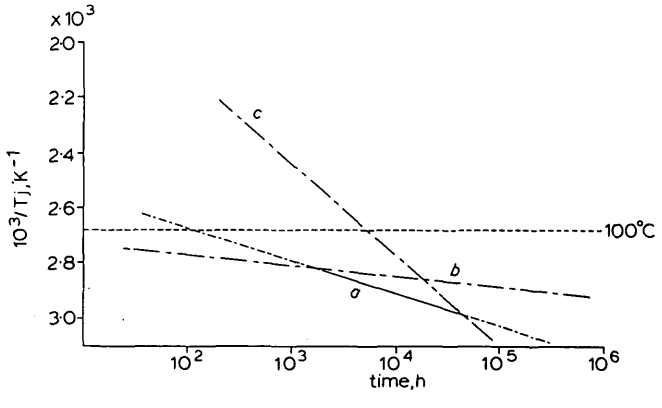


**Fig. 19**
*Life/temperature characteristic of germanium p-n-p alloy transistors based on ageing of $I_{CBO}$*

*a* Experimental curve
*b* and *c* Possible curves for other failure modes

### 6.3 Semiconductor materials and processes

The semiconductor, on which the discovery of the transistor was based, was *n*-type germanium. The donor impurities (phosphorus, antimony or arsenic) which increase the conductivity of pure or intrinsic germanium and convert it to *n*-type, and the acceptor impurities (boron, indium or gallium) which lead to *p*-type material, are fundamental to transistor action. There was, however, even in the early days, an alternative material, silicon, which has the same electronic configuration in the outer or valence ring of electrons. The same impurities could be used with silicon to produce transistor structures. Bell Telephone Laboratories at this time found the impurities easier to control in germanium than in silicon and they therefore turned first to the former material in their structures. Indeed, they used germanium in the first transistorised transalantic system (TAT-5, 720 circuits) as late as 1970.

There was, however, one semiconductor property where germanium was less satisfactory than silicon, the size of the gap $E_g$. For germanium $E_g$ (the spacing in electron volts between the top of the valence band of energy levels and the bottom of the conduction band) is 0·72 eV, whereas for silicon the gap is 1·11 eV. The lower bandgap in germanium limits the range of transistor operation to junction temperatures of not more than about 90° C. Above this temperature intrinsic conduction predominates and the leakage currents are excessive. If silicon is used, on the other hand, the wider bandgap raises the upper limit of transistor action to around 200° C. The advantages resulting from possible higher junction temperatures encouraged the development of silicon technology in the mid 1950s and thereafter.

It is worth recording that, in the mid-1950s, a modified version of the alloy junction transistor was introduced and for a brief period gave promise of better performance with cutoff frequencies around 60 MHz. This was the surface barrier transistor in which the semiconductor wafer was thinned by electrolytic etching to give narrower base widths than were possible by the earlier alloy process. These devices had counteracting disadvantages as the narrow bases led to lower collector voltages to avoid punch-through. Correction by higher base doping increased collector capacitances and reduced breakdown voltages.

Nevertheless, work on germanium continued at Dollis Hill until the late 1950s, but the balance of advantage was to swing decisively to silicon by the end of the decade. The results of the life-test exercise described in the previous Section underlined the growth of leakage current as the main cause of early failure and this, in its turn, indicated that contamination in processing and unsatisfactory encapsulation were probably at the root of the problem. Special attention was directed towards investigating the effects of ambient atmosphere on unprotected devices.

Techniques were also developed for examining faulty units, particularly through the use of microsectioning.[28] These techniques included choice of the correct mounting medium (a thermosetting epoxy resin), design of stainless-steel work holders and a special lapping machine which removes between 0·10 and 0·25 mm/h using a suspension of 5 $\mu$m maximum-diameter corundum abrasive in water. A final 2-stage polishing process is needed to produce a surface free from scratches and other defects when viewed at a magnification of x 100. Although some information is obtainable from the lapped and polished surface, even more can be obtained after etching with, for example, $HNO_3$ (70%), $CH_3COOH$ (99%) and HF (48%) in the ratio of 5 : 3 : 3. In this way the junction positions in alloy transistors can be clearly seen and wafers of germanium or silicon less than 6 $\mu$m in thickness can be sectioned without damage or loss of edge detail.

This technique of microsectioning did not make it possible to reveal diffused junctions and these had been introduced around 1955. In the diffusion process, dopants are introduced into the semiconductor surface from a gaseous ambient in a furnace at a temperature of about 1000° C. The process is compatible with the batch processing of slices and has, therefore, economic advantages. Technically, with accurate control of temperature, of ambient dopant concentration and of diffusion times, it is possible to obtain a much better control of junction depth, and thus of base-width, than with the alloy-type transistors.

A more important advantage of the diffusion process was, however, the introduction of the graded base by Kroemer.[29] This concept of a high doping level near the emitter junction, diminishing across the base towards the collector junction, had several major advantages, a reduced transit time, low base resistance (if the base contact is near the emitter contact), high punch-through voltage and low collector capacitance. Used in surface barrier transistors the graded base led to the micro-alloy diffused transistor.

The speed with which one technological process followed another in this decade left little opportunity for the British Post Office to stabilise its development work in a way which would lead to simultaneous solution of the problems of adequate performance and long-term reliability. Indeed, the rapid changes were a reflection of the fact that such solutions had not yet been achieved, particularly in the area of reliability. There was, for example, no confidence that the advantages of the micro-alloy diffused transistor would be retained over operational life. Nevertheless, much useful information and technological experience was gained in following the advances that were made each year. One more new device was to be developed before stability was reached at the end of the decade: the mesa transistor which had its major impact in 1959.

The mesa trsansistor was generally a double-diffused device with the base diffusion carried out over the whole surface, and the size of the collector capacitance reduced finally by etching the surface to leave a small plateau or 'mesa'. There were problems arising from the connection of the base lead and the solution here was helped by the development of the thermocompression bond. In addition the unprotected surface, praticularly in the region of the *p-n-*p junctions, was a hazard. Impurity traces on the surface changed with time, leading to instabilities in current gain and leakage. A final chemical etch to conclude the fabrication proved to be only a palliative and gave rise to an excessive spread of characteristics.

Transistion frequencies ($f_T$) of 100 MHz or more were achieved and mesa devices were generally preferred to the alloy-diffused transistors, only to be outclassed in turn by the advent of silicon planar technology invented by Hoerni[30] in 1959. This new process was to retain pre-eminence over a long period, from 1960 to the present day, and like the indirectly heated oxide-cathode thermionic valve 15 years before, formed the foundation on which the submarine-system active devices of the late 1960s and early 1970s were to be developed.

## 7. First cable to use the new technology (1960–64)

### 7.1 The new silicon planar technology

Towards the end of the 1950s, serious consideration was being given to the development of a submarine system using transistors in place of valves as the active elements in the repeater. In 1959 discussion on the relative merits of common emitter and common base operation led to a preference for the former, which could give a more stable system with fewer regulating devices. Nevertheless, the technology to tbe used in device fabrication was still fluid with the mesa transistor as the preferred choice.

The decision, in 1960, to increase the capacity of the Anglo-Belgian number 6 cable from 216 to 420 circuits by the insertion of two transitorised repeaters lent urgency to the problem of choosing the best technology. As late as October 1960 the British Post Office considered a silicon mesa unit as the best choice on the grounds of reliability, but by September 1961 opinions had changed in favour of silicon planar technology. SGS-Fairchild could offer the silicon planar type 2N916 which had adequate performance, with a transition frequency better than 400 MHz and a total power dissipation of around 250 mW. In addition, the type 2N916 was a scaled down version of the type-2N1613 which had been shown, in the Minuteman reliability programme, to have a much higher level of reliability than a comparable mesa device. It was therefore decided to examine the possibility of using the type 2N916 in the Anglo-Belgian system. In doing so, account was taken of the advantages of the new technology, which are discussed below. It was also decided to undertake a comprehensive reliability proving exercise on the new device type. The use of a commercial device in the first transistorised submarine system would follow the precedent set some 16 years earlier when the CV1065-type valve was used in the first repeatered submarine systems.

The basic silicon planar technology developed by Hoerni (at Fairchild) has remained substantially unaltered to the present day. The main features have been described in many places and the methods used at Dollis Hill have been published.[31]

The new process differed in several respects from the earlier technologies but the most significant change was the introduction of a passivating layer of silicon dioxide over the surface of the device which was, as the name implies, substantially planar. This layer gave promise of an improved reliability by protecting the sensitive surface from the effects of impurity traces which had been shown to lead to instabilities. A photolithographic process was then used to cut holes in the oxide layer to expose the underlying (*n*-type) silicon in appropriate patterns in preparation for the diffusion, first of boron (to form the base electrode), and then of phosphorus (for the emitter) so producing an *n-p-n* device.

It will be appreciated that, although the first oxide layer is pure, being formed thermally from steam generated from high-purity water, it will later be contaminated by boron and phosphorus and, consequently, some growth of borosilicate and phosphosilicate glass takes place. It was claimed by Hoerni that the successful passivating action of the oxide was due, in large part, to this doping of the oxide and that pure silicon oxide was not adequate as a passivating agent.

The second significant change was the introduction of the expitaxial layer, although this was not exclusively associated with silicon planar technology. Hitherto, there had been some difficulty in choosing the best resistivity for the collector region. A high collector-emitter saturation voltage is incompatible with optimum power outputs, and high saturation voltages result from large collector series resistances. The collector region forms the major part of the thickness of the silicon wafer in which the transistors are formed (of the order of 95%) and, for mechanical reasons, it is not possible to reduce the thickness much below 100 μm. In addition, high collector resistivity is needed for low output capacitances and high collector breakdown voltages. In summary, a high-resistivity collector with a low series resistance was needed together with a reasonably thick slice – apparently irreconcilable objectives.

The problem was resolved by the introduction of the expitaxial process whereby a thin (low-resistance) layer of high-resisvity silicon was grown on a thick low-resistivity (low-resistance) substrate layer of the same material. The thin layer (or expitaxial layer) forms an exact match and continuation of the crystal lattice of the thick substrate, so making the whole structure the monocrystal necessary for high carrier mobility and long carrier lifetimes. The emitter/base and base/collector junctions are formed entirely within the expitaxial layer and so satisfactory capacitances and breakdown voltages are achieved.

The planar structure is shown in Fig. 20 in vertical cross-section. It will be noted that the intersections of the junctions with the slice surface are entirely under the oxide layer and, therefore, these sensitive areas will be well protected from surface contamination. Although the vertical dimensions have diminished and the horizontal geometry has changed over the past decade, the basic structure has remained substantially unaltered.

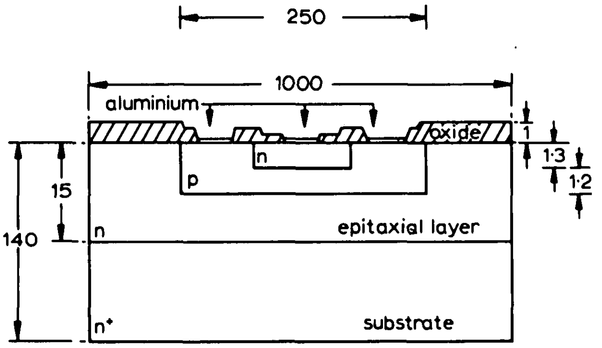


**Fig. 20**
*Silicon planar transistor in vertical cross-section*

It was at first felt at Dollis Hill that the expitaxial structure might introduce unreliability, possibly through the presence of a high proportion of induced crystal defects. Two actions were taken to study this problem. An in-house expitaxial facility, based on vapour-phase growth, was developed to discover techniques for producing low-defect slices. In addition, a method was developed to study how crystal dislocation defects affect the characteristics of transistors. This method[32] was based on that first described by Lang[33] and was known as X-ray projection topography. It had the great advantage of being nondestructive and the slices, after examination, could be used for device fabrication.

In particular, the new technique was used during the various stages of expitaxial fabrication to show changes in crystal structure after the layer is formed, after oxide growth and after the diffusion processes.[34] A systematic study of the changes in dislocation distribution could be related to the final electrical characteristics of the device. As a result of this work the number of dislocations introduced during epitaxy was substantially reduced.

In time, however, excellent quality slices were produced on a large scale commercially and a reliability problem in relation to defects did not materialise. In consequence the in-house fabrication facility was discontinued. All transistors produced by the British Post Office (or at STC Semiconductors Ltd) for submarine systems have had epitaxial structures and use the silicon planar technology.

### 7.2 Early reliability studies on silicon planar devices

The importance of using a reliable active device in the repeaters of the Anglo-Belgian number 6 cable made it essential to undertake exhaustive tests on both the electrical and mechanical performance of the 2N916-type transistor.

The reliability target for the system required not more than one repeater failure every five years. In general, as the failure of any one amplifier transistor can cause system failure, and if there are $n$ of these components in the system, the reliability of the system ($R_s$), expressed as the probability of survival, is related to the reliability of the component ($R_c$) by the equation

$$R_s = R_c^n \tag{9}$$

In the Anglo-Belgian cable, with only two repeaters (and six transistors per repeater) in tandem, $R_s = 0{\cdot}5$, $n = 12$ and $R_c = 0{\cdot}944$. The transistor reliability target is thus a modest 94·4% probability of survival for five years. However, for the future, submarine systems for shallow waters might be designed with 50 repeaters, and three transistors per repeater, with a need to limit the repeater failures to a maximum of 3 in 20 years. Then $R_s = 0{\cdot}94$, $n = 150$ and $R_c = 0{\cdot}9996$. In this instance a 99·96% probability of survival for 20 years would be required of the transistors : a far more difficult target to meet. Although it was believed that silicon planar technology could provide transistors to match such targets, proof was needed. To this end, a reliability testing programme[35] was planned for the type-2N916 transistors which was comparable in size with the one undertaken on germanium-alloy transistors some five years earlier (Section 6.2).

To provide devices for use in the Anglo-Belgian system, with a surplus for later requirements and with an adequate number for destructive testing, an order for 1500 type-2N916 transistors was placed by the British Post Office with the manufacturer, SGS-Fairchild Ltd. A further 500 transistors were included for use by the Anglo-Belgian system contractor (Submarine Cables Ltd.) in possible private ventures. All 2000 were provided from one production batch. The measurements used to validate the electrical reliability were made by the system contractor to a plan devised by the British Post Office and the analysis of the results was carried out at Dollis Hill.

At this time the assessment of mechanical reliability placed heavy emphais on centrifuge testing. The transistors were mounted so that the force on the wire bonds was in the outward normal direction from the silicon surface. After storing at temperatures ranging from 300° C to 366° C for 120 h, to ensure that any bond weakening due to metallic interdiffusion had proceeded to the limit, the devices were subjected to accelerations of 10 000 g to 62 000 g in steps of 10 000 g (last step 12 000 g) for a few minutes on each step. Only one failure, an emitter open circuit, was found in 96 samples tested from the production order of 2000.

Validation of the electrical reliability over a period as long as 25 years made it essential to discover a technique for compressing this time span into a testing period of a few months. The possibility of using temperature as an accelerating factor has already been mentioned[26] and its systematic application was developed by Peck[36] and employed in the 2N916 exercise. Two different techniques were used, the step-stress and the steady over-stress methods.

The step-stress method involves operating a small batch (say 30) of the transistors under normal d.c. conditions for a series of equal periods or steps of time $t$, at a constant junction temperature $T$ for each step. Usually $t$ is chosen to be 20 h and, if a second test batch is needed, 165 h. The temperature $T$ for the first step is chosen to be around 300° C and is raised by some 20° C for each subsequent step.

