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Volume 45 FEBRUARY 1954 Part 2

PROCEEDINGS AT THE FOUR HUNDRED AND FORTY-FIRST GENERAL MEETING

Held at Kelvin House, corner Marshall and Hollard Streets, Johannesburg

Thursday, 25th February 1954

J. P. ANDERSON (President) was in the Chair and opened the meeting at 8 p.m.

There were present 80 members and visitors and the Secretary.

MINUTES

The minutes of the annual general meeting held on the 28th January 1954, were taken as read and were confirmed.

MEMBERSHIP

The President announced that in terms of By-Law 5.2.4 the Council had elected the undermentioned candidates to membership of the Institute in the following grades :—

Associate Members : CECIL GEORGE CLARKE, DAVID LEES.

Graduates : HUGH MARX, GRAHAM SELBOURNE MEAKER.

Students : DEREK JOHN HUDSON, FREDERIK HENDRIK SWANEPOEL.

Transfer from Associate Member to Member : EDWARD LORRAINE DAMANT.

Transfer from Associate to Associate Member : ROBERT VICTOR DALE.

Transfer from Student to Graduate : GERHARD CILLIERS DURAND, IAN CAMERON FRASER, PETER MARSHALL, MALCOLM JOHN MCLACHLAN.

Transfer from Student to Associate : BRIAN DAVID LAVERY, ALMA MAGENNIS.

CO-OPTED AS MEMBER OF COUNCIL

The President announced that, in terms of Clause 3.8 of the Institute's Constitution, the Council had co-opted Mr M. Hewitson as a Member of Council for the 1954 Session, as representing the Department of Posts and Telegraphs.

PAPER AND DISCUSSION

F. G. MCDONALD (Member) presented an abridged version of his paper entitled ' The electrical uses of aluminium.'

The President proposed a vote of thanks to the author for his paper and C. R. Hallé (read by E. W. Trotter (Associate Member)), H. A. S. Dunk, R. G. Hulley, P. L. Vergottini (Member), H. L. Dawe (Companion) (read by E. W. Dixon (Associate Member)), N. G. Beveridge (Associate Member), G. Williams (Member), M. Hewitson (Member) (read by W. Cormack (Associate Member)) and A. A. Middlecote (Associate Member) (read by H. P. Alexander (Member)) contributed to the discussion.

The President declared the meeting closed at 9.40 p.m.

Institute Notes

Cape Western Local Centre

Another outstanding and successful meeting of the Cape Western Local Centre was held in the Railway Institute, Adderley Street, Cape Town, on Thursday, 18th February, 1954.

The lecture on the design, manufacture, development and application of the Transistor was given by Mr J. Zawels who has just returned from four years of study in the United States where he participated in Transistor research with the G.E.C., R.C.A. and M.I.T.

The lecture aroused great interest as indicated by the attendance of 62.

Invitations to attend the lecture were sent to the Royal Society of South Africa, Cape Town members of the British Institute of Radio Engineers and to physicists of the University of Cape Town.

Mr Zawels gave a general account of the development and present application of the Transistor as an introduction to his lecture and sample transistors were on view. Later he described several types of transistors and their various circuits together with a lucid description of the methods of manufacture and the materials employed. The lecturer compared the Transistor with the Thermionic Valve and concluded wih a masterly exposition of the physics of the appliance.

Many members and visitors participated in the subsequent discussion which was of a very high order.

At the outset the Chairman, Mr C. G. Downie presented the certificate awarded by the Council in Johannesburg to Mr R. R. Gilmour for his contribution to the discussion on the paper entitled 'A 66-kV grid in Northern Rhodesia,' by T. K. A. Douglas, A.M. (s.a.)I.E.E., (*Transactions*, February, 1952).

The meeting concluded with a vote of thanks to the lecturer at 10.30 p.m.

Education and Bursary Scheme

The attention of Students is drawn to the Institute's Education and Bursary Scheme which has been established for the purpose of assisting Students of the Institute.

Institute Bursaries are made available each year to selected Students with the primary object of affording them some financial assistance in their technical studies.

Full details of the scheme appear on page 100 and those students wishing to apply for a bursary may obtain the necessary form from the Secretary of the Institute, P.O. Box 5907, Johannesburg.

All applications for 1955 bursaries must be in the hands of the Secretary not later than the 31st July, 1954.

THE ELECTRICAL USES OF ALUMINIUM

By F. G. McDONALD (Member)

SUMMARY

This paper gives an account of the uses being made of aluminium in the electrical industry.

The physical properties of aluminium are briefly stated, in comparison with the properties of other engineering materials.

Some notes are given on sources of supply and on price trends.

The use of aluminium for overhead lines is discussed in some detail, with particular reference to conditions in South Africa.

A summary is given of progress to date with the use of aluminium in insulated cables. Its use for busbars is briefly discussed, and some notes are given of the use being made of it in the manufacture of electrical plant.

CONTENTS

INTRODUCTION

Before 1939, aluminium had a recognized place in the electrical industry but was used substantially only in the limited fields of high-voltage transmission lines, rural distribution lines, and sometimes conductors for heavy current. In other fields, copper was almost invariably used, and its choice was usually sound economically.

Since 1939 the growth of the electricity supply industry has continued at a rate which has surprised all but the most far-seeing engineers. All over the world to-day, electrical loads are two to three times what they were in 1939, and it must be considered probable that by 1960 these loads will have doubled again.

During the war, vital materials in all countries were under strict control and it came to be accepted that strategic metals must necessarily be scarce; after 1946, the first period was one of continued shortages and this has been followed by a period of bewildering price changes.

In 1953, it seems to be evident that the growth of the electricity supply industry is overtaking the capacity of the copper-producing industry; it seems very unlikely that there will ever again be enough copper for it to be used as it was used before the war—freely and without thought of conserving it. It seems clear that aluminium must be used in future years for more and more of the purposes for which copper has been the customary material and that more and more electrical engineers must use the metal in their daily work.

This paper is presented to give electrical engineers in this country up-to-date information concerning the newer metal; it is hoped that the paper will assist to prevent some of the errors and waste which must be introduced when old tried methods are being replaced by new.

2. THE PROPERTIES OF ALUMINIUM

2·1 *Physical and mechanical properties*

The important properties of aluminium, from the point of view of the electrical engineer, are its lightness, its electrical conductivity, and its resistance to corrosion.

Aluminium of commercial grade has a purity ranging between 99·2 and 99·5 per cent; this material is familiar to everybody; it is used for domestic hollow-ware, containers, panelling, building sheet, etc.

When aluminium is referred to in this paper, aluminium of 'EC' or electrical conductor purity, 99·5 per cent minimum, is intended. This grade has the same mechanical properties as commercial purity metal.

Aluminium is a wrought alloy, and its properties are dependent on the amount of cold working it has undergone. Fig. 1 shows how the ultimate tensile strength and elongation vary between the soft or fully-annealed state, and the hard or fully-worked state. When no state of work-hardening is specified the properties of half-hard metal are usually implied.

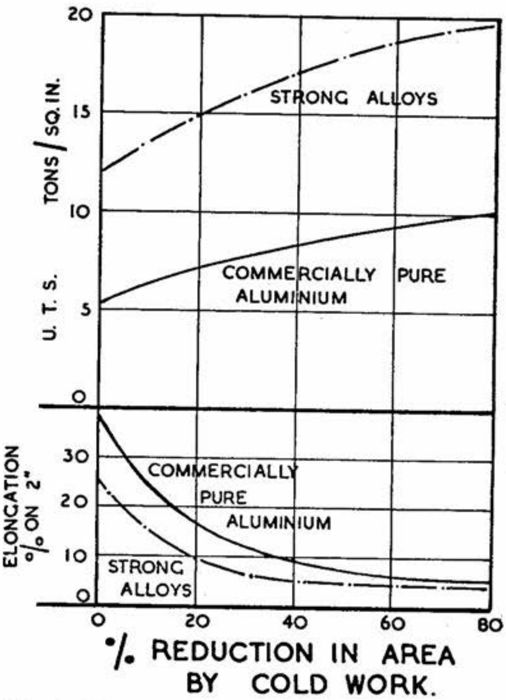

Fig. 1—Mechanical properties of aluminium showing variation with degree of cold work

Other important mechanical properties of half-hard aluminium are :—

Ultimate shear stress : $5\frac{1}{2}$ tons per sq.in.
Ultimate bearing stress : $13\frac{1}{2}$ tons per sq.in.
Brinnell hardness number : 38 tons per sq.in.
Young's modulus : 10 000 000 lb/sq.in.
Torsion modulus : 3 800 000 lb/sq.in.
Poisson's ratio : 0·32

For convenience, some of the physical constants of aluminium are given in Table I, compared with those of copper.

2·2 *Electrical properties*

The electrical conductivity of EC grade hard-drawn aluminium wire is 61 per cent of the International Annealed Copper Standard (IACS) at 68°F (20°C). For hard-drawn copper wire, it is 97 per cent. Thus, for the same conductivity, an aluminium wire must be about 25 per cent larger in diameter than a copper wire. This larger conductor will be just less than half the weight of the copper wire. Table II sets out comparative figures for both metals, for easy reference.

The conductivity of aluminium increases slightly when it is annealed, but it is usual to use only the one resistance value (for hard-drawn wire) for aluminium in any temper.

No definite figure can be given for the conductivety of commercial purity aluminium, as some impurities affect conductivity more than others. Typical values lie between 57 per cent and 59 per cent of IACS—from 3 to 6 per cent below that of EC grade metal.

2·3 *Chemical properties*

The outstanding property of aluminium, from the chemical point of view, is its affinity for oxygen. A film of oxide forms spontaneously on any surface exposed to the air. This film is transparent and is relatively inert chemically. It is to this protective film that aluminium owes its high resistance to chemical and atmospheric attack. This film is a non-conductor of electricity ; it is very thin (about 0·000 008 inch) but tends to thicken with age and prolonged exposure.

2·3·1 Corrosion in air

Many tests have shown that the rate of corrosion of aluminium in air falls off with time, according to an exponential law, until finally it almost ceases ; at this point the oxide film is thick enough to seal off the metal below completely from the atmosphere.

Comparative tests under scientific control in various parts of the world suggest that aluminium is perhaps longer lived than any commercial metal excepting only lead. In South Africa, aluminium used in the clear atmosphere of the inland areas will be

TABLE I

	Aluminium	Copper
Atomic weight	26·97	63·54
Weight—lb per cub. in.	0·098	0·321
Specific gravity	2·71	8·89
Melting point °C	659·8	1 082·6
Boiling point °C	1 800	2 325
Latent heat of fusion calories per gm	93·5	48·9
Specific heat calories per gm 0°—500°C	0·24	0·092
Coefficient of linear expansion per °C	0·000 023	0·000 017
Thermal conductivity (Silver = 100)	57	94
Heat of combustion to oxide B.Th.U. per lb. ...	(Al_2O_3) 12 800	(CuO) 1 090

TABLE II

ELECTRICAL PROPERTIES OF ALUMINIUM

	Hard-drawn aluminium wire	Hard-drawn copper wire	Annealed copper wire
Conductivity at 20°C	61 per cent of I.A.C.S.*	97 per cent of I.A.C.S.	100 per cent
Resistivity in microhms per c.c. at 20°C	2·828*	1·774	1·72
Constant mass temperature coefficient of resistance per °C at 20°C	0·004 03	0·003 81	0·003 81

* B.S. 215/1934 sets the slightly lower standard of 2·845 microhms per c.c. for resistivity, corresponding to a conductivity of 60·6 per cent I.A.C.S.

virtually everlasting. Specimens of stranded conductor taken from overhead lines erected on the Reef about 20 to 25 years ago have presented an almost new appearance, with the centre strands still bright.

Conditions at the coast are of course much more arduous but do not affect the relation between the behaviour of aluminium and of other metals. Laboratory tests were recently made on some 7/·144-inch aluminium stranded conductor erected in Milnerton, Cape Town, from 1914 till 1927 and subsequently stored in the open. The tensile strength and elongation of the conductor, tested in 1952, exceeded the requirements of B.S. 215/1934, although this standard did not exist when the conductor was fabricated.

2·3·2 Galvanic corrosion

Aluminium may corrode when it is in the presence of a more noble dissimilar metal *in the presence of an electrolyte*. The severity of the corrosion will depend on the conductivity of the moisture present, the relative electrical resistance of the joint between the two metals and the relative electro-chemical activity of the two metals in the particular environment.

It is usually safe to couple aluminium with zinc and cadmium ; it is never safe, when moisture is present, to couple aluminium with brass or copper. This problem is discussed in more detail later.

2·3·3 Corrosion in soil

It would be difficult and dangerous to make any general statement about the behaviour of aluminium in soil. There are records of aluminium in buried situations giving trouble-free life for very long periods ; and there are instances where aluminium has been destroyed in two or three years. In well-drained soils, aluminium can usually be expected to have a long life ; in most conditions, its life will be at least as long as for galvanized steel.

The composition of soils can vary widely from one locality to another and from point to point within a small area, so that a classification of soils, from a corrosion point of view, would be too cumbersome to be useful. Aluminium is quickly attacked by lime and is susceptible to electrolytic corrosion arising from contacts with other metals or from stray currents.

The protection of aluminium when buried in the ground would seem to be essential.

2·4 *Thermal properties*

The most important thermal properties of aluminium have been set out in Table I.

Attention is drawn to its thermal conductivity (60 per cent of that of copper) and to its specific heat (2·6 times that of copper). Conductors of the two metals of equivalent resistance will conduct heat at a similar rate, but the aluminium conductor will have rather greater heat content and a larger surface area.

A property of aluminium which has resulted in some specialized uses is its reflectivity, which is only slightly affected by the natural oxide film because of its transparency and thinness.

2·5 *Aluminium alloys*

The formation and behaviour of alloys is a complex subject beyond the scope of this paper ; it is only important to recognize that light alloys which are basically aluminium, and which look like aluminium, may have very different properties.

High strength is usually attained at the expense of ease of fabrication and sometimes with a reduction in resistance to corrosion.

The most widely used alloys are those which have copper as their main alloying constituent. These alloys are all of the heat-treatable type. As a class, they have poor corrosion resistance and are not widely used in electrical work ; in sheet form they are usually supplied as 'Alclad' with a thin layer of pure aluminium on one or both sides to provide the surface which must resist attack.

A warning should be given : when secondary metal—usually remelted scrap—is used, the amount of copper-bearing scrap in the melt is of very great importance in determining the corrosion resistance of the product ; large quantities of sheet manufactured from secondary metal—most of it copper-bearing alloy from aircraft scrap—were dumped in this country after the war ; in coastal areas this sheet was sometimes destroyed after only a few months.

3. THE SUPPLY OF ALUMINIUM

3·1 *Raw materials*

To produce one pound of aluminium, the most important requirements are four to six pounds of aluminium ore, or bauxite, and approximately ten kWh of electricity.

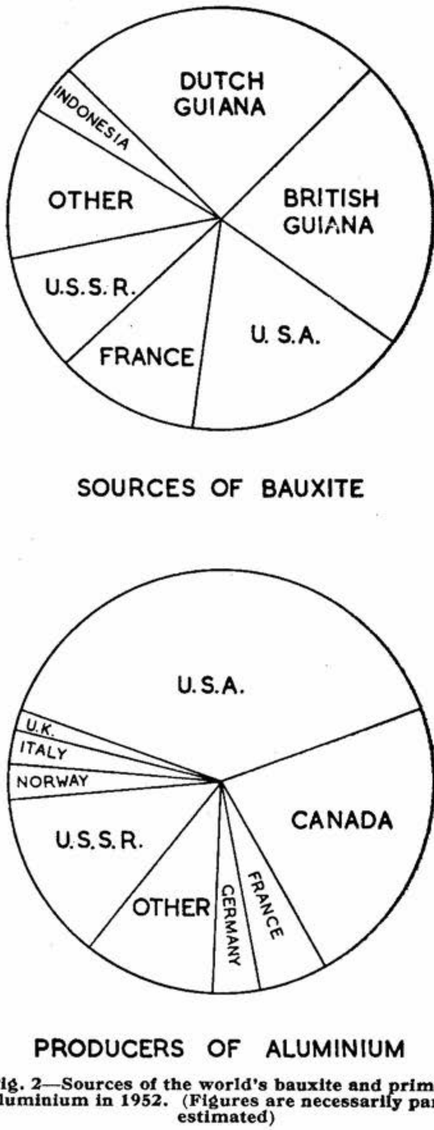

Fig. 2—Sources of the world's bauxite and primary aluminium in 1952. (Figures are necessarily partly estimated)

Bearing in mind that bauxite occurs in large deposits at or near the surface and is relatively cheap, it follows that the production of aluminium in quantity, and its price, depends more on the availability and cost of electric power than on the supply of ore. The two charts in Fig. 2 show the world's sources of bauxite and of primary aluminium in 1951. Except for the U.S.S.R., France is the only country in which bauxite is mined where aluminium is produced on any scale. The bulk of the primary aluminium used in Great Britain, South Africa and the other Commonwealth countries originates in Canada and is produced by hydro-electric power.

3·2 *Extraction of aluminium*

The extraction of aluminium from its ores is unusual; most metals are reduced from their ores and subsequently refined to remove impurities; aluminium is purified in its natural form—as hydrated alumina—and is then reduced. The two main operations are—

i the preparation of pure alumina (Al_2O_3) from the bauxite; and

ii the electrolysis of alumina to obtain metal.

The process of electrolysis is of interest. Each cell works at about 5 or 6 volts; currents range from 8 000 to 50 000 amperes, depending on the size of the cell. Cells are connected together in series, forming 'pot-lines,' and each pot-line is supplied by a source of direct current. Rectifiers for this duty range up to 9 000 kVA, and operate at voltages between 200V and 900V depending on the length of the pot-line.

3·3 *Growth of the industry*

Aluminium was first isolated in 1825 and first produced on a commercial scale in 1888. The industry has grown rapidly and the volume of aluminium now being produced exceeds the combined volume of copper, lead and zinc—see Fig. 3. This rate of growth is continuing at the present time. It would not be possible for the production of any other non-ferrous metal to be expanded similarly—all are won by expensive mining methods and all have limited ore reserves.

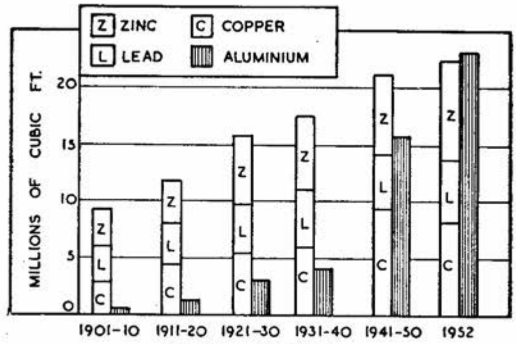

Fig. 3—The growth of the aluminium industry

3·4 *Price trends*

The dollar price of aluminium at this date (20·5 cents per lb for commercial ingot) compares with the price in 1939 of 20 cents per lb, and is lower than the 1929 price of 24·3 cents per lb. The prices of copper, lead, zinc and tin are all more than double their pre-war levels; even pig iron has increased by about 60 per cent. Fig. 4 shows how sterling prices of non-ferrous metals have varied over the past thirty years. The market prices of base metals will, in all probability, remain uncertain for several years to come but the overall trend is clear. The important fact to the electrical engineer is that whereas aluminium, before the war,

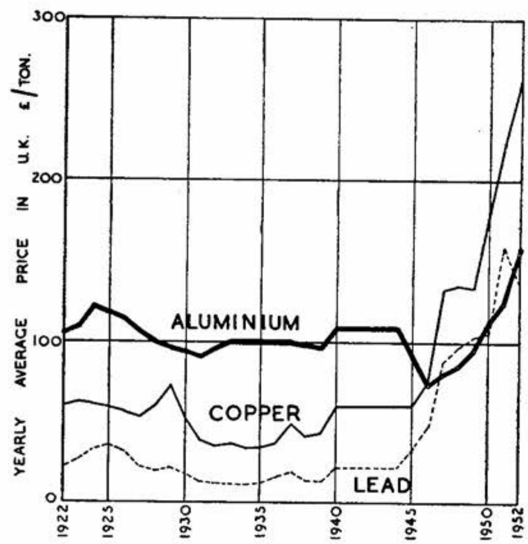

Fig. 4—Chart showing how sterling prices of base metals have varied over the past 30 years

was twice as expensive per ton as copper, it is now much the cheaper.

