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# DESIGN, MATERIAL AND PERFORMANCE OF PLUGS AND SOCKETS FOR ELECTRONIC SWITCHING APPLICATIONS

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SUMMARY

From experience gained with plugs and sockets used in electro-mechanical telephone-switching apparatus and further experience of their use in association with electronic equipment, the necessity to improve their performance and reliability soon became apparent. Extensive research into the study of materials has led to the formation of a test specification which has the objective of determining plug and socket reliability for an anticipated usage of 30 years. This specification is given in an Appendix. Two designs satisfying this specification are outlined.

## (1) INTRODUCTION

The precedent for electronic equipment in telephone-switching applications is set by the British Post Office standard type of electro-mechanical step-by-step switching equipment, which uses relatively small groups of relays and electro-mechanical switches on demountable units. These units are generally independent in functional operation, so that the occurrence of a fault, while slightly degrading the service provided by the system, does not necessitate the provision of spare equipment to maintain service during the fault-clearance time. The electrical requirements are generally rugged in character: a 50 V supply is used, and contacts carry mainly direct currents not generally less than 25 mA at signal speeds not usually exceeding 10 impulses/sec. The plugs and sockets used in the major part of the system have not therefore had to meet very exacting requirements.

The mechanical design has incorporated methods of utilizing the unit weight, which is typically 8 lb, to assist in overcoming the high contact forces on the 32 nickel-silver contact springs used in the socket.

The introduction of electronic equipment into telephone switching has presented an entirely different range of requirements both from system and electrical considerations. With the very high speeds of operation which are available with electronic equipment, the tendency has been to replace the previous independent small groups of equipment by larger blocks. These blocks are capable of dealing with a large number of individual functions on a one-at-a-time basis. Some functions of the switching operations for a complete telephone exchange may be dependent upon one common block of equipment, with, of course, provision for a suitable standby block to maintain service under fault conditions in the former. A new problem is then presented in the degree of reliability and maintainability required for this common equipment. It concerns both the individual components in it and the devices used to connect it to the rest of the system. Whether such equipment should be permanently wired to the rest of the system or should be capable of easy disconnection, either in whole or in part, is the problem requiring solution by the design engineer taking cognizance of new equipment methods. The system reliability of plugs and sockets is therefore a very important point in this consideration. Furthermore, the electrical requirements have increased in severity, and while standardization of an interconnection method is desirable, the range of requirements makes this extremely difficult. Depending upon the components used as the elements of the system, the electrical requirements can vary between extremely wide limits, namely: voltage, 50 $\mu$V–300 V; currents, 100 $\mu$A–3 A; and frequency, up to 10 Mc/s.

Until recently it was often considered that a plug-and-socket connection merely required two metallic members to be brought into contact with a reasonable force. The mechanism of this connection has, however, received considerable attention since the introduction of low-voltage electronic switching. Although much has yet to be learned of this subject, there is now sufficient information to guide the designer and engineer in the choice of materials and performance of reliable plugs and sockets.

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## (2) EXPERIENCE IN RETROSPECT

### (2.1) Speech-Circuit Fault

The use of the previously mentioned standard electro-mechanical plugs and sockets for connection of electro-mechanical trunk switching circuits gave an early indication of the potential unreliability of the plugs and sockets where only low voltages were applied. In this instance some of the contacts were carrying only the alternating speech current and the direct 50 V supply was isolated by capacitors, with the result that under certain semi-tropical ambient conditions, a fading of the transmitted speech was observed. This was eliminated by the now well-known technique of 'contact wetting', which in this case was provided by having a steady direct current of ½ mA flowing through the contacts and supplied from the 50 V source.

### (2.2) Valve-Heater Feed Fault

Occasional disconnection faults have developed in plugs and sockets permanently feeding currents of 1 A or more from 6 V a.c. sources to valve heaters. This type of fault is attributed in general to the contact force being insufficient to disrupt tarnish films. Experience of the fault has been confined to nickel silver, but it is understood that copper and silver contacts have failed in a similar manner owing to the passage of fairly high currents. In the case of conventional telephone plugs and sockets with nickel-silver contacts and a contact force of 100–300 g, the following sequence of events has been detected:

(*a*) Atmospheric pollution produces a tarnish film on the contact surface which increases the initial contact resistance.
(*b*) Continuous passage of current causes heating of the contact constriction resistance.
(*c*) This heating accelerates corrosion of the constriction, as nickel-silver corrosion is greatly accelerated by increased temperatures.
(*d*) The contact resistance increases as the metallic constriction corrodes and the consequent rate of heating also increases.
(*e*) Eventually the melting voltage of the nickel silver is reached

at approximately 500 mV, which coincides with a contact resistance of 500 mΩ and a current of 1 A.

(*f*) At this point the constriction fuses and, dependent upon the nature of the adjacent corrosion, the contact becomes a disconnection or restores itself to a lower order of resistance.

It has been found that the connections can be restored by applying a slightly higher voltage, and no faults have been encountered on conventional 50 V supplies.

The higher voltage in this case almost invariably disrupts the tarnish film, and it is to this principle of wetted 50 V circuits that electro-mechanical equipment owes much of its reliability.

### (2.3) Field Results

Information derived from apparatus in actual service is of great value but suffers many shortcomings. First, its accuracy depends upon the population from which it is derived, but this is possibly more reliable than the figures obtained from small-population accelerated life tests. It also suffers from the inadequacy of fault-analysis reports and is very dependent upon the standard of maintenance. Furthermore, ambient operating conditions produce widely differing results, and the time required to accumulate sufficient information to form a reliable basis for computation for long-life equipment is probably the most serious shortcoming. However, it is reasonable to assume some serious significance from the comparison of field reliability of electronic components and their associated plugs and sockets.