The wear-out mechanism of the transistor was still considered to be dependent on diffusion phenomena, and this dependence suggested a linear relation between $\log t$ (considered as the time to failure) and $1/T$. A normal (or Gaussian) distribution of failures with respect to either $\log t$ or $1/T$ ($T$ in $K$) was therefore assumed. The criterion of failure was chosen to be the deterioration of $h_{fe}$ (and, therefore, of $h_{FE}$ which is closely related). This choice was made because changes in the forward current transfer ratio control the gain changes in submarine amplifiers which are additive in their effect on system performance. In addition, significant changes in $h_{FE}$ occurred in advance of changes in any other transistor parameter affecting amplifier performance. This observation was not only found to be true for the 2N916 exercise but also for all subsequent batches of high-reliability transistors tested at Dollis Hill.

For these tests a change in $h_{FE}$ greater than 1·5 dB (or about 20%) was chosen as the failure criterion and was measured by logging changes in $I_B$ and $I_E$ and using the relationship

$$I_B/I_E = (1 + h_{FE})^{-1} \tag{10}$$

Plots of the cumulative percentage of failures against $10^3/T$ for step-stress tests with $t = 20$ h and 165 h are shown in Fig. 21. The experiment was continued for some seven steps until about 50% of the transistors failed. Consequently, a total time of less than 3 months was needed.

The steady over-stress test is similar in concept but in this case two large batches, each of 200 transistors, were tested at fixed values of $T$, 200° C and 220° C, respectively, for a period of about six months. For this test the cumulative percentage of failures was plotted against log $t$ (Fig. 22). For both step-stress and steady over-stress tests the transistors were mounted in electrically insulated thermal clamps in groups of 100 transistors on aluminium blocks in ovens. Selector switches outside the oven were used to connect each transistor in turn to the data logger.

The plots in Figs. 21 and 22 intersect the 1% cumulative failure level and yield four points relating time and temperature. These points are plotted as log $t$ against $10^3/T$ to give an Arrhenius line (Fig. 23) which may be extrapolated down to normal operating temperatures. For the type-2N916 transistors under test it can therefore be predicted that not more than 1% may be expected to deteriorate by more than 1·5 dB in gain in 25 years if their junction temperature is kept below 100° C. The expected reliability of the silicon planar technology was supported by these results and confidence of a satisfactory life for the Anglo-Belgian cable was strengthened.

The SGS-Fairchild type-2N916 transistors were used in both repeater amplifiers at 16 and 32 nautical miles, respectively, from the La Panne terminal. The total length from St Margaret's Bay, Kent to La Panne was 48 nautical miles. There have been no transistor failures during system life from 1965 to date.

### 7.3 Electrical characteristics

The more important electrical characteristics of the type-2N916 transistor are given in Table 4.

**Table 4**
ELECTRICAL CHARACTERISTICS OF THE TYPE-2N916 TRANSISTOR
All limits refer to 25°C ambient unless otherwise stated.

| Parameter | Test condition | Limits | |
|---|---|---|---|
| | | Min | Max |
| $h_{FE}$ | $I_C = 10$ mA, $V_{CE} = 1$ V | 75 | 150 |
| $V_{BE(SAT)}$ | $I_C = 10$ mA, $I_B = 1$ mA | | 0·9 V |
| $V_{CE(SAT)}$ | $I_C = 10$ mA, $I_B = 1$ mA | | 0·5 V |
| $h_{fe}$ | $I_C = 10$ mA, $V_{CE} = 15$ V<br>$f = 100$ MHz | 4 | 6 |
| $C_{ob}$ | $V_{CB} = 5$ V, $I_E = 0$ | | 5·5 pF |
| $I_{CBO}$ | $V_{CB} = 15$ V, $I_E = 0$ | | 10 nA |
| $I_{CBO}$ | $V_{CB} = 15$ V, $I_E = 0$<br>$T = 150$°C | | 10 μA |
| $V_{BR(CBO)}$ | $I_C = 10$ μA, $I_E = 0$ | 45 V | |
| $V_{CEO(SUST)}$ | $I_C = 100$ mA (pulsed)<br>$I_B = 0$ | 25 V | |
| $V_{BR(EBO)}$ | $I_E = 10$ μA, $I_c = 0$ | 5 V | |
| $N_f$ | $I_C = 1·5$ mA, $V_{CE} = 10$<br>$f = 4$ MHz, $R_G = 510$ ohms | | 4·5 dB |
| Thermal resistance (junction-case) | | | 146°C/W (nominal) |

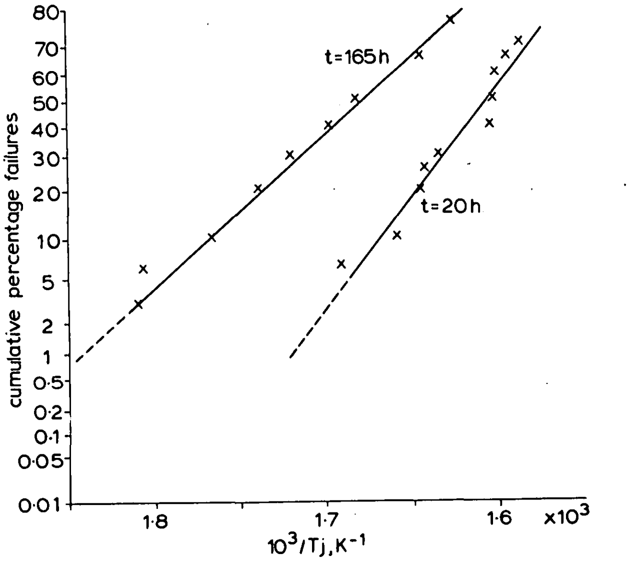


**Fig. 21**
*Cummulative % failures in step-stress tests of type 2N916 transistors*

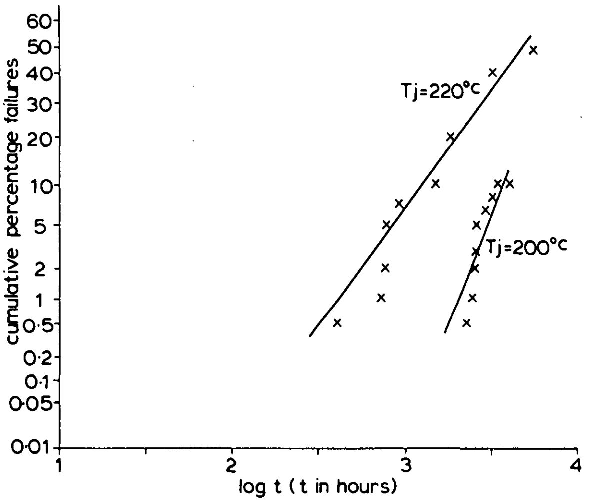


**Fig. 22**
*Cumulative % failures in steady over-stress tests of type 2N916 transistors*

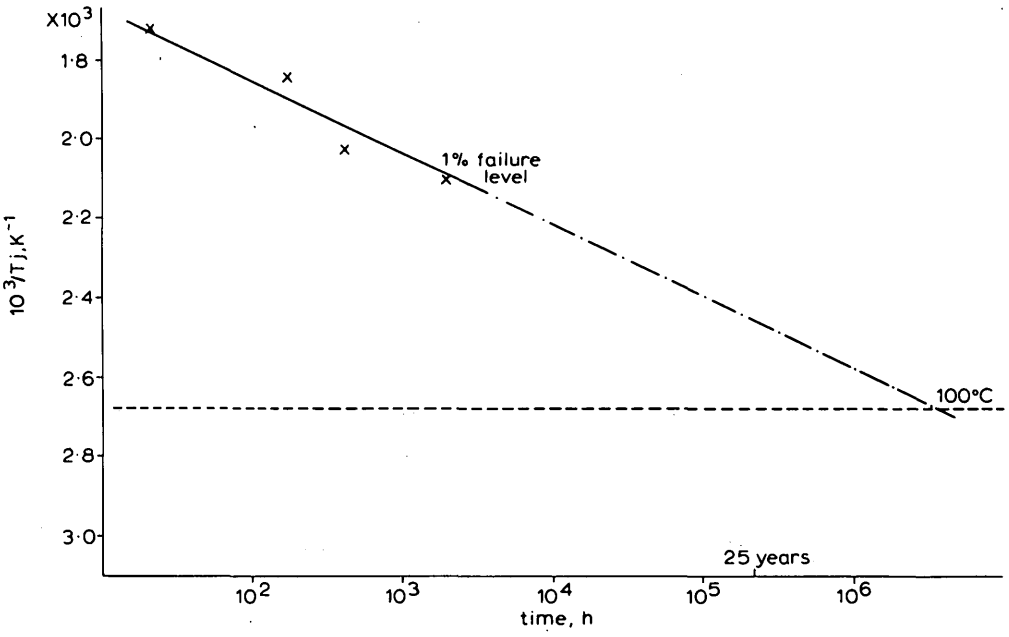


**Fig. 23**
*Life-prediction line (Arrhenius plot) for type-2N916 transistors*

## 8 Development of the first British submarine transistor (1961–68)

### 8.1 A dual approach

Although confidence in the suitability of the type-2N916 transistor for submarine usage was gained through early tests and the results of the Minuteman project, it was, nevertheless, considered that a British source of such a vital component should be provided. This could be achieved in two ways, first, by placing a device development contract with a British company and, second, by undertaking an in-house development exercise. Because of the importance of the task, it was decided to follow both courses in parallel.

The assistance of the Royal Naval Scientific Service, CVD Office, was sought in placing a contract for a transistor development in the UK. The salient features were that:

(*a*) not more than 0·1% should fail in the first 10 years when dissipating not more than 0·1 W in free air at a temperature not greater than 20°C
(*b*) the value of $h_{fe}$ (at $I_c = 10\,\text{mA}$, $V_{ce} = 10\,\text{V}$, $f = 100\,\text{MHz}$) should be not less than 4 at the end of life
(*c*) the maximum value of $C_{ob}$ at $V_{CB} = 10\,\text{V}$, $I_E = 0$ should be 4 pF.
(*b*) the maximum value of thermal resistance, junction to case, should be 150°C/W

The company chosen was the STC Transistor Division at Footscray (later known as STC Semiconductors Ltd.), the transistor was coded type VX7806 and the contract placed in October 1961.

Work on the contract continued until mid 1963 by which time samples of transistors for both output and input stage use were ready for test. Preparations for providing some 1500 life-test positions at Footscray were sufficiently well advanced to permit a full reliability assessment to commence in 1964.

At about the same time as the VX7806 contract was signed work was started in the Transistor Development and Production Unit (a larger organisation developed from the original Transistor Group) at Dollis Hill with the objective of developing a transistor type specifically for use in submarine systems. The transistor was planned to have an electrical performance equivalent to that of the type-2N916 transistor. Great emphasis would be placed on reliability at every stage of development as well as in preparing for production. The basic technological processes have already been referred to[31] and typical physical features chosen as part of the design plan were:

| | | |
|---|---|---|
| (*i*) substrate thickness | 125 $\mu$m | Antimony doped with resistivity less than 0·01 ohm cm |
| (*ii*) epitaxial layer thickness | 15 $\mu$m | Phosphorus doped with resistivity about 2 $\Omega$ cm |
| (*iii*) junction depths | | |
| emitter-base | 1·3 $\mu$m | |
| base-collector | 2·5 $\mu$m | |

A number of investigations to improve reliability and establish viable production techniques were undertaken and will be described later. By 1964 sufficient progress had been made to permit a choice between further work on the VX7806- type transistor and on the new British Post Office transistor, coded type 4A (4 = transition frequency in MHz/100). This choice was influenced by the wish to involve STC in the development of a second, more advanced, transistor for submarine usage and by the discovery of a new, potentially very reliable, contact system for the type 4A (see next Section).

For these reasons, work on the VX7806 was discontinued and efforts concentrated on the type 4A. Within a year, however, STC Semiconductors were to undertake a parallel development of the type 4A in addition to their work on the more advanced transistor.

The concept of a dual approach by the British Post Office and STC to both the development and production of high-reliability transistors for submarine systems deliberately followed the same pattern used in the case of thermionic valves.

This bipartite plan was continued as a general principle throughout the 1960s and early 1970s.

### 8.2 A new contact system

Transistor failures may not always occur as a result of the operation of the wear-out mechanism discussed in Section 7.2. Another mode of failure was briefly mentioned in the paragraph on assessment of mechanical reliability, namely an emitter open circuit. Such failures, if they occur as isolated cases, could be classified as random or rogue. On the other hand, there is a danger that the rogue failure in early life could become the endemic failure of later years. Attention was therefore directed to the contact system of the type 4A transistor.

During the early 1960s there was a most favoured contact system for silicon planar transistors. Connection to the collector region was effected by brazing the silicon chip to the gold-plated header. An evaporated aluminium metallisation was defined precisely by photolithography on the emitter and base regions of the chip surface and gold bonding wires were connected between the aluminium film and the posts of the header lead out wires. The method of connecting the wires to the posts and the aluminium film made use of thermocompression bonds; the bond wire was pressed on to the bonding surface whilst maintaining both wire and surface at an elevated temperature.

There were therefore two metals used in forming the connections to emitter and base, gold and aluminium. Unfortunately, intermetallic compounds can be formed, and some of these are detrimental both to mechanical strength and electrical conductivity. The tan, gold-rich phase, $Au_2$ Al, formed with silicon as a catalyst, is particularly dangerous to ultrahigh reliability, being both brittle and of low electrical conductivity.

There are, however, reasons for using both gold and aluminium. The latter forms a good ohmic contact to $p, p^+$ and $n^+$ regions of silicon devices whereas gold does not. An all-gold system would require controlled evaporation of doped gold which is a difficult technological process. The alternative all-aluminium system has its problems. Aluminium forms a good bonding wire when judged solely on the criteria of resistivity and density (a low density and, therefore, mass reduces the force experienced by a bond when the transistor is subject to shock acceleration). On the other hand, aluminium bond wires are not successful when either of the only two then known forms of thermocompression bond are used, the chisel and the ball bond (Fig. 24). The chisel bond is relatively weak mechanically when used with aluminium and the ball bond cannot be used due to the formation of a film of $Al_2O_3$ when and however the wire is heated for form the ball.

Nevertheless, the advantages of an all-aluminium system in avoiding intermetallic compounds, in high conductivity and in low density are too great to be disregarded. A detailed investigation of thermocompression bonding was undertaken by the British Post Office and a new type of thermocompression bond was invented[37] which satisfied the following requirements:

(*a*) sufficient lateral plastic flow of metal must occur at the bond interface to rupture thin films of oxides or other contaminents over the whole of the bond area
(*b*) the wire cross-sectional area must not be reduced significantly by the bonding operation
(*c*) the area of the bond should be approximately equal to the cross-sectional area of the wire

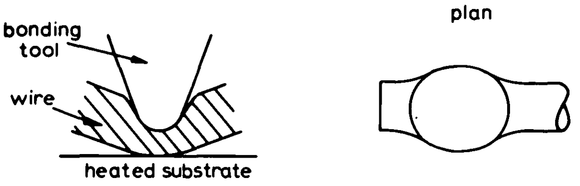
The new bond was called the 'eyelet bond', from its appearance, and during its formation considerably more lateral plastic flow occurred than for either the ball or chisel bonds. The new bond is also shown in Fig. 24 together with a cross-section of the bonding tool. The best results were obtained when *d*, the diameter of the flat circular bonding tip, equalled the diameter of the bond wire.