In most electrical applications it is not price per ton that is important but price per cubic foot. Aluminium is easily the cheapest of the non-ferrous metals on a volume basis and it does not seem possible that it can be displaced from this position in the foreseeable future.

3·5 *Aluminium versus copper*

The present expansion of copper mining in Africa tends to blind engineers in this country to the fact that world production is not increasing. Estimates of the world's reserves of copper show only enough to last for 40–50 years at present rates of consumption. This makes it obvious that the electrical industry, which doubles its requirements each ten years, cannot remain almost completely dependent on copper.

As far as we in this country are concerned, enough copper is available for our own needs. But the metal is an important export and dollar earner; it seems likely that the electrical industry here must follow general practice overseas and change over gradually to aluminium.

4. ALUMINIUM CONDUCTORS FOR TRANSMISSION LINES

4·1 *South African experience*

A large fund of experience in the erection of transmission lines using aluminium conductor steel reinforced now exists in South Africa and the suitability of the material for local conditions has been clearly established.

The 132-kV Witbank/Brakpan line, erected in 1926, used a.c.s.r., and it has been used for all 132-kV lines erected since then by the Electricity Supply Commission (E.S.C.) and for a large number of lines at lower voltages all over the country. In Rhodesia, over 80 per cent of all lines at voltages of 33 kV and above erected by the E.S.C. during the past ten years have used a.c.s.r.

This wide acceptance of a.c.s.r. has influenced South African manufacturers towards starting its manufacture locally. Manufacture of a.c.s.r. was not started in this country before the war because galvanized steel wire of suitable quality was not then available. Wire suitable for steel cores is now manufactured in South Africa and the local stranding of a.c.s.r. got under way during the second half of 1953. This development will certainly increase the rate at which aluminium comes into general use at all voltages.

The wide use already made of a.c.s.r. shows that its advantages are clearly understood by transmission-line engineers and they need not be set down here. It is proposed to touch only on some matters where the use of aluminium has raised new points of discussion.

4·2 *Specification and ultimate strength*

A.C.S.R. used in South Africa is manufactured in accordance with the requirements of B.S. 215 : 1934 — Hard-drawn aluminium and steel-cored aluminium conductors for overhead power transmission purposes. This specification was amended in January 1952 and is at present being completely revised. The equivalent North American specifications are ASTM Designation B.230–50T and Canadian Engineering Standards Association C.49–1940. One of the more apparent differences, to the user, between the British standard in its present form and the North American specifications is that the British standard defines the strength of a conductor as

> 98 per cent of the sum of the strengths of the aluminium wires plus 85 per cent of the sum of the strengths of the steel wires.

The American specifications define the ultimate strength of a conductor as the sum of the ultimate strengths of the aluminium wires plus the sum of the values of stress at 1-per cent elongation of the galvanized steel wires.

Both methods give substantially the same strength for the same conductor but the North American method illustrates what is one of the practical assets of a.c.s.r.—it is not possible to take into account the full strength of the steel core when determining the ultimate strength of a.c.s.r.; this is because the aluminium strands have a lower elongation and must fail first when a conductor is tested to destruction. In practice, this means that an a.c.s.r. has a reserve of mechanical strength. In the event of an accident—a damaged support or a tree across a line, a span may be loaded above its ultimate design load. The aluminium wires may break, but the steel wires, with their greater elongation, will keep on stretching, increasing the sag and lowering the tension; the line may hold up until repairs can be made and damage may be confined to the one span.

4·3 *Sags and tensions*

When calculating sags for homogeneous conductors, it is usual to work with a definite value for the modulus of elasticity of the material. This can also be done for a.c.s.r.—the modulus varies for different conductors according to the proportion of steel to aluminium in their make-up. However, the choice of a fixed modulus is not really justified, the modulus of a stranded conductor is usually less than that of a single wire; it depends to some extent on the number of wires and on their lay. With a composite conductor like a.c.s.r. the modulus varies with load and temperature because the proportion of load carried by the two portions of the cable is being changed.

With a.c.s.r. it is reasonable to assume fixed values for the modulus when making rough calculations of sags and tensions. When accuracy is required it is preferable to base calculations on stress/strain curves taken in actual experiment on the particular size of conductor concerned. This eliminates assumptions and gives results that are completely reliable in practice.

A graphic method of deriving sag/tension charts from stress/strain curves has been standardized which eliminates laborious calculations.

To allow for the increase in sag which takes place with a conductor of any material after its first loading, it is common practice when erecting lines to prestress the conductors; this involves pulling them up to say 60 or 70 per cent of their breaking load and subsequently releasing the tension before making off. For large sizes of conductor the tensions required are very high and prestressing subjects towers and stays to heavy stresses which are higher than working loads impose and which are avoidable. For this reason it is preferable to string to initial sags and let the final sags come naturally. Using the graphic method, two sag/tension charts are derived. One based on the stress/strain curve for new conductor gives the initial sags and is used when erecting the conductor; the other based on the stress/strain curve for conductor which has been previously loaded gives the final sags and is used to determine what the ground clearance will be after the conductor has been loaded in service.

It may be several years, if ever, before a conductor is subjected to its maximum design load and settles down to its final sag.

On short spans, the difference between initial and final sags is small and may be disregarded. On long spans such as are common with a.c.s.r. the effect of the permanent set is important and must be allowed for in design.

4·4 *Vibration*

Vibration is a problem which arises with conductors of any material when they are strung at high tensions. Serious vibration can result in fracture of strands at the points of support.

When a conductor is vibrating, it is subjected to additional stresses at the point of support above the static stresses of the direct tension in the span and the bending stress due to the sag.

These additional stresses are—

i bending stress, resulting from the deformation of the loops during vibration
ii increased tension caused by the increase in length of the vibrating cable.

These additional stresses are oscillating and failures which follow them are fatigue failures—breaks are clear and sharp with no adjacent reduction of area.

As with other types of repetition of stress, the number of reversals which results in fatigue failure, or the endurance limit, depends on what relation the alternating stress bears to the ultimate tensile strength of the material. If the stress in the conductor is low, then continued vibration over long periods will not result in fracture.

To ensure that vibration, if it occurs, will not result in stresses which exceed the fatigue limit of the conductor, it is usual with a.c.s.r. to set the following limits on the stringing tensions:—

i Initial unloaded tension shall not exceed one-third of the breaking load *ii* Final unloaded tension shall not exceed one-quarter of the breaking load.

The unloaded conditions (in South Africa the tensions at 22°F without wind) are taken, because this is the condition in which vibration can be most dangerous.

4·4·1 Armour rods

The maximum stress in a conductor, due to both static load and vibration, is at the points of support. To reinforce the conductor at these points, armour rods have been developed. Though primarily used for reinforcement, they also have a definite value for damping out vibration, when it occurs.

4·4·2 Dampers

It has sometimes been the case that Stockbridge dampers have been fitted on a line, without armour rods.

Stockbridge dampers are useful in suppressing vibration when it occurs but do nothing if the conditions do not arise which set up vibration.

It is generally preferable that armour rods should be fitted, as standard, on all lines. They have a positive function; they add strength where required and improve the mechanical construction of the span.

The best practice is perhaps to fit armour rods throughout on a new line and to fit dampers initially only on those spans which are specially important or specially inaccessible and on those sections of line where geographical considerations suggest that vibration may occur. If at a later date vibration, or a tendency towards it, is noted on any spans, it is comparatively easy to fit dampers on these sections.

The present tendency towards light and structurally efficient towers is bringing new attention to the problems of conductor vibration. When conductors are strung to give unloaded tensions well inside the fatigue limit of the material, and when armour rods are fitted, vibration of the conductor is often more dangerous to the tower structure than to the conductor itself.

Failure of tower members, due to conductor vibration, is not uncommon; neither is the breaking-off of arcing horns on insulators. It would often be worthwhile to install vibration dampers to prevent damage of this sort.

4·5 *Regulations*

Although conductors in South Africa are never required to carry very heavy superimposed loads, it does not follow directly that line design is simpler here or that longer spans or higher tensions can be used here than in colder climates. This is because stringing tensions must be kept within limits to avoid vibration trouble; although conductors here under the worst condition must carry less load, they cannot be strung to give lesser sags or higher tensions, under everyday conditions, than lines elsewhere. Also, it is because statutory regulations impose factors of safety which limit maximum design tensions.

The term 'factor of safety' is a misnomer where conductor design is concerned. A slack line has a very high factor of safety but is less safe than a line which is properly tensioned.

The S.A.I.E.E. Code of Practice for overhead lines sets the maximum tension in a conductor, at 22°F with a wind load of 9 lb per sq.ft., at 40 per cent of the breaking load.

Providing that everyday tensions are within safe limits, there is no mechanical reason why maximum tensions should be limited to this extent—it would be permissible, and is being done in overseas countries, to erect conductor so that its tension under the designed worst operating tensions reaches 60 per cent or 70 per cent of the breaking load. Such a design would make it possible to make better use of the available strength of all types of conductor than can be done at present: in particular, better use could be made of a.c.s.r. with its high strength/weight ratio.

It is worth mentioning that though the overhead line regulations at present in force in the United Kingdom set a factor of safety of 2, it seems probable that when new regulations are promulgated these will make no mention of the term 'factor of safety' and will permit higher tensions for maximum design loadings.[1]

5. ALUMINIUM CONDUCTORS FOR RURAL LINES

5·1 *Capital costs*

In designing a rural electrification scheme, the consideration which overrides every other is that capital costs must be kept low so that their ratio to the revenue anticipated is not too outrageous. This is so in any country—in South Africa it is especially true.

It follows that aluminium, under present conditions, is a natural choice for rural lines. It seems certain that many thousands of miles of light lines using a.c.s.r. must be erected in South Africa during the next few years.

5·2 *Choice of aluminium conductor*

All of the following types of aluminium conductor have been used for rural lines under different conditions :—

i Aluminium stranded conductor (not reinforced)

ii Ordinary 6/1 concentric strandings of a.c.s.r. Both the above types have been used in South Africa

iii 'Smooth body' strandings. These are seven-strand conductors, usually with a larger steel core than ordinary seven-strand a.c.s.r., which are drawn through a closing die after stranding to give a smooth outer surface of reduced diameter. They have been developed primarily for light long-span lines erected under North American conditions. The two types in common use are type 150, with 150 per cent of the strength of 6/1 a.c.s.r. of the same conductivity, and type 200 which is twice as strong as the equivalent 6/1 a.c.s.r. To the best of the author's knowledge, no conductors of this type have yet been erected in South Africa

iv Special strandings. To meet special requirements, either for high strength or for particular requirements like river crossings, conductor can be produced with any required degree of reinforcement. A common stranding in small sizes is 3 aluminium/4 steel, which has 4½ times the breaking load of 6/1 a.c.s.r. of equivalent conductivity

v Aluminium-alloy conductors. These have been used on the Continent and in Great Britain to a fair extent but have made no headway at all in North America. The most commonly used alloy conductor in the United Kingdom, known as 'Silmalec,' contains 0·5 per cent silicon and 0·5 per cent magnesium. Similar conductors used on the Continent are 'Aldrey' and 'Almelec.' These alloys must be heat-treated to obtain their full mechanical properties, which makes them expensive—more expensive than a.c.s.r. Their resistance to atmospheric corrosion is good and comparable with that of EC grade metal.

Aluminium-alloy conductors have approximately the same strength as the same size of hard-drawn copper with half the conductivity and only one-third of its weight.

Alloy conductors, as compared with a.c.s.r., have the advantage of being homogeneous so that, in general, the problem of making joints and connections is simplified. On the other hand, they have not the versatility of a.c.s.r. and are not so strong. It is worth noting here that some of the criticism which is directed against composite conductors (criticism on which much of the support for alloy conductors is based), couples a.c.s.r. with steel-cored copper. Steel-cored copper conductors have not proved satisfactory in service ; the reason is that copper is more noble than zinc or steel and its presence therefore encourages corrosion of the galvanized steel core.

An objection sometimes raised to the use of alloy conductors for rural lines in South Africa is that veld fires may cause partial annealing and loss of the properties obtained by heat treatment. This objection applies to unreinforced conductors of any material.

5·3 *Minimum-cost lines*

Rural schemes usually include a big mileage of light lines feeding single consumers or groups of consumers. Such lines carry only light loads—mechanical strength rather than current-carrying capacity determines the size of conductors used—the problem becomes simply one of building a reliable high-voltage line at minimum cost.

For these lines, the minimum strength requirement of the Code of Practice

TABLE III
CONDUCTOR FOR RURAL LINES OF MINIMUM COST
(For minimum breaking load 1 518 lb)

Conductor	Stranding	Copper equivalent cross-section—sq. in.	Breaking load	Weight/mile	Comparative cost based on copper at £230 per ton	Remarks
Copper ...	3/·104	0·025	1 518	530	100	—
a.c.s.r. ...	6/1/·083	0·02	1 720	300	50	Nearest British standard size above 1 518 lb breaking load
a.c.s.r. ...	6/1/·075	0·016	1 518	246	41	Non-standard 6/1 stranding giving strength required
Smooth-body a.c.s.r. ...	Type 150	0·013	1 725	252	37	Nearest standard size of smooth-body conductor above 1 518 lb breaking load
a.c.s.r. ...	3/4/·0661 special	0·006	2 620	311	33	Smallest standard size of 3/4 stranded conductor
a.c.s.r. ...	3/4/·051	0·003 5	1 518	240	20	Non-standard 3/4 stranding giving strength required

(1 518 lb for 3/·104-inch copper) is usually the basis for the selection of a conductor.

In Table III particulars are given of conductors of various types which could be considered in comparison with 3/·104-inch copper. The table suggests that if farm electrification is ever to be started in South Africa on a really big scale and thousands of miles of ultra-light lines are required, a special stranding with a high ratio of steel may give the best overall results. Such a stranding could not be used in coastal areas where exposed galvanized steel could not be expected to have a long life but it could be considered for most farming areas in South Africa.

5·4 *Rural feeder lines*

For the main network of a rural system, heavier lines are required, to carry the full load of the district served without too great a voltage drop. These lines must commonly act as distributors as well as main feeders in that supplies are tapped from them to consumers along their route and this makes it necessary to design them as distribution lines rather than as cross-country transmission lines.

For these lines, standard 6/1 strandings are usually used and are quite satisfactory, though it is possible that the use of aluminium stranded conductor would sometimes be more economical.

5·5 *Wood poles*

Some discussion about poles is relevant in considering conductors for rural lines, essentially because high-strength conductors like a.c.s.r. cannot be used to full advantage if poles are not available which are strong enough to carry long spans.

The use of creosoted wood poles for overhead lines has become generally accepted in South Africa—for rural lines any other type of pole could hardly be considered. It is only in comparatively recent years that this industry has become established and it is not yet easy to say how supplies of poles compare with demand. Particularly, it is only during the past two years—since the publication in November 1951 of S.A.B.S. 339/1951—Standard Specification for creosoted wooden telephone, telegraph, electric light and power transmission poles—that most engineers in this country have been able to select and specify poles on any scientific basis.

As regards species, it seems already clear that, if all users required poles of Strength Groups AA or A, there would not be enough poles to go round. If any extensive schemes were started for rural electrification in the fairly near future, it is probable that Saligna gum poles of Strength Group B would be used. This is at present the most common timber, and perhaps because the tree grows comparatively easily and quickly, it is being planted more and more, sometimes in place of stronger trees. Saligna is of approximately the same strength as Southern pine and Scots pine, which are extensively used in the United Kingdom and in Scotland, and is certainly strong enough to be very useful for electrical requirements.

As regards diameters, most undertakings in this country have been in the habit of using very slender poles in comparison to sizes used overseas. The result is, of course, that large diameter poles (of, say, 10 inch or more at the ground line) are not easily obtainable.

In effect, at the present time, the design of rural lines in this country is restricted by the strength of the available wood poles.

For minimum-cost spur lines, Saligna poles of small diameter are strong enough to carry spans as long as are practicable. For heavier feeder lines, the sizes of pole commonly available are not strong enough for long-span lines.

In practice, until poles of larger diameter are easily obtainable, which would enable lines to be built to make use of the full strength of a.c.s.r., it will often be found that the cheapest construction for feeder lines is to use aluminium stranded conductor, unreinforced. With this conductor, sags at high temperatures are large and tensions low so that, to avoid the danger of lines clashing together during winds, spans must be limited or clearances increased. Generally speaking, spans should be limited to about 250 ft or 300 ft and at such spans line design is very little different from usual practice with copper conductor.

This suggestion—that for feeder lines, unreinforced conductor on moderate spans may best meet local conditions—applies only to lines at voltages up to 11 kV. At higher voltages, the more important cost insulators usually swings the balance in favour of long-span construction even if this precludes the use of single-pole supports.

It is not desired to imply that our dependence on comparatively weak and slender poles limits the erection of rural lines in this country. It is desired rather to point out that line constructions which have proved most economical overseas are not necessarily to be aimed at here. In particular, the development of specially strong strandings for rural lines, which has brought much benefit in America, seems unlikely to be of advantage here.

Before leaving this subject, it is relevant to mention the contention sometimes raised that, because an aluminium conductor is larger in diameter than its copper equivalent, therefore wind loads are higher. This contention is true but its importance, as it affects the mechanical design of a line, should not be over-emphasized. The load on a support is the resultant of the wind load and the dead weight of the conductor and, except for the smallest sizes, the lighter weight of aluminium more than offsets the higher wind load and results in a smaller resultant load. Also, because of the lesser sag of a.c.s.r., poles are shorter, the overturning moments set up do not increase in the same proportion as the wind loads.

5·6 *Erection*

Few special remarks need be made about the erection of rural lines using aluminium conductor.

5·6·1 Armour rods

As for transmission lines, the use of armour rods will ensure long life from conductors and is to be recommended for all except minimum-cost lines. For small sizes of conductor, armour rods are of straight wire, not tapered as for transmission line sizes and, of course, are cheaper.

For lines run at low tensions where vibration is not likely, armour rods may very safely be omitted. It is usual then to wrap the conductor with soft aluminium tape at points of support to prevent abrasion. Two layers of this soft tape, wrapped round the conductor in opposite directions, give it considerable extra stiffness and afford a large measure of protection against vibration damage.

5·6·2 Midspan joints

For the small sizes of conductor used in rural work, twisting or 'Macintyre' joints are simple and effective. Their use is well-known with all types of conductor.

5·6·3 Tubular compression fittings

Compression accessories are in general use for transmission lines and accessories of this type manufactured from tube are available for small conductors for dead ends or mid-span joints. They are unlikely to be much used in this country to replace snubbing-type dead-end clamps and twisting joints. They have been developed mainly for use with smooth body or other forms of high-strength a.c.s.r. which, for reasons already given, seem likely to find only limited application in South Africa.

6. ALUMINIUM CONDUCTORS FOR OVERHEAD URBAN DISTRIBUTION LINES

6·1 *Economy*

It is only since the war that aluminium conductor has been much used for urban distribution ; for short-span lines its lightness gives it no important technical advantage and it is coming into use only because it is cheaper than copper. With copper conductor, the numerous connections required for distribution lines can be made very simply and this would ensure its continued use even if it were slightly dearer than aluminium.

However, the savings to be made by using aluminium, even after taking into account the greater cost of making connections, are now too great to be overlooked; since 1950 over thirty undertakings in South Africa have erected aluminium distribution lines.

It is usually found that when an undertaking has been using it for long enough to get accustomed to the changes in technique that are necessary, it becomes liked by the men who handle it ; its light weight makes erection easy, an advantage which once appreciated is not readily given up.

6·2 *Aluminium stranded conductor*

Line spans in low-voltage distribution are not fixed by considering strengths of conductors or of poles but by practical points, such as distances between streets, lengths of lot frontages or spacing of trees. In most towns, ordinary spans are between 120 and 130 feet, rarely outside the range 100–180 feet.