**Table 1**

PERCENTAGE FAILURE RATES PER 1 000 HOURS

| No. | Hours in operation | Plugs and sockets | | Resistors | | | | Point-contact diodes | | Valves | | Transistors | | Soldered wiring joints | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Grade 1 | | Grade 2 | | | | | | | | | |
| | | Number of connections | Failure rate | Number | Failure rate | Number | Failure rate | Number | Failure rate | Number | Failure rate | Number | Failure rate | Number | Failure rate |
| 1 | 11 186 | (*a*) 9 760<br>(*b*) 21 000 | 0·97<br>1·15 | 10 000 | 0·004 6 | 86 000 | 0·000 6 | 15 000 | 0·009 5 | 700 | 1·57 | Nil | — | 372 000 | 0·002 5 |
| 2 | 7 224 | (*a*) 9 370<br>(*b*) 44 | 0<br>0 | | | 4 700 | 0·012 | 6 436 | 0·011 | 630 | 0·088 | Nil | — | 100 000 | 0·000 57 |
| 3 | 8 000 | 44 000 | 0·002 3* | 30 000 | 0·001 4 | 64 000 | 0·000 3 | 58 000 | 0·015 | Nil | — | 13 000 | 0·020 | 383 000 | 0·000 5 |

* Includes only those faults which required replacement or cleaning and not 'pull out and reinsert to clear' faults.

The information in Table 1 is derived from three electronic switching systems which use different equipment practices and different plugs and sockets for the interconnection of their sub-units. They are all operating within the United Kingdom. Failure rates in all cases are quoted in percentages per 1 000 h, and an indication of the population is given as well as the time over which the survey has been conducted. Information on the reliability of other components is included for comparison. The Table shows the inconsistency of many results obtained from separate sources, thereby leading to the view that generalization should be precluded.

## (3) BRIEF STUDY OF CONTACTS

The mechanism of contact in a plug and socket is one where for a long period connection can be established by the mechanical mating of conductors and broken by their separation. There is no great fundamental difference between the basic requirements for a plug-and-socket connection and that of a switch contact. Practical requirements, however, often dictate that the former employs larger forces, different shapes for the mating contacts and fewer mechanical operations in service. These differences add their own problems to the study of contacts, and both these and the common science of contacts will be dealt with briefly.

### (3.1) Contact Area

As no surface is perfectly flat, electrical contact between metallic surfaces is established through asperities on different spots. The area of these contact points or spots is determined by the applied force and elastic properties of the contact surfaces. At low forces, generally 200 g or less, most metals in bulk operate in their elastic range, although the tips of the asperities are first deformed plastically. In the case of a hemispherical contact on a plane surface the radius, $a$, of the contact area is given by

$$a \propto F^{1/3} \text{ in the elastic range}$$

For certain metals,

$$a = 1 \cdot 11 \left(\frac{Fr}{E}\right)^{1/3}$$

where $F$ = Force.

$r$ = Radius of contact.

$E$ = Young's modulus.

At high forces, plastic flow of the metal occurs, and the minimum force necessary is a function of the metal hardness. Under these conditions the above law changes to $a \propto F^{1/2}$.

### (3.2) Pole and Contact Resistances

The total electrical resistance of a plug and socket is the sum of three distinct resistances, namely pole resistance, constriction resistance and filmic resistance.

Contact resistance is that obtaining at the contact interface and is due solely to constriction and filmic resistances. Pole resistance, on the other hand, has nothing to do with the contact resistance; it is the fixed metallic resistance of the poles, including, in some designs, lengths of wiring.

In most plugs and sockets for telecommunications use the pole resistance is considerably greater than the contact resistance. As a low consistent contact resistance is the requirement for reliability, it is apparent that the pole and contact resistances should be defined separately. Unfortunately, most specifications for plugs and sockets treat contact resistance as the total electrical resistance, and accordingly a good design could be condemned for having a fairly high, but constant, pole resistance and a negligible true contact resistance. To avoid further controversy these quantities will be treated separately.

(3.2.1) **Pole Resistance.**

Pole resistance is defined as the fixed metallic resistance existing between the wiring points of a plug-and-socket assembly due entirely to the poles themselves. This quantity is of considerable importance in determining the current-carrying capacity due to the normal $I^2R$ heating and its effect on the associated material characteristics. In multi-pole assemblies a resistance of only a few milliohms per pole on full current rating is therefore a limiting factor of current-carrying capacity in plugs and sockets.

The measurement of pole resistance is carried out at a reasonable current, generally 1 A or the rated current, after welding the mating contact surfaces together. Welding is necessary to eliminate contact resistance, and it has been found that the discharge of a 32 $\mu$F capacitor, charged to 230 V, through the contact will provide a satisfactory temporary weld on most plugs and sockets.

(3.2.2) **Contact Resistance—Constriction and Filmic**

The constriction resistance of a contact is due to the resistance about the contact asperities through the contact areas described in Section 3.1. As the contact asperities at low forces are usually separated to some extent by tarnish films or absorbed gas layers, the true constriction resistance of a metal is determined *in vacuo* on chemically clean surfaces. The well-known formula for this resistance for long constrictions is $R = \rho/2a$, where $\rho$ is the metal resistivity.

The filmic resistance of a contact is dependent upon the nature of the film, its thickness, and the force and voltage applied. For the unbroken film on contacts the resistance is given by $R \propto \sigma t/\pi a^2$, where $\sigma$ is the film resistivity and $t$ is its thickness.

The resistance of a film is normally due to electron passage by the tunnel effect in thin films and conduction or semiconduction in thick films. If the applied voltage exceeds the work function of the contact metals or is sufficient to disrupt the film, the resistance of the film becomes voltage dependent.

It has been found by Fairweather[1] that the application of a low voltage of less than approximately 100 mV is insufficient to affect the film, and the resistance so determined is fixed to the very lowest voltages. Thus the measurement of contact resistance, i.e. constriction and filmic resistances, for low-voltage plugs and sockets is established by measurement with an open-circuit potential not exceeding 100 mV. It is preferred that an alternating current at 200–1 500 c/s be used as this eliminates the rectifying effects of certain films, but d.c. measurements can also be made at this voltage in both directions to detect rectification.