During the course of development the breaking load of eyelet bonds was compared with the breaking load of chisel and ball bonds between the same materials. In all cases the eyelet bonds attained higher breaking loads than the chisel bond by a factor or two or more and equal breaking loads with the ball bond whenever the latter could be used. Strong eyelet bonds can be made to oxidised aluminium films to which ball bonds had failed to adhere and, in addition, aluminium wire can be eyelet bonded direct to Kovar posts. However, with specification control on the maximum thickness of gold plating on the header posts and with three bonds on each post, no failure of a post/wire bond has ever occurred. At this stage of development all bonds were tested by a tensile force of 0·5–1·0 g immediately after fabication and the record of subsequent performance has been exceptionally good. By the end of 1974 some 4600 transistors of British Post Office manufacture were on the sea bed (more than 3 8000 bonds) and there has been but one failure. There have been no bond failures in the even greater number of transistors subjected to electrical or mechanical over-stress testing or in any of the submarine transistors manufactured by STC Semiconductors, where the same eyelet bonding system is used.

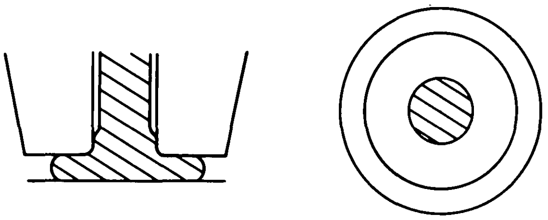
### 8.3 The choice: valve or transistor

Between 1961 and 1965 the Commonwealth cable (including CANTAT, COMPAC and SEACOM) was completed and the Lisbon-South Africa cable was laid in 1968. Valve provision for these projects marked the culmination of the efforts of the Thermionics Group and of the STC Paignton Unit.

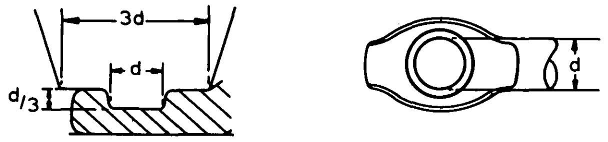
In 1962-63, while the thermionic valve was reaching the zenith of its application in submarine telephony, the British Post Office Engineering Department (Lines Branch) was actively considering new submarine systems in the North Sea. Following the trend towards higher performance noted in Section 5.1, larger capacity systems were now required (up to 5 MHz bandwidth). As repeater amplifier design experience was available in or approaching this region for both valve and transistor amplifiers, system design engineers were faced with a choice of active element.



a.chisel



b.ball bond



c.eyelet

**Fig. 24**
*Formation of principal bond structures*

There were two main factors to take into account: performance and reliability. On performance, advantage lay with the transistor. The physical limitation of grid-wire diameter and spacing, coupled with the inability to obtain satisfactory performance with screen voltages much below 35 V, made the 5A/190G type a terminal device and 3 MHz a limiting bandwidth for thermionic valves. On the other hand, the type-2N916 transistor, with a supply voltage below 20, had by no means reached the frequency performance limit of bipolar transistors. This device had already permitted the design of a 4 MHz bandwidth amplifier.

Overall confidence in the reliability of the 10P- and 5A/190G-type valves enabled the British Post Office, in 1963, to claim that parallel amplifiers were no longer necessary in shallow waters. Limitations in repeater performance were too great if parallel transistor amplifiers were used. A single amplifier reliability comparison had thus to be made between valves and transistors. The failure to accelerate valve mechanisms quantitatively, the excellent early results of the first silicon transistor reliability exercise and the reliability of the new transistor bond gave a margin of advantage to the transistor.

The transistor excelled therefore, in general terms, in both performance and reliability. This conclusion had, however, to be confirmed in particular for the transistor type chosen for future system use. There were two alternative devices on which the argument could be based, the SGS-Fairchild type 2N916 and the British Post Office type 4A.

Apart from the advantage of the type 4A in permitting close liaison between device and amplifier design engineers in the UK, this type was preferred for three other reasons. First, a mechanically more reliable lead bond was used, secondly, an all-aluminium bond contact was employed and thirdly, manufacturing tolerances were tighter.

For these reasons considerable effort was directed towards development of the type 4A for production from 1964 onwards, although tests on the type 2N916 were continued in parallel. By the summer of 1965, quantities of type 4A transistors were being produced at Dollis Hill. The reliability assessment had gone far enough to confirm that life prediction on gain failure was almost identical with that made for the type 2N916 and also to confirm that mechanical reliability was satisfactory. One other later result of the type 2N916 reliability exercise gave decisive support to the adoption of the all-aluminium eyelet bond. Although the type 2N916 was satisfactory on gain change with life, one parameter, $V_{BE\,(SAT)}$, had showed unacceptable increases associated with the growth of intermetallic compounds at the bond contacts. These changes could not occur in the type 4A.

By 1965 the decision to abandon the thermionic valve in future submarine systems was taken with the firm assurance that a British transistor could be produced for a wide bandwidth amplifier to meet the high reliability standards required for submarine-system usage. The Lisbon-South Africa was to be the last cable in which thermionic valves would be used.

### 8.4 High-capacity systems in the North Sea and English Channel

In 1962 a firm requirement arose for two new high-capacity cables (400 or more circuits) from the UK to Holland and the Channel Islands. The need for a third cable linking the UK and Norway was made known in 1963. In this year a draft specification for a 5 MHz submerged repeater system for shallow waters was issued. It required the probability of survival of a system of 60 repeaters to be at least 0·75 over a period of five years. Eqn. 9 can again be used to calculate the consequential transistor reliability on the assumption that the active device constitutes the only failure risk. Thus with $R_s$ equal to 0·75 and $n$ equal to 180 (for a 3-stage amplifier) the necessary value of $R_c$ was 0·9984. The probability of survival (99·84%) required over a 5-year period is a more onerous requirement than was needed for the Anglo-Belgian number 6 cable but still much less severe than the 20-year guarantee suggested as an ultimate target. As indicated before, opinion was moving in favour of the type 4A during 1964 but there remained one consequence to be agreed with the system contractor. The results in Fig. 23 (and results to be presented later) emphasise the increase in predicted life as the operating temperature is reduced. Amplifier transistors must therefore be provided with efficient heat sinks to ensure a high-conductivity heat drain and the lowest possible operating temperature. The type 4A encapsulation (TO-5) is larger than that of the type 2N916 (TO-18) and a larger diameter heat sink was needed. The necessary modification was agreed in 1964.

By autumn on 1965 the type 4A production plan was in full operation and a continuous assessment of the product was being made. The successful type 4A reliability studies, briefly mentioned in the last Section, consisted of a step-stress exercise on 180 devices which yielded an Arrhenius line almost identical with that in Fig. 23 for the type 2N916, a result compatible with the system-reliability specification. At about this time the concept of screening tests was introduced to exclude atypical devices. All transistors were stored at 350°C for 3 h and only those which were stable or showed small increases in gain were accepted for system use or over-stress assessment. In addition, a sample of 10 transistors from each successful production slice was tested at $T_j = 290°\mathrm{C}$ for 20 h with $V_{CE} = 14\,\mathrm{V}$ and $I_C = 10\,\mathrm{mA}$. Out of 254 transistors tested there were no failures, this time judged on the basis of

$$\frac{\Delta h_{FE}}{h_{FE}} = 10\%\ \text{maximum} \qquad (11)$$

measured with $I_C = 10\,\mathrm{mA}$. Operation at 290°C for 20 h is approximately equivalent to 20 years of working life. Finally, those transistors intended for system use were given an operational test at $T_j = 60°\mathrm{C}$ (some 10 deg C higher than the temperature encountered in the output stage of the amplifier with $T_{case} = 25°\mathrm{C}$ and a dissipation of 350 mW) for 1500 h. Very stable performance was obtained showing no changes in any parameter within the accuracy of measurement over the test period, which is equivalent to 4 months for an output stage and 1 year for 1st and 2nd-stage amplifier transistors.

On the basis of the success of these and other assessment tests transistors were supplied to the contractor (Submarine Cables Ltd.) for use in the three systems. The numbers involved are given in Table 5 below.

**Table 5**
NUMBER OF TRANSISTORS SUPPLIED

| System | No of working Repeaters | No of transistors in working repeaters | No of transistors in spare repeaters |
|---|---|---|---|
| UK–Netherlands | 14 | 42 | 6 |
| UK–Norway | 52 | 156 | 15 |
| Bournemough–Jersey | 18 | 54 | 9 |

Transistors for supervisory circuits are excluded here, and hereafter, from production totals. Although these devices are usually the same type as the active elements, the specification requirements are much less severe in both performance and reliability.

The Bournemouth–Jersey cable was laid in 1967 and the other cables in 1968.

### 8.5 Type-4A usage in deep-water systems

Until 1965 the development of transistors for submarine telephony had been concentrated on shallow-water applications but in that year a requirement arose which foreshadowed future transoceanic system usage. The Lisbon–South Africa cable was due to be laid in 1968 and an extension north to the UK was needed, a distance of 1000 nautical miles in deep water.

At the outset three proposals were considered:

(i) a 3 MHz system, 360 (3 kHz) circuits
(ii) a 5 MHz system, 480 (4 kHz) circuits
(iii) a 10 MHz system, 900 (4 kHz) circuits

The attraction of the first proposal had already been diminished by the forecast successful outcome of the second, which was being used for the systems mentioned in the previous section. The third proposal required the new advanced transistor briefly mentioned in Section 8.1, and this would not be available for a 1968 r.f.s. date. In consequence of these factors the second proposal was adopted in June 1965. The British Post Office accepted the task of providing the necessary 4A type amplifier transistors to the system contractor (STC). Excluding spares, 128 working repeaters were needed, each including a 3-stage amplifier.

Later, in 1966, the Canada–Burmuda (CANBER) 5 MHz system was planned, using a similar amplifier. This cable (810 nm) landing in Nova Scotia would also be laid in deep water and 640 (3 kHz) channels were required. Again, the British Post Office was asked to provide 4A-type transistors to the contractor Submarine Cables Ltd. (SCL).

These two new cables introduced a radical change in the reliability target for the active devices. The previous longest shallow-water system (UK–Norway) needed less than 200 amplifier transistors and only specified reliability in terms of a five-year period. Now, almost 500 transistors were required per system and the deep-water route made the recovery of faulty repeaters more difficult and more expensive. Reliability over 20 years was called for, and accepted as a practical target on the basis of the earlier successful validation programmes.

Specifically, it was guaranteed that less than one transistor in 500 would fail in an operating life of 20 years; failure was defined as a change of ± 10% in current gain, a change of greater than 30 mV in a saturation voltage or an increase in the leakage current of either *p-n* junction to 2 $\mu$A.

Some of the technological problems encountered and overcome in meeting this guarantee are described in the next section. However, following the bipartite plan mentioned in Section 8.1, a contract was placed with STC Semiconductors Ltd in 1966 for the development and production of 4A-type transistors to meet the two specifications for input (4A2B) and output (4A2C) use. Some 1000 devices were ordered to provide a second source in the event of failure to meet production targets at Dollis Hill.

### 8.6 Technical problems and solutions

By the mid-1960s the type-4A design was well established and few serious problems arose in connection with electrical performance. The major effort of the teams at Dollis Hill and Footscray was directed towards the problem of ensuring reliability.

The main failure mode was still the deterioration of current gain ($h_{FE}$) although growth of leakage current early in life sometimes indicated inadequate processing. In all cases, the cause of failure was still identified with surface contamination, and, for the special case of particulate contamination, the importance of the problem was recognised in the decision to commission a clean room at Dollis Hill for transistor production.[38] The working area of the room was 47 m$^2$ and air input filters excluded particles exceeding 0·5 $\mu$m diameter. The relative humidity was maintained at 40% and the temperature at 21°C. These conditions, with fluorescent lighting, made working conditions pleasant for the staff, who changed into garments designed to reduce dust and fibre generation before entering the room. Dust counts showed that, except around the entrance, it was unusual to detect particles greater than 1 $\mu$m in diameter within the room. A similar clean room was installed at Footscray.

In 1965, during the production of transistors for the early shallow-water systems (the first time the clean room had been used for fully accredited submarine-transistor production) tests on a large batch (over 500) of transistors showed that device failure could be expected in five years. Although the system specification only defined reliability over a five-year period, the prospect of large-scale transistor failures at the end of this time was unacceptable.

In detecting these failures use was made of $h_{FE}$ measurements at low collector currents (0·1 mA in place of the working current of 10 mA). Changes in low current gain are a very sensitive technique for detecting the onset failure as the rate of decay of $h_{FE}$ at 0·1 mA is much greater than at either 1 mA or 10 mA. The cause of the failure was traced to the encapsulation process and was symptomatic of hydrogen or hydrocarbon contamination. In an attempt to improve processing, it was found that more careful removal of photoresist residues by a slice bake, after metallisation, at 500°C for 1 h in dry air, stabilised the surface and reduced both channel leakage and deterioration in $h_{FE}$. The problem of bonding to the consequent aluminium oxide was solved by the adoption of the eyelet bond (see Section 8.2). In addition, improved can and header cleaning was introduced, and the headed and wired devices together with their serially numbered cans were baked at 300°C for 1 h in dry nitrogen before encapsulation, also in pure dry nitrogen (obtained from the liquid) plus 10% oxygen.[39] Corrosion of the internal bonding wires, due to the release of chlorides and water within the encapsulation, was also reduced by these improved processing techniques. An earlier bake at 800°C for 30 min in dry nitrogen, after the last oxidation, cleared hydroxyl ions and further aided the stability of $h_{FE}$.

During this investigation it was demonstrated that complete recovery of failed devices (shown by restoration of low current $h_{FE}$ to its original value) could be achieved by opening the can and removing the silica passivating layer. This brief experiment provided additional confirmation that surface contamination was the prime cause of failure.

Following these improvements in production technology, the task of providing devices for the UK–Netherlands, the UK–Norway and the Bournemouth–Jersey systems was successfully completed and the production and quality control sequence was documented.[40] Further technological problems were, however, to arise in provisioning the new deep-water cables and the main cause of the new problems arose from changes in materials and piece-parts. Although slice processing (including photoresist, diffusion and oxidation techniques), heading, bonding and encapsulation were undertaken in house, the silicon slices, bonding wire, cans and headers were all obtained from sources outside the UK, over which there was little control.

A very serious problem arose in 1967 when signs of general surface corrosion and grain boundary corrosion were detected in the region near the external junction between the meniscus of the glass seal and the gold plating of the kovar leads and header shell. The defect occurred on a batch of headers being used for the production of transistors intended for the UK–Portugal system. It was not present on headers when they were received but developed on those subjected to production processes and then exposed to normal atmospheric ambients for some months. The corrosion was basically rust and probably involved transport of iron along a grain boundary and subsequent conversion to iron oxide or hydroxide at the surface. Taken to its extreme the defect could have led to complete fracture of the lead wire.

One solution to this problem might have been to change to a different and immune header type. Such a course would, however, have delayed production by a year and still might have been subject to header batch variation. As an alternative it was decided to attempt an immediate solution which could give complete immunity to all header types or batches. This plan involved coating the underside of the header with high-purity silicone varnish (material code MS994) to a thickness of about 50 $\mu$m. Tests showed that this treatment was an effective long-term corrosion inhibitor even under conditions of 90% r.h. and 75°C.[39] It has been used to protect the metal glass seals of all submerged repeater transistors made subsequent to the early shallow-water systems and there have been no cases of fractured or corrosion damaged leads. The efficiency of the process can also be illustrated by the effect it has on the reduction of leakage current growth with time. This is shown in Fig. 25.[*1]

One factor contributing to leakage and corrosion hazards on the header was identified[39] in the type of glass used for the header seals. Clear or opal matched glass seals are preferred to heavily pigmented glasses since, after the high temperatures used in production and validation, excessive leakage currents occur in the latter case, together with indications of corrosion both of the internal aluminium bonding wire and of the external leads. The advantage of the clear glass headers is clearly shown in Fig. 26[4*] when leakage current is plotted against temperature for the two header types. Another

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[*] BAKER, D.: Private communication, 1970

factor contributing to the danger of collector/emitter channel leakage is the excessive out diffusion of boron from the surface of the base region into the oxide passivating layer leading to surface inversion. The oxidation schedules were adjusted to minimise the probability of out diffusion.