Neither are sags and tensions fixed by considering strengths of conductors or safety factors, though these are the statutory basis for line design ; in practice lines are sagged to empirical rules. Except in the very smallest sizes, conductors are rarely tensioned to reach the permissible 40 per cent of breaking load under the worst loading conditions. To work to design limits of tension would simply mean unnecessary expenditure on heavy poles and stays at terminal poles and angles. That is to say, in ordinary practice full use is not made of the strength of copper. Even more, the higher strength of a.c.s.r. is of no advantage. For short-span lines, aluminium stranded

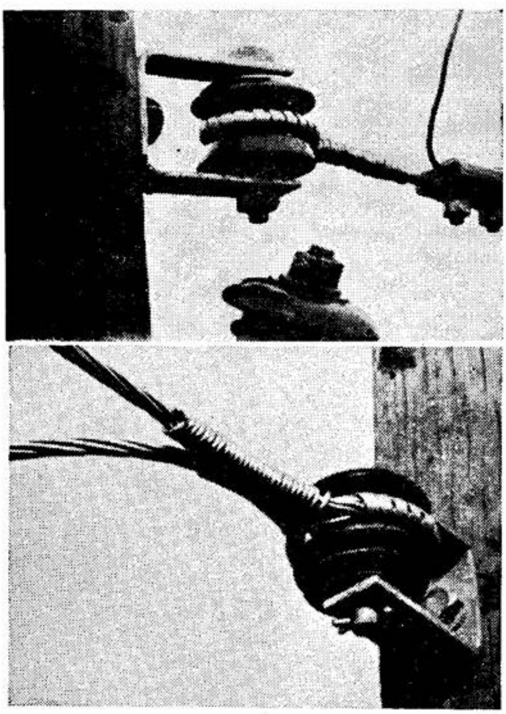

Fig. 5—Erection of aluminium stranded conductor. Making-off

conductor is used. It is amply strong for the duty (its strength/weight ratio is above that for copper). Aluminium can be pulled up in still air, at midday temperatures, to the same sags as are normal for copper; it will then have a few inches more sag at 122°F and a few inches less at 22°F. Poles, insulators, crossarms, stays and spacings can be used without change and few changes are necessary in methods of erection.

6·3 *Erection methods*

6·3·1 Strain poles

Typical make-offs are shown in Fig. 5.

The use of flat armour wire is always advisable to prevent abrasion of the conductor strands at the point of support. One size of flat armour wire (0·05-inch thick by 0·3-inch wide, approximately 60 ft per lb) has been found satisfactory for all sizes of conductor. The wire is annealed dead soft and is easily and quickly applied.

Binding wires used for aluminium should be much stouter than are commonly used for copper. For conductor above 0·06 sq.in. it is reasonable to use for binders loose strands of the conductor itself; for smaller conductors, it is advisable to use larger strands. The neatest, tightest and most effective binds are made with annealed binding wire.

6·3·2 Intermediate poles

Binding to pin or spool insulators can be done as described for rural lines using a

TABLE IV

MAKING OUTDOOR CONNECTIONS TO ALUMINIUM CONDUCTOR

What to know	What to do
Aluminium oxidizes rapidly and covers itself with a film of grey oxide which is insulating and which gives aluminium its property of corrosion resistance	Before assembling connectors, the contact surfaces of both clamps and conductor should be liberally coated with a corrosion inhibiting compound, and brushed through the coating with a wire scratch brush. The compound prevents the formation of a new oxide film. Old and dirty wire should first be cleaned of loose deposit
Aluminium has a coefficient of expansion 36 per cent greater than that of copper	For permanently tight connections, use aluminium fittings on aluminium conductor
Aluminium is not as tough as copper, and creeps more easily under load	Connectors should be used which have a large area of contact
In the presence of moisture, electrolytic corrosion is set up when aluminium is in contact with other metals, particularly copper	Avoid aluminium/copper connections wherever possible, or arrange for them to be made indoors, in a dry situation, instead of at the pole top. Seal connectors against the ingress of moisture. Brush corrosion-inhibiting compound well into the strands of the conductors, and into the grooves and edges of the connectors. The inside surfaces of the connectors which must come into contact with the copper conductor should be protected by a thick plating of a buffer metal; tin is preferred but cadmium is sometimes used. Sometimes the connector is protected by a cast-in copper lining
The salts of copper corrode aluminium	Erect copper/aluminium connectors with the copper side underneath, so that copper salts are not washed by rain on to the alumnium conductor beneath
Light alloys that look like aluminium are not always aluminium, and often have very different properties	Connectors must be made of pure aluminium or of alloys with good corrosion resistance
Not all who use connectors read instructions	It should be difficult to use connectors the wrong way round, or upside down.

layer of soft armour wire or of the binding wire itself to give protection to the conductor against abrasion. It would be very unusual to use armour rods on short-span lines.

6·3·3 Midspan joints

Midspan joints are infrequent in short-span lines, because conductor lengths are very long in comparison to span lengths. When they are required, they are best made using twisting joints. For aluminium stranded conductor, only short joints allowing four complete twists are required to develop the full strength of the conductor.

Tension joints in aluminium stranded conductor can be made by 'marrying' strands or splicing; such joints are not reliable, they will nearly always stretch under load.

6·4 *Connections*

As a general rule, in its expansion into new fields, the progress of aluminium has been not slow, but at least deliberate. New developments have been carefully studied and step-by-step progress has been planned before expansion on a large scale has taken place.

As regards the invasion of aluminium into the field of low-voltage overhead distribution, however, the industry appears to have been caught napping to some extent.

The few instances before the war when aluminium had been used for low-voltage lines were most of them examples of single lines erected to supply a particular load. These jobs had been engineered more or less as a transmission line is engineered, in that any connections and tappings to be made were known in advance and suitable accessories for making these connections were ordered together with the conductor. There were no instances before the war of aluminium being used on any scale for supply lines in a developing area, where the reinforcement, modification and extension of mains is a continuous process.

When, suddenly, undertakings in America were faced with the necessity of using aluminium for day-to-day extensions, there was no recognized technique already developed. In an effort to fill the gap, American manufacturers brought out a large selection of accessories and connectors based on a variety of ideas.

Some manufacturers of copper-alloy accessories for copper conductors made the same items of aluminium alloy and put them forward for use with aluminium; others put forward the same bronze accessory but plated it with tin, zinc or cadmium. Some developed new designs, all combined to give the American distribution engineer a wide range to pick from and ample opportunity for test and experiment.

It is fairly clear now what factors decide whether a connection on an aluminium

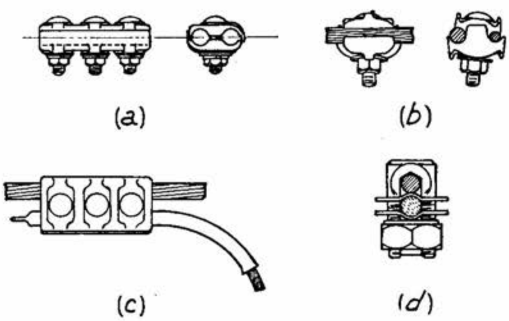

Fig. 6—Connectors for distribution lines. Figs. (a) (b) (c) Parallel-groove clamps satisfactory for aluminium conductor. Fig. (d) Split-bolt connector unsuitable for aluminium

conductor is likely to give reliable and trouble-free life. The most important are set out in Table IV.

Some remarks are given on some of the more important types of connector in the light of this table. (See Fig. 6.)

6·4·1 Parallel-groove clamps (Fig. 6 (a))

These are the oldest and still the most commonly used type of connector. When used for aluminium/copper connections, the copper side is coated with tin or lined with a cast-in copper lining. Their advantage is simplicity; disadvantages—that the better designs are necessarily comparatively bulky and expensive and that a wide range of clamps must be carried to suit all possible sizes of connections.

Clamps of this type are being widely used in South Africa. In coastal areas, for copper/aluminium connections proper sealing with anti-corrosive compound is essential. Instances have occurred on the Natal coast where connectors of this type, not sealed with compound, have failed completely after only nine months' service. In inland areas, no troubles have ever been reported.

6·4·2 Universal parallel-groove clamps (Fig. 6 (b))

These are made exactly as p.g. clamps but have only one bolt on a spherical seating so that they can clamp on a range of sizes of conductor. Their advantages are simplicity and, further, few sizes cover all requirements. Their disadvantage is that their small area of contact makes them unsuitable for carrying heavy currents.

These clamps are being widely used in this country, usually for service tappings.

6·4·3 Aluminium sheath for copper conductor (Fig. 6 (c))

This idea is much used on the Continent and excellent reports are given of its efficiency. Some clamps of this sort are in use in this country. A thin-walled aluminium tube supplied loose (closed at one end and full of anti-corrosive compound) is used in an ordinary p.g. clamp. Except for the small area at the tip of the tube (where slight corrosion of the aluminium would be of no importance), there is no possible path for electrolytic action to start.

6·4·4 'Split-bolt' connectors or line taps (Fig. 6 (d))

These are made variously of aluminium alloy or of tin or cadmium-plated copper alloy. Where conductors of different metals are used, bi-metal washers or spacers are placed between the two conductors.

These fittings are of course very commonly used with copper conductor. For aluminium they are undesirable because of their small contact area; they should not be considered except for very light currents.

'4-bolt' connectors and hinged connectors would usually be excellent for overhead-line work, except that they are too expensive for use in quantity.

6·4·5 Compression fittings (Fig. 7)

Compression fittings are standard for transmission lines and have been commonly used in North America for many years for small conductors. It is only recently, however, that compression taps for low-voltage distribution have become available. They can be expected to be superior to other forms of connector from nearly all points of view. Small sizes up to about 0·05-sq.in. equivalent can be used with a 'bolt-cropper' type of compressor; for larger conductors a light hydraulic compressor is required. At the time of writing, connectors of this type have not yet been used in South Africa.

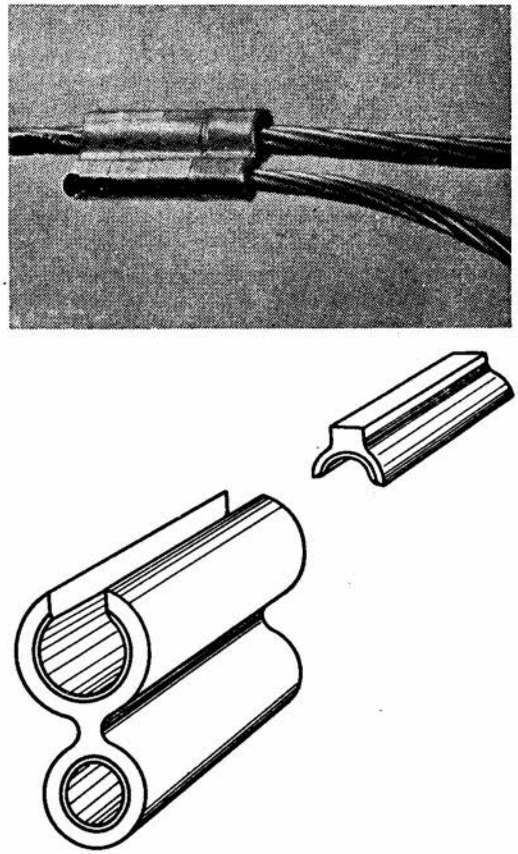

Fig. 7—Compression line taps for aluminium lines

7. ALUMINIUM CONDUCTORS FOR OVERHEAD TELEPHONE LINES

Communication lines built of a.c.s.r. have been in use since 1926 in many countries.

To assess the suitability of a conductor for telephone service, the inductance, capacity and leakance per mile are required to determine the loss per mile in decibels. Some comparative figures between a.c.s.r. and copper for telephone use are given in Fig. 8.

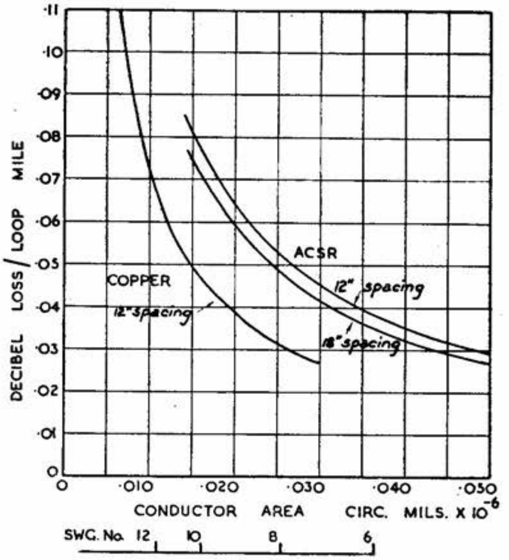

Fig. 8—Telephone line loss for copper and a.c.s.r. conductors. Based on 1 000 cycles/sec, dry leakage, at 25°C

From this chart it can be seen that the losses for a.c.s.r. are higher than those for equivalent sizes of copper at the same spacing. The difference is due to the increased diameter and to the internal inductance caused by the spiralling of the strands round the steel core. It can also be seen that, if the a.c.s.r. lines are spaced 18 inches apart, the loss is approximately the same as for the equivalent size of copper at 12-inch spacing. This is the usual practice when a.c.s.r. lines are erected and this is the main objection to the use of a.c.s.r.

For telephone lines, the use of compression fittings for joints and terminations is very clearly justified as these can be relied on to give long and trouble-free life without any increase in resistance.

In effect, to consider the use of a.c.s.r. would involve the re-design of some items of pole-line hardware and the re-training of a portion of the artisan staff.

Nevertheless, very substantial savings could be made in the price paid for conductor which would certainly justify a.c.s.r. being considered—perhaps first for two-wire lines in country areas.

8. ALUMINIUM IN INSULATED CABLES

8·1 *Underground cables*

Because by far the largest proportion of insulated cables are made for burying in the ground, the weight of cable has never been considered important and aluminium did not suggest itself for this use while copper and lead were easily available.

In recent years, however, economics have forced a re-examination of the traditional methods of making cables.

At this date, aluminium is being used in insulated cables in England, Germany and in North America. It is being used both for sheathing and for conductor and occasionally for armouring. In each application, present signs point to an expanding use.

8·2 *Cable sheaths*

Very rapid progress is being made in the production of aluminium-sheathed cables.

The methods of production that have been used to date have been given publicity and need not be described here.

Intensive research is being given to the problem of designing a press for the direct extrusion of an aluminium sheath on to a cable core; the temperature required for extrusion is high and the plastic range is short, so the problem is a difficult one. Research into this problem started in Germany before the war; it is now going on in Germany, Great Britain and the U.S.A. At this date the difficulties do not appear insurmountable and it is likely that cables with extruded sheaths will soon be available—perhaps within the next twelve months.

At the same time, developments during the last few months in the manufacture of aluminium irrigation tubes, in both Britain and N. America, has brought a realization that extrusion may not be after all the best method of making thin-walled tubes; both argon-arc welding, as in the Pirelli process, and high-frequency induction welding, are being used to produce tubes, with results that are very promising indeed. A plant for producing welded-seam sheathes would be much less expensive than a direct-extrusion press.

8·2·1 The properties of aluminium sheathing

A comparison of the properties of aluminium and lead (Table V) makes it obvious that aluminium is not being used in this application as a substitute.

In brief, aluminium is one-quarter as heavy as lead, six times as strong, seven times as hard, has 25 times the resistance to vibration fatigue and seven times the electrical conductivity. On the debit side, it requires a protective covering to give the same reliability from the point of view of resistance to corrosion.

The high strength and creep resistance of aluminium as compared with lead make aluminium sheathings incomparably the better from the point of view of resistance to internal pressure. Lead tube distends under pressures very much lower than are required to burst it, probably the primary cause of troublesome compound migration. Aluminium tube starts to distend only after a comparatively high yield stress has been reached.

8·2·2 Price

A clear comparison of price is not possible, because the cost of application of the two metals must be very different.

An over-simplified picture, on the basis of metal cost only, shows very markedly in favour of aluminium. On a cable 12 inches long and 2-inch diameter, and allowing for an aluminium sheath 90 per cent as thick as a standard lead sheath, lead at 9d per lb (£84 per long ton) would cost 35d per foot, aluminium at 17d per lb (£160 per ton) would cost 14d per foot.

8·2·3 Applications of aluminium-sheathed cable

Obviously the use of aluminium in place of lead will allow important changes in some aspects of practical electrical engineering :—

i the armouring of underground cables will probably cease to be general practice

ii systems can be developed to make use of the high-conductivity sheath for carrying load currents

iii as experience is gained of aluminium-sheathed cables in service, it seems probable that limiting conductor temperatures may be increased and higher current ratings approved for existing standard sizes of conductor.

Aluminium-sheathed cables seem certain to take over completely from lead during the next few years in fields where light weight is of importance, e.g. aerial cables or cables on board ship, and in fields where

TABLE V

PROPERTIES OF LEAD AND ALUMINIUM FOR CABLE SHEATHING

	Lead	Aluminium
Tensile strength, lb/sq. in.	2 000	13—16 000
0·1 per cent proof stress, lb/sq. in.	700	7—10 000
Stress to give creep rate of approx. 0·1 per cent per year, lb/sq. in.	100	4 000
Elongation per cent	25—35	7—10
Hardness	4·5	28—35
Endurance limit, lb/sq. in. (stress to fracture at 10 cycles)	± 400	± 7 000
Specific gravity	11·4	2·7
Electrical conductivity (per cent of copper) ...	8·68 per cent	61 per cent
Thermal conductivity (cgs)	0·082	0·53
Melting point	327°C	659°C
Specific heat, cals/gm	0·032 5	0·24
Coefficient of linear expansion per °C	29×10^{-6}	23×10^{-6}

Note: Most of these properties have considerable variation; the figures given are general approximations.

its economic advantage are most outstanding, e.g. telephone cables, co-axial cables, industrial cables for surface wiring and high-voltage oil-filled and gas-pressure cables. The general progress made in this country for power cables will depend to a large extent on how soon local manufacture is started.

8·3 *Aluminium conductors in insulated cables*

The use of aluminium conductors to replace copper in underground cables is not so obvious a development as the use of aluminium for sheathing. Nevertheless, aluminium is being increasingly used for cable cores, and its use results in savings; closer study indicates that its wide use eventually is economically inevitable.

For the same resistance, a circular aluminium conductor must be 1·27 times the diameter of a copper conductor. This means more insulating material and a larger overall diameter. At first sight, this increase is considerable; in practice it is not so big or so important.

8·3·1 Current ratings

The current rating of a cable depends on its temperature rise under load—that is to say, on the physical size of the cable and its ability to dissipate heat. For the same temperature rise, an aluminium cable can have the same I^2R loss as a copper cable. The ratio of current-carrying capacities for cables of equal size is therefore equal to the square root of the ratio of conductivities, or 78 per cent.

In practice, this is an oversimplification. Because the larger size of aluminium cables means greater heat-dissipating area and lower reactance, the effective current-carrying capacities for three-core aluminium cables can be up to 86 per cent of those of copper cables of the same size. The standard factor used in America is 84 per cent—this is optimistic for small sizes. A good average round figure for ordinary work is 80 per cent. On this basis, the weight of an aluminium conductor is only 38 per cent of the weight of its copper equivalent.

Tables of rating factors have been prepared for all classes of cable and in all types of installation, so that it is an easy matter to select an aluminium cable for any load using existing known ratings for standard sizes of copper cables. Both in Britain and in America aluminium-cored cables are being manufactured, not to a new range of sizes, but to the same dimensions and specifications as standard copper cables. So far, this practice, which has much to recommend it, but it seems likely that in the future better use of aluminium will be obtained by using fewer strands of larger diameter than present standards for copper. This follows on the better compaction that can be given to aluminium cores.

It is therefore desirable that current rating tables should be set up for aluminium. Aluminium cables differ from copper in inductive effect, including skin effect, proximity effect, sheath, armour and conduit losses; also, when sheaths are aluminium, it is unnecessary to determine current loadings by temperature-rise figures fixed for lead.

8·3·2 Mechanical and physical properties

For insulated cables, aluminium is used in the half- or three-quarter-hard condition, and copper fully annealed. Comparative stress/strain curves for both metals are shown in Fig. 9.