The current passed during this measurement should be limited to prevent $I^2R$ heating of the asperities, and not more than 100 mA has been found satisfactory in the evaluation of electronic-switching plugs and sockets.

## (3.3) Contact Films and Corrosion

All metal surfaces in air become coated with films of absorbed gases, water vapour, etc. The thickness of these films depends upon the surface energy of the metal and can range from one or two molecules in the case of gold to many more for transition elements such as nickel. The influence of these films on the electrical performance of plugs and sockets is negligible as they permit low-resistance tunnel conduction[4] at contact forces of a few grammes.

Apart from the above, the transition elements, notably nickel, palladium and platinum, exhibit an affinity for organic vapours which they can catalyse to a polymer under certain conditions. Work by Germer and Smith,[2] and Hermance and Egan[3] indicates that friction is necessary for this phenomenon, and catalytic cracking of organic and silicone oils by suppressed sparking with these contact metals has been found. As this effect is confined to rubbing or repetitive contacting it is not relevant nor has it been found detrimental to static plug-and-socket contacts.

Corrosion and tarnish films are the main causes of faults on plugs and sockets. Under normal atmospheric conditions, metal contacts can be divided into two classes, namely noble and base. The noble metals—gold, platinum, palladium, rhodium, etc.—are characterized by freedom from corrosion and tarnish-film formation under the normal atmospheric conditions encountered in electronic-switching applications. Base metals on the other hand—brass, nickel-silver, phosphor-bronze, tin, etc.—become coated with corrosion and tarnish films, and dependent upon the composition of the surrounding atmosphere, these can be mixtures of oxides, sulphates, sulphides, carbonates, etc. These films develop not only on the open surfaces of the contacts but also on the asperities of the mated assemblies. As certain metals will corrode indefinitely, this latter feature, commonly termed 'interstitial corrosion', will eventually destroy the asperities completely.

Corrosion films are generally insulating or semiconductors and are voltage dependent (see Section 2.2) in their resistive properties. For reliable low-voltage operation it is therefore necessary to abolish corrosion films completely from the contact interface. This can be accomplished in two ways: either by employing a non-tarnishing noble contact or by applying sufficient mechanical force to disrupt the film.

The former method is generally chosen for multi-pole plugs and sockets as the use of a noble metal permits a low contact force (usually around 100 g), and this in turn permits reasonable insertion and withdrawal of the assembly. The high cost of noble metals is one drawback, however, and it has been established that an electro-deposit of gold or palladium of minimum thickness 0·000 2 in is necessary on the contact face of certain base metals to prevent tarnishing under practical environmental testing.

The use of high contact forces on base-metal contacts is applied when the number of poles is small or insertion and withdrawal forces are of no consequence.

It has been shown by Fairweather[1] that a minimum force, dependent upon the basis metal, is required to disrupt conventional tarnish films. The following are quoted: silver, 300 g; brass, 1 000 g; stainless steel, 3 000 g.

This principle is employed in other forms of electrical connections, such as solderless wrapped joints, clinched tags, taper tag connectors, etc. One disadvantage is the amount of mechanical wear on the contact surfaces, which tends to limit the number of insertions and withdrawals.

As corrosion is a variable condition that often takes years to develop and depends largely upon environment, it is necessary to test plugs and sockets for this feature under accelerated conditions to simulate the worst that can obtain in practice. Many authorities have worked on corrosion testing, particularly for protective finishes, but there is no test that simulates all practical conditions. Working on this assumption, a test method has been developed which is far more demanding than any condition under which electronic-switching apparatus can be operated. The test is based on the toxic maxima for two separate sulphur gases in air and is interpolated from several years into 48 h as follows: 24 h in sulphur dioxide approximately 1% in air at a high relative humidity, followed by 24 h in hydrogen sulphide approximately 1% in air at a high relative humidity.

This test produces copious corrosion on common base metals and readily detects porosity in precious-metal deposits on base metals. It has been applied to more than 40 types of commercial plug and socket prior to low-voltage testing and in every case has discriminated between reliable and unreliable products.

### (3.4) Constriction Heating

The effect of constriction heating is dealt with by Holm[4] and Llewellyn Jones.[5] It is due to current passing through the constriction or contact asperities, and when the voltage drop assumes certain values such asperities can soften, melt or boil. These values are dependent upon the contact materials, and typical figures are quoted by Holm as:

| | Gold | Copper | Nickel |
|---|---|---|---|
| | mV | mV | mV |
| Softening .. | 80 | 120 | 220 |
| Melting .. | 430 | 430 | 650 |
| Boiling .. | 900 | 790 | — |

In any contact a softening or melting of the asperities will result in their collapse if the contact force is sufficient, and the corresponding reduction in resistance will reduce the voltage drop accordingly. When the contacts are covered with tarnish films a melting of the construction can result in the contacts becoming separated by the films if the force is insufficient to disrupt them. Gradual constriction heating in the case of base metals due to continuous passage of current can also result in the asperities becoming oxidized and corroding away until the resistance reaches a value equivalent to the melting voltage for the current flowing.

It has been found that reliable plugs and sockets, i.e. those with a consistently low contact resistance on gas exposure and low-voltage tests, do not exhibit this effect in practice if the current and contact resistance produce a voltage drop of less than the softening voltage. Apart from extraneous heating due to pole resistance it is therefore necessary to ensure that the rated current for a plug and socket is compatible with the contact resistance and contact metal employed.

From the design aspect this resolves into: the product of maximum current and contact resistance should be less than the softening voltage.

If this product is exceeded there is a danger of the contact welding and this can damage precious metal deposits on subsequent withdrawal.

Plugs and sockets that fail the reliability test owing to tarnish films and low forces can develop disconnections due to this effect. A case was cited in Section 2.2 where nickel-silver contacts developed disconnections when a current of 1 A flowed from a 6 V source to feed valve heaters.

### (3.5) Insertion and Withdrawal Forces

The insertion and withdrawal force of a plug and socket is dependent upon the shape and flexure of the contacts, contact force, surface finish, materials, etc. There is no complete equation relating these factors, but it is established that an increasing contact force will produce an increasing traction force due in part to normal friction.