A further hazard arising from bought-in material was discovered just before the corrosion investigation. Once again, serious degradation of low current $h_{FE}$ was noted on a batch of transistors, this time in spite of the excellent results of probe measurements at the slice stage.[41] The production sequence was carefully monitored and, in consequence, attention was directed towards the aluminium wire bonding the device to the header posts. Contamination of the wire was suspected and improvement was obtained by cleaning the wire in ethyl alcohol before bonding. By comparing two batches of type-4A transistors on stepstress it was shown that an order of magnitude increase in life expectancy could be achieved through using this cleaning process.

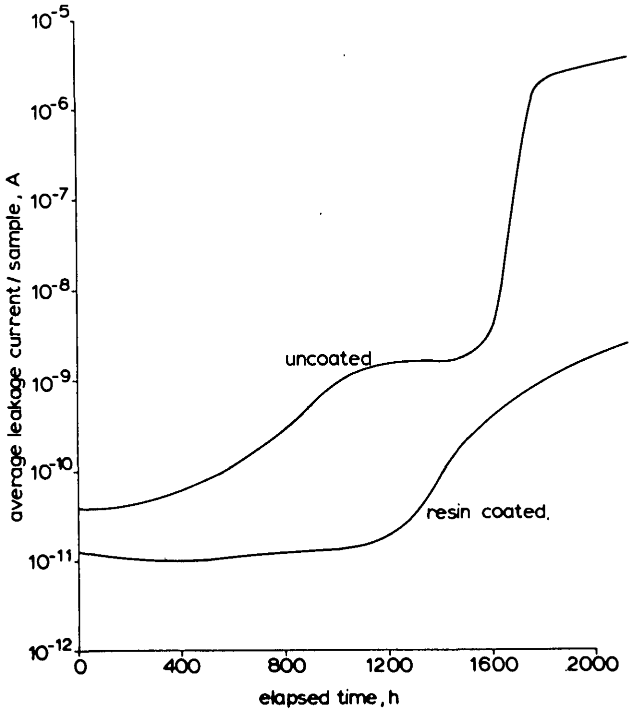

**Fig. 25**
*TO-5 corrosion tests Variation of leakage current with time for headers stored with 20 V bias applied between each lead and the Kovar shell at 80% r.h. and 75°C*

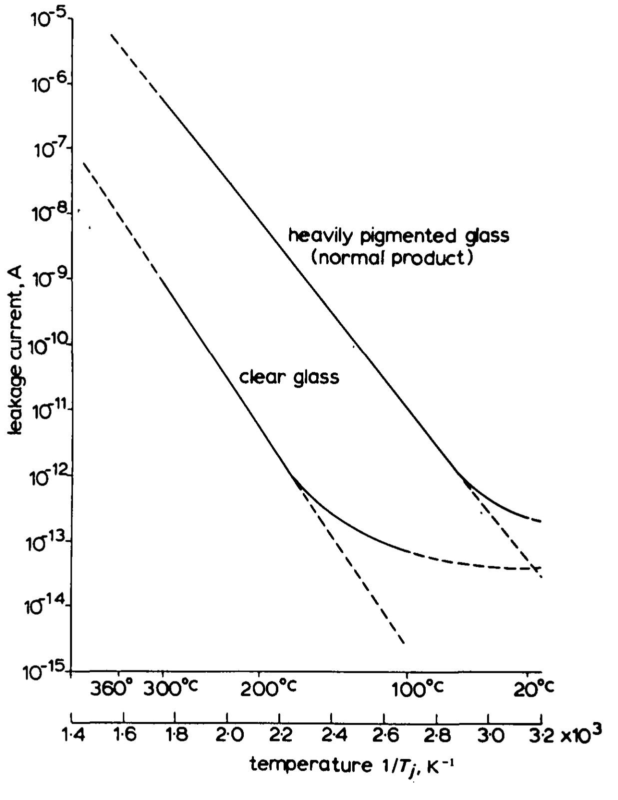

**Fig. 26**
*Variation of leakage current with temperature for TO-5 headers with either heavily pigmented or clear glass*

Chemical analysis showed that contamination of the wire by long-chain fatty acids, probably stearic acid, was present to the level of 0·05 μg/mg of wire. The stearic acid is removable by washing but, if left on the wire, it can, during long periods of normal operation, or more quickly during high-temperature overstress, react with the aluminium, releasing hydrogen which depresses the $h_{FE}$.

After this sequence of investigation and development, ending in early 1968, sufficient confidence was gained to start production of transistors for the UK–Portgual and CANBER systems.

### 8.7 Provisioning deep-water systems

The task of supplying over 500 type-4A devices for both the UK–Portgual and the CANBER systems started in January 1968 and was completed in one year. In addition, in the same year, 160 type-4A devices were provided to SCL for a non-Post Office system between Italy and Greece. It was accepted that the British Post Office should assist British Industry by providing transistors of guaranteed reliability for private-venture submarine systems where there was no conflict with the needs of British Post Office submarine systems.

Slice production was undertaken with continuous monitoring of all processes and each transistor on a slice was individually numbered and visually inspected for defects. Continuous quality control and 100% visual inspection under high magnification demands high yields if excessive cost is to be avoided. A comprehensive production control system[39] was developed to maximise yields and stabilise the devices.

After heading and bonding another visual inspection was carried out to exclude assembly or processing defects and each transistor was photographed before encapsulation in a serially numbered can. A complete case history of each transistor was filed as a record.

Following encapsulation, all transistors were subjected to a more comprehensive screening programme than was hitherto used. They were first stored at 350°C for 3 h. This treatment anneals out the stress of header bonding and takes up any residual oxygen within the can, so revealing the effect of residual contaminants if they are present. The second screen was a short over-stress, 20 h at normal bias with a junction temperature of 200°C, equal to a substantial fraction of a system life of 20 years under normal operating conditions. Measurements of electrical parameters were made before and after each screening process. Provided changes in performance detected by these measurements were kept within specified limits, it was shown, by subsequent accelerated testing, that the current gain of each transistor may be expected to remain stable within ± 2% for an operational life of more than 20 years (Fig. 27[*]). The screening was further assisted by a step-stress exercise, using sample transistors from each silicon slice, as a continuous check on production quality; any change in failure mode or significant change in failure level resulting in a slice rejection and corrective action.

Finally, a mechanical screen was introduced and all transistors were subjected to a controlled-drop test of 0·9 m. No resultant changes in electrical performance or in mechanical structure (detected visually) were allowed. This test took the place of the earlier centrifuge testing which had always involved a real danger of damaging the transistors during the test.

To support the accuracy of the screens in excluding defective or nonstandard transistors, and also to validate the guarantee of reliability, the final step in the provisioning sequence was one of product evaluation. Transistors which passed to screens were selected by random numbers for operational test, before system use, for large-scale destructive steady over-stress tests, for additional postscreen-step-stress assessment or for mechanical evaluation (Fig. 28).

The operational test was similar to that described in Section 8.4 but was extended to 3000 h. The steady over-stress tests were undertaken using the techniques described in Section 7.2 but with larger batch sizes.[43] These larger batches were needed to ensure that the first failure on each stress level represented a real 0·2% (the 1 in 500 called for in the specification). Consequently, 500 transistors were placed on test at each of the three stress levels, $T_j$ = 220, 260 and 300°C. Typical results are shown in Figs. 29 and 30.

Previously, mechanical evaluation of the transistor had been undertaken as part of the quality control before screening. From this time onwards, the mechanical evaluation also formed part of the validation procedure and included tests on lead fatigue, lead torque, lead pull, leakage and thermal shock.

[*] BAKER, D.: Private communication, 1970

Any transistor failure during product evaluation, at a level equal to or greater than the specified value of 1 in 500, would result in rejection of the whole batch of transistors being validated, and a restart of production, unless the case history of the failures clearly indicated that identification and withdrawal of the defective devices could be assured. Fortunately, no such failures occurred in 1968 and provisioning proceeded smoothly towards a successful conclusion.

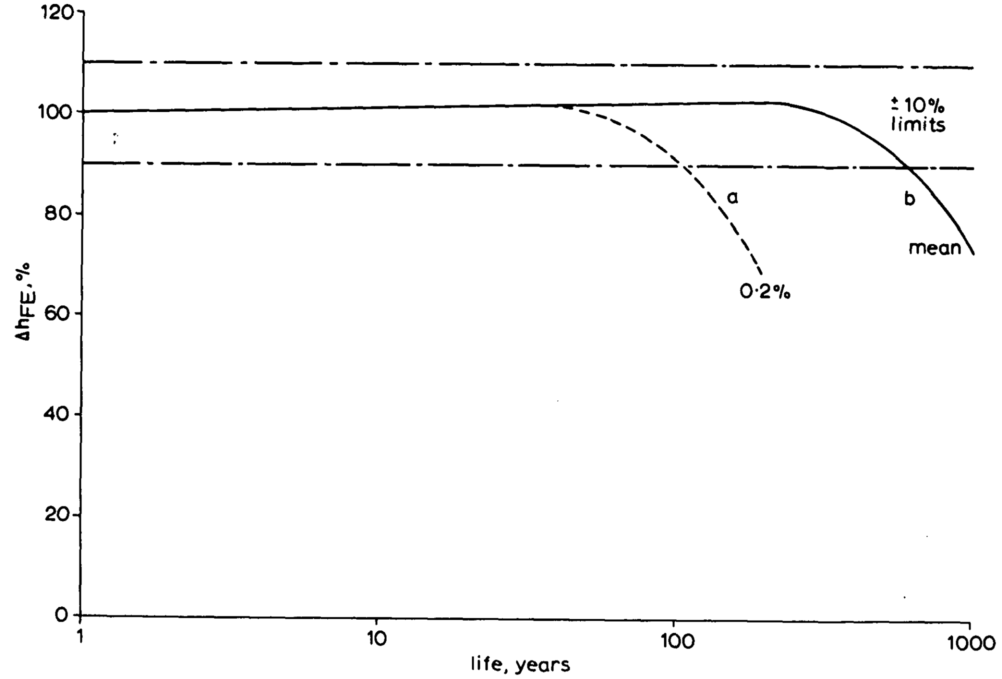

**Fig. 27**
*Predicted variation of current gain during operating life for system containing 500 type 4A transistors*

*a* First predicted transistor failure
*b* Mean predicted life behaviour
All other transistor parameters are expected to remain unchanged during the whole of the predicted operating life time

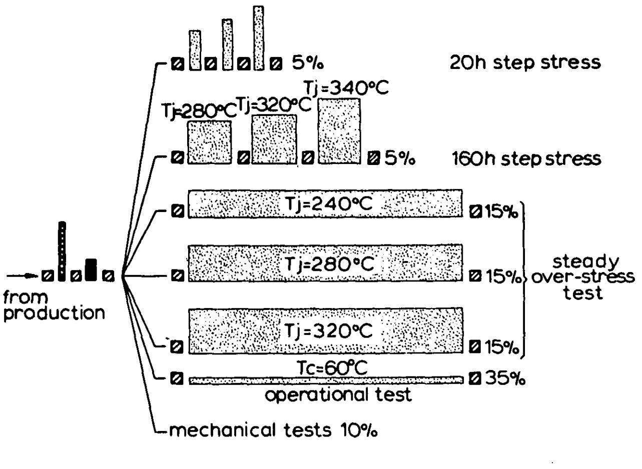

**Fig. 28**
*Typical test programme for type-4A and -10A transistors*

▨ Measurement $T_c = 25°C$
▩ Storage $T_j = 350°C$
■ Burnin $T_j = 200°C$

### 8.8 Surge protection

It is appropriate at this stage of increasing system length, to mention briefly the problem of surge protection. Submarine systems, both valve and transistor, are power fed from each end and trawler damage can earth the centre conductor and send a high-voltage surge through adjacent repeaters: the longer the cable the higher the surge voltage.

In the earlier cables with valved repeaters, quick-operating-gas-discharge tubes across transmission paths and the amplifier d.c. supply were used to protect the valves and other components.[43] In the new transistorised systems the gas tubes alone were not sufficiently fast to protect the more sensitive amplifier transistors and new arrangements were required.

A series chain (for redundancy) of large Zener diodes, STC-type VX 7954, was connected across the d.c. supply terminals of the transistor amplifier to limit the voltage during a fault surge. Surge voltages across the power-separating filters were kept to a tolerable level by gas-discharge tubes, but large fast surges which pass these were prevented from damaging amplifier transistors by unbiased small signal diodes (Fairchild-type 1N3595) at the amplifier input and similar, back-biased, diodes (to avoid imparing linearity) at the output.[44]

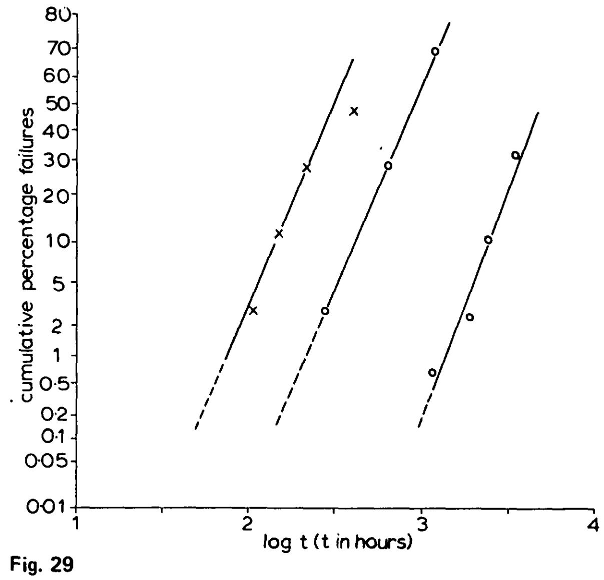

**Fig. 29**
*Cumulative % failures in steady over-stress tests of type-4A transistors used in deep-water systems*

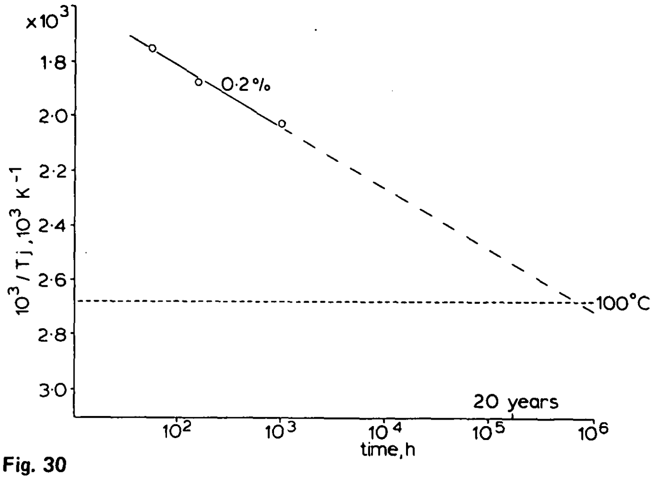

**Fig. 30**
*Life prediction line for type-4A transistors used in deep-water systems*

### 8.9 Characteristics of the type-4A transistor

The chief electrical characteristics of the type-4A transistor are given in Table 6 and the surface geometry is shown in Fig. 31.