In ability to absorb energy loads without permanent distortion (which is represented

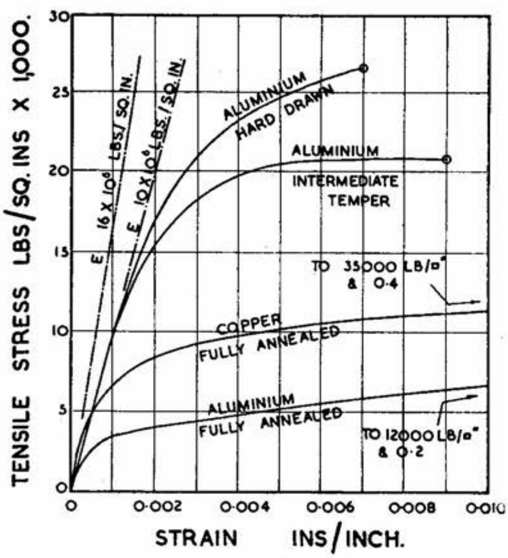

Fig. 9—Comparative stress/strain curves for aluminium and copper wires

graphically by the area below the curve up to the elastic limit), aluminium is superior; the ratios for half-hard aluminium, copper, and soft aluminium are in the approximate ratios 30 : 5 : 1. In ultimate ability to absorb energy without fracture, which is a measure of toughness (represented by the total area under the stress/strain curve) copper is very much the better. In fatigue resistance—ability to withstand cyclic variations of a given stress—aluminium and copper are roughly the same, except that aluminium has the lower elongation and is therefore more sensitive to local surface irregularities which set up concentrations of stress.

The higher co-efficient of thermal expansion of aluminium must give rise to more movement than in a copper cable; the effect of this in service can be found only by experience—so far records do not indicate that it will be a source of trouble.[2]

The total heat-storage capacity of an aluminium conductor compares with that of an equivalent copper conductor, because of the high specific heat of the lighter metal. Under short-circuit conditions, therefore, both types of cable will show about the same rate of rise in temperature. With the same current, though, aluminium will fuse more quickly than copper, because of its lower melting point. Again, only experience will show whether this is important. So far results show no apparent difference.

In general, there seems to be no reason why aluminium conductor should not give completely satisfactory service in insulated cables. Its strength, except in the fully-annealed condition, is more than adequate to accept all treatment to which copper cables are normally subjected and it should be remembered that, because of their lightness, aluminium cables will not be subjected to the same heavy treatment. Aluminium will begin to anneal at about 150°C, so that when there is any chance of heavily-loaded cables reaching such a temperature, they must be installed in such a way that mechanical stresses on the conductors do not exceed the strength of soft aluminium.

For rubber cables, aluminium has the advantage that it is not attacked by sulphur. Neither does it form in paper-insulated cables the soap compounds that are produced by oil heated in the presence of copper.

8·3·3 Jointing

Methods for making 'wipes' on aluminium sheaths are well known and need not be described in this paper. Generally, lead jointing sleeves are used and the same practice is followed as with lead sheaths, except that the aluminium sheath must be first tinned before it can be soldered; this requires special flux and solder but a relatively easily acquired technique. Moisture should be excluded from finished plumbs.

For jointing conductor cores, no practice has yet been evolved which can be described as standard. The multiplicity of methods which are in use suggest that no present method is the completely correct and obvious one. In Britain, the preference seems to be for soldered connections. The best-known methods require techniques very similar to the ordinary practice for joining copper conductors; special non-corrosive fluxes are used to remove the oxide film and prevent its reforming and ordinary tinned copper ferrules are used. Aluminium cores can be safely soldered to copper because such joints will invariably be kept dry.

8·3·4 Applications

On the Continent, aluminium conductor almost completely displaced copper for underground cables during the war; in America and in Britain there was no incentive to its use on any important scale until 1947 when the price of copper first leapt beyond the price of aluminium; its use is now well established in both countries.

Where lightness is of direct value—in ship building, in mines or for rising mains—all aluminium cables will no doubt soon become standard. For aerial cables or catenary cables they are the obvious choice. For underground distribution cables, economics will ensure increasing use for aluminium.

At high voltages, for equal current ratings, the larger size of an aluminium core results in a lower dielectric stress in the insulation and it is by no means necessary that the quantity of insulation required at any voltage must vary in direct ratio with the diameter of the conductor.

8·4 *Light metal armouring*

Aluminium is not widely used as an armouring for underground cables; nevertheless, its use for this purpose in the future is by no means improbable. The price of galvanized steel wire has already reached a level which has resulted in its replacement by aluminium in a large number of applications. Aluminium-alloy armouring has sometimes been specified for power cables where these are required for installation in conditions known to be aggressive to steel or where non-magnetic armouring is required. It has given very good results when used for undersea cables.

8·5 *Overhead service cables*

Insulated aluminium cables for overhead services are already being manufactured in South Africa. Their advantages over copper cables are—

i their lightness, which means reduced pulls both on house roofs and on poles carrying overhead lines

ii when aluminium service mains are in use, the use of aluminium service cables transfers the aluminium/copper connection from the pole-top to a dry location in the service box or inside the house.

As is being done with underground cables, no new range of sizes is being developed for aluminium cables but aluminium cables are being produced in the same sizes as have already been standardized for copper. Table VI gives the sizes and equivalents for the aluminium cables most usually used.

TABLE VI

ALUMINIUM EQUIVALENTS OF COPPER STRANDINGS FOR SERVICES

Copper area sq. in.	Copper stranding	Aluminium stranding
0·014 5	7/·052	7/·064
0·022 5	7/·064	7/·083
0·03	19/·044	19/·056
0·04	19/·052	19/·064
0·06	19/·064	19/·083

Solid-drawn copper conductors have been used in South Africa for services and solid-drawn aluminium conductors could also be used. Stranded conductors are to be preferred; apart from the fact that they can be pulled up more easily and evenly, the low elongation and the sensitivity of aluminium to 'notch effect' would seem to indicate that solid conductors, under tension and subject to vibration, are not desirable.

The Standard Regulations for the Wiring of Premises sets the size of 0·012 8 sq.in. copper (No. 10 s.w.g.) as the minimum size of an aerial conductor. An aluminium conductor of the same strength (approx. 750 lb) would have a cross-sectional area of about 0·027 sq.in., stranding say 7/·066-inch. Presumably this would be the smallest size that should be used.

8·6 *Aerial cables*

Aerial power cables are not much used in this country. In America, high-voltage feeders in city areas are sometimes run on poles instead of underground and aluminium-cored and -sheathed cables are already being used for such purposes. It is unlikely that this idea of overhead power cables will ever be popular in South African cities; nevertheless, the advent of aluminium cables opens up possibilities for aerial cables which have not so far been considered.

Possibilities that come to mind are—

i pilot protection cables for underground feeders or overhead lines

ii feeder cables for electric railways, haulages or tramways

iii cables for farm electrification.

8·7 *Aluminium cables for internal wiring*

The use of insulated aluminium conductors for indoor wiring started in Europe about 1934 and became standard there during the war. Its use in America started only in 1947 when aluminium wires were approved both by the Underwriters' Association in the U.S.A. and by the Standards Association in Canada. Since then a large amount of experience has been accumulated.

There were at first some unfortunate experiences and had it not been for the conservatism of users, which prevented a sudden large-scale swingover to aluminium, the consequences may have been serious. Initial troubles were due to the fact that hard-drawn aluminium as used for overhead conductors was, perhaps quite reasonably, used for insulated cables and also to the fact that tinned copper connectors of the same design as normally used for copper were widely advertised as being suitable for aluminium in indoor applications. Hard-drawn aluminium proved to be too low in ductility for bending into joint boxes and fractures of wires followed kinking at bends or nicking at make-offs. Tinned copper connections tended to loosen in service.

With the substitution of intermediate-temper aluminium with its increased ductility and flexibility and with the use of suitable connectors, plus the training of engineers and electricians in the correct use of the new materials, the serviceability of aluminium installations has been raised to the standard experienced with other conductor materials.

Nevertheless, a change-over on a big scale from copper to aluminium in this field is not anticipated in America in the foreseeable future and certainly seems most improbable in South Africa.

The following factors lead to this opinion :

i a very large number of workmen are concerned who will all need re-training
ii millions of units of wiring equipment are concerned most of which will require modification to terminals and wiring entries
iii important changes will be required to the standard regulations for the wiring of buildings ; besides new current-rating tables, all tables concerning conduit capacities will be affected.

Perhaps the most probable first application of aluminium on any scale will be for low-cost housing ; prefabricated wiring could certainly be cheapened by using aluminium. Aluminium can also be expected to come into use for telephone wiring and similar light-current purposes.

8·7·1 Earthing conductors

The use of aluminium for earthing is at present not possible in South Africa because the Standard Wiring Regulations lay down that earthing leads must be of copper or bronze. S.A.B.S. 03–1952 Code of Practice for the Protection of Buildings against Lightning also recommends the use of copper or copper and brass alloys for lightning conductor.

The increasing use of aluminium in building work—for roofs, flashings, gutters and downpipes, spandrels and facings, window and door-frames — often makes copper undesirable for earthing leads. Copper is also unsuitable when aluminium conduit is used or when aluminium is used for metalclad switchgear or equipment. It would therefore seem that some amendment to the present regulations must soon be made. There can be no valid reason why, if aluminium is accepted for carrying power currents, it should not also be used for earthing conductor.

Aluminium is approved as an earthing conductor in the U.S. Code for Lightning Protection ; copper or copper-clad steel is still used for the earth rod. The junction between the aluminium earthing leads and the buried copper is made above ground.[3]

9. ALUMINIUM BUSBAR CONDUCTORS

9·1 *Economy*

The use of aluminium conductors for heavy-current busbars was well-established before the war. The greater bulk of aluminium as compared with copper is usually not a disadvantage in this application; the ratio of the weight of an aluminium conductor to an equivalent copper conductor is therefore particularly favourable in this use and aluminium was often found to be the more economical material even when the metal per ton was more expensive than copper. At post-war prices, aluminium installations are commonly less than one-third the cost of equivalent copper.

9·2 *Size and weight ratios*

We have already noted that for equal temperature rise an aluminium conductor will carry 78 per cent of the full-load current of a copper conductor of the same dimensions ; for busbar conductors of the two metals of equal current rating the size and weight ratios depend on the shape of the conductors.

In practice, for flat bars equal temperature rise is obtained in either of two ways :—

i an aluminium bar must be 50 per cent thicker than the copper. The ratio of weights in this case is 1 : 2·2
ii an aluminium bar must be 25 per cent wider than the copper. The ratio of weights in this case is 1 : 2·6.

The second alternative offers the more economical use of material. For tubular and channel sections, simple rules cannot be stated; for estimating figures it is usually safe to assume that an aluminium installation will weigh 40 per cent as much as its copper equivalent.

9·3 *Strength and deflection*

It is quite wrong to assume, as is sometimes done, that because aluminium is not as strong as copper an aluminium busbar will be less rigid than a copper one.

All busbar conductors are essentially beams and the deflections of beams, under all conditions of loading, are expressed by formulae of the type

$$\text{Deflection} = \frac{K \times Wl^3}{EI}$$

In these formulae
W is proportional to 2·7 for aluminium and to 8·9 for copper;
E is 10 000 000 lb per sq.in. for aluminium and 16 000 000 for copper.

The ratio $\frac{W}{E}$ for aluminium is thus twice as great as for copper so that the static deflection of an aluminium conductor is only half that of a copper conductor of the same section and on the same span. When bars of equal rating are considered the aluminium bar is always much the stiffer.

9·4 *Jointing and erection*

9·4·1 Bolted joints

Bolted joints in aluminium busbar are made in the same way as for copper. Laps equal to the width of the bar are usually sufficient.

Galvanized or cadmium-plated bolts are suitable. Washers and spring washers should be used both under the bolt head and under the nut.

In preparing contact surfaces, the exclusion of air should be aimed at, as with copper. Aluminium surfaces should be treated as follows:—

i thoroughly clean the surfaces with emery cloth
ii coat the surfaces liberally with a grease or oxide-inhibitor
iii abrade this coating with a wire brush or steel wool, to remove the oxide film from the aluminium
iv assemble the joint without removing the coating and tighten up.

For aluminium to copper connections the same procedure should be followed.

9·4·2 Welded joints

Aluminium busbar installations can be made very economically by brazing or welding; the results are neat and efficient. Welding shows to greatest advantage for heavy-current installations; splice plates, drilled holes, and bolts are eliminated, and weight is saved.

9·5 *Applications*

Aluminium is being used for busbar conductors in nearly every sort of application. It is very commonly used for heavy-current installations in power stations and industrial plants and is being used in factory-made switchgear.

For overhead busbar systems, where its lightness is of particular value, aluminium has the disadvantage that it is not suitable for 'plug-in' connections—the oxide film must be removed before a good heavy-current connection can be made. Nevertheless aluminium busbars, silver-plated, are being used in this application with complete success. Silver plating on aluminium involves first plating with zinc, then with copper, and finally with silver, so that much of the initial price advantage disappears. Nevertheless installations of this sort are economic, particularly for the heavier currents, and the advantage of light weight ensures that they will become increasingly common.

10. ALUMINIUM IN ELECTRICAL PLANT

10·1 *Cost incentive*

Aluminium is used in electrical plant for a variety of purposes, more often because of its light weight, resistance to corrosion and non-magnetic properties than because of its conductivity. For carrying current, its use has usually presented technical difficulties which there has been little incentive to solve. In the last few years, the incentive has been provided in its lower cost and much study has therefore been given to the problems involved.

In many cases the problems have been solved for particular items of equipment and, as the methods used become known, aluminium can be expected to become more and more identified with the electrical industry.

In this section some of the more important and interesting applications of aluminium are outlined.

10·2 *Aluminium conductors in rotating machinery*

The light weight of aluminium makes it desirable for rotor windings where centrifugal forces are of importance.

For squirrel-cage rotors of small induction motors, aluminium is well known to be effective. The cages are usually die-cast. Alloys containing two to five per cent silicon were formerly used for this purpose to obtain easier casting properties but the tendency to-day is towards the use of pure aluminium. At the present time such rotors are not regularly made in diameters above about 15 inches, though in the United States rotors up to 30-inch diameter have been die-cast.

With wound rotors the use of aluminium may sometimes mean that the size of motor must be increased. With small fractional-horsepower motors, this has not proved to be always the case and aluminium-wound motors are standard in some American-built domestic appliances.

Motors have been wound using anodized aluminium wires. (Anodizing increases by artificial means the natural coating of non-conducting oxide on an aluminium wire.) Tests indicate that better cooling properties are afforded than with ordinary insulation, and that very heavy overloads can be carried since the insulation is not affected by temperature.

Aluminium die-castings are frequently used in small motors for casings and end frames and for ventilating fans.

For the rotors of very large turbo-generators, one major American manufacturer has recently announced the use of a new alloy 'Condal.' This alloy has very high resistance to creep and exceptional thermal stability and is only slightly lower in conductivity than EC grade aluminium. At 25°C its compressive yield strength is more than four times that of EC metal; at 140°C its creep under compression, at moderate stresses, is less than one-fiftieth and at high stresses it is relatively still less.

10·3 *Switchgear*

The use of aluminium busbars has already been discussed. Aluminium is included in B.S. 159/1932 'Busbars and busbar connections in air, oil or compound,' and there seems to be nothing to prevent its being used increasingly in switchgear.

Switchgear components like fuse-boxes or conduit or cable joint boxes are frequently made of cast aluminium and it is also being used, sometimes after anodizing, for instrument panels and for panels on cubicle-type switches.

In small gear (up to 100-ampere), contactors and other moving parts may be of aluminium or aluminium alloy to reduce inertia.

In large oil circuit-breakers cover plates are being made of light alloy in place of fabricated steel with non-magnetic inserts and it is also being used for phase shields inside the breakers.

10·4 *Transformers*

Aluminium windings have not yet been used in transformers to any great extent; ordinary designs of oil-immersed transformers depend on compact coils with close spacing of the turns. A change to aluminium windings must be accompanied by a change in insulation methods if complete re-design is to be avoided.

Such transformers as have been built, in sizes up to 2 000 kVA, have proved quite satisfactory in service.

In dry-type transformers aluminium would seem to be more easily justified. Not only are insulation clearances usually bigger but these transformers are often required to be portable and the reduction in weight is of value. A fairly large number of air-insulated transformers with aluminium windings are now in service and the use of aluminium is likely to extend gradually from this beginning.

It seems probable that in large transformers aluminium will first be used in large quantities not for windings but for mechanical parts. Very big transformers are now being built in large numbers and more and more often a major design problem is the transfer of the transformer from the maker's works to the place of use. It follows that efforts must be directed to making more use of the permissible weight.

The substitution of aluminium alloy for mild steel plate for tanks, tank covers and radiators of very large units would often be justified. Considerable weight-saving could also be made if aluminium alloy were used for core plates and for fittings instead of steel or cast-iron.

Tests that have been made indicate that transformer oils in service will increase in acidity more slowly when in contact with aluminium windings than with copper. From this aspect, the substitution of aluminium for steel in tanks, particularly for tank tops and fittings above oil level, will bring important advantages.

10·4·1 Reactors

For the windings of current-limiting reactors, aluminium has established itself as the economic material. Reactors wound with aluminium are usually about 25 per cent lighter than equivalent equipment using copper and are correspondingly cheaper.

It is worth noting that the South African Railways Administration has designed, built and put into service in traction substations several large dry-type air-core reactors with aluminium conductor; in this matter, the S.A.R. would seem to have anticipated a practice which has now become recognized overseas.

10·5 *Electric traction*

Aluminium conductor is often used for overhead feeders on electric railway systems. In this country, examples are the Randfontein/Welverdiend extension and the recently completed line to Worcester.

Because such conductors are run on the closely-spaced masts erected for the catenary wires, aluminium stranded conductor (without steel reinforcement) is usually preferred.

A.C.S.R. or aluminium stranded conductor is also suitable for catenary wires or for systems where feeder and catenary wire are combined.

For trolley wires, aluminium would not appear, at first sight, to be a very suitable material. Nevertheless, it was put to this use on the Continent during the war simply because copper was unobtainable. Aluminium alone was not very successful; aluminium alloys gave better results but proved to be clearly inferior to copper. Composite wires of steel and aluminium were made in several forms and proved, in many cases, to be very successful.

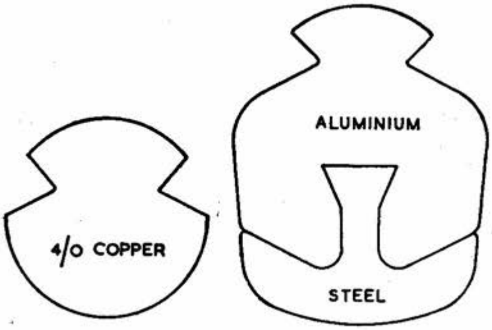

Fig. 10—Composite aluminium/steel grooved trolley wire. (For comparison, the standard British 4/0 s.w.g. trolley wire is shown alongside)

At the present time, trials of a composite conductor on the Paris Metropolitan Tramways are being watched with great interest. The profile of the conductor used is shown in Fig. 10.

A section of route was equipped with this type of contact wire in 1947 and its performance in service, in comparison with copper wire and cadmium copper erected alongside, is being carefully watched. At the date of the last published report—in October 1951—the composite wire had been subjected to approximately 510 000 passages of collector shoes and was only very slightly worn. The wear up to that time forecast a life exceeding the normal life of copper wire under the same conditions.[4]

The composite wire is claimed to have advantages besides that of reduced first cost. When copper is used, a proportion of the cross-section is provided for wear and the rest for conductivity; it is usual to replace wires when worn to about 60 per cent of their original section ; with the composite wire, a relatively cheap material—steel—is worn away and the conductor size is maintained throughout the life of the wire.

The lighter composite wire has lighter sags resulting in smoother wear and less trouble from accentuated wear at points of support.