At certain forces, characteristic of the metals and degree of surface film, there is a marked increase in friction. This is usually termed 'galling' or 'cold-welding' and normally requires a sliding or tangential movement in addition to the normal contact force. Several theories exist for this mechanism: in one case a removal of surface films by mechanical force will bring the metals into sufficient proximity for electron bonding to occur, and in another, frictional heat melts the contact asperities and causes fusion or welding. Over long periods intermetallic diffusion can also occur at high normal contact forces and produce welding, e.g. wrapped connections. The effect is deliberately utilized in other fields for producing cold-welded joints in aluminium, etc.

In the case of pure gold, which is inherently free from strongly bound surface films, cold welding can take place during tangential traction at normal forces of 500 g. In one experiment a pure-gold finish was applied to a connector employing a large contact force and a substantially base-metal contact. This substitution resulted in an increase of insertion force from 15 to 55 lb due to cold welding. Several insertions and withdrawals also damaged the finish severely. The application of liquid lubricants was quite ineffective in overcoming this condition as they were readily displaced from their loose bonding to the gold by the high forces. A compromise was later obtained by employing a gold alloy containing traces of cobalt and indium, the former promoting hardness and the latter lubrication.

To avoid cold welding on plugs and sockets it is advisable to keep the contact force as low as possible, dependent upon the metal employed and other requirements, such as contact resistance, etc. The use of gold at forces in excess of 200 g should be treated with extreme caution on this account.

### (3.6) Silver Migration and Metal Whiskers

Migration of silver in plugs and sockets is a well-known phenomenon. It has been investigated by most workers involved in telecommunications and can be described as the electrochemical migration of silver from solid-silver or silver-plated contacts over or through dielectric materials, and in many cases producing electrical breakdown of the dielectric. Certain dielectrics are much more prone to this trouble than others owing to traces of active chemicals and low insulation resistance, which permits a high leakage current to support migration.

Plugs and sockets employing silver contacts can be examined for this feature by submitting the assembly to an appropriate climatic test[6] (B.S. 2011: 1954) of high relative humidity with the rated direct voltage applied between some adjacent contacts. A marked deterioration in insulation resistance between these contacts compared with the others is usually an indication of silver migration.

Many metals have been examined for migration. Of those applicable to electrical contacts it would appear that silver alone is capable of this effect and even eutectic alloys of silver-copper are free from migration troubles.

Metal whiskers can be a source of insulation failure in plugs and sockets when they bridge adjacent contacts. These whiskers are growths of crystals from the basis metal, attributed to strain, or crystals of chemical salts of the basis metal. The conditions for whisker growths vary enormously, and it is known that silver will develop whiskers in sulphurous atmospheres, cadmium and tin in organic vapours, etc. Whisker growth, although fairly rare, takes several months to develop under the necessary ambient conditions and does not normally present a problem when open plugs and sockets are disturbed at a greater frequency than this. In sealed or semi-sealed assemblies for extreme reliability it is preferred that a non-whiskering metal be employed, and to date no evidence has been found of noble metals such as gold and palladium growing whiskers under a large range of conditions.

## (4) MATERIALS FOR PLUGS AND SOCKETS

To avoid a catalogue of properties under this heading, a subdivision of the more recent materials and associated processes will be presented. For general properties reference should be made to the appropriate manufacturers' specifications.

### (4.1) Dielectric Materials

The dielectric employed in a plug and socket is almost invariably the mechanical support for the contact members. Its properties are dictated by the performance specification with regard to climatic category, dimensional stability, insulation resistance, voltage proof, frequency range and sufficient mechanical robustness for manufacture and serviceability.

One material which fulfils most of the needs for electronic-switching application is a nylon-filled phenolic to B.S. 771, type L2. It offers a good combination of flexibility in moulding requirements together with insulation resistance and dimensional stability at a reasonable price.

Diallyl-phthalate and epoxy-resin mouldings with various types of filler are two of the more recent thermosetting plastics that are finding more specialized usage. The former material possesses good heat resistance (up to 150° C) together with good electrical properties, and the latter extremely low mould shrinkage coupled with high insulation resistance.

Glass-filled alkyds are also worthy of mention as they possess extremely high mechanical strength, heat resistance and electrical properties. The moulding of glass-filled alkyds requires careful consideration, however, but most of the trouble stems from a low bulk density in the powder, which demands additional accommodation in the mould, and from the problem of flash removal in view of its strength. The three materials mentioned are considerably more expensive than type L2 phenolic and are justifiable for special requirements.

Thermoplastic materials have not received much consideration for plug-and-socket mouldings owing to their general inability to withstand the temporary heat of a soldering iron on the associated contact. The fire hazard associated with many thermoplastics is also condemnatory when considering electrical applications.

One thermoplastic with a reduced fire risk and classed as self-extinguishing is nylon. Although several grades of nylon exist, one considered suitable for certain types of plug and socket is the type 11 possessing lower water absorption and correspondingly improved dimensional stability. The melting-point of this material is approximately 150° C, and soldering of associated contacts must therefore be made with dexterity if damage is to be avoided.

A recent addition to the limited range of self-extinguishing thermoplastics is the generic series of polycarbonates. These materials are characterized by extremely good electrical properties, dimensional stability and a melting-point of 180° C. One proprietary grade is outstandingly tough and will snap back to its original shape after severe mechanical distortion.

### (4.2) Pole Materials

The requirements of the basic pole materials are generally rigidity for the plug and a flexible material for the socket. Plug contacts can be dismissed fairly readily as their rigidity demands a generous section of low resistivity to reduce $I^2R$ heating. For normal applications, hard brass, copper or nickel-silver are satisfactory.