**Table 6**
ELECTRICAL CHARACTERISTICS OF THE TYPE-4A TRANSISTOR

| Characteristic | Test conditions (case temperature = 25°C) | Limits 4A2B Min | Max | 4A2C Min | Max |
|---|---|---|---|---|---|
| $I_{EBO}$ | $V_{EB} = 3V$ | - | 100nA | - | 100nA |
| $I_{CBO}$ | $V_{CB} = 15V$ | - | 10nA | - | 10nA |
| $h_{FE}$ | $I_E = 0{\cdot}1mA$<br>$V_{CE} = 10V$ | 50 | 200 | 35 | 150 |
| $h_{FE}$ | $I_E = 10mA$<br>$V_{CE} = 10V$ | 100 | 200 | - | - |
| $h_{FE}$ | $I_E = 35mA$<br>$V_{CE} = 15V$ | - | - | 75 | 150 |
| $h_{fe}$(100MHz) | $I_E = 10mA$<br>$V_{CE} = 10V$ | 4·0 | 5·5 | - | - |
| $h_{fe}$ (100MHz) | $I_E = 35mA$<br>$V_{CE} = 15V$ | - | - | 3·5 | 5·0 |
| $C_{ob}$ | $I_E = 0$<br>$V_{CB} = 5V$ | 2·0pF | 4·0pF | 2·0pF | 4·0pF |
| $V_{BE(SAT)}$ | $I_C = 50mA$<br>$I_B = 1{\cdot}5mA$ | 1·75V | 1·0V | 0·75V | 1·0V |
| $V_{CEO(SUST)}$ | $I_C = 10mA$ (pulsed) | 25V | - | 35V | - |
| $N$(1MHz) | $I_C = 1mA$<br>$V_{CE} = 6V$ | - | 3·5dB | - | - |
| Thermal resistance (junction case) | | | 65°C/W (nominal) | | |

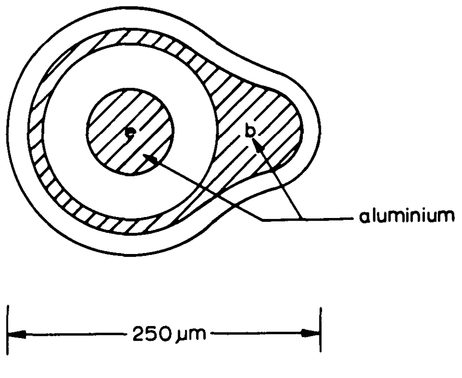

**Fig. 31**
*Surface geometry of type-4A transistor*

### 8.10 Early transistors in the USA and France

During the 1960s developments in both the USA and France led to a change in submarine systems from thermionic valves to transistors. At Bell Telephone Laboratories a substantial body of experience with germanium diffused-base transistors provided confidence that a submarine reliability target for a failure rate of better than 0·0005% per 1000 h could be attained with this transistor type.[45a] The first Bell transistorised submarine system, SF, was consequently designed around this device (coded L2287/8 for input and output versions, respectively) and was used for the TAT-5 cable linking the USA and Spain in 1970. The transition frequencies of these transistors were 950 and 750 MHz, respectively.

The choice of germanium for the transistor material involved a validation technique differing in one important respect from that used in the UK. The high-level over-stress acceleration tests on representative batches were not employed and reliance was placed on 100% ageing under worst-case power and temperature conditions, a test bearing a close relationship with the operational tests mentioned in Sections 8.4 and 8.7.

In France, as in the UK, device development followed the course of silicon planar bipolar technology. The first type (type SM03) had a structure comparable with the type 4A with a somewhat lower transition frequency (150–200 MHz). It was used in the Marseilles-Beyrouth system in 1970[45b] which provided 160 (3 kHz) channels.

Improved versions (types SM04 and SM05) for input and output use, respectively, were designed with minimum transition frequencies of 300 and 400 MHz.[45c] A beryllium heat sink improved the thermal impedance. These devices were used in the St. Tropez-St. Raphael system in 1970 and in the second Marseilles-Algiers cable in 1972, providing 640 (3 kHz) channels.

## 9 Transistor for trans-oceanic systems (1963-1974)

### 9.1 First plans

The period when the 2N916/4A types transistors were used in submarine repeaters corresponded closely to the earlier CV1065-6P12-10P-type-valve period. During both periods, there was an acceptance of the state-of-the-art electrical performance of the devices with major development effort concentrated on reliability. In 1963, however, the British Post Office formulated plans for a new transistor type, for possible transoceanic usage, with a performance which was as far ahead of the type 4A as the 8P-type valve was in advance of the earlier valve designs.

Action was taken well before any firm operational need because of the long development time (at least five years between design and first production) caused by the difficulties encountered in achieving simultaneously high performance and exceptional reliability. Because of this extended development phase a factor of at least 2 in system capacity growth was needed and, consequently, the target transition frequency of the new family of devices (type 10A) was chosen to be around 1 GHz. (To ensure minimum distortion, due to phase change caused by the transistor over the working bandwidth, it is necessary that $f_T$ should be about 100 times greater than the highest frequency used.) At this time, it was believed that any decision to develop transistors with transition frequencies higher than 1 GHz would involve a substantial risk that the necessary ultrahigh reliability would not be attainable within the five-year development span.

As the type 10A was the first submarine transistor design to be specially commissioned, as distinct from adapting an established design, more attention was concentrated on matching the device to the circuit than had hitherto been necessary. Although the earlier type 4A was used in all stages of the 5 MHz amplifier, it was considered that two versions of the new type would be more efficient. The transistor design for the first two stages was therefore directed towards providing a low-current, low-noise version for the highest practical transition frequency of around 1 GHz, whereas the design for the output stage provided high power with maximum linearity, and the accepted possibility of a somewhat lower transition frequency.

The surface geometry of the type 4A was circular but a change was necessary for the type 10A. The increase in $f_T$ required a narrower base width, 0·5 µm compared with the 1·2 µm of the type 4A, and this reduction led to an increase in the emitter-edge crowding effect. In brief, the narrow base width causes high base-spreading resistance (the resistance between the base contact and the base region beneath the centre of the emitter); this in turn causes maximum forward bias at the emitter edge and minimum bias under the centre of the emitter. Thus, the emitter edge plays a major role in transistor action, most of the current being crowded there. It is necessary, therefore, to increase the emitter junction periphery to a maximum within the limits of a total emitter area designed to minimise emitter capacitance.

An interdigitated structure was the first and most satisfactory solution to this problem and the dimensions were analysed as early as 1958.[46] Such a structure was used for both versions of the new transistor family, the type 10A2 for the first two stages with a dissipation rating of 250 mW and the type 10A 10, rated at 1 W, for the output stage. The basic design unit was the type 10A2 (Fig. 32*a*) with two emitter areas (each measuring 25 x 87·5 µm) commoned by aluminium metallisation stripes (12 µm wide) extended over the protective oxide, the junction areas being too small for wires to be bonded there. Three similar commoned-base-contact stripes were provided, one between and one on either side of the two emitter stripes. This basic design unit was repeated four times in a symmetrical arrangement (Fig. 32*b*) for the type-10A10 transistor, the objective being to equalise the temperature as far as possible between all emitter areas and so to improve the equality of current sharing between emitters and, hence, the overall linearity of the device.

The early design work was undertaken at the same time as the STC team at Footscray were working on the VX7806 contract. The importance of the new 10A-type venture for future transoceanic systems led, however, to the closure of the VX7806 work and the involvement of Footscray in development of the 10A-type family. Once again, the STC device effort was organised through the CVD office and the code VX7808 was allocated to the projected input transistor and VX7809 to the output.

Work of the British Post Office and STC teams[47,48] proceeded in collaboration for about a year but the surface geometries chosen by the two teams were different. By early 1965, it was clear that the target specifications could be met but it was essential that transistors made by the two production units should be interchangeable in the appropriate positions of the three-stage amplifier. This facility would be unlikely if the devices were not structurally very similar. To avoid delay it was decided to use the British Post Office surface geometry design for production of the type 10A2 (VX7808) and a modified STC design for the type 10A10 (VX7809).

The new geometry for the type 10A10 is shown in Fig. 33. Similar concepts of symmetry and current sharing applied, although the design unit (again repeated four times) was somewhat larger than the type 10A2.

Two specifications were written for the type 10A2 transistor for use in the first and second stages of the amplifier. Transistors selected for the first stage were coded type 10A2A and for the second, type 10A2B. The CVD code VX7808 was reserved for the type 10A2B and a new code (VX7813) allocated to the type 10A2B.

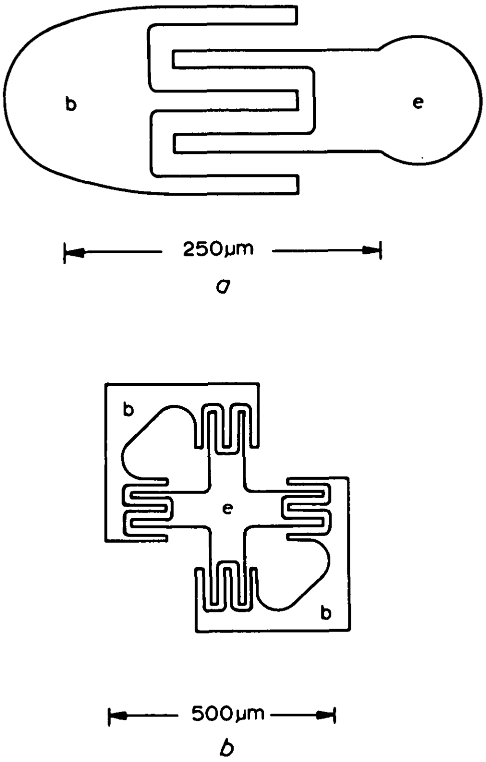

**Fig. 32**
*Metallisation patterns*

*a* Type-10A2 transistor
*b* Type-10A10 transistor

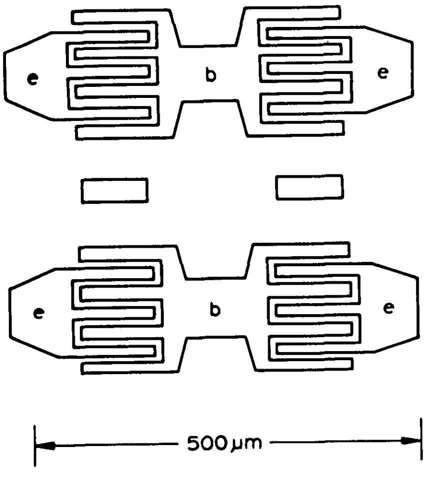

**Fig. 33**
*Metallisation pattern for the final type-10A10 transistor*

### 9.2 Technological problems and solutions

The development of the 10A type family, from 1965 onwards, proceeded in parallel with the development and production of the type 4A. Many of the techniques adopted to improve the lower-frequency transistor were equally applicable to the high-frequency device but there were new problems which required attention.

One area giving rise to concern was the encapsulation. The protection of the metal/glass interfaces on the header by silicone varnish, to eliminate corrosion, was carried forward from the type 4A to the type 10A.

A solid header contributed to a reduction in thermal resistance, this was especially important in view of the high dissipation of heat in the type 10A10. There remained, however, for both transistor types, the danger that lead bending close to the glass meniscus could give rise to fractured glass and possible loss of hermeticity. To avoid this possibility an alumina disc, with holes positioned to take the lead wires, was attached to the header shell flange of the type 4A and the same solution was used for the new 10A type encapsulation. This technique was adopted in 1968 for all devices of both types.

The thermal problems of the new type had not been completely solved by the adoption of the solid header. It was still necessary to provide an efficient heat sink and the simple spring-clip version, into which the type 4A was inserted in the amplifier, was not considered adequate for the new type. A better design, which clamped on to the flange of the can and header, was suggested and this kept the can rim temperature below the specified 25°C maximum. However, this new heat sink caused measurement problems during the screening and validation phases. Neither the high-frequency measuring jigs nor the operational test rig could be used with the heat sink in position and, in addition, problems arising from self oscillation could arise.

A new form of encapsulation was suggested in late 1967 to overcome these difficulties. A thick-walled can (TO-5 dimensions as for the type 4A) was attached to a metal stud which could be screwed into the chassis of the amplifier. In this way, the transistor would be associated effectively with its heat sink from the moment of encapsulation, and all measurements could be made under conditions very similar to those of the amplifier usage.

In the earlier 4A type transistor the collector lead was not isolated from the can and header but, for the new amplifier design, isolation was considered advantageous. Isolation could be arranged internally by a metallised beryllia mounting pad on the header and by insulating the collector lead wire in the same way as for emitter and base leads. An alternative compromise was, however, adopted which avoided the hazards of handling beryllia and which isolated the can from the heat sink and chassis. The isolation was achieved by interposing an alumina disc between the can and the stud (Fig. 34).

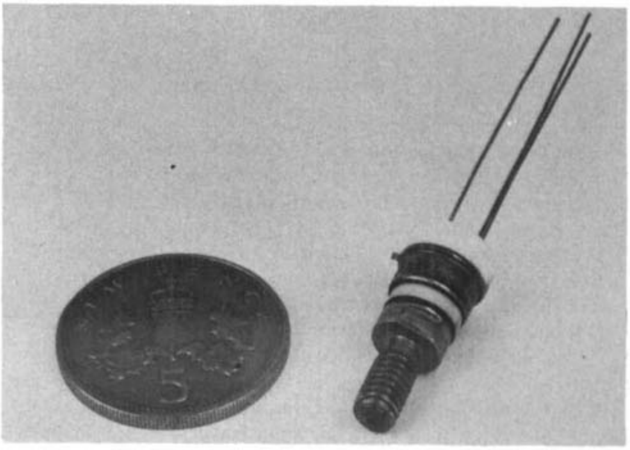

**Fig. 34**
*Typė-10A transistor showing stud mounting with alumina discs*

There were also technical problems associated with the testing and validation of the 10A-type transistors which could only be solved by amending the techniques developed for testing the 4A-type (see Section 8.7). The length of leads required to connect transistors mounted on oven doors to power supplies and the data logger had already caused self oscillation in some devices, leading to unacceptable changes in ageing trends. It was therefore decided to abandon thermal stressing in ovens in favour of a block-testing technique. Each block consists of an electrically heated well lagged bar of aluminium into which thirty 10A-type transistors are heat-sinked in batches of five (Fig. 35). The test leads on p.c.b.s are short and the whole block can be easily transported from the thermal-stressing location to a measurement position from time to time to monitor the trends in electrical characteristics. This arrangement proved to be more economical in space, and electrically more stable, than the oven version.

**Fig. 35**
*Life-test block for type-10A transistors*

Changes in the method of data collection were also introduced. In the earlier validations the data was logged automatically with a punched-tape output which was processed on a central computer to give a page printout of 12 d.c. parameters for each transistor (plus a.c. parameters, taken manually, if required) and a statistical analysis of batch results.[40] This method suffers from a lack of flexibility as the testing procedures and test parameters have to be decided in advance and the data logger wired accordingly. The detection of faults or device failures is also not easy. In view of these difficulties, and of the growth in production and testing of submarine transistors, it was decided to obtain an on-line computer to log and process the validation measurements. The computer chosen was a small IBM 1130 and it provided the following facilities for:

(*a*) detecting errors by self-checking procedures
(*b*) storing and comparing results to bring attention to faulty devices or measurement instability
(*c*) analysing results to demonstrate manufacturing control and to detect 'rogue' devices
(*d*) dealing with a large measurement load and providing early information to production engineers at a time when it is most useful to them.

Means were provided for interfacing the blocks of transistors (from the thermal-stressing laboratory) with the computer and fourteen d.c. parameters could be measured on each transistor including leakage measurements, measurements of d.c. $h_{FE}$ and measurements of breakdown and working voltages.