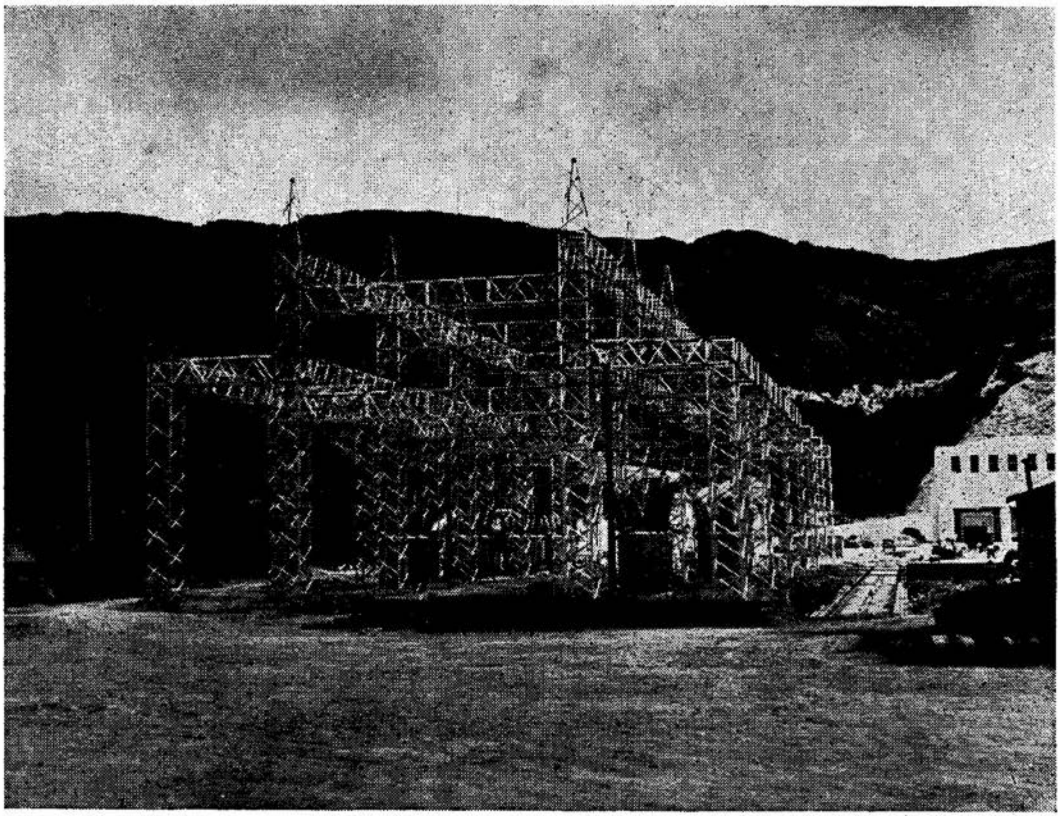

Fig. 11—Aluminium-alloy substation structure. Photograph by courtesy of New Zealand State Hydro - Electric Department and Canterbury Engineering Company, Christchurch

During the period of the tests on a busy route there have, of course, been several accidents and dewirements ; the damage done to the various wires suggests that the composite wire is less liable to be burnt down during short-circuits than is copper.

10·6 *Aluminium for structural work*

For electrical structures, where painting involves shutdowns or which must be erected in inaccessible positions involving high costs for transport to site and erection, aluminium alloys are often economic. Fig. 11 is a photograph of a substation structure in New Zealand built of extruded sections of a medium-strength alloy. Aluminium alloy is being considered in Great Britain for the top hampers of transmission line towers. On the Continent it is being used for complete towers of the type built up from sections of conical tubes.

In America, aluminium is being used for tubular street-lighting standards and for lighting brackets—this last is an application which should find acceptance in South Africa.

10·7 *Miscellaneous*

Aluminium is important in electronics and telecommunications. It is used in meters and instruments, in lighting fittings and domestic appliances.

An exhaustive list of its applications in the electrical industry would not be of great value and would soon become out of date. The following notes concern a few of the more interesting applications.

10·7·1 For cranes

Aluminium is used for the windings of lifting magnets because it is obviously important that a lifting magnet should be as light as possible in relation to its lifting capacity. Aluminium-alloy collector rails were used on a travelling gantry crane recently installed in a Canadian steelworks.

10·7·2 Lampcaps

Aluminium caps for g.e.s., b.c. and fluorescent lamps are now being used on a large scale by some of the most important lamp manufacturers in both America and Great Britain. The entry of aluminium into this field is noteworthy as an example of how, in the long run, price and availability decide what material is used for any given purpose.

Up till June 1950, British manufacturers had made lampcaps exclusively from brass. Aluminium has no apparent technical advantages over brass for this use and some obvious disadvantages; notably the difficulty of soldering connections and the fact that aluminium caps must often be used in brass lampholders.

The manufacture of lampcaps involves a succession of operations which are carried out at high speed and a change from brass to aluminium must obviously have meant a lot of work and a number of snags to be ironed out. By the end of 1951, caps for fluorescent lamps were being manufactured exclusively of aluminium and aluminium was firmly established for bayonet and screw caps.

At the present time, it seems probable that in another two or three years aluminium will have taken over completely from brass for all standard sizes of lampcaps except perhaps for low-voltage screw-cap lamps and for prefocussed lamps which have soldered-on skirts.

It also seems likely that lampholders will follow the same course during the next few years.

10·7·3 Domestic irons

A very interesting new application is the light-alloy electric iron. First introduced only about two years ago, this appliance has proved amazingly successful. The usual reaction to the suggestion of a light-weight iron is that the idea is absurd—that weight is essential for the process of ironing. In practice, it is found that the lightweight iron, with quick-acting thermostat, is altogether easier and quicker to use.

The actual heat content of a lightweight iron is not much different from that of a conventional iron because of the higher specific heat of aluminium.

11. CONCLUSION

This paper is an attempt to summarize the uses which are being made of aluminium in the electrical industry and to indicate, where these uses are new, why aluminium has been adopted.

Since 1946, aluminium has been applied to many duties which were formerly filled by other metals—usually copper, lead or steel. It has very different properties from these metals and its adoption usually means that some changes—of greater or less importance—should be made in methods or designs.

When its properties are properly understood, and the metal used in ways which are appropriate, aluminium will give the same reliable service to the expanding electrical industry as has been given in the past by the older metals.

12. ACKNOWLEDGMENTS

In compiling this paper, the author has drawn freely from the publications of the Aluminium Limited Group of Companies and from the technical files of Aluminium Company of South Africa, with whose permission the paper is published. At the same time he should make it quite clear that when views and opinions are expressed in the paper, these are his own and not necessarily those of the Company with which he is associated.

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DISCUSSION

C. R. Hallé (*contributed*) : This excellent paper by Mr McDonald is the logical outcome of the zeal and enthusiasm he displayed when, as my Assistant Electrical Engineer, he had to overcome the serious difficulties due to the copper shortage impeding our abnormal post-war electrical development.

In 1949 he first advocated the use of a.c.s.r. conductors for a new h.v. line to be erected ; we have since used over 25 tons of plain aluminium and a.c.s.r. conductors for both h.v. and l.v. distribution, and have purchased very little bare copper for the past three years.

On 1951 prices our aluminium conductor worked out at £150 per mile against the copper equivalent of £318. Present prices still show a saving of nearly 50 per cent on conductors alone.

Using 4 wire all aluminium l.v. vertical construction on wood poles our total costs are approximately £570 per 1 000 yards as against £772 using copper.

The fittings for aluminium conductors cost more but against this there is easier erection and a possible saving on stays as shown by the following comparative sag and tension figures recently taken.

Service tee offs.—We have been using both Bowthorpe line taps, with one side provided with a sleeve for copper to aluminium connections, and parallel groove clamps.

We have used Macintyre joints and have been liberal with No-ox-id compound ; we have experienced no troubles nor do we anticipate any.

While congratulating Mr McDonald on the width of his survey and the time and energy he has devoted to it, I cannot help regretting the conservation of most of us engineers in not having made fuller use before this of such an obvious advantage to our profession.

H. A. S. Dunk : I appreciate the opportunity of attending this Institute meeting, and being permitted to contribute to the discussion. The author is to be congratulated on covering the subject so ably.

The majority of people present will be linked with one or more aspects covered and, in my own case, it is from the viewpoint of the cable manufacturer.

I support the author's remarks regarding the local production of a.c.s.r. and all aluminium conductors for overhead use. These conductors are now being manufactured in South Africa up to the best accepted standards of quality, and are fully in accordance with standard specifications. Overseas, and particularly in the United Kingdom, aluminium is being increasingly used in underground power cables, both as sheathing and for the conductors. The method of sheathing application is still in a state of development, and when these matters have been finalized, there is little doubt that the South African Cable industry will embrace this use of aluminium.

There is one point that I would like to make regarding the Union's demand for

COMPARATIVE SAG/TENSION DATA FOR ALUMINIUM AND COPPER CONDUCTORS

Wire	Temp	Span feet	Sag inches	Tension lb
Al. 'Oxlip' 7/·174 ...	60°F	210	16·5	790
0·1 sq.in. equiv ...	80°F	210	22·8	570
Copper	60°F	200	14	1 745
0·1 sq.in.	80°F	200	16	1 473

a.c.s.r. and all aluminium conductors. In the past, supplies of these conductors have been mainly from European, American or Canadian sources, which has led to engineers requesting materials in accordance with the standard specifications of those countries.

The full range of conductor sizes as covered in these specifications require varying methods of construction as regards wire size and stranding. The adoption of one standard—B.S. 215—would assist local production in economic manufacture.

The author refers to the unavailability in the past of suitable connectors for use with aluminium conductors. It is perhaps right to state here that this position is now being resolved. The local manufacture of some of the connectors has already commenced, and will ultimately cover the full range. This should encourage the increased use of aluminium conductors for l.v. schemes.

One of the major factors impeding the increased use of aluminium is a reluctance on the part of some users to change to a material with which they have had little or no experience. Furthermore, reports have been circulated which exaggerate the problems of copper to aluminium joints. A number of engineers who have obtained this experience have expressed their liking for aluminium, and their intention to continue using it. As regards the copper to alumnium joint, there are now three well accepted methods of dealing with this matter. The use of fittings with a suitable metal barrier to combat galvanic action, the use of aluminium sleeves filled with a suitable inhibiting paste, or the use of aluminium conductor overhead service cable. This latter method has many advantages as it allows the aluminium to copper conjunction to be made inside the building in a well protected position. Information available from American sources indicates that fully satisfactory service life is being obtained even in the worst coastal areas.

It is noted that current rating of aluminium conductor power cables as a percentage of equal size copper conductors has been assessed as 78 to 84 per cent. It is considered that further experience of aluminium cables may ultimately lead to an accepted increase in current ratings, which will further add to the economic advantage of aluminium.

The author refers to the relative coefficients of thermal expansion of copper and aluminium, particularly with respect to the longitudinal movement of conductors within a power cable. The fact that aluminium expands 38 per cent more than copper is of greater importance when considering jointing. A soldering method of jointing which has been in use since the adoption of aluminium conductors uses a conventional copper ferrule. This is surely not ideal practice, and if soldering is to be the method of jointing, I suggest that the ferrule should also be of aluminium. In America experience has been obtained with a compression joint for underground power cables, and it is suggested that this method requires further consideration.

The reference to aluminium for internal wiring cables presents a problem not easily solved. Over and above the points covered by the author is the question of conduit capacity. In some instances this may well cancel the price advantage of the cable itself.

F. G. McDonald (Member) (*in reply*): The author is in agreement with Mr Dunk on all points he raises, none of which require further discussion.

In connection with the larger sizes of conduit which are required when aluminium conductor is used instead of copper for internal wiring work, several analyses have been made by the author of actual jobs, to check what the change would involve. (It is only rarely that all the conduits on a job are filled to capacity).

On one check of thirteen conduit sizes to carry three copper conductors of ratings 15-200A, only ten were satisfactory for equivalent aluminium sizes.

On another check, only eight out of forty items of conduit on a job had to be increased in size to take aluminium.

As regards appliance terminals, a check of 61 different appliances, all rated 30A, showed that only eight would accept the recommended size of aluminium conductor. Of 125 appliances of higher rating, only ten were suitable.

R. G. Hulley: Distribution engineers are notoriously conservative and it takes a long time to change their habits. As always however, economics will in the end dictate the course that one must follow, and there is no doubt that the paper that Mr McDonald has presented is a timely and major contribution to our art, and is likely to be used in the future as a standard work when dealing with aluminium.

It is a well-known fact that up till now, the cost of electricity to the consumer has risen very little upon pre-war levels, compared with other commodities. The chief reason for this is the fact that the major portion of the capital plant of the majority of electricity undertakings was purchased and installed at pre-war levels.

This state of affairs however, does not hold for undertakings that have developed since the war. With these undertakings, interest and redemption of capital is the major item on the expenditure account. In order that electricity may be produced at rates comparable with the established undertakings, it is vital that every effort be made to reduce capital costs without sacrificing efficiency and standards of construction.

For the past two years my firm has been recommending aluminium for new municipal distribution schemes, with the object of keeping capital costs down to a minimum. We were at first rather dubious about what troubles we might be letting ourselves in for. Our experience has been that with aluminium conductor, particularly for low-voltage distribution, considerable savings can be made and, at the same time, no practical difficulties have been experienced in erection. Linesmen who have received all their training and experience with copper have very quickly mastered the technique of aluminium. With the larger cross section conductors of the order of 0·1 copper equipment, savings of up to 50 per cent of the conductor costs have been made.

We are now quite confident that in recommending aluminium to our clients, we are doing the right thing for them, and our latest scheme for a completely new distribution network for a small Free State town, is 100 per cent aluminium. For rural electrification there is no doubt that the possibilities of small sized, steel cored aluminium are considerable. The average spacing of farms in South Africa is such that with accepted standards, the capital costs of providing a supply makes this type of scheme uneconomic. I shall appreciate it if Mr McDonald could give us more information on the possibilities of 0·0035 copper equivalent a.c.s.r. Is this conductor at present in general use overseas; and has it been used in South Africa ?

F. G. McDonald (Member) (*in reply*): No use has yet been made in this country of 3/4/·051 inch a.c.s.r., though some 3/4/·0661 inch, a Canadian Standard Size, has been used.

The main purpose of Table III was to show that a.c.s.r. does not have fixed properties—by varying the proportion of steel and aluminium, strandings can be chosen to suit any special requirement of conductivity, strength or cost. There seems to be no reason why an a.c.s.r. stranded 3/4/·051 inch should not give very satisfactory results in inland areas.

P. L. Vergottini (Member): Mr McDonald is to be congratulated on his very interesting and comprehensive review of the uses that are being made of aluminium in the electrical industry at present.

The trend of increasing capital cost of generating and distribution equipment is well known to all of you and it is our duty as engineers to do our utmost to reduce this figure provided it is not at the expense of good practice and sound engineering.

As the population of the world increases and the standard of living is raised so will the demand for more and more electricity become an everyday occurrence and in view of the fact that the supply of copper is limited, we will be forced to use an alternative metal wherever practicable—perhaps this condition already exists.

I remember the time when copper conductors were purchased at £100 and less per ton and when its use in the electrical industry was not only technically but economically sound. However, with copper at £230 per ton its use no longer becomes economical when you could use half the weight of aluminium at £160 per ton.

About 18 months ago I gave a talk to the members of the Reef Electrical Engineers Association, which is an Association of Municipal Electrical Engineers and which holds bi-monthly meetings to discuss our common problems. My talk was about aluminium conductors and how it could help us to overcome the shortage of copper. Samples of aluminium conductor and accessories obtained from the City Electrical

Engineer, Pietermaritzburg was obtained and I showed how they were used.

A sample of all-aluminium conductor, approximately 0·070 square inch equivalent recently recovered from Randfontein which had been erected at least 25 years ago was also shown. The specimen appeared almost as new.

Other known instances of aluminium used successfully for overhead mains in this country are in Cape Town, Pietermaritzburg, Krugersdorp, Germiston, Benoni, Brakpan, Witbank, Howick and Worcester.

When I gave my talk, aluminium conductor was a new idea to most of the engineers who heard it. Today it is in use by many of the towns along the Reef and its use will become more and more popular not only of the very big savings which its use does bring about, but because once electricians get used to handling aluminium they prefer it to copper.

H. L. Dawe (Companion) (*contributed*): Mr McDonald's paper is full of interest, and I congratulate him on the manner in which he has presented the subject and I feel sure that many will find this reference to the electrical uses of aluminium of great value in our daily occupations.

The author's reasonings, that aluminium will play a more important part in electrical engineering as years go by, seem convincing, consequently one should make a study of the past experiences with this metal to be sure that one is able to make full use of any advantages it has to offer from a technical, practical and economic aspect.

Having been privileged to commence the pioneering and introduction of the 'first in the world' commercially produced seamless aluminium sheathed cables, into Southern Africa a few years ago, I have been particularly interested in Mr McDonald's paper and am certain that he has aroused a further interest in the uses of commercially pure aluminium.

Seamless aluminium sheathed cables have been given wide publicity regarding the method of manufacture, etc., and it may be of interest to know that over 3 000 miles of this cable has already been produced by one British factory, many hundred thousand feet of which have been installed in this vast territory between the Belgian Congo and the confluence of the Indian and Atlantic oceans.

As a substitution for lead sheathing, seamless aluminium sheathing for power and lighting cables can today be manufactured for working pressures from low voltages to extra high voltages, the limitations being the availability of the diameter of the tube. Gas pressure supertension types offer economic advantage on account of the non-necessity to use mechanical reinforcement as required by lead sheathed types, to cater for internal pressures of the order of 200 lb per sq.in. Lighting and control cables with seamless aluminium sheathing have been referred to as the wiring with its own conduit.

Two power stations in Southern Africa have been cabled with aluminium sheathed cables and the extensions to both these power stations are being carried out with similar cables, which is a testimony for aluminium in electrical engineering.

In a great number of installations steel armouring is considered unnecessary when aluminium sheathed cables are supplied, and it would be interesting to know what the saving in cost would be on this account only, when more and more of these cables are used.

A well designed and novel scheme, for the cathodic protection of a long pipeline, was recently carried out in the middle East, with the use of 11 000-volt insulated aluminium conductors protected with seamless aluminium sheathing, supported by a catenary wire fixed to an existing telegraph pole line. Rectifier stations were required every 5 to 10 miles throughout the length of the pipeline, and this aluminium cable development made the scheme a practical possibility without necessitating any alterations to the existing arrangement of telegraph crossarms and conductors.

In Mr McDonald's comments regarding the jointing of aluminium sheathed cables, he refers to the sheathing having to be tinned with a special flux and solder. I agree about the solder, which by the way is made in South Africa, but no special flux is used, in fact no flux at all is required.

I have confined this short contribution to aluminium sheathed cables in particular, but before closing I would like to refer to two matters of practical interest concerning the author's remarks on the presence of moisture with aluminium.

A few years ago the Cunard-White Star Liner R.M.S. Aquitania, was handed over to the ship breakers after 36 years of exacting service.

When the liner was originally designed, it was decided to instal busbars and connecting links of commercially pure aluminium. The main switchboard dealt with the output of four, 400-kW generators by a 3-wire system, running 220 volts across outers. The busbars concerned were 5 inch by ½ inch, each outer being made of three such bars in parallel. The length of the busbars was about 40 feet and was made of three lengths. Four joints were thus involved, each being of the fishplate type, 6 inches long. Each joint was made up without the use of vaseline and was tied with ten ½ inch brass bolts with copper nuts. Neither bars nor joints were protected in any way.

Whilst this sytem scarcely conforms with modern practice, no trouble was experienced and little done beyond routine maintenance for those 36 years. This practice would be deprecated today.

In addition to this main installation, there were 14 auxiliary switchboards in various parts of the ship, each using 2 inch by ⅜ inch aluminium busbars.

Throughout her service in varying climates, much condensation inevitably occurred, and it is reported that the port side generator room busbars developed a grey deposit due to this cause. A reassuring feature was that neither aluminium/aluminium, nor aluminium/copper joints showed any signs of corrosion, and the equipment was considered good for many years to come.