The choice of socket-contact base material is governed by the contact-force/deflection requirement to provide a reliable contact compatible with the finishes. Base-metal-finished contacts demanding high forces require a substantial bending moment or ancillary spring to provide the force. In electronic-switching applications, base metals (or quasi-precious silver and its alloys) are used as finishes only in plugs and sockets employing a limited number of poles to be consistent with reasonable insertion and withdrawal forces. This condition is confined essentially to test points, taper tag connectors and thermionic plug-in valve sockets. The material selection is based on electrical conductivity, contact design, contact-force/deflection requirement and elastic limit, and can range from brass to stainless steel.

Most electronic-switching multi-pole plugs and sockets are finished with precious metals and require contact forces of approximately 100 g for reliable operation. Socket springs can provide this force directly by the use of low-rate designs utilizing beryllium-copper, nickel-silver or phosphor-bronze as the basis metal. This is the usual procedure, and a close control of contact form and elastic properties is essential for consistent forces at high deflections. Beryllium-copper has one possible advantage in this respect in that the elastic properties are imparted to the spring by heat treatment after forming. Nickel-silver and phosphor-bronze, on the other hand, are work-hardened metals, and the form must be fabricated from this spring temper material without exceeding the yield point at the centre of flexure.

Certain proprietary sockets employ low-rate ancillary springs to supply the contact force to soft or inelastic socket contacts. This technique has an advantage in permitting a flexibility of spring design without affecting the contact shape itself. Another claim for this method in the case of twin (two-sided) socket contacts is that the contact interface becomes the datum face for registration rather than a secondary point such as a moulding. Materials for the ancillary spring are beryllium-copper, phosphor-bronze, spring steel, etc., and the section (e.g. wire or strip) offers unlimited choice.

### (4.3) Contact Finishes

The contact finish of a plug and socket is all-important in terms of reliability. As mentioned earlier, the choice rests between high mechanical forces and base metals or low mechanical forces and precious metals.

The most common base-metal finishes are silver or electro-tin, preferably flow brightened. These metals require contact forces of 300 and 1 000 g, respectively, to disrupt the naturally occurring tarnish films. It is a common practice in the case of silver to apply a temporary protectant such as petroleum jelly or grease to reduce the rate of tarnishing. The degree of protection afforded is dependent upon the quantity of grease and environment. Thin films which are desirable from the handling aspect offer a short-term improvement, and it is for this reason that they must be removed for accelerated testing of connectors in sulphur gases.

Multi-pole plugs and sockets with low insertion and withdrawal forces usually employ precious-metal finishes on the contact surfaces. The most satisfactory deposits to date are gold or palladium, and it has been found necessary to apply a minimum thickness of 0·000 2 in in both cases to base metals if they are to pass the gas-exposure test without noticeable corrosion. These finishes then offer complete reliability at contact forces of 100 g.

The deposition of heavy films of precious metals has introduced a new complexity to plating problems. A strict control in processing is necessary both in base-metal pretreatment and in the plating itself. For economic reasons it is essential to restrict the thickness of deposit without falling below the minimum 0·000 2 in. Quality control of precious-metal plating is essential, and in addition to routine analysis of solutions, continuous filtration, utilization of distilled deionized water, etc., the following routine is applied to samples from each batch of

500 gold- or palladium-plated contacts for electronic-switching applications:

Adhesion of deposit tested by flexing and burnishing.
Weight check for average deposit (complete batch).
Section and photomicrograph one typical sample from four batches.
Apply gas exposure test to three typical samples.

The type of plating process adopted depends upon the nature of the contact itself. In the case of contacts for the modular socket and 22-point socket, barrel plating is employed, and experience has shown this to be a consistent and reliable process when adequately controlled. Vat plating by individual wiring of components is applied to small quantities of contacts, large-area contacts, printed-wiring boards and in all cases where barrel plating is impracticable. Vat plating normally demands a fairly accurate disposition of anodes to prevent 'current robbing' by the nearer components, and to this end mechanical movement of the components is advocated.

The choice between gold and palladium is one of imminent concern. Pure gold is rarely employed for contact finishes owing to its relative softness and large grain size, which is conducive to porosity. Most contact finishes are obtained from proprietary solutions of gold containing traces of silver, nickel, cobalt, indium or other metals to increase the hardness, lustre or lubricity. The number of varieties is considerable and each type claims a particular merit either in processing or subsequent performance. It is recognized in the main that at least 95% gold in the deposited film is essential. The plugs and sockets referred to in Section 6 employ a hard, bright gold containing approximately 1% silver. Palladium deposits are comparatively new in the electrical industry. The merit of palladium lies in its cost, which for a given volume is roughly one-third that of gold. The academic disadvantage of palladium is an increased contact resistance due to its higher resistivity and hardness. On gas-exposure tests, low-stress palladium deposits compare favourably with gold deposits in maintaining a constant contact resistance, which is the standard for reliability.

Deposits of palladium are being applied to plugs and sockets for low-voltage operation on subscriber trunk-dialling equipment. The wider usage of palladium for this type of work will depend upon present investigations by various authorities into the parameters of plating conditions and salt formulation.

Special mention must be made of the printed-wiring board as a plug and its associated precious-metal contact. The chemical processing of printed-wiring boards is quite critical, and an immediate solution has been the use of mechanical board attachments to eliminate processing of the board itself. These attachments fall into the same category as normal contacts and can be gold or palladium plated.

In the interest of space saving and economy it is considered that direct plating of the printed wiring is advisable provided that the end-product is satisfactory. This is difficult to achieve on account of variations in proprietary laminates and the attack of the copper-to-fibre bond by chemical processing. Bond attack is attributed to the presence of ionized alkali metals or hydrogen cavitation in the catolyte layer during plating. In the worst cases this can produce complete detachment of the copper from the board.

As most gold solutions are complexed with alkali metals, they are unsuitable for printed-wiring-board plating. Recent acid solutions of gold are superior in this respect, and mechanical knocking of the board during plating is advocated to detach hydrogen bubbles from the cathode surface. Sequestered complexes of gold can be used by the Dalic process of rubbing a wet impregnated-pad anode over the contact surfaces to deposit gold.