One more fundamental failure mode was studied.[52] This mode was associated with the reliability of the metal-semiconductor contact used for the interdigitated structure of the 10A-type transistors. The use of long aluminium stripes as emitter contacts carrying a high current density suggested that electromigration might be a problem. The effect of this phenomenon was described by Black in 1969.[53] At current densities above $10^5$ or $10^6$ A/cm$^2$ the momentum exchange between conduction electrons and thermally activated metal ions could cause the latter to move in the direction of the electron flow, so creating voids in the metal film and, finally, open circuits. This model may be expressed in the following form:

$$\text{Mean time to failure (m.t.t.f.)} = \frac{a \exp (E_a/kT)}{CJ^2} \qquad (12)$$

where
$a$ = area of cross section of film, cm$^2$
$E_a$ = activation energy, eV
$J$ = current density, A/cm$^2$
$T$ = film temperature K
$C$ = constant

A curve using eqn. 12 is plotted in Fig. 36 using data based on the 10A-type transistor metallisation. Failures conforming to this curve were not, however, found in practice. In 6000 10A-type devices tested for 3000 h or longer, at a current density of $5 \times 10^4$ A/cm$^2$ and temperature ranging from 200 to 280°C, there have been no open-circuit failures. A second failure mode, other than the basic gain failure mode, has nevertheless been identified by which all devices fail ultimately due to emitter-base short circuits. This mode is also illustrated in Fig. 36.

Failures by this mode have been examined and show hillocks in the emitter contact area. After removal of the Al film, pits are seen in the Si underlying the contact pad and silicon precipitates (the hillocks) at

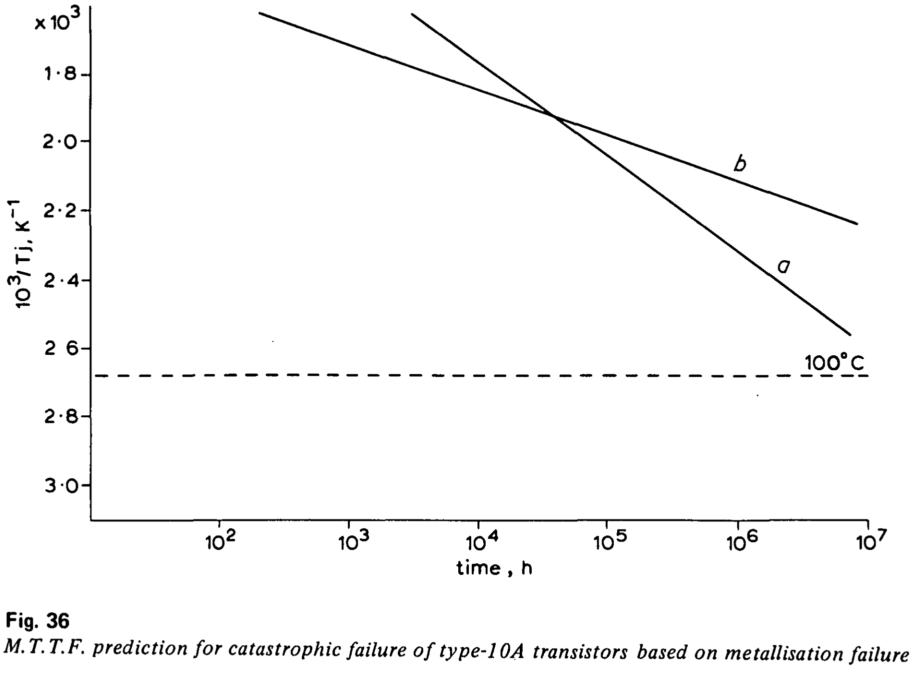

**Fig. 36**
*M.T.T.F. prediction for catastrophic failure of type-10A transistors based on metallisation failure*

*a* M.T.T.F. predicted from Black's data
$a = 2{\cdot}5\ 10^{-7}$ cm$^2$ $J = 5{\cdot}10^4$ A cm$^{-2}$
$C = 5{\cdot}10^{-13}$ $E_a = 0{\cdot}84$ eV
*b* M.T.T.F. from over-stress tests

the further end of the contact area. It is known that Si dissolves in the Al film and that this interaction limits the applicability of Al contacts to devices with junctory depths of the order of 0·4 $\mu$m. It was therefore proposed that electromigration of Si rather than Al was the cause of observed failure mode, the Si moving laterally to form the hillocks and Al moving into the vacant sites in the underlying Si emitter. More Si would then dissolve in the Al to replace that moving away by electromigration and further Al would penetrate the emitter until an emitter-base short circuit occurred.

This investigation of the metal-contact failure mode indicated that short-circuit failures of the 10A-type transistor at 100°C would occur well after the first failures due to the basic gain failure mode and outside the system life expectancy of 25 years. This result gave additional confidence in the chosen contact design.

### 9.3 Trial in shallow waters

Before considering the application of the new 10A-type transistor in submarine systems it should be recorded that the supply of 4A-type devices for 5 MHz systems continued steadily throughout the later period of the 10A-type development. After provisioning the CANBER system, delivery (in partnership with STC Semiconductors) commenced for MAT-1, a cable extending the transatlantic TAT 5 system from Spain to Italy. This work, completed in 1969, was followed by the supply of 228 transistors for the new UK–Spain cable in 1970-71. The British Post Office supply of 4A-type transistors for 5 MHz submarine systems terminated with the provisioning of the Orkney-Shetland cable in 1971-72.

Although the type 10A was intended for an oceanic system, it was necessary, as in all earlier submarine device developments, to assess the new transistor first in a shallow-water application. It was forecast that traffic growth across the North Sea and Channel would, by the early 1970s, require new systems to supplement the 5 MHz transistorised cables laid in 1967-68. Amplifiers for higher-capacity systems were therefore developed by both STC and SCL and both designs made use of the 10A-type transistor. During 1970, however, STC acquired a controlling interest in SCL and, in consequence, the STC 14 MHz amplifier design[49] was adopted to succeed the earlier 5 MHz amplifiers and to provide 1840 (3 kHz) channels.

The design of the STC amplifier was profoundly affected by a new problem which arose in the later 1960s when the American Telephone and Telegraph Company were laying a system in the Pacific.[50,51] Until this time all UK and US repeatered submarine systems (excluding the first US systems) provided both directions of transmission over a single cable with a common amplifier in the way briefly described in Section 2.1: all performed satisfactorily. In the ATT system the temporary bypassing of an equaliser allowed excess gain in one section and gave rise to overload instability (sometimes known as nonlinear singing) displayed by the onset of noise which made the system unworkable and which, under some conditions, could not be cleared. The explanation put forward by Bell Telephone Laboratories suggested the creation of a positive feedback loop in the section having excess gain. The loop included a link between the high-frequency (h.f.) transmission path in one direction with the low-frequency (l.f.) path in the other direction, through generation of intermodulation products in the common overloaded amplifiers. As excess gain could also be caused by sea temperature changes it was necessary to increase stability margins on the 5 MHz systems being laid between 1967 and 1969. For the new higher-capacity systems, however, British Post Office work on a 12 MHz amplifier suggested that it would be better to use separate l.f. and h.f. amplifiers for each direction of transmission. This technique was used for the STC 14 MHz amplifier. The twin amplifier did not, however, provide the redundancy of the earlier parallel valve amplifiers.

Plans for three new high-capacity cables across the North Sea were announced as early as 1967 linking the UK to Germany, Belgium and the Netherlands and a fourth cable to Denmark was forecast shortly afterwards. In 1969 the possibility of a fifth cable between the UK and Guernsey was discussed. After the adoption of the STC amplifier design in 1970 all these systems were given the general code NS23 (North Sea system with a capacity of 23 supergroups). It was decided that the Post Office would supply the 10A-type transistors for the h.f. amplifiers (2 type 10A2 and 1 type 10A10) and STC Semiconductors* would supply the 4A type transistors for the l.f. amplifiers in addition to the supervisory transistors.

Delivery of 10A-type transistors from Dollis Hill started in late 1970 and continued until mid 1971, by which time provisioning of all five cables mentioned above was completed. In addition, within the same period, 168 10A2-type transistors had been supplied to STC to assist the completion of the PENCAN and PENBAL 14 MHz systems between Spain and the Canary Islands and the Balearic Islands, respectively.

The method of transistor validation used for NS23 systems corresponded with that described in Section 8.7 and, as an example, results of the over-stress tests carried out on a sample of 1032 type-10A2 transistors are summarised in Fig. 37. Predicted life at the 0·2% level when operated at a junction temperature of 100°C and at a dissipation of 250 mW is greater than 100 years. There were no rejects on a 2000 h operational test of any of the 675 type-10A2 transistors intended for system use, nor any movement of characteristics within the limits of measurement accuracy. A sample of 441 transistors passed all mechanical and hermeticity tests.

As a final mechanical test all devices supplied to systems were subjected to an axial pull test of 9·1 kg (20 lb) maintained for a period of 30s before final visual inspection and shipping. Further tests were carried out on an additional 400 stud assemblies to confirm that the mechanical strengths of devices subjected to and passing the 9·1 kg (20 lb) pull test were not degraded.

All the NS23 systems were laid between 1971 and 1973 and, in addition, 10A-type transistors were supplied to STC for the h.f. amplifiers in the Florida-Bahama system commissioned in late 1972.

### 9.4 Quality assurance

The methods employed by the British Post Office in providing devices for submarine systems fall under four main headings, improved production processes to yield performance and reliability, screening to exclude atypical devices, validation procedures to support the reliability predictions and quality assurance or control at all stages of production and testing. The latter has been discussed before (Sections 4.6 and 8.7) in relation to the valves and transistors chosen for operational use.[47] During the NS23 provisioning programme, improvements to quality assurance (q.a.) procedures were introduced to form a comprehensive system stabilised by fabrication experience.

A full range of q.a. checks (before screening) include pre-and post-encapsulation inspection, hermeticity measurements, weld and chip sectioning, tests of the assembly machines and analysis of the gas used for bond welding. After the operational test (part of the validation procedure), quality is controlled by careful specification of the release procedure. The q.a. sequence is completed by the rigorous visual inspection and tests undertaken on the piece parts used in fabrication.

The objective of the pre-encapsulation tests is to eliminate those devices having chip defects, due to processing errors and poor workmanship, which could lead to premature failure. Attention is specially directed towards metallisation, oxide and diffusion faults, towards wafter scribing and fracturing, wire-bonding and chip-mounting processes, and towards the presence of foreign material. The post-encapsulation tests are designed to exclude unsuitable devices from final selection, although some of those excluded are used for validation testing. The can welds, the gold plating, lead wires, header glass, stud, can, ceramic discs and metal/ceramic braze are all examined. The pre-and post-encapsulation tests are undertaken on all devices; hermeticity tests and sectioning are carried out on sample devices taken on a daily or weekly basis.

The purpose of the final release procedure is to ensure that all devices intended for system use are within the specification and packed to an acceptable standard. The release specification (RZ1048) includes the stud pull test mentioned in the previous Section and requires that all devices be fully characterised in terms of some 12 electrical parameters. The definitions of acceptable changes on operational test are redefined with precision, rather than in the very general terms used in Section 8.4. A very detailed visual inspection specification (RZ1039) is also a part of final release with special attention paid to 'witness marks'. Transistors for use in submerged repeaters should be free from visual blemishes when released from the production unit, thus allowing a simple definition of 'witness marks' to indicate possible damage due to subsequent mishandling. It was not, however, found possible in manufacture to maintain complete freedom from blemishes, but those accepted as not affecting the reliability are fully recorded on the release certificate.

The piece parts required for the transistor (chip, bonding wire, header, can, stud and two ceramic discs) are far smaller in number than the 50 or so required for the thermionic valve. Their quality is, however, just as important for ensuring a reliable device and, after the chip itself(all of which are probe tested), the header is perhaps the most important of the seven; it is used here as an example of piece part q.a. Commercial firms were reluctant to supply headers to the necessary exacting specification but, nevertheless, batches of headers

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* After 1970, ITT Semiconductors

were obtained occasionally which were entirely satisfactory. Some of the criteria for reliable headers have already been discussed (Sections 8.6 and 9.2) and by 1972 it was possible to issue a very comprehensive specification for TO-5 solid headers requiring some 20 q.a. tests before batch acceptance. The clauses included dimensional checks, visual inspection, measurement of leakage current and gold-plating thickness, mechanical tests, thermal tests and an assessment of header properties after subjection to processing and usage. Particular attention was paid to an assessment of possible corrosion of header leads under conditions of 75°C and a relative humidity of 75%

This system of piece part q.a. based on the purchase, testing and, sometimes, rejection of large batches was used from 1968 onwards and, although expensive, gave confidence in the reliability of the piece-parts as an important contribution to overall device reliability. All the q.a. procedures described here were used in the first transistorised transoceanic submarine project to be undertaken by the UK.

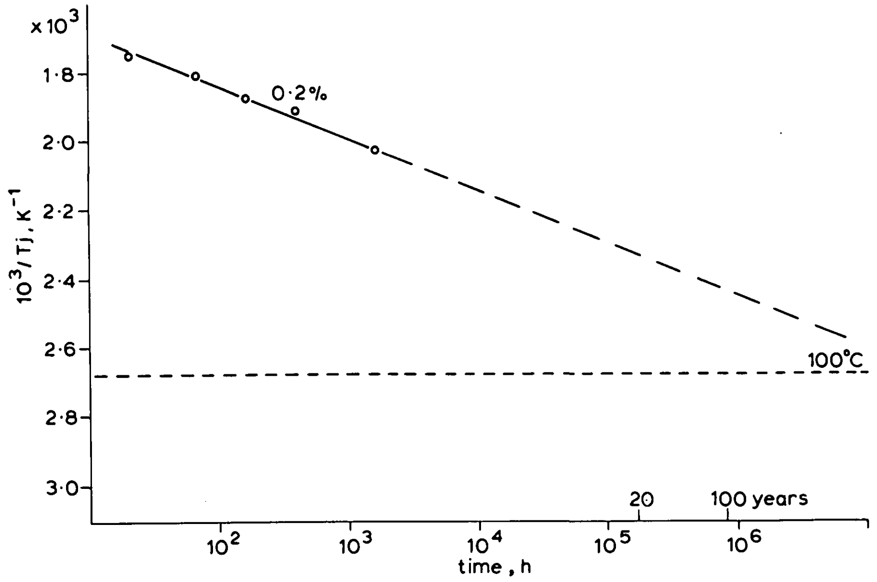

**Fig. 37**
*Life prediction line for type-10A2 transistor used in NS23 systems*

### 9.5 Plans for the CANTAT-2 system

By the end of the 1960s there were three transatlantic cables linking Britain with North America, TAT-1 (initially 36 (4 kHz) speech channels in the main section, doubled later), CANTAT-1 (80 (3 kHz) channels) and TAT-3 (128 (3 kHz) channels). Only in CANTAT-1 were all the repeaters and active elements designed and manufactured in the UK.

TAT-3, the last of the three, was completed in 1963. By 1970 growth in traffic required some consideration of the need for a new system and meetings were held between the British Post Office and the Canadian Overseas Telecommunications Corporation (COTC) to discuss the possibility of a submarine cable using the STC 14 MHz amplifier and providing 1840 (3 kHz) channels. Both the Transistor Unit at Dollis Hill and the ITT Unit at Footscray were able to confirm that, in their view, transistor provisioning for a transoceanic crossing could be completed by 1972, thus permitting, on this count, a ready-for-service date (r.f.s.) of 1974. This timing was important in view of an expected r.f.s. date of 1976 for a new high-capacity USA system, the SG incorporating 4000 channels.

In making this forecast, the two units used a figure of 4000 transistors as the probable requirement for signal-path devices, divided equally between types 4A and 10A. For confidence in product reliability over a system life of 20 years it was therefore necessary to prove that the rogue or random failures should be at a level of less than 1 in 4000 and to demonstrate a single parameter failure mode at the same level. The proof and demonstration would require many more devices than had been manufactured for any previous system.