The other matter of interest, in view of Mr McDonald's reference to aluminium's high resistance to corrosion due to a film of oxide forming on the surface, is concerning Gilbert's statue of Eros in Piccadilly Circus, London.

Cast in 1893, unveiled in 1894, Eros has been exposed, except for certain periods during two world wars, for over half a century, to all the rigours of the London atmosphere and has suffered no harm.

N. G. Beveridge (Associate Member):

General

As the pioneer of the production of copper wire and stranded cables for overhead power lines in this country it is with mixed feelings that one has listened to Mr McDonald's paper. In a paper I read to the Institute some time ago it was pointed out that it was copper that had made possible the electrical age in which we live. The production and distribution of electricity in most countries is an essential part of our modern civilization and it is not conceivable that this wonderful aid to mankind can ever be allowed to decline because any one metal or commodity is not available.

It is true as the author points out that the world's reserves of copper are not as great as probably electrical engineers would like and he has therefore done a service to the industry by bringing to their notice the ability of aluminium to meet the needs particularly of electrical distribution.

In this country and the Rhodesias we are fortunate in having good supplies of copper and in fact last year an article appeared in the Journal 'Commerce and Industry' recommending the installation of a copper electrolytic refining plant in the Union.

However today with a world shortage of copper the price has risen to fantastic heights compared to prices before the war and electrical engineers, who are ever in the forefront of efficiency and reliability at reasonable costs must take into account that aluminium does now provide a means of distribution of electrical energy at generally lower costs than copper.

Aluminium conductors for transmission lines

There are many main transmission lines throughout the world today where steel-cored aluminium is used as the conductor and although it is probably true that in the past difficulties were experienced with these lines due to vibration and that an engineer in charge of a main transmission line had greater confidence in copper, present-day knowledge and technique has increased to such a degree that it can confidently be stated that an a.s.c.v. line need cause engineers no undue worry at all.

Rural lines

Although it is undoubtedly true that in most cases an aluminium rural or urban overhead line can be erected more cheaply than with copper, I believe it would be of general interest if the author could give more detailed information than is contained in Table III.

Aluminium in insulated cables

One recently read again a paper delivered in London in 1913 by the chief engineer of a large cable making concern and in his address he points out that whilst copper is a well understood and consistently reliable metal, there is no inherent electrical reason why insulated aluminium conductors should not be used for all purposes and at all working pressures, and it is purely a matter of economic consideration.

Production

Having produced copper conductors for over 20 years, one, like most manufacturers has an affection for the product they make, but producers like engineers have to move with the times and as undoubtedly the amount of aluminium available today is much greater than in past years and is now the cheapest of metals for the electrical industry, it is only in the nature of things that electrical engineers will wish to use such a metal and as has been mentioned by the author, local producers of wires and cables have entered this field of endeavour, and a few details about the manufacturing side may be of interest.

Rolling

It is normal to start with a bar of 4 inches or 6 inches square section in varying lengths from 52 inches to 80 inches depending on furnace capacity and the layout of the mill. The rolling temperature of aluminium is approximately 410°C and at this temperature it has the same appearance as when cold. Owing to its soft nature the wirebar is placed in a carrier which in turn rests on the skid bars in the reheating furnace. When the bar is removed for rolling the carrier is replaced at the charging end of the furnace.

Aluminium has a protective coat of oxide under all conditions with the result that no heavy scaling takes places as in the case with copper and steel, and it is therefore not necessary to flood the rolls with water. As a roll pass lubricant it is usual to use whitening or chalk on the roughing passes and paraffin on the finishing passes.

The comparative softness of the metal introduces difficulties in guiding which are overcome by the use of roller guides on the inlet side and hard wooden guides and steel rollers on the outgoing side, but surprisingly enough owing to the low stiffness factor, it is very springy and more difficult to handle during the rolling operation than other harder metals, and is normally coiled in larger eye diameter. Aluminium rod is required by the wire mill in either $\frac{3}{8}$ inch diameter or 0·330 inch diameter.

A new development in rolling is the Properzi process which consists basically of a continuous casting process which delivers a hot bar of 1·2 square inch section to an 11 pass continuous mill producing $\frac{3}{8}$ inch diameter rod.

Wiredrawing

Aluminium being very ductile is readily drawn on continuous cascade type wiredrawing machines. As there is not any scale, pickling is unnecessary and the rod is fed to the machine with successive coils welded by the flash upset method of butt welding.

Precautions that have to be taken during drawing are as follows—The lubricant must be filtered before re-circulation as a large amount of swarf is formed.

Mineral oils must be added to the normal types of non-ferrous wiredrawing lubricants or a straight oil should be used. The latter has the disadvantage of inadequate cooling at speeds in the region of 3 000 ft per minute. Capstan slip must be reduced to a minimum on the last three dies of the train to prevent scoring of the wire.

Aluminium may be drawn dry through a soap lubricant in the same manner as steel wire. Owing to its work hardening properties it is necessary to give an intermediate anneal when drawing finer sizes.

Stranding

The stranding of aluminium presents no difficulties to manufacturers who have experience of copper or steel. The bunching dies and plates must be free from all grooves with an adequate radius on the ingoing side, normally the lays are shorter than for copper.

As the author mentions, specification quality galvanized steel wire is available in South Africa and manufacturing facilities are available for the production of aluminium wires, but aluminium is not readily available and has to be imported by sea and it is desirable that stocks of aluminium bars be held in this country by makers of the virgin aluminium to ensure that the local producers can effect satisfactory delivery of aluminium wires and strands to the electrical industry.

In conclusion the author is to be congratulated on a very interesting paper presented in an able and competent manner.

F. G. McDonald (Member) (*in reply*): The author is grateful to Mr Beveridge for his outstanding contribution. Mr Beveridge has asked for more information about rural lines than is given in Table III.

As noted in the reply to Mr Hulley's contribution, Table III was prepared with a particular object; to demonstrate the versatility of a.c.s.r. as compared with the fixed properties of a homogeneous conductor.

The Table should not be studied in any other light, and should certainly not be used as a guide for conductor selection. Full information about the mechanical or electrical properties of all standard sizes of a.c.s.r. and about all types of strandings, are available instandard specifications and in manufacturers' literature, and there is not space here to enlarge very much on the subject.

As regards Mr Beveridge's concluding remark, that stocks of aluminium should be maintained in this country by the producers, the author agrees that this would be desirable. In the past there has never been enough aluminium to satisfy all demands, and producers of virgin aluminium have been able to sell all the metal they could produce. If present schemes for expanding aluminium production in North America, and perhaps on the Gold Coast, result in metal supplies becoming easier, then it seems very probable that producing companies will think about maintaining stocks of metal in non-producing countries.

G. Williams (Member): I had expected one of my senior engineers to make a contribution to this paper but as he has apparently been remiss, the duty has devolved upon me to do the discussion. I am sorry I did not come prepared for it.

We on the railways, have gone in of late years quite considerably for the use of aluminium, particularly for our very large cross section feeders. With the present price of copper, the economies of electrification now depend largely upon the cost of conductors on our very heavy sections and the first application of aluminium was on the Welverdiend Section, where aluminium feeder was used from Braamfontein to Welverdiend, to give a total cross section on the overhead equipment of 1 sq.in. copper equivalent.

We were at the outset a little nervous in using aluminium for this purpose on a section where a large number of steam trains operated. The span is 220 feet and tensioned to approximately the same sag as the catenary, we used a steel cored aluminium feeder. Since that time with further knowledge and our experience in handling and putting up aluminium wire, gave us greater confidence.

On our new electrification in the Cape area, we erected throughout the minimum of 1 aq.in. copper equivalent in the overhead equipment and from Wellington to Touws River and on the Stellenbosch loop, we have erected approximately 150 miles of aluminium feeder of approximately 0·5 sq.in. copper equivalent, the remaining conductivity being in the copper catenary and the copper contact wire.

Because of the light weight of this conductor we supported the feeder from the same string of insulators that normally supported the catenary over the centre of the track. Only its light weight enabled us to do this instead of supporting on a separate set of insulators on the outside of the mast, which is the normal method when using copper feeders.

In order that the catenary vibration should not be transmitted to the aluminium feeder, it is carried in a specially designed double suspension clamp of heavily galvanized malleable cast iron, the aluminium feeder merely resting in a rocking support above the fixed catenary support. The two wires are thus able to vibrate or move independantly of one another. The support of course, gives no electrical conductivity except the incidental contact. The actual conductivity being provided by special clamps connected between the catenary and the feeder at regular intervals. We are confident since putting this feeder up that we need anticipate no trouble with it.

Furthermore, we have manufactured all of our main reactors for all the Cape substations and also our later substations in other parts of the country, from solid aluminium conductor of 0·25 sq.in. equivalent these used to be made of copper. The coil is made from four conductors of 0·25 sq.in. equivalent, in parallel, the coil diameter being about 6·6 inches air spaced and clamped. We found that the light weight of these reactors was of very great advantage particularly as the reactors are mounted in a very difficult position in a substation. All our latest substations have been equipped with aluminium bus-bars of large sizes. We have also erected steel cored aluminium earth wires throughout on the Cape electrification and are now giving consideration to equipping a section of electrification with steel cored aluminium conductor for the catenary. The problem in these cases arises from the fact that there are a large number of droppers between the aluminium catenary and the copper contact, but this is under investigation and we hope very soon to find a satisfactory solution to the problem.

It will be seen that on railway electrification in this country, the use of aluminium has made very rapid strides in the last few years and we confidently expect that it will make still greater strides in the next few years.

M. Hewitson (Member) (*contributed*): I would like to refer particularly to the author's reference in section 7 to the use of aluminium for communication services.

The physical and electrical requirements for the several classes of telephone route differ according to whether the routes will carry for example, mainly audio circuits or mainly multi-channel carrier circuits.

An extreme example of the first class is the type of route erected for farm lines. For these routes transposition requirements are simple and long span construction using relatively high-loss, high-strength conductors satisfies requirements.

Normal routes of this type have spans of 220 to 264 feet and employ conductors of copperweld (0·104 inches diameter) or mild steel (0·119 6 inch diameter) which have losses (at 800 cycles per second) of 0·15 db and 0·25 db per mile and breaking loads of 1 177 and 600 lb respectively.

Hence where transmission requirements can be met by the use of the mild steel wire the use of aluminium either solid, stranded or steel cored, as a substitute could not be economically justified. Even as a substitute for copperweld the cost of an equally strong aluminium conductor would be greater.

In so far as major (or carrier) routes are concerned the increased frequency band transmitted (up to 150 Kc/s) and the greater power level required for carrier working has increased enormously the cross-talk problem. In consequence transposition intervals have had to be shortened (e.g. from 440 yards on farm routes to 44 yards on J3 routes), so that for these routes the normal span in 132 feet and extra high strength in conductors is not of prime importance.

The normal conductors used in South Africa on main trunk routes are hard drawn copper, 0·137 inch diameter for primary circuits and 0·112 inch diameter for secondary circuits. These wires having breaking loads of 945 and 645 pounds respectively.

There are several standard sizes of British and American aluminium conductor which have strength and resistance qualities not inferior to the copper conductor normally used; examples of these are shown in Tables A and B.

Table C compares copper and aluminium wires for *equal resistance* per unit length.

It will be seen from Table C that the much lower basic price of aluminium is offset by the much higher fabricating cost of stranded wires and the apparent saving in cost is reduced to some 16 per cent to 27 per cent in favour of aluminium as compared with copper. For example, a saving of £20 per circuit mile (5s. per pole position per wire) would be obtained on a major trunk circuit if aluminium conductors were used in place of hard drawn copper, 300 lb per mile.

There are several factors, however which tend to offset this apparent economic advantage viz. :—

(*a*) the wind loading is increased by 35·6 per cent for a solid conductor of nearly equivalent resistance but nearly 45 per cent if the smallest practicable equivalent size of steel cored aluminium conductor (*vide* Table B) is used. This will obviously restrict the carrying capacity (by 8 to 12 circuits in certain cases) on some types of main line pole. Where the pole is strong enough of course, the reduced sag necessary because of the greater breaking load of steel cored aluminium will enable more arms to be erected before the permissible clearance to ground is reached.

(*b*) The larger diameter and high tension/weight ratio of equivalent aluminium conductors will increase the susceptibility to damage from wind vibration and necessitate the use of dampers etc. so increasing the cost of erection. In addition conductors will need to be bound in at every insulator including point type transpositions which is not the case with copper where transposition points are unbound.

(*c*) Because the conductor is softer special care must be exercised when handling and erecting e.g. the wire must not be pulled over metal arms etc.

(*d*) Maintenance costs are likely to be higher with aluminium.

TABLE A

POSSIBLE SUBSTITUTES FOR 200 LB PER MILE HARD DRAWN COPPER

Type of conductor	Hard drawn	A.C.S.R.	A.C.S.R.	Comparative constants of 200 H.D.C.
Make up	Solid	6 al 0·0661 1 steel 0·0661	6 al 0·059 1 steel 0·059	Solid
Overall diameter in inches	0·186	0·198	0·177	0·112
Weight in lb per mile	168	190	152	200
Aluminium area in sq.in.	0·027 2	0·020 62	0·016 4	—
Weight in lb per mile of aluminium ...	168	129	103	—
Resistance—Ohms per mile	2·57	3·53	4·471	4·3
Breaking load—lb	645	1 165	915	645
Attenuation at 800-c/s db per mile ...	—	0·052	—	0·06
Attenuation at 150 Kc/s-db per mile ...	—	0·27	—	0·315
Impedance at 100 Kc/s	—	565	—	—

It will be seen from Table B that steel core reinforcement is not essential for conductors used on major trunk routes but that stranded hard drawn aluminium or solid aluminium alloy will meet the strength requirements at the cost of an increase of 87·5 per cent and 22·3 per cent in resultant loading respectively as compared with copper.

Reports as to the ability of aluminium conductors to resist corrosion are conflicting and some further information on this aspect would be welcomed.

TABLE B

POSSIBLE SUBSTITUTES FOR 300 LB PER MILE HARD DRAWN COPPER

Type of conductor	Aluminium alloy	Aluminium alloy	Hard drawn aluminium	A.C.S.R.	A.C.S.R.	Comparative constants of 300 H.D.C.
Make up	Solid	3/·111	3/·132	6 al 0·066 1 1 steel 0·066 1	6 al 0·074 3 1 steel 0·074 3	Solid
Overall diameter in inches	0·185	0·239	0·285	0·198	0·223	0·137
Weight in lb per mile	170	181	259	190	240	300
Al area in sq.in. ...	0·027	0·029 1	0·040 2	0·020 6	0·026	0·014 74
Weight in lb per mile of al	170	181	259	129	163	—
Resistance. Ohms per mile	2·99	2·799	1·737	3·53	2·80	2·867
Breaking load ...	1 100	1 210	995	1 165	1 455	945
Attenuation at 800 c/s	—	—	—	0·052	—	0·042
Attenuation at 140 kc/s	0·247	—	—	0·27	—	0·256
Impedance at 100 kc/s in ohms	530	—	—	565	—	572
Wind load in lb for 44 yd span at 15 lb per sq.in. of plane surface	18·3	23·66	28·215	19·6 Inferior to 300 lb H.D.C. for audio ccts	22·18	13·5
Resultant of weight and wind pressure for 44 yard span ...	18·9	24·1	28·95	20·8	23	15·45

Relative future price levels of copper and aluminium also will have an important bearing on the matter. Prices of both metals have shown a downward trend since 1951 in the case of copper and 1952 in the case of aluminium, but whereas aluminium (ingot form) is about 87·5 per cent above the 1948 price level, copper (wire bars) is still more than 170 per cent higher in price now than in 1948.

In general therefore the case for aluminium for communication routes does not appear to be too attractive but field trials would be necessary to determine the relative importance of the factors mentioned.

In communication cables however, where conductor strength is not important and full advantage can be taken of the favourable weight and price ratio of aluminium the

TABLE C

	Copper	Aluminium
Cross sectional area ...	1	1·61
Diameter	1	1·27
Weight	1	0·488
Breaking load	1	0·64
Cost (ingot)	1	0·325
Cost (fabricated) ...	1	0·84
Cost (do)	1	0·73-·82 for equal loss at carrier frequencies

picture is somewhat different, the only disadvantages being jointing and increased overall diameters. The former difficulty is, it is understood, being surmounted in a satisfactory and practicable manner and the latter is important only in respect of the larger sizes of cable.

F. G. McDONALD (Member) (*in reply*): The author is very grateful indeed to Mr Hewitson for his very valuable contribution, the tables he has prepared will be of permanent value.

The author is not qualified to comment on many of the points raised.

The comparison given in Table C between the cost of drawn copper and of stranded aluminium of equal resistance is not in line with present conditions; the ratio is given as 1 : 0·84, suggesting a very high fabricating cost for aluminium conductor. Actual costs of material from South African manufacturers indicate that the costs of fabricating both metals, volume for volume, are about the same. The present ratio is something less than 1 : 0·5.

Of course, if the cost of steel reinforcement, when required, is added in as part of the cost of fabricating aluminium strand, then the ratio becomes less attractive but it does not often rise above 1 : 0·65.

Another comparison that is rather misleading is the statement that 'even as a substitute for copperweld, the cost of an equally strong aluminium conductor would be greater.' This could only be true if the two conductors had very different conductivities.

Mr Hewitson has not included in his tables any figures for special strandings of a.c.s.r., or for smooth-body conductors, but has considered only 6/1 strandings. In some respects both 3/4 and smooth body strandings are superior to 6/1 strandings for light telephone constructions.

In some European countries, notably Hungary, very extensive use has been made of aluminium for telephone lines, and its suitability for the job has been proved by many years of satisfactory performance. The exact degree of economy that can be achieved can only be found by full-scale tests, and it is hoped that the field trials suggested by Mr Hewitson may be put in hand to obtain an actual assessment of the possibilities of aluminium under South African conditions.

A. A. MIDDLECOTE (Associate Member) (*contributed*): We are indebted to Mr McDonald for his timely paper. I think we will all agree that with decreasing stocks of copper available more use must be made of substitutes and in electrical engineering it will be appreciated that aluminium is the more important substitute.

It may be fairly stated that a great deal of the prejudice against aluminium that exists in South Africa was initiated by the use of copper bearing aluminium alloys which Mr McDonald states were dumped at the end of the second world war. To the average man these alloys were plain aluminium and as a result of the consequent early corrosion which took place when these alloys were used in coastal areas, aluminium was condemned. On the other hand there are many cases where aluminium overhead conductors have been used on transmission lines in coastal areas and have given longer life than the steel structures. More recently the use of aluminium on the latest American transatlantic liners must have done much to restore the good name of aluminium. Mr McDonald has rightly stressed the importance of prevention of electrolytic corrosion of the aluminium by ensuring that the correct alloys and fittings are used with aluminium. He has left very little further to say except that if his recommendations are intelligently observed good results can be obtained.

On its credit side are the good properties of aluminium as regards performance in industrial atmospheres where its resistance to the sulphur gases is superior to that of copper.

As regards the use of aluminium for conductors in cables it is worth noting that the higher specific heat of aluminium results in a cable which has a higher short circuit current rating than the equivalent copper cables. This is rather an important point these days where the size of cable is often determined not by the rated current requirements but by the short circuit currents of the circuit in which the cable is used. Generally speaking the short circuit rating of an luminium cable will be 30 per cent higher than that of an equivalent copper conductor cable.

I do not, however, favour the use of aluminium on high speed rotors. On account of the high coefficient of linear expansion (33 per dent higher than copper) more trouble can be expected due to distortion of the windings. One is familiar with the trouble already encountered with copper conductors used on high speed rotors where, owing to the large centrifugal forces between the conductors and wedges the thermal expansion of the conductors is taken up as a permanent strain. When the rotor finally stops and cools off, the conductors are consequently shorter and this results in distortion of the end windings. This type of trouble will be much aggravated if aluminium is used.

It would also be undesirable to use aluminium conductors on machines subject to vibration and shock due to the lower fatigue resistance of aluminium when compared with copper.

As regards the use of steel tipped traction contact wires it would be interesting to hear what type of pantograph strip was used in this connection.