A promising vat deposit on printed wiring is palladium from a neutral bath. This process is operated at room temperature and the solution is agitated by air bubbling. Printed-wiring boards for electronic-switching equipment employ this finish, which appears most satisfactory on prototype appraisal on certain grades of board. The selection of adhesives and copper priming by copper-clad-laminate manufacturers is a vexing problem and manifests itself during precious-metal plating. Each combination of materials from different grades and different suppliers of laminates is affected to a varying extent by plating techniques. Some grades have proved almost impossible to process due to bond attack, and it is essential that one grade is used exclusively for a given production batch. The indications are that a new specification will be required for boards to be used for direct plating and other requirements adjusted accordingly.

The objections to the use of a plated board as a plug are the possibilities of copper detachment during insertion and of board warpage reducing the contact force. These points have yet to be proved on a long-term basis in association with a compatible socket.

## (5) EQUIPMENT PRACTICE REQUIREMENTS

In view of the difficulties in ensuring a reliable plug and socket for a wide range of applications, it is first desirable to review the various factors which, individually or jointly, may determine the need to have demountable equipment in order that their significance can be assessed when designing new equipment. The reliability and long-life requirements for telecommunications, particularly of telephone switching apparatus under widely varying climatic conditions in world-wide application, are probably more exacting than for most other uses, and the reliance upon controlled ambient conditions for continuance of operation is ill-founded, since reasonable service should be maintained under the most adverse conditions. Furthermore, while different equipment applications may appear to demand different approaches in connection techniques, the desirability of standardization of interconnection media should not be overlooked. The tendency to perpetuate the accessibility and flexibility requirements of the system development stages should be avoided in final design since development tends to accentuate these requirements. They may not be of the same importance when considered as actual maintenance aids, so that the additional cost and complexity of the number and variety of plugs and sockets may not be justifiable in final equipment practice.

Factors to be considered in the determination of the need to provide demountable equipment are given in the following Sections.

### (5.1) Transportation

Transportation problems arise where the weight of the complete equipment may be such as to incur handling difficulties or demand a mounting framework of excessive strength in order to withstand the hazards of transportation. Additionally a requirement may exist to permit interconnection of mounting frameworks on site prior to commissioning of the whole equipment. In these cases the subdivision of equipment bears little relationship to system functions, and the alternative of plug-in equipment to wired-in methods may be considered an advantage in the reduction of effort required in installation at the working site.

### (5.2) Standardization for Design Flexibility

System design can be expedited by the standardization of small functional units, commonly referred to as building blocks, which in themselves may be separate pieces of equipment. The size of the unit will be determined by the degree of standardization down to the consideration of plugging in individual components. The interconnection of these blocks, by either plugs and sockets or permanent wiring, is initially most likely to follow the development stage requirements, so that final determination of the method of interconnection should be arrived at from consideration of other factors. However, the system design may be affected by the decision whether to use plugs and sockets in respect of making arrangements for spare equipment.

### (5.3) Standardization for Manufacture

Manufacturing costs are most likely to be reduced and production problems eased by the adoption of flow methods in the production of standardized sub-units, such as printed-wiring-board assemblies. The method of interconnection should not be dictated solely by production methods, but the differing costs incurred in using the various modes of interconnection should be analysed in respect of their contribution to overall equipment cost.

### (5.4) Standardization for Testing

Factory functioning of small standard sub-units is advantageous when mass-production methods are employed, and is preferable to full system testing of completely interwired assemblies. In this case, if the sub-units have their individual plugs or sockets, the testing is expedited, but ingenious designs are available which permit the temporary use of permanent wiring points as plug-and-socket connections during testing, so that the determination of the final interconnection method need not be controlled by factory testing requirements.

### (5.5) Maintenance

Maintenance is probably the most important factor in determining the necessity to use plug-and-socket connections since, as previously explained, the use of high-speed electronic techniques places an increased emphasis on component reliability, so that when faults do occur it is necessary to effect the most rapid restoration of service. It is therefore desirable to replace a faulty unit by a spare and to effect the repair without increasing the system fault-clearance time. Additionally, it is not generally desirable to interfere with permanent interconnection wiring to gain access for clearance of faults. In some applications the replacement of faulty components on common equipment *in situ* may be precluded owing to the danger of inadvertently introducing faults on standby equipment which has taken over automatically to maintain service. Other costly means of isolation may therefore be entailed as alternatives to plugs and sockets. If spare sub-units are to be provided, their contribution to the initial capital expenditure can materially affect the economics of the system and hence the tendency is to provide the minimum from a cost aspect. Thus, where standardization has led to small sub-units, only a minimum number of the various basic building blocks need be provided as spares, but this infers, for rapid replacement, a maximum number of plugs and sockets. This philosophy should not be accepted without detailed analysis, since it may be that overall costs can be reduced by reducing the number of plugs and sockets and equipping larger demountable units. The saving thus effected on plugs and sockets will be negated to some extent by the extra cost of a wider variety of larger spare units. As an example, in a general survey of three different electronic control equipments in a developmental state which use printed-wiring boards with different multi-point plugs and sockets, the plugs and sockets represented in each case approximately 3% of the total equipment cost. Thus final equipment design will have to consider the optimizing of cost within this limit, determined by reducing the number of plugs and sockets and off-setting the increased cost of spare units.

Accessibility to components for purposes of maintenance should not greatly influence the choice of interconnection methods, since the provision of adequate testing points should furnish the requirements of fault tracing, and in addition the ultimate reliance of plugs and sockets, if used, is desirable in order to remove any doubt as to their reliability when tracing faults.