Despite the magnitude of the task, conviction in the ability to meet and overcome the problem was, by this time, based on firm foundations. The British Post Office had already handed over about 2000 4A-type transistors to contractors for submarine use and, by the end of 1969, about 1100 of these were on the sea bed, having completed more than $5 \times 10^6$ transistor-hours operation without a single failure. Exhaustive tests on a further 8000 4A-type transistors had also been completed and had yielded the following information:

(i) Only one parameter failure mode was detected within a system life of 25 years and that was the deterioration in current gain
(ii) An extrapolated reliability based on this mode suggested less than one failure in 4000 in 25 years
(iii) Confirmation of the extrapolation by satisfactory operational test results
(iv) A rogue-failure level not worse than 1 in 10 000 in 25 years
(v) A pattern of improving stability over the years consistent with improved control of physical processes.

Test results on 500 10A-type transistors provided identical information, at a lower level of confidence, on items (i)–(iii) and a zero rogue-failure incidence as far as the tests had gone. There was, therefore, some evidence of a link between 4A-type experience and that to be expected from 10A-type production. For all these reasons the British Post Office felt itself capable of meeting the challenge of a transoceanic provisioning programme.

Despite optimism it was realised that a measure of insurance against failure was essential. The principle of batch rejection outlined in the final paragraph of Section 8.7 still applied, and the consequent danger of involving the whole transoceanic submarine project in costly delays had to be faced.

By the autumn of 1970 the probability of joint support for a transoceanic system by the UK and Canada had increased and a more precise estimate of the number of transistors required for the signal path was available, 1600 of each type, 4A and 10A. Device-production plans had to be formulated before final approval by the two governments to meet the r.f.s. date and the following programme was agreed:

Type-10A
(*a*) The British Post Office was to commence manufacture of 2 batches, each of 800 transistors, in November 1970
(*b*) ITT Semiconductors was to commence manufacture of one batch of 800 in March 1971

Type-4A
(*a*) The CANTAT-2 authority was to purchase 800 transistors from the British Post Office stock pile in early 1971
(*b*) ITT Semiconductors was to commence manufacture of 2 batches of 800 each in March 1971

By this arrangement it was expected to meet the r.f.s. date, provided not more than one batch of each type failed validation. A batch size of 800 would reduce the cost of batch failure whilst still permitting validation at the 1 in 4000 level. The truth of the last statement can be seen by listing, as an example, the planned number of transistors to be manufactured to meet the British Post Office commitment to provide two batches of 800 10A-type transistors

*Batch A*

| Type | Operational | Steady overstress | Step stress | Mechanical | Total |
|---|---|---|---|---|---|
| 10A2 | 625 | 1500 | 500 | 500 | 3125 |
| 10A10 | 325 | 1500 | 500 | 500 | 2825 |
| | | | | | 5950 |

*Batch B* (if A is successful)

| Type | Operational | Steady overstress | Step stress | Mechanical | Total |
|---|---|---|---|---|---|
| 10A2 | 625 | 500 | 250 | 500 | 1875 |
| 10A10 | 325 | 500 | 250 | 500 | 1575 |
| | | | | | 3450 |

Final agreement to the project was given in March 1971 and the contract for CANTAT-2 was placed with Standard Telephones and Cables Ltd. in June of that year.

### 9.6 Production methods and problems

The production processes used by the British Post Office for CANTAT-2 were based on the valuable experience gained during the solution of technical problems associated with both 4A-type and 10A-type development (see Sections 8.2, 8.6 and 9.2). The screening used to exclude atypical devices was that described in Section 8.7, with the exception that the mechanical screen was amended to substitute a controlled drop test of 0·61 m (2 t), instead of 0·9 m (3 ft), for the 10A-type device, due to the more massive stud structure. The q.a. procedures have been outlined in Section 9.4 and the validation results (based on techniques described successively in Sections 7.2, 8.4, 8.7 and 9.3) will be considered in the next section.

Both the British Post Office and ITT started production in 1971 but each encountered severe problems which caused modifications to the production plan outlined earlier.

The first Dollis Hill production batch (A) of 10A-type transistors failed in the autumn of 1971 because of a variety of causes, some internal some external, which reduced yields to such an extent that there were insufficient devices to give a statistical basis for qualification for deep-water usage. The causes included national power failures, which put boron-diffusion furnaces out of action for a month, inferior material, processing problems and defects in testing equipment, which was kept in service too long by the commissioning problems of the new on-line computer. The consequences of this failure were not, however, entirely adverse as they allowed identification of hazards at an early stage and time for correction. The following batch B was entirely successful as was the insurance batch C.

The ITT team was not so fortunate. They also encountered a failure pattern, but at a late stage (in mid 1972) which did not allow time for full recovery within the CANTAT programme. Both types 4A and 10A showed severe yield losses on visual inspection. The type-4A programme was completed by a restart of production at Dollis Hill which was made possible by the early failure and subsequent recovery.

### 9.7 Validation

Validation and delivery of the 10A and 4A type transistors proceeded during 1972 and 1973 to a successful conclusion in time for the n.f.s. date in 1974, despite continuously diminishing delivery date margins. The helpful cooperation of the STC Repeater Production Unit at North Woolwich played no small part in this team effort.

Although the planned production figures listed in Section 9.5 were not quite attained, the total was sufficient to meet the needs of meaningful statistical assessment. The transistors produced at Dollis Hill are listed below

| Type | Operational | Steady overstress | Step stress | Mechanical | Total |
|---|---|---|---|---|---|
| 10A2 | | 1876 | 874 | 594 | 7882 |
| 10A10 | 1316 | 1641 | 1156 | 425 | |
| 4A | 837 | 1482 | 532 | 470 | 3321 |

The 4A-type total excludes the devices supplied from the British Post Office stockpile.

Arrhenius plots for the 10A-type transistors are shown in Fig. 38 and extrapolation demonstrated lives well in excess of 20 years at a junction temperature of 100°C. The type 4A results were analysed and presented in a new form[54] using a statistical rather than a graphical approach. It was possible, from the steady overstress data, to predict at a 95% confidence level, that no device failure would occur in a total of 4000 transistors during a 20 year service life. The step-stress results also supported this conclusion. In all cases, failure was judged to occur at a 10% decrease in $h_{FE}$ under operational bias. There were no failures on operational tests on this basis, but a small percentage of devices were exluded from system use for small, but atypical, changes in parameters.

As indicated in Section 8.7 mechanical evaluation was included in the validation procedure and was now treated very systematically. The mechanical specification (RZ 1040) with 18 clauses includes dimensional checks, visual inspection, thermal shock, high-temperature storage, drop tests, stud and wire-pull tests, leak tests, wire-bond tests, lead fatigue and torque tests, solderability and d.c. checks of electrical performance after certain of the mechanical tests. In many cases (e.g. fatigue, torque, stud and wire-pull tests) cumulative failure curves, on the basis of a log normal distribution, were plotted to allow extrapolation down to the 1 in 4000 (0·025%) level to meet the specification requirements. There were no specification failures in 1489 transistors tested.

The results of ITT validation, on devices which could be excluded from the failure pattern mentioned earlier, were equally satisfactory. The Arrhenius plots showed extrapolated lives in excess of 20 years and the results of mechanical and operational tests were also within the specification. Some hundreds of 10A-type and 4A-type transistors from Footscray were used in operational repeaters.

The inauguration of CANTAT-2 took place on 21st June 1974 when the Prime Minister of the UK, Mr. Harold Wilson, spoke over the new cable link to Premier Pierre Trudeau of Canada. At the opening date CANTAT-2 was the biggest single telephone cable ever to span the

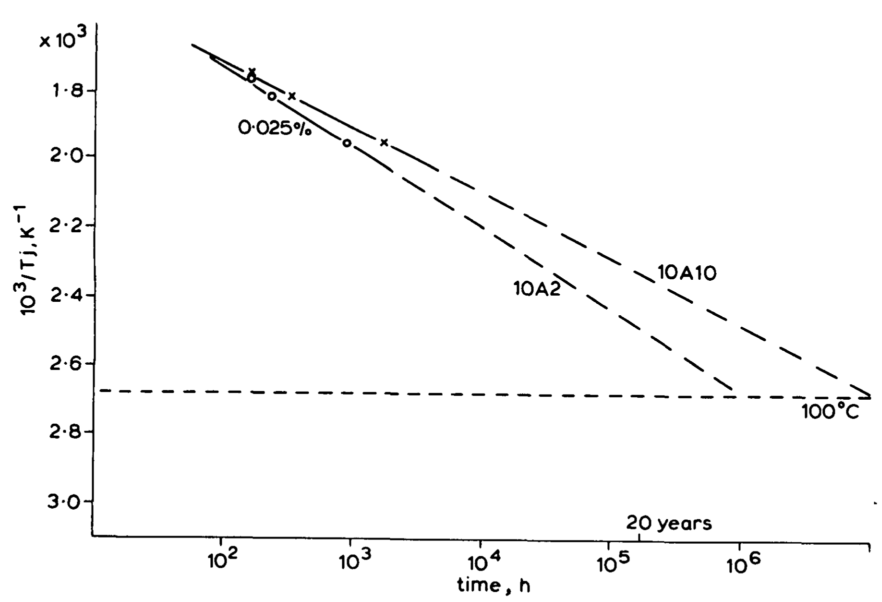

**Fig. 38**
*Life prediction lines for type-10A2 and type-10A10 transistors used in CANTAT-2*

the Atlantic and the most advanced submarine system in the world. It more than doubled the number of telephone circuits in the previous cables linking Europe with North America.

In support of the validation described above there were, by the opening date, some 4600 British Post Office transistors (2800 type-4A and 1800 type-10A) on the sea bed in eighteen submarine systems, including CANTAT-2. These transistors had completed 65 million device-hours operation with but one failure (a type 4A-wire bond in one of the early North Sea systems). At the end of 1975 the device-hours reached a total of 129 million with no further failures.

### 9.8 Characteristics of the 10A-type transistor

The chief electrical characteristics of the 10A-type transistor are given in Table 7.

**Table 7**

ELECTRICAL CHARACTERISTICS OF THE 10A-TYPE TRANSISTOR

| Characteristic | Test conditions (case temperature 25°) | Limits | | | | | |
|---|---|---|---|---|---|---|---|
| | | 10A2A | | 10A2B | | 10A10 | |
| | | Min | Max | Min | Max | Min | Max |
| $I_{EBO}$ | $V_{EB} = 2V$ | - | 100nA | - | 100nA | - | 100nA |
| $I_{CBO}$ | $V_{CB} = 7{\cdot}5V$ | - | 10nA | - | 10nA | - | - |
| | $V_{CB} = 20V$ | - | - | - | - | - | 10nA |
| $h_{FE}$ | $I_C = 6mA\ V_{CE} = 7{\cdot}5V$ | 100 | 200 | - | - | - | - |
| | $I_C = 25mA\ V_{CE} = 7{\cdot}5V$ | - | - | 100 | 200 | - | - |
| | $I_C = 150mA\ V_{CE} = 10V$ | - | - | - | - | 100 | 200 |
| $h_{fe}$ (250MHz) | $I_C = 6mA\ V_{CE} = 7{\cdot}5V$ | 3·0 | 4·5 | - | - | - | - |
| | $I_C = 25mA\ V_{CE} = 7{\cdot}5V$ | - | - | 3·5 | 5·0 | - | - |
| | $I_C = 150mA\ V_{CE} = 10V$ | - | - | - | - | 3·5 | 5·0 |
| $C_{ob}$ | $V_{CB} = 7{\cdot}5V$ | - | 3·0pF | - | 3·0pF | - | - |
| | $V_{CB} = 10V$ | - | - | - | - | - | 10pF |
| $V_{BE}$ (Wkg) | $I_C = 25mA\ V_{CE} = 7{\cdot}5V$ | 0·65V | 0·80V | 0·65V | 0·80V | - | - |
| | $I_C = 150mA\ V_{CE} = 10V$ | - | - | - | - | 0·65V | 0·80V |
| $V_{CE(SAT)}$ | $I_B = 2mA\ I_C = 50mA$ | - | 0·5V | - | 0·5V | - | - |
| | $I_B = 5mA\ I_C = 300mA$ | - | - | - | - | - | 0·5V |
| $N$(1 amd 10MHz) | $I_C = 6mA\ V_{CE} = 5V$ $R_G = 200$ | - | 4·0dB | - | 6·0dB | - | - |
| Thermal resistance (junction stud) | | 100°C/W | | 100°C/W (nominal) | | 60°C/W | |

## 10 Cost benefits

An estimate can be made of the total effort spent on research and development over the period of this review and on production of the active elements in submarine systems. Between 1946 and 1968 about 250 man years of professional effort was expended on thermionic valves and between 1960 and 1974 around 370 man years on transistors. Both the Thermonics Group and the Transistor Unit employed, in addition, production teams which, at maximum, included about 65 men and women. Peak effort on valves was reached in 1962 and on transistors in 1973.

The development period of a new device from design inception to start of production, occupies some five or six years and there is evidence that this time span is increasing as device performance improves. However, the development of one submarine active element proceeds in parallel with the production of its predecessor. Consequently, during the period of maximum deployment, the total research and production expenditure on transistors was about £0·6 M a year (1973 prices) and on valves around £0·13 M a year (1962 prices). In each case the proportion spent on research amounted to about 1/5 of the total expenditure. At the peak of production about 600 repeater quality 10P-type valves a year were produced and a total of around 1500 fully validated 4A-type and 10A-type transistors were made during 1972.

These figures, although imprecise, indicate clearly that submarine devices are expensive in comparison with similar perfomance devices made to less exacting reliability standards. Justification for the high cost rests upon three main considerations, first on the total value of and revenue from the submarine systems laid in consequence, among other factors, of the successful development and production of high-performance, highly reliable active elements, second on the reduction in cost per unit channel length which has taken place over the years, and third on virtual elimination both of the loss of revenue due to a repeater fault deriving from active-element failure and also of the cost of repair. Nevertheless, cost reduction is a worthwhile objective and one attempt is described in Section 11.

The approximate cost for TAT-1 in 1956 was £15 M, £8 M for CANTAT-1 in 1961, and for the whole Commonwealth system (including CANTAT-1) between 1961 and 1966, £88 M. For the transistorised systems, the North Sea and Channel cables laid between 1968 and 1973 cost around £10 M and the UK-Portugal and CANBER systems together cost about the same amount. CANTAT-2 costs amounted to £30 M. The earning potential of these systems is high and it has been known for cables to recover their capital costs in the first few years.

The reduction in cost per unit channel length is, in large part, due to the second of the main themes mentioned in the Introduction, namely the effort to develop devices capable of amplification at ever higher frequencies. It is illustrated in Fig. 39 using as a base the system costs incurred at the date of laying and, therefore, at prices then current. It will be observed that the cost per unit channel length for TAT-1 (1956) is about 30 times that for CANTAT-2 (1974). In taking account of inflation this factor would be further increased.

In 1972 a Queen's Award to Industry was granted to the British Post Office Research Department for technical innovation in the development and production of high-quality transistors for use in submarine systems.