Mr McDonald's reference to the wiring regulations and the South African Bureau of Standards (S.A.B.S.) and American codes for the protection of buildings against lightning and the use of aluminium for this purpose is interesting. The S.A.B.S. code is likely to be revised in the near future and consideration will no doubt be given to allowing aluminium conductors as a substitute for copper. In this event the code should provide some safeguard in regard to the manner in which the connection is to be made between the aluminium conductor and the copper earthing rod. For instance, the connection should be made above ground level so that it may be inspected periodically and thus corrosion difficulties may be avoided.

With the copper supply position becoming so acute one feels that the time is ripe for the rationalization of the use of copper and aluminium. The electrical engineers should form a code for the use of these two basic minerals to ensure that each is used to the best advantage. Briefly this would restrict the use of aluminium to die cast rotors, cables, transmission lines, reactors and most applications where light weight is important. Copper could then be reserved for cases where its higher conductivity, smaller dimensional size and superior mechanical properties would be of value.

F. G. McDonald (*in reply*): Mr Middlecote is thanked for his remarks; he has introduced some new points for consideration.

As regards the use of aluminium windings in rotors, much of the trouble that has been experienced with copper windings is due simply to the weight of the windings, and to the large centrifugal forces which are set up when they spin. The light weight of aluminium is tremendously important for the windings of high speed rotors, and it is impossible to agree with Mr Middlecote when he says that distortion of end windings, when aluminium is used, will be aggravated. The same applies to his remarks about machines being subjected to vibration and shock. The light inertia of aluminium windings coupled with the low modulus of the material, makes them in fact specially suitable for withstanding vibration and shock.

Steel collector shoes are in use on the Paris trams which run on the aluminium/steel trolley wire referred to in section 10.5. The published figures on these tests indicate that the life obtained from copper of cadmium copper trolley wires is much shorter than the lives usually expected from trolley wires in this country, where collector shoes having carbon inserts are the rule. It is suggested that the test of the aluminium/steel trolley wire is all the more severe because steel collector shoes are in use.

The author is pleased to note that the revised S.A.B.S. Code for the Protection of Buildings from Lightning will probably permit the use of aluminium lightning conductor; he agrees that an aluminium lightning conductor system should be jointed to a copper earth rod above ground, using a suitable connector.

The author does not favour a code for the rationalization of the use of copper and aluminium, as recommended in Mr Middlecote's last paragraph.

C. G. Downie (Member) (*contributed*): To date considerable experience has been acquired in the use of aluminium conductors for extra high voltage transmission lines and there is no longer a doubt that economies can be effected thereby. The extent of the overall saving is variable however and is dependent on many factors introduced by the design of the line and the nature of the terrain traversed quite apart from the obvious effect of fluctuations of metal prices.

Owing to the many variables involved and because the design of low tension lines is largely determined by factors which have little play upon the design of e.h.v. lines it is considered unwise to apply the economics of e.h.v. line construction to low voltage distribution lines. Important factors in the case of the latter are that spans are determined mainly by the size of building plots and further that the cost of a pole is not closely related to the length of the span or the size or number of conductors supported.

In view of this we are rather loathe to accept figures indicating large overall savings based purely on estimates. A saving of 50 per cent may be indicated on the cost of conductors alone but when allowing for the high cost of fittings in addition to increased cost of erection the saving is reduced to approximately 26 per cent as compared with an all copper installation. Allowing, in addition for poles, cross arms, stays, etc., the cost of which is the same for both systems, the overall saving is reduced to a far less impressive figure.

Also the corrosion problem due to the sea air is a serious one in many parts of the Cape Peninsula. It is therefore considered that before the use of aluminium conductors on low voltage distribution lines could be accepted with any degree of confidence much more operating experience with this type of equipment would be necessary.

We disagree with Mr McDonald's contention that the erection costs for copper and aluminium conductors are about the same. It is considered that the erection costs for aluminium conductors and service connections would exceed those for copper conductors by at least 30 per cent when account is taken of the following factors :—

(*a*) The care which must be taken to avoid tearing the surface of the conductor in drawing over cross arms, walls, fences etc.

(*b*) The need to protect the conductor against abrasion by the application of armouring tape at every point of support.

(*c*) The additional time taken in the thorough preparation of contact surfaces and application of oxidation inhibiting grease prior to the fitting of joint clamps.

F. G. McDonald (Member) (*in reply*) : Most of the discussion on my paper has been in favour of aluminium ; Mr Downie's contribution is therefore specially welcomed because he has set down some arguments against the change to aluminium for distribution work.

Mr Downie queries the savings that can be made by using aluminium because they must be based partly on estimates. Surely this is always the case ; in considering any change it is always necessary to weigh against each other all the gains and all the losses that can be foreseen, and some of the figures must be estimates.

It is quite possible that on a low voltage line with a very large number of connections, and with costs as they are today, the higher cost of connectors may reduce the saving on the conductor items of a particular job to 26 per cent, instead of the 50 per cent which would be obtained on a line with infrequent connections. A saving of 26 per cent would seem to be worth thinking about.

It seems to be quite fallacious to argue that, because a saving of 26 per cent can be made on the conductor items only, and not also on the poles and cross arms, therefore the saving is not very important after all.

As regards erection costs, Mr Downie's estimates are very pessimistic indeed, but there has been ample evidence, from previous contributors to the discussion, who have had actual experience of aluminium, that the first two of his objections are bogeys. In section 9.3, it has been explained that the deflection of an aluminium conductor is only half that of a copper conductor of the same section and on the same span. This applies of course to conductors during erection, not under tension. An aluminium conductor is 27 per cent larger in diameter than its copper equivalent, and the modulus of inertia of its section is 2·6 times as big.

In practice, therefore, an aluminium conductor drawn across two supports will deflect less than one-third as much as an equivalent copper conductor, and will have less than one-third of the tendency to kink. It is entirely wrong to thing about a conductor as light as aluminium having to withstand the treatment that is required to handle a conductor as heavy as copper.

The precautions that are recommended when handling aluminium are no more than should be taken by a conscientious workman working with copper, and if these precautions are not taken, the chance of damage to a conductor is no greater, and is probably less, than with copper.

The author has seen aluminium conductor subjected to some very rough handling indeed.

On one point, the author is in complete agreement with Mr Downie. It is possible to take liberties with aluminium/copper joins in inland areas. Such liberties must not be taken at the coast. Sea air will almost certainly set up electrolytic corrosion in a joint that is not properly made, and if Mr Downie cannot be certain that all concerned can be instructed in the correct methods of making joints, and can be relied on to use those methods, then he is correct in postponing a change to aluminium in his department.

It is only fair to add that if it were possible to obtain compression accessories easily in this country, it would be possible to make out a very much better case for a change to aluminium for low voltage lines in a city like Cape Town than can be made out when plans are based on the use of bolted clamps.

VARIABLE-FREQUENCY CRYSTAL-CONTROLLED RECEIVERS AND GENERATORS

By T. L. WADLEY *

(This paper was presented to the Light Current Section of the Institute at a meeting on 11*th August* 1953)

CONTENTS

1. INTRODUCTION

The continually increasing use which is made of the limited radio-frequency spectrum has made increasing demands on the precision of radio equipment. In particular, the need for accurately controlling frequency has become necessary. The development of quartz crystal oscillators of high-frequency stability, for controlling the frequency of both a transmitter and the associated receiver to operate on a predetermined channel, has provided an ideal solution.

However, for equipment in which flexibility of frequency is required, it has been usual to fall back on an *L.C.* oscillator, compensated for temperature. Using this technique it is difficult to meet modern requirements in respect of transmitter stability, and difficult in respect of receivers to exploit fully the selectivity of narrow-band filters. In addition, it is frequently necessary to provide auxiliary frequency-measuring equipment.

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Various systems have been devised to apply the stability of crystal control to multifrequency equipment. Numerous crystals may be used directly or in various combinations. Such systems can become very complex when anything like complete flexibility is required, and are often confined to producing a number of fixed channels rather than a continuously variable device.

An attractive possibility is to make use of the harmonic spectrum of a single crystal. The problem is then to separate the required harmonic from the adjacent harmonics with sufficient suppression of the latter and to interpolate between the harmonics if necessary. One possibility is to synchronize an oscillator to the harmonic required. The ability of such an oscillator to remain locked to the required frequency depends upon the level of the synchronizing signal being high and its ability to discriminate against the adjacent signal depends upon the synchronizing signal being weak. These conflicting requirements make it impossible to design a satisfactory arrangement of this nature, without the use of something of the nature of an a.f.c. device which exploits the short-term stability of the tuned circuit. Difficulties then arise in ensuring that the device is brought into the required operating condition and remains there. It is also difficult to apply interpolation to such a system.

The basic problem of separating harmonics of this nature is one of filtering, however the selection may be performed. As in the case of the selectivity of a radio receiver, the solution to the basic problem lies in providing the necessary number of circuits in the filtering arrangements and, if necessary, in transforming the frequency at which the filtering is performed. The degree of adjacent channel suppression and width of filtering band may then be adjusted separately. This cannot be done with anything in the nature of a single circuit.

In the simplest arrangement a variable multi-element filter may be designed to cover the required range with the required bandpass, say, about equal to the spacing of the harmonics. The adjacent suppression required will then determine the number of elements.

By heterodyning the harmonic spectrum by means of a variable oscillator and mixer, the filter may be made of fixed frequency. The advantage of this heterodyning is two-fold, the filtering frequency becomes fixed and a more suitable choice of filtering frequency may be made. This is the basic principle of the devices which are to be described in this paper. This principle gives rise to harmonic-selecting devices to which interpolation between harmonics may easily be applied. The devices have effectively long scales, using mechanically simple dials. The calibration may be linear at all frequencies and the scales read directly in frequency. The principles may be applied to both frequency generators and receivers for a variety of purposes over any span of frequencies.

In the case of receivers the principle has been adapted to a multiple heterodyne receiver covering the span 0 to 30 Mc/sec based on a 1-Mc/sec crystal.

A generator based on the same principle covering 0 to 20 Mc/sec has been built based on a 100-kc/sec crystal.

2. GENERAL PRINCIPLES APPLIED TO GENERATORS

Fig. 1 refers to the general principle of selecting the harmonics.

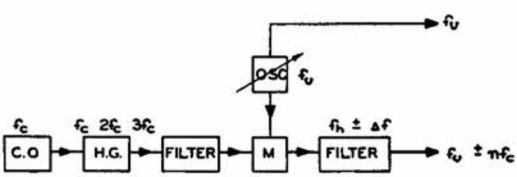


Fig. 1

The crystal oscillator of frequency f_c is followed by a harmonic generator which produces the harmonic spectrum f_c, $2f_c$, $3f_c$, etc., all of similar amplitude. The waveform of this spectrum is a short pulse of recurrence equal to f_c and of duration less than a half cycle of the highest harmonic required. This is followed by a filter, which may be required to remove unwanted harmonics. The harmonic spectrum is then shifted in frequency by the mixer M_1 by means of the variable oscillator f_v and a harmonic which then lies within the band-

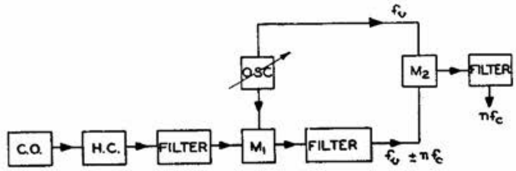


Fig. 2

pass of the filter in the mixer output is filtered out. The filter output is $f_v \pm nf_c$. The filtered harmonic thus occurs as the difference between this frequency and the frequency f_v of the variable oscillator. The harmonic which has been selected in this way may be made use of in a variety of ways.

In the simplest case the two frequencies f_v and $f_v \pm nf_c$ are applied to a second mixer M_2 as shown in Fig. 2 and the harmonic nf_c extracted by a suitable filter.

The choice of frequency to which the harmonic frequencies are heterodyned is determined by the following consideration. The number of filter sections required to produce a given suppression of the adjacent unwanted harmonic does not depend on the frequency chosen once the bandpass of the filter has been decided upon. This bandpass should be a large fraction of the harmonic spacing, perhaps even equal to the spacing, if the setting of the variable oscillator is not to be critical. The filter frequency may therefore be made as high as the circuit Q's will allow and, if this frequency is made higher than the highest harmonic required, the image frequencies of the two mixers may be removed by low-pass filters, and the device will operate over as large a range as required by means of a single oscillator range.

To place the filter frequency within the harmonic range, or below the lowest harmonic required, would restrict the range of coverage to considerably less than a two-to-one interval if all filters were fixed or, alternatively, it would become necessary to make the two image filters variable and ganged to the oscillator and perhaps switch ranges also, if a wide coverage were required.

In the devices to be described, a frequency higher than the highest harmonic is used for filtering with the advantages mentioned. Practical circuit Q's limit the span of harmonics which can be selected to the order of 30 to 50 and perhaps 100 in the limiting case.

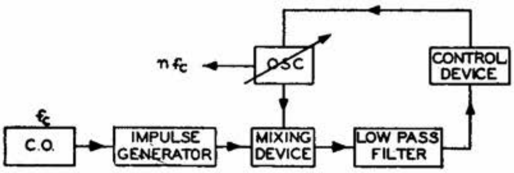


Fig. 3

This is sufficient for certain purposes and when a further subdivision of frequencies is required, methods of compounding the principle may be used as described later.

It is interesting to compare the system with the device known as the 'impulse-governed oscillator.'[1] The latter may be described as conforming to the general principle outlined above, in which the filtering frequency is centred around zero. This is shown in its simplest form in Fig. 3. The impulse generator following the crystal oscillator performs the same function as the harmonic generator, that is, produces a harmonic spectrum in which all harmonics are of similar amplitude. The oscillator to be impulse-governed corresponds to the variable oscillator. This is fed together with the impulse to the mixing device (phase discriminator) which corresponds to M_1. The output of this, which in the steady state is at zero frequency, is fed via a quick-acting coupling circuit (low-pass filter of suitable cut off) to a control device which corresponds to M_2 in that it modulates (in the steady-state frequency controls) the oscillator. The advantage of the choice of zero as the filtering frequency is that in the steady state the image at the input to the mixing device M_1 is coincident with the wanted channel, and the sidebands and the oscillator frequency in the output are coincident and therefore no input or output filtering is required or indeed possible. When the device is responding to disturbance of the oscillator constants, this coincidence breaks down but this is perhaps of no account. The bandpass of the coupling from the mixing device to control device determines the capture range in the same way as the bandpass of the harmonic filter determines the non-critical range of the variable oscillator and, similarly, a coupling from the mixing device to the control device, which is too fast-acting or which cuts off in frequency too slowly will result in the adjacent harmonics appearing in the output in strength, in the same way that they would occur as a result of too wide a harmonic filter or a filter with insufficient edge suppression. An advantage of the impulse-governed oscillator is that narrowness of the filter bandpass is not likely to be restricted by circuit Q's and consequently a large number of harmonics may be selected in this way, although the range will be restricted to that of the oscillator unless it is bandswitched.

The above comparison is valid only in the steady state of the impulse-governed oscillator. In the state corresponding to the impulse-governed oscillator being unlocked, that is, when adjusted between harmonics, the system under discussion has no output. It is a passive device which has only one possible mode of operation for any adjustment.

The advantage of the system under discussion is that interpolation between the harmonics may easily be added as shown in Fig. 4. Furthermore, the harmonic which has been selected as in Fig. 1 may be applied to the control of a receiver indirectly without deriving the harmonic, to give certain advantages which will be described below.

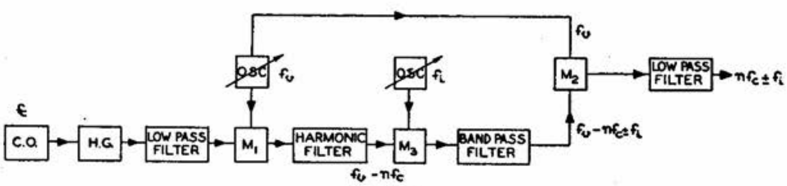


Fig. 4

Fig. 4 shows a mixer M_3 and interpolation oscillator of frequency f_i which shifts the frequency of the harmonic-filter output by a variable amount usually equal to the spacing between the harmonics. The following filter separates the shifted frequency from the other sideband and harmonic-filter frequency. The output of the device is then $nf_c \pm f_i$ depending upon which sideband is used.

All the filters in the system are fixed. The two variable oscillators are brought out to two dials, the calibration of f_v being in whole numbers intervals of f_c, and its setting to the required whole number need not be exact. The total scale length is the length of the interpolation dial multiplied by the number of harmonic intervals. The frequency scale on both dials may be made linear by quite easy shaping of the condensers, with the scale from zero to the required maximum.

The principle may be extended so that the interpolation oscillator f_i is replaced by a generator of the same nature as Fig. 4 in which all elements are of a correspondingly lower order and, if necessary, the process may be repeated indefinitely, say, on a decade system. The detailed design of such a system will be discussed later.

3. GENERAL PRINCIPLES APPLIED TO RECEIVERS

The generators described above may be used as the local oscillator of a normal heterodyne receiver, with obvious advantage to the stability and setability of the frequency scale. There is some difficulty in providing pre-selection in a receiver of this nature, unless the pre-selection is controlled separately from the main tuning, on account of the fact that the frequency law of the local oscillator is not suitable for ganging to *L.C.* circuits at the signal frequency, unless a somewhat complicated system is devised.

By integrating the general principles described with a multiple heterodyne receiver certain advantages may be obtained. The first intermediate frequency may be made higher than the band covered by the receiver and, consequently, the image response may be removed by a fixed low-pass filter. The receiver input may be aperiodic when this is desirable, otherwise pre-selection may be provided in addition and switched in and adjusted separately.

The receivers to be described in this paper are of this nature. Figs. 5, 6 and 7 show three variations of the principle. That of Fig. 5 is considered the most useful and its design will be discussed in detail.

Referring to Fig. 5, the system in the dotted lines is seen to be that of Fig. 1 in which the harmonics of a 1-Mc/sec crystal are filtered at 37·5 Mc/sec. The oscillator covers 40·5 to 69·5 Mc/sec for a receiver covering 0 to 30 Mc/sec, the harmonics from the 3rd to the 32nd being used. The two frequencies, f_v and $f_v - nf_c$, instead of being combined to derive nf_c, are applied as the oscillator voltages to the first and second mixers of a multiple heterodyne. The first i.f. is 40 Mc/sec and has a bandpass somewhat wider than the spacing of the harmonics. The first mixer is preceded by a low-pass filter to remove the image response and the response to the 40-Mc/sec i.f. This is preceded by the necessary r.f. amplifiers and pre-selective circuits as required. The net effect of these two conversions is to transform the signal frequency by an exact integral number of Mc/sec. By way of example, consider a signal frequency say 15·4 Mc/sec. The 18th harmonic is used. f_v is set to 55·5 Mc/sec and the 18th harmonic is thus filtered at 37·5 Mc/sec. In the signal channel 55·5 Mc/sec heterodynes the incoming 15·4 Mc/sec to 40·1 Mc/sec which is within the first i.f. bandpass. The second conversion with 37·5 Mc/sec gives 2·6 Mc/sec. This is finally detected by a 2 to 3-Mc/sec interpolation receiver shown within the dotted lines. The signal frequency band 15 to 16 Mc/sec is transferred and actually inverted to 3 to 2 Mc/sec. This inversion is of no account and arises out of the fact that the harmonic-filter frequency is below the first i.f. This is done to avoid using the harmonic of zero order for the band 2 to 3 Mc/sec.