### (5.6) Reliability

The rate of provision of plugs and sockets for interconnection can be related to component reliability in the need for rapid maitenance, referred to in the preceding Section, and the vulnerability of the system design to disruption of service by the particular fault. Where continuity of service has to be guaranteed in the presence of a faulty component, it is necessary to provide duplicate equipment or some other accepted form of security[8,9] with the inherent increase in cost. Hence, if the assumption can be made that plugs and sockets have a certain, though perhaps small, unreliability, it should be postulated that their inclusion should not increase the overall unreliability of the system. Thus the maximum number of individual interconnection points can be determined by their own reliability in relation to that of the total number of components they serve. That is, if the fault rate of an individual plug-and-socket connection point is one-tenth that of the equipment component fault rate, and it is assumed that an increase of one-hundredth of the fault rate has no overall effect, then plug-and-socket points should not be provided at a rate greater than one for ten components. The difficulty in achieving this, where basic building blocks are individually interconnected, may be appreciated in considering typically a transistorized bistable circuit which requires 8 leads (4 power, 2 inputs and 2 outputs) and contains only 22 components, i.e. approximately one connection per three components. This consideration therefore suggests the desirability to reduce the number of such connection points by increasing the size of the unit served by plugs and sockets, but it is then implicitly necessary to ensure greater reliability of the plug-and-socket connections in order that the apparatus reliability is not solely determined by the plug-and-socket reliability. In general, a measure of balance must be obtained between reliability and maintainability by the intelligent application of plugs and sockets based on knowledge of their performance and, where possible, careful segregation of components into groups of higher and lower reliability. The former do not require as much accessibility; the latter require, and without decreasing overall reliability can be provided with, accessibility by an increased number of plugs and sockets.

### (5.7) System Flexibility

Plugs and sockets may be demanded where flexibility is essential and where manual change-over is tolerable.

Summarizing, plugs and sockets contribute a small, though significant, contribution to total equipment cost, and careful consideration is necessary in their use to ensure a satisfactory balance between the requirements of maintainability and overall reliability. Endeavours being made to attain perfectly reliable plugs and sockets tend to increase their cost either by the use of noble-metal plating or increased contact force with attendant complicated insertion and withdrawal mechanism for multi-point plugs and sockets. With improvements in electronic component reliability, increased reliability of connectors will be an ever-increasing demand, so that it is difficult to envisage a significant reduction in their cost, and their economic application will require continual surveillance.

## (6) PRACTICAL DESIGNS

### (6.1) Modular Socket and Associated Printed-Wiring Board

Careful study of laboratory investigation reports and cost analysis of all the enumerated variations led to the conclusion that the ideal combination from a functional point of view would result in a socket not only too bulky for present-day requirements, where the emphasis is upon miniaturization, but also that production costs would be prohibitive. It was decided to produce a design which exhaustive tests had proved would be robust and reliable and which would meet the circuit and environmental requirements and yet could be produced at a reasonable price. Details of the design are as follows.

Preformed, low-tension-gain phosphor-bronze springs are employed, each spring having two limbs to provide connection by one limb on each side of the printed board, thus providing a double contact. The springs are gold plated all over to a thickness of 0·0002 in. Partial plating was ruled out on the consideration that the labour charges involved in jig mounting for plating would more than outweigh the cost of the additional precious metal required for overall plating. The contact ends of the springs are flat and mate with embossed contacts provided on the printed board, an arrangement which provides the most straightforward tooling proposition. The tag ends are designed for solderless wrapped connections. Solderless wire wrapping is a form of wiring which is finding increasing application. This method was used at Brixton telephone exchange in 1955 and in the United States over ten years ago.[10] Although long-life experience has not yet been obtained, there is every confidence that at least 40 years' life will be obtained from correctly made joints.

Thermosetting nylon-loaded phenolic material is used for the mouldings in view of its excellent mechanical and electrical properties. The minimum tensile strength of the material is 7 500 lb/in$^2$ and the minimum impact strength 0·15 ft-lb/in. The surface resistivity after water immersion is $10^{11}\,\Omega$ (minimum), the volume resistivity is $10^{11}\,\Omega$-cm and the electric strength is 100 V/mil at 90° C (minimum). The mouldings are open ended and provide 26 contact positions on 0·150 in centres (Fig. 1).

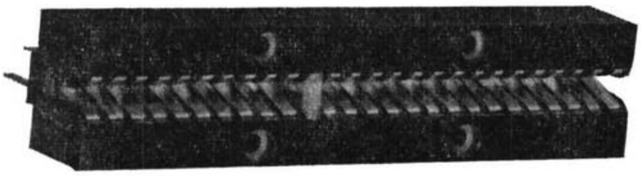

**Fig. 1.**—Modular socket fitted with 25 contact springs.

By suitable adjustment to the moulding tools, shorter mouldings in units of five contact positions can be readily provided. Mounting holes are positioned in the mouldings with this flexibility of length of view. Wider printed boards requiring more than 26 contact positions can be catered for by providing two or more sockets, end to end, without any loss of positions due to intervening fixing screws.

A moulded-nylon polarizing piece may be inserted in any contact position in place of the contact spring. This engages in a slot in the printed board and serves to locate accurately the board in the socket. By suitably positioning the polarizing piece and the slot in the board it is ensured that only the correct type of board is inserted in the socket.

The printed board which forms the plug is fitted with U-shaped contact plates, which extend over both faces and edge of the board. The contact plates, which are gold plated to a thickness of 0·0002 in, are fixed to the board with preformed lengths of bare tinned copper wire, which pass through two holes in each contact plate and the board. The copper wire and the plates are soldered to the printed foil conductor. It was decided not to rely upon single rivets for fixing the contact plates to avoid the danger of the plates pivoting about the rivets and causing high-resistance joints or disconnections in use. Each limb is provided with a hemispherical embossing at the point of contact with the socket spring. The embossings concentrate the spring forces at specific points in a similar manner to the conventional solid domed contact but at lower production costs.

### (6.2) 22-Point Socket and Associated Printed Board

A second type of plug and socket has been developed.[11] Fig. 2 depicts the preferred size, which is 22-way. The socket body is moulded in thermosetting nylon-loaded phenolic material and is so shaped that a minimum amount of machining is required on the printed edge of the printed-wiring board. The overall width is 0·384 in, giving a minimum 0·4 in socket spacing on the 0·2 in shelf module.