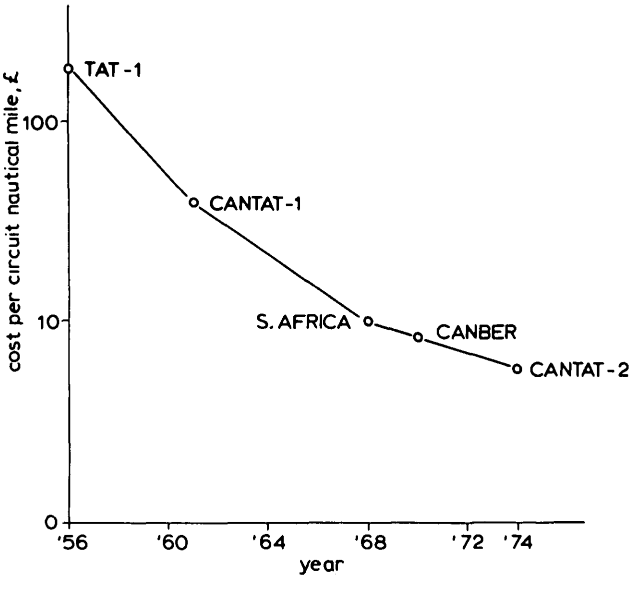

**Fig. 39**
*Cost per circuit nautical mile for valve and transistor submarine systems between 1956 and 1974*

## 11 Future developments

The future development of submarine telephony, in so far as it is dependent on the active elements, is presently based on research and development work which started some years ago and is still continuing. In February 1969 the development of a 25 MHz submarine system was considered as a possible successor to the 12/14 MHz systems being planned for the early 1970s. A new family of transistors would clearly be required and in April 1969 the British Post Office planned a development programme with four main targets:

(*a*) to optimise current and temperature distributions in multi-emitter structures, including operation under surge and continuous overload
(*b*) to continue work on passivation with a view to the eventual elimination of the need for hermetic encapsulation
(*c*) to investigate the properties of gold/refractory-metal contact systems able to operate at higher temperatures and current densities than was possible with aluminium
(*d*) to develop a reliable microwave transistor encapsulation

Three test-vehicle transistors were designed to judge the progress made in meeting these objectives, all with $f_T$ values between 3 and 4 GHz and each with maximum rated dissipation of 50, 200 and 1000 mW, respectively. During 1969, the concept of using transistors designed for submarine application in other British Post Office systems was emphasised. If this diversification could be shown to be practicable, rationalisation of research and development effort would be possible with consequent economic advantage. This theme is being developed and may produce savings in the late 1970s.

**Table 8**

BRIEF SPECIFICATION OF 40 TYPE FAMILY (1969)

40A-type transistor, low noise input
$f_T$ = 4·0 − 5·0 GHz at $V_{CE}$ = 7V, $I_C$ = 5 mA
$h_{FE}$ = 40 − 80 at $V_{CE}$ = 7V, $I_C$ = 5 mA
$C_{cb}$ = 0·4 pF max at $V_{CB}$ = 7V
$N_F$ = 4·5 dB max at $I_C$ = 3 mA $f$ = 2 GHZ
$N_F$ = 2·5 dB max at $I_C$ = 3 mA $f$ = 500 MHZ
$P_{max}$ = 100 mW

40B-type transistor, intermediate
$f_T$ = 4·0 − 5·0 GHz at $V_{CE}$ = 7V, $I_C$ = 15 mA
$H_{FE}$ = 40 − 80 at $V_{CE}$ = 7V, $I_C$ = 15 mA
$C_{cb}$ = 0·6 pF max at $V_{CB}$ = 7V
$P_{max}$ = 250 mW

40C-type output stage with low intermodulation distortion
$f_T$ = 3·0 − 4·0 GHZ at $V_{CE}$ = 10V $I_C$ = 60 mA
$h_{FE}$ = 40 − 80 at $V_{CE}$ = 10V $I_C$ = 60 mA
$C_{cb}$ = 3·0 pF max at $V_{CB}$ = 10V
$P_{max}$ = 1·0 W

Towards the end of 1969 draft specifications were written, converting the test-vehicle transistors into prototype submarine devices, coded types 40A, 40B and 40C. The functions and characteristics of each device are listed briefly in Table 8.

Taking the items of the development programme in sequence, the current and temperature distribution of the output device have been optimised by the adoption of a 'cartwheel' surface geometry using eighteen emitter 'spokes' each with two emitter fingers making contact with 36 emitter areas, 5 μm wide. Investigation of operation under surge and overload conditions is still in progress. To improve yields and to assist in validation testing a chip has been designed which contains all members of the 40-type family and this opportunity has been taken to use type 40A as a base-emitter surge-protection diode for type 40C.

Work on passivation continues with the objective of eliminating the hermetic package and so obtaining the higher performance resulting from a hybrid approach with bonded transistor chips. This form of circuit will almost certainly be used for devices of higher performance than type 40.

The major problem associated with the metallisation/bond structure has been solved. As indicated in the work described in Section 9.2 an all aluminium system is not possible for devices with junction depths less than 0·4 μm[52] and this excludes the type 40 family where the emitter junction is at a depth of about 0·3 μm. A refractory metal/Au contact is possible as an alternative and an Au/Ti system provides satisfactory contact between the Ti and $p^+$ or $n^+$ regions, with no reaction between the Si and Ti at processing temperatures. Work at Dollis Hill[52] has shown that type-40 transistors employing 0·5 μm Ti plus 0·5 μm Au contacts have excellent long-term reliability when operating at $3{\cdot}5 \times 10^5$ A cm$^{-2}$. A step-stress test, after a normal high-temperature screen, revealed no significant change in contact resistance until the 20 h step at 355°C was reached. An m.t.t.f. curve is shown in Fig. 40 indicating an activation energy of 1·8 eV for Au diffusion through Ti. Some evidence of an electron-interaction-enhanced diffusion mechanism was obtained [compare curves (*a*) and (*b*)]. Strong emphasis was placed, however, on the dependence of long-term stability on the control of technology, e.g. on film deposition, film purity, pattern definition and on control of subsequent high-temperature processing. Recent work at lower stress levels for longer periods has confirmed the earlier step-stress results on the suitability of Au/Ti metallising and Au eyelet bonds.

A reliable ceramic strip-line package with isolated copper stud mounting has been developed for the family and provides a hermetic encapsulation. It was not considered that available commercial packages met the requirements imposed by submarine-system standards.

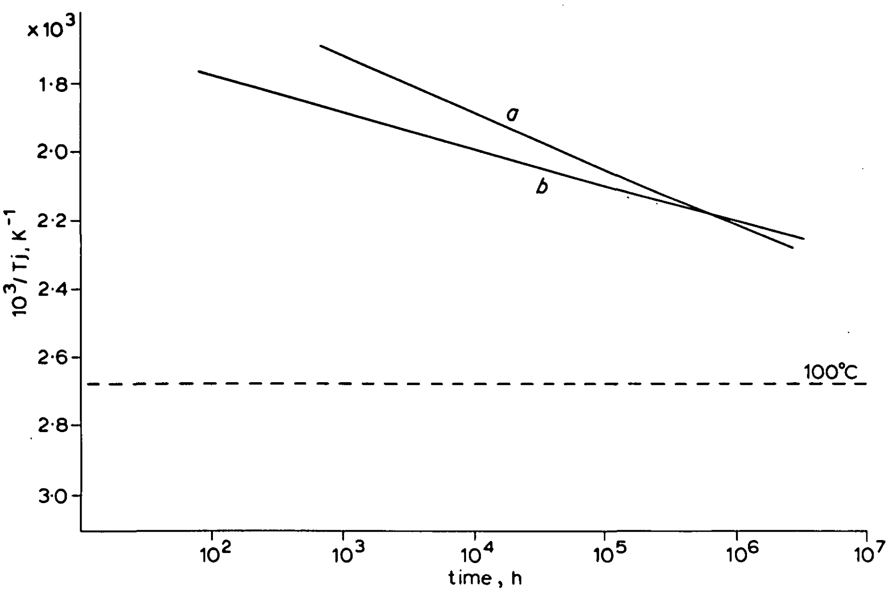

**Fig. 40**
*M.T.T.F. prediction for the 40-type transistor using Ti-Au metallisation*

*a* Under storage conditions
*b* Under normal bias ($J = 3{\cdot}5 \times 10^5$ A cm$^{-2}$)

In addition to the 4-part development programme, one other major change to submarine transistor processing arose in 1972 as a result of technological progress elsewhere, supported specifically by computer simulation of transistor structures undertaken at Dollis Hill. It was deomonstrated that arsenic diffused emitters showed advantages when compared with conventional phosphorus doping. The steep-fronted arsenic diffusion profile obtained with minimum surface damage improves the cut-off frequency and lowers the base resistance for a given doping level, so providing a better noise performance. An arsenic diffusion system was developed and adapted for future type-40 fabrication.

The most important technical problem requiring further attention in connection with future wideband systems is that of surge protection. The satisfactory solutions used for the type-4A and type-10A transistors are no longer adequate for the smaller type-40 structures. It is not likely that the intrinsic capability of the transistor for withstanding the expected surges consequent upon fracture of the cable can be markedly increased. As a result, a much greater effort is required on protective circuits and on protective devices if this family is to be used in long systems; although plans already exist for a 45 MHz (not 25 MHz as was first thought in 1969) shallow-water system using type-40 devices.

A second contemporary problem relates to the production programme of type-40 transistors and is more concerned with validation and device costs. Faced with a more competitive climate for the world wide sale of submarine systems, there is a real need for contractors to consider ways and means of reducing costs, without sacrificing quality, for the whole system and for the active elements in particular.

As an outcome both the British Post Office and STC agreed to accept transistors, manufactured and screened in the same way as earlier products, as part of the same batch family and therefore of the same reliability, without the destruction of a major proportion of the later products in large-scale over-stress tests. The transistors supplied for submarine use would be identical in all respects to those supplied in the past but the level of confidence would be reduced by the assumption, which is considered valid, that the performance of devices during screening and sample step stress may be used to demonstrate membership of the proven family. This reduction in validation testing will permit a substantial reduction in device costs.

There may well be a need for submarine systems in the 1980s with a capacity of 200 supergroups (16 000 circuits compared with the 5000 circuits made possible by 40-type transistors and the 1840 by the 10A-type). Considerable thought has therefore been given to the possibility of developing devices with a frequency performance beyond that of the type 40.

In the late 1960s the British Post Office effort was directed to the investigation of techniques for advancing the design of high frequency transistors. The chosen method was to gain knowledge and expertise in design and development by making use of computer-aided modelling procedures. One peripheral output of this work has already been mentioned, the change from phosphorus to arsenic for emitter diffusion in type-40 structures, although the general design techniques were not developed soon enough for overall application to the type-40 family. The main application for the computer-aided design study was intended to be the development of a transistor to follow the type-40 family and success in this may be better assessed in the next year or two.

A solution to the problem of amplifier design for a 200 supergroup submarine system may lie either in using a larger number of type-40 transistors or in developing a new higher frequency design. The former method could lead to severe reliability problems and so pursuit of the second solution would be well worthwhile. In addition to utilising computer aided design methods, account must be taken of limitations of bipolar technology and of the possibility of using alternative structures. Restraints on the further development of bipolar transistors do arise from the need to reduce simultaneously both emitter finger width and base width in attempting to improve high-frequency gain and to reduce noise. Using photolithography to its limit of around 1 $\mu$m spacing and the best available control of doping profiles (possibly with the assistance of ion-implantation) it may be possible to develop a type-80 transistor ($f_T \simeq 8$ GHz) which could, with sufficient development effort lead to devices of the necessary reliability for a 200 supergroup system. Such a device could also, with minimal modification, serve as an active element in the transistor amplifiers of 19 GHz radio-relay-system repeaters. This approach is now being attempted and may be linked to the changeover from a packaged transistor to a passivated chip/thin-film hybrid structure more suitable for the high-frequency performance required.

All submarine systems considered to date are based on analogue transmission and there is a very high probability that the 200 supergroup system will also be an analogue system. Indeed the bipolar transistor is particularly suitable for the wideband matching that is needed for such systems. However, it is possible that digital transmission will replace analogue, at least for future very-high-capacity North Sea systems, and there may then be a place for the field effect transistor with better gain and noise than the bipolar at frequencies beyond 4 GHz. Whether this device will be fabricated in silicon or whether advantage can be taken of the higher electron mobility in gallium arsenide, and of the existance of semi-insulating gallium arsenide for isolation, will depend on a successful study and development of the stability and reliability of this material and on the acquisition of technological experience offering the promise of matching the great volume of silicon expertise now available.

In view of the ability here and now to see ahead to the type-80, and its possible successor, it is not believed that the future development of submarine telephony will be limited, at least in the next fifteen years, by failure to develop the necessary active elements. Indeed, it is possible in the future, as in the past, that the activities of device development engineers will stimulate new system design as soon as confidence in the performance and reliability of the new families is established. The effort required will nevertheless be substantial and the technical problems to be surmounted for both type-80 and a field-effect transistor are at least as great as the problems presently associated with type-40 development and should not be underestimated.

At the same time as work on the 40- and 80-type transistors was in progress in the UK, a parallel activity was being undertaken in the USA and France. In Bell Telephone Laboratories the design of the SG submarine system was in hand, with the intention of laying TAT-6 in 1976 between the USA and France. This system will provide about 4000 circuits. The transistors developed for use in this system are silicon planar bipolar devices, a departure from the germanium transistors used for TAT-5 and a step that brings submarine-transistor development in America on the same course as that followed in Europe. In France the plans for the S 25 system have been formulated[55] using highly reliable transistors with a performance which would permit some 3440 (3 kHz) channels.

## 12 Conclusion

This review is a record of a research, development and production effort extending over a quarter century with a single major objective, namely, to develop and produce the active elements needed for submarine systems in a way which meets British Post Office requirements and also keeps the United Kingdom in the forefront of world technological advance in this field.

While concentrating on the work of British Post Office teams the review recognises and appreciates the complementary role played by the teams at STC Paignton for thermionic valves and at ITT Semiconductors Footscray for transistors.

It is a measure of joint British Post Office and industry success that, so far, for both valves and transistors, the British effort has kept pace with the other major submarine development organisations in America and France. Japan is now increasing its interest in submarine telephony and economic and technical competition is growing. Future national effort may be helped by device design rationalisation which could allow a single transistor family to be used in several applications, inland as well as submarine. In addition, the considerable expertise gained in the technology of transistor relaibility through the submarine projects has proved, and continues to prove, invaluable in the much wider context of general device reliability in British Post Office systems.

It is believed by the author that the foundations necessary to support the British effort in this important area of international telecommuncations have been well laid. There can, however, be no reliance on past success if future viability is to be assured. Continuous evolution of organisation and methods must be used to maintain a competitive position in support both of British Post Office development of overseas telephony and also of national exports.

## 14 Acknowledgments

It has been the author's privilege to be associated with the development and production of active elements for submarine systems for the whole period of the review and to present this account of the work of colleagues in the British Post Office and Industry

The project owes much to the direction of Dr. G.H. Metson and Dr. J.R. Tillman for thermionic valve and transistor development, respectively, the contributions of Dr. F.H. Reynolds on valve design, and D. Baker on transistor design play a major role. The helpful cooperation of D.C. Rogers, F. Haegele and Dr. G.B. Thomas at the STC Valve Division and ITT Semiconductors has been greatly appreciated.

Acknowledgment is due to all members of the Thermionics Group, the Transistor Development and Production Unit and the STC teams at Paignton and Footscray who contributed to the research development and production of valves and transistors for submarine systems. All these teams in their turn will acknowledge the help guidance and collaboration of the system engineers in the British Post Office, in Submarine Cables Ltd. and in the STC Submerged Repeater Division.

Both the Thermionics Group and the Transistor Unit have enjoyed a long, close and fruitful association with submarine-device workers outside the UK, the names of J.O. McNally, L.E. Miller and Dr. A. Wahl in the USA and P. Blanquart and J. Ramond in France should be mentioned here.

In conclusion the author's personal thanks for many helpful discussions are due to D. Baker on whose shoulders will probably fall the duty of writing the next review of the continuing development of active devices for submarine telephone systems.

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