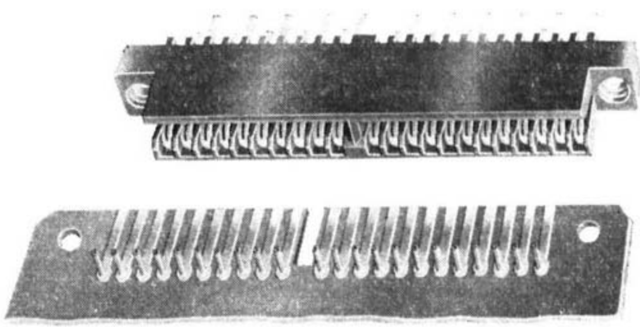

**Fig. 2.**—22-point socket and part of a printed-wiring board fitted with 22 contact plates.

A bridge-piece, offset from the centre of the moulding and forming an integral part of it, mates with a corresponding slot in the edge of the printed-wiring board. This aligns the contact pads accurately with the contact springs and prevents the board from being inserted the wrong way. If, in addition, a coded registration is required to ensure that only one type of board can be inserted into a particular socket, one spring is removed and replaced by a metal insert. At the rear of the socket, the moulding is relieved around the tags to avoid moisture traps.

A low-rate beryllium-copper twin-contacted spring is used. It is designed to maintain a minimum contact force of 100 g under all possible adverse conditions of misalignment, warping and extreme tolerance of board thickness and socket part dimensions. To minimize wear of the contact surfaces and to locate the point of contact, the ends of the springs are spoon-shaped. The terminating end of the spring is formed into a channel section to give rigidity. To retain the contact spring within the moulding, a small projecting tag formed in the spring engages in a corresponding recess in the body of the moulding. A gold-plated phosphor-bronze contact strip, riveted and soldered to the etched foil of the printed board, is used to form the plug contact. The strips fit into notches machined in the edge of the board to prevent sideways movement.

## (7) CONCLUSION

It has been shown that reliable plugs and sockets can be designed to meet the stringent demands of electronic equipment. It is apparent, however, that the requirements necessitate an increase in the cost of the item and careful consideration must be exercised in their provision on economic grounds. The application of plugs and sockets permits flexibility in design and maintenance, the requirements of the latter being inherently related to the component reliability. Plug-and-socket research must proceed apace, and it is evident that a combination of design, material utilization and improved processing can effect further improvements both in performance and economics.

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## (9) APPENDIX: PERFORMANCE SPECIFICATION FOR PLUGS AND SOCKETS

The following specification was produced to cover reliable low-voltage plugs and sockets for use in electronic switching. It is based on contact studies and an extensive evaluation of many commercial types of plugs and sockets under a variety of environments. Although it will vary in detail for differing types of assembly the principle can be applied generally.

(*a*) *Contact finish.*—Approved finish, e.g. minimum of 0·0002 in gold. The finish to withstand right-angle bending of the contact without peeling or flaking, and in addition burnishing with a copper disc (B.S. 1224: 1959, Appendix B) without blistering.

(*b*) *Insertion and withdrawal forces.*—Maximum forces are specified dependent upon design. Typical values range from 3 oz to 1 lb per connection.

(*c*) *Pole resistance.*—Determined at 2·5 V, 1 A (a.c. or d.c.) after discharge of 32 $\mu$F capacitor charged to 230 V through a typical connection. Resistance varies for types, but a normal value is 3 m$\Omega$.

(*d*) *Contact resistance.*—Measured at less than 100 mV (peak open-circuit), 1 kc/s and less than 100 mA. Resistance less pole resistance must not exceed 5 m$\Omega$ or as specified.

(*e*) *Gas exposure.*—Insert and withdraw 20 times and then vapour degrease assemblies to remove organic protective deposits if any. Submit separated plug and socket to gas exposure—sulphur dioxide and sulphuretted hydrogen [see (*l*)].

(*f*) *Contact resistance.*—On the first insertion after gas exposure the contact resistance measured as (*d*) above must not exceed 8 m$\Omega$ or have increased by more than 5 m$\Omega$.

(*g*) *Climatic insulation and voltage proof.*—Appropriate category to B.S. 2011: 1954. Insulation resistance to exceed 100 M$\Omega$ and to withstand the requisite voltage-proof test after specified recovery.

(*h*) *Current rating.*—The rated current shall be applied to all connections in series with the plug and socket at the appropriate B.S. 2011: 1954 dry-heat temperature for 24 h. The plug and socket shall not show a temperature rise of more than 20° C and the contact resistance shall meet requirement (*f*).

(*i*) *Silver migration.*—When silver is used, apply B.S. 2011: 1954 wet-heat test with rated direct voltage between adjacent contacts. Insulation resistance must exceed requirements for (*g*).

(*j*) *Wear.*—Plugs and socket to be inserted and withdrawn 500 times (or as required). Contact resistance must not exceed (*f*) and contact surfaces must not exhibit excessive wear.

(*k*) *Termination.*—As specified either suitable for gun wrapping or tinned with tin-lead solder.

(*l*) *Gas exposure.*—Initial work on gas exposure indicated that gas concentrations had a pronounced effect on relative humidity owing to a 3-phase equilibrium condition. To eliminate controversy in specifying percentages of gas and relative humidity it is preferred to describe the *modus operandi*:

Chamber to consist of conventional glass desiccator and lid of 8–12 litres internal volume and containing a perforated glazed ceramic plate. Chamber maintained at 15–25° C.

The plugs and sockets are placed on the ceramic plate, operative face upwards.

Distilled water 0·5 ml is dispensed into the base of the desiccator beneath the ceramic plate.

A clean dry gas jar of 100 ml capacity is filled with sulphur dioxide, which is transferred to the desiccator and the desiccator closed.

After 24 h the desiccator is opened and allowed to stand for one hour.

The gas jar is then filled with sulphuretted hydrogen (prepared from ferrous sulphide and hydrochloric acid) and placed in the desiccator as above.

After 24 h the desiccator is opened and the plug and socket allowed to recover for 4 h before insertion and testing.