The setting of the oscillator f_v is not critical provided the 18th harmonic lies within the harmonic-filter bandpass, as may be seen by assuming f_v to be, say, 55·4 Mc/sec in the above example. The image response of the first mixer would be about 95·5 Mc/sec and can be adequately suppressed by the low-pass filter. The image response of the second mixer lies between

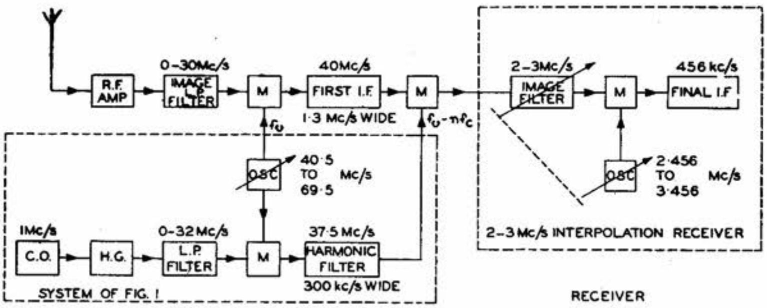


Fig. 5

34·5 and 35·5 Mc/sec and is removed by the first i.f. filter. The 2 to 3-Mc/sec interpolating receiver may be of any suitable design to give the final selectivity required. Its detailed design will be considered later. At this stage it might be noted that the final i.f. is open to choice and may be made as low as necessary, say, 100 kc/sec. This is

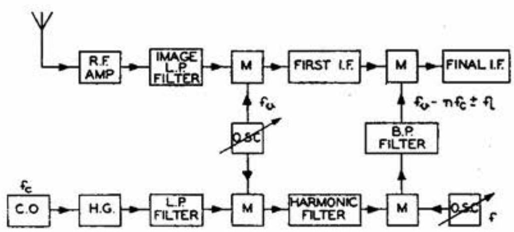


Fig. 6

an advantage shared with most multiple heterodyne receivers. The interpolation receiver may itself be a receiver of the nature of the whole of Fig. 5 of a lower order of frequency, if a finer degree of control is required, or the oscillator of the interpolation receiver may be a generator of the type described previously.

The receivers of Fig. 6 and 7 are variations of the receiver of Fig. 5. Fig. 6 may be described as a double heterodyne to which the interpolation arrangement of Fig. 4 has been applied. It has the disadvantage that the final i.f. must be considerably more than half the harmonic interval, that is, 500 kc/sec unless the first i.f. is narrow and variable. Even with a high final i.f. the design of the first i.f. for image protection of the second mix is difficult. The receiver of Fig. 7 may have a fairly low final i.f. as the second i.f. filter may be made as narrow as the harmonic filter but it is more than likely that harmonics of the interpolation oscillator in the signal channel would give trouble. The receivers of Fig. 6 and 7 will not be discussed further. That of Fig. 5 will form the basis of a detailed discussion.

4. DESIGN OF HARMONIC GENERATORS

Before dealing with the receiver in detail the design of the harmonic generators which is common to all equipment of this type will be discussed. To produce the harmonic spectrum with all harmonics approximately equal in amplitude requires

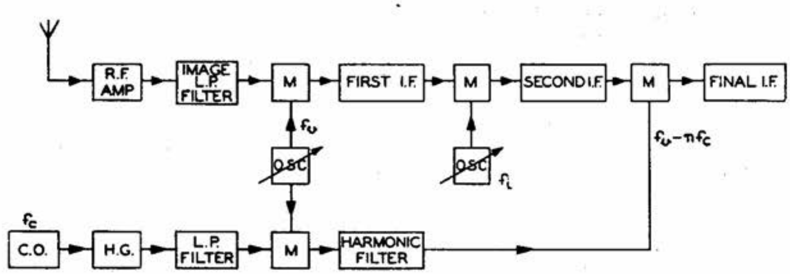


Fig. 7

in effect the production of a pulse of duration less than half a period of the highest at a recurrence of the crystal frequency. For the receiver described, this is a pulse of about 0·01 microseconds at 1-Mc/sec recurrence.

A very simple way of doing this is shown in Fig. 8. A high mutual-conductance pentode is driven from a sinusoidal source of sufficient swing via a short time-constant coupling, in such a way that the voltage passes through the grid base of the valve at the highest rate of change of the voltage wave. This corresponds to the point when $V\sin 2\pi f_c t$ is zero and the rate of change is $2\pi f_c V$ volts/sec. A peak voltage of, say, 50 volts gives a rate of change of

give a voltage pulse of the required dimensions. The back kick will be quite small if the screen constants are correctly adjusted. There is a tendency for the 4th harmonic to be weakened if this adjustment is wrong.

4·1 *Level of harmonics at harmonic mixer*

The pulses from the harmonic generator are applied to the harmonic mixer via a low-pass filter to remove the harmonic spectrum above the wanted maximum. The impedance of this filter should be higher than the impedance of the differentiating inductance at the highest frequency. This usually presents no problem as the pulse can in general be made at a far higher

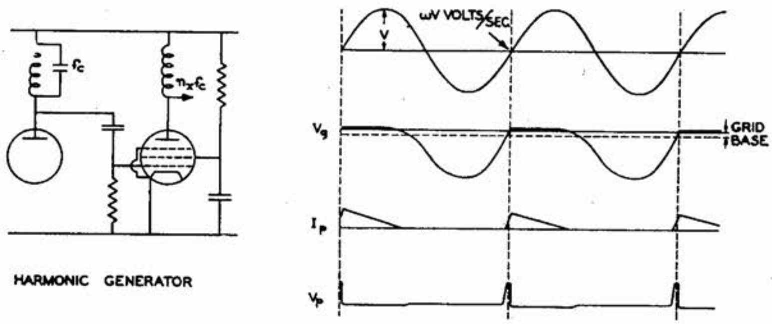


Fig. 8

3×10^8 volts/sec which would cause the grid voltage to swing through a grid base of 3 volts in 0·01 microsecond. The time constant of the grid circuit is adjusted to achieve this, a time constant of about one-fifth of the period being required. Values of 10 pf and 22 000 ohms are approximately correct for a 1-Mc/sec spectrum. After sweeping through the grid base the grid draws current for about a quarter cycle after which the valve cuts off relatively slowly at the peak of the voltage wave but returns again to the grid base at the next instant the wave is at its maximum rate. By suitably adjusting the screen time constant, the plate current can be made to cut off slowly immediately the valve is switched on, this rate of change being negligibly small compared with the rate of switching on. A plate-current wave as shown in the diagram results. The plate load is made inductive and this results in the differentiation of the current wave to

level than is required and kept suitably small by reducing this inductance, although in a receiver it is perhaps better to make the inductance a maximum and reduce the level by reducing the screen voltage of the harominc generator, in order to avoid producing a higher harmonic current which may couple into the signal circuits.

The level of the pulse at the mixer grid must not be more than about one-third volt otherwise the non-linearity of the grid characteristic will distort this pulse and re-introduce the unwanted harmonic spectrum which the low-pass filter has removed. This will give rise to image components and harmonics at the harmonic-filter frequency in the harmonic-filter output. By keeping the level down to, say, one-third volt these effects will given rise to spurious frequencies in the harmonic-filter output some 60 to 70 db below the wanted harmonic. Reducing the level below one-third volt would improve this effect but would give rise to spurious noise frequencies for the following reason. For the case of 30 harmonics, one-third volt pulse level corresponds to harmonics of about 10 millivolts each at the mixer grid. The equivalent noise level at the grid of a mixer of the type used, usually a pentagrid or similar, is a few microvolts, referred to a bandpass of, say, 10 kc/sec, which is representative of the final bandpass in which these effects will be observed in an average case. This noise level is thus some 70 db down on each harmonic and therefore the one-third volt level of the pulse represents a compromise between these two effects.

A conversion gain of 100 or more is required from the grid of the harmonic mixer to the output of the harmonic-filter circuits to produce a signal of useful level in most cases. This involves perhaps two amplifiers following the mixer at higher frequencies and perhaps one at lower frequencies.

To reduce the effect of the reformed harmonic spectrum at about the harmonic-filtering frequency and also to simplify the design of the low-pass filter, the harmonic-filtering frequency can with advantage be placed between two harmonic frequencies, for example, 37·5 Mc/sec in the case of the receiver of Fig. 5.

4·2 *Design of filters*

Efficient filtering is essential at all stages of these devices. The degree of filtering required is often more than can be provided by simple coupling circuits, say, a coupled pair of tuned circuits between two mixers, particularly in cases where no amplifier is required between such mixers. In these cases multi-element filters are required with from perhaps four to seven sections.

Low-pass filters may be of the simplest type if the lowest frequency at which they are required to attentuate is well removed from their cut-off frequency. Resonant sections may be used when these frequencies cannot be well separated, although in general an extra section or two is preferable to an extra tuning adjustment. At frequencies up to about 30 Mc/sec satisfactory low-pass filters may be made with surge impedances up to 1 000 ohms using valve capacities only at the ends.

The bandpass filters required are usually fairly narrow compared with their centre frequency. This requirement can be most easily met by a number of inductively coupled circuits as shown in Fig. 9. These tuned circuits are inductively coupled to the adjacent coils only. Coupling to other sections is avoided by enclosing the filter in a screening tube, or long box of such a cross-section that the wave attenuation down it is high. This is achieved by making the cross-sectional dimensions comparable with the coil spacing. The attenuation of such a filter to frequencies well away from the operating frequency is extremely high, the effect of stray modes of coupling being small. This is important in the case of receiver designs as will be explained below.

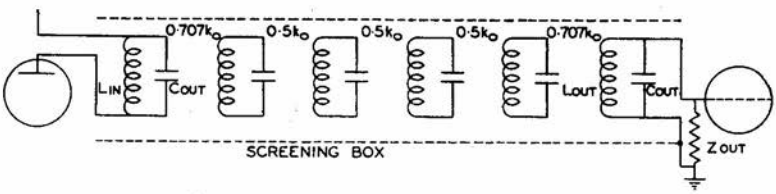


Fig. 9

Electrical design details for these filters are as follows :—

$$\text{If } k_0 = \frac{\text{bandpass}}{\text{centre/frequency}}$$

then end sections are coupled $0{\cdot}707\ k_o$

and intermediate couplings are $0{\cdot}5\ k_o$

$Z_{in} = \dfrac{Z_{Cin}}{k_o}$; $Z_{out} = \dfrac{Z_{Cout}}{k_o}$; voltage transformation $= \sqrt{\dfrac{Z_{out}}{Z_{in}}}$

where $Z_{Cin} = Z_{Lin}$ at the centre frequency.

The filter is terminated in a resistance $= Z_{out}$.

The input and output sections may be of any suitable impedance to meet the valve requirements. The intermediate sections may be any impedance provided the coefficient of coupling to adjacent sections is as shown. All coils should have as high a Q as possible to minimize insertion less but in any case must have a Q greater than $\frac{2}{k_o}$.

More complicated filter designs can result in some economy of components but often require special care in adjustment. In the case of bandpass filters in which the band is wide relative to the centre frequency, more involved designs must be resorted to but, for most purposes in these applications, the above filters have proved simple and satisfactory.

5. DETAILED CONSIDERATION OF RECEIVER DESIGN

The receiver of Fig. 5 has been investigated in detail and the necessary design precautions and requirements will now be discussed.

5·1 *Selection of frequencies and filter performance required*

The range covered (0 to 30 Mc/sec) represents the requirement of a general purpose short-wave receiver. The band 0 to 1 Mc/sec is included although the filtering arrangements have broken down as will be explained later but, nevertheless, its inclusion is quite useful. No attempt, however, is made to provide high performance at these low frequencies.

The first i.f. is 40 Mc/sec. This is well removed from the top r.f. frequency of 30 Mc/sec and the signal-image filter can be easily designed to have at least 60-db suppression at 40 Mc/sec. Its bandpass of 1·3 Mc/sec is designed to accommodate the 1 Mc/sec-wide signal channel plus 300 kc/sec tolerance for the setting of the first oscillator.

The harmonic-filter frequency of 37·5 Mc/sec is below the first i.f. and the harmonics 3 to 32 are used. Placing this frequency above the first i.f., that is, 42·5 Mc/sec, would involve the use of the harmonics −2, −1, 0, 1, 2 up to 27 Mc/sec. Some difficulty then arises in separating the first harmonic from that of order zero, that is, the oscillator frequency. The oscillator is very much stronger than each harmonic at the harmonic mixer unless a balanced mix is used. In this case the difficulty, although relieved, would still exist.

The harmonic-image filter must pass 32 Mc/sec and suppress 37·5 Mc/sec by some 60 db. Some further protection against 37 and 38 Mc/sec is provided by the choice of 37·5 Mc/sec as the filtering frequency. This image filter is not quite as easy as the signal-image filter as the frequencies involved represent the minimum for a simple low-pass design for reasonable number of sections. Hence the original choice of 40 Mc/sec for the first i.f.

The choice of interpolation frequency 2 to 3 Mc/sec arises from a number of reasons. The possible alternative 1 to 2 Mc/sec would give trouble with intermodulation products from the second mixer, which may exist up to 1·3 Mc/sec, this being the bandpass of the first i.f. filter. The image protection of the second mixer would be somewhat more difficult although this is not a real limitation. The severest requirement would be the adjacent harmonic suppression required from the harmonic filter, as these harmonics would have to be down some 120 db at least on the required harmonic otherwise they would demodulate against the required harmonic to give a blocking signal at one end of the interpolation scale. With the interpolation frequency 2 to 3 Mc/sec the adjacent Mc/sec harmonics need only be down some 60 to 80 db to avoid the formation of spurious channels on adjacent r.f. signals removed 1 Mc/sec from the main signal. These channels receive a further slight protection as they exist outside the edge of the first i.f. filter. The harmonic-filter suppression at the harmonic two removed from the required harmonic must then be down some 120 db or more and this can be achieved fairly easily.

The choice of interpolation frequency 1·5 to 2·5 Mc/sec is possible but would lead to less elegant scales.

The final i.f. frequency in this design was chosen as 456 kc/sec simply to make use of standard i.f. transformers. In this case two loosely coupled circuits at the 2 to 3 Mc/sec image filter are sufficient to make the image due to the final mix down some 70 db. A standard three-gang condenser is used in the interpolation section for this purpose. The interpolation oscillator frequency coverage follows from the above.

There are a multitude of other possible designs for the interpolation section. Two of these may be mentioned. A final i.f. of 750 kc/sec or so would enable a fixed 2 to 3 Mc/sec image filter to be used, with possible advantage in, say, a panoramic receiver with a 1-Mc/sec display. Some trouble would perhaps arise with intermodulation products in the third mixer. The other possibility is to use a lower i.f. of, say, 100 kc/sec with its obvious advantages, although this would involve perhaps three sections of image protection at the 2 to 3-Mc/sec filter.

The design of the first i.f. filter is usually set by the requirement that it must effectively prevent the first oscillator voltage appearing in the second mixer on the band 1 to 2 Mc/sec, that is, when the first oscillator is set to 41·5 Mc/sec approximately. This cannot be done on the band 0 to 1-Mc/sec as the first oscillator at 40·5 Mc/sec then lies within one edge of the first i.f. filter. This explains the remarks on this point referred to above. This effect gives rise to spurious signals on this band but the band is nevertheless included in this design for what it is worth. The effect may be minimised by a balanced first mix, although this was not done in the design under discussion. For the band 1 to 2-Mc/sec this suppression at 41·5 Mc/sec should be as high as is economically practical, say, about 40 to 60 db down. If this requirement is met, other requirements of this filter, that is, image protection of the second mixer will be more than adequate.

5·2 *Spurious signals*

The generation of spurious signals is a feature of all multiple heterodyne receivers which must be carefully considered in the design of such receivers. In addition to these other spurious signals peculiar to the receiver under discussion must be guarded against.

The most common source of these signals arises from the fundamental or harmonics of any one oscillator breaking into any mixer other than that with which it is associated, to heterodyne with the fundamental or harmonics of the oscillator associated with this mixer to give a frequency equal to that to which the following circuits are sensitive. The combinations in which these can exist are almost without number and the harmonics concerned often extend into the hundreds and even thousands of Mc/sec. The level at which these signals can cause trouble can be of the order of microvolts or less, at the mixer concerned.

These spurious signals can be completely eliminated once their cause is fully understood. The first requirement is that each oscillator and its associated mixer be placed, together with any amplifier and components associated with the input or output in a separate screened compartment. Secondly, these compartments must be connected via the necessary filters which transmit only the band of frequencies required. Spurious modes of coupling between the elements of the filter must be avoided. For instance, an ordinary i.f. transformer can have a spurious mode of coupling which constitutes a high-pass filter to some very high frequency in which the shunt inductances of the condenser leads are coupled via stray capacity. The screened multi-section filters described in paragraph 4·2 are very effective in eliminating such effects. Thirdly, the power leads to each compartment must be filtered by single-section low-pass filters, with particular attention to the very high frequency efficiency of such filters.

The first and second mixers of this receiver are more susceptible to this trouble than the third mixer as their oscillator frequencies are of the same order. Nevertheless, in this receiver, a spurious mode of coupling from the second to third mix arose due to a parallel resonance of the fixed capacity on the 2 to 3-Mc/sec variable condensers, with the inductance of the rotor and stator plates, to give a band-pass coupling with stray capacities to 37·5 Mc/sec in a certain position of the plates. This 37·5 Mc/sec gave spurious signals in the third mix with a harmonic between the 11th and 16th of the interpolation oscillator. Re-distribution of the components to give a low-pass mode to the spurious coupling removed the trouble.

These spurious signals, if they do occur in this receiver, can always be shifted away from the channel to which the receiver is tuned by a re-setting of the first oscillator.

A more difficult sort of spurious signal peculiar to this receiver occurs at the zero and 1 000-kc/sec mark on the interpolation dial. This can arise from a number of causes although the effect is the same. Firstly, inadequate performance of the harmonic filter at the second and third harmonic removed from the wanted harmonic as explained in section 5·1. This can occur as a result of bad bonding of the longitudinal joints of the filter screen, destroying the wave-attenuating property of the screen, even although the design of the filter is adequate. A second cause is direct leakage of the second and third harmonic from the crystal oscillator and harmonic generator section into the third mix. This is unlikely with good power filtering and general screening. A third cause is direct leakage of the harmonic spectrum into the input of the receiver or first mixer. The same remark applies to this. Fourthly, the harmonic spectrum can couple into the first mix via the harmonic mixer as they are fed from the same oscillator. This effect can cause considerable trouble in the design. Its elimination requires the use of a pentagrid mixer for the harmonic mixer, with small coupling between grids, and electron coupling with a broad-band circuit from the plate of the first oscillator to the harmonic mixer whilst the signal mixer is supplied from the oscillator tuned circuit in the cathode. Fifthly, the frequency components 39·5 Mc/sec and 40·5 Mc/sec which are generated in the harmonic mixer can couple into the first i.f. filter or first mixer. This can be eliminated by the measures under case four and by avoiding coupling between the input of the harmonic-filter and the first i.f.-filter.

When all these points have been attended to, this source of trouble disappears with the possible exception of direct break through from the crystal oscillator when the receiver is set to 1 Mc/sec.

5·3 *Spurious channels*

Spurious channels of the nature of true image channels arising at any signal mixer can, in this receiver, be reduced to negligible proportions and are usually difficult to detect at all. Spurious channels can also arise due to the spurious frequency components in the output of the harmonic filter as explained in Section 4·1. These channels, which arise in the second mix, will be as much down on the main channel as these spurious frequencies are down on the wanted harmonic, that is, some 60 to 70 db. These channels move with respect to the main channel as the first oscillator is displaced. This, in fact, applies to any spurious effect in either the first or second mixer with the exception of cross-modulation effects in so far as a shift of the first oscillator constitutes a shift of the first i.f., without any corresponding shift of the main channel. These remarks, however, do not apply to any effect in the third mixer, for example, direct-image or second-harmonic conversion.

A broad noise channel can also occur as a result of the noise components of the harmonic filter which will also be down some 70 db on the main channel.

5·4 *Cross-modulations, intermodulations and levels*

It is often convenient to work the input stages of this receiver aperiodic when conditions permit. This is particularly attractive in this receiver due to lack of image troubles. Also with modern valves quite satisfactory noise figures can be obtained for this purpose. Aperiodic or alternatively wide-band pre-amplifiers are often used extensively in suitably sited receiving stations, and hence favour the use of an aperiodic input.

The design of the receiver for this purpose must be considered particularly in regard to cross-modulations and intermodulations as affected by the level at which each mixer works.

Intermodulations are unlikely to arise at the third mix on account of the frequency bands involved, nor are they likely at the second mix for the same reason explained in Section 5·1. They will, however, occur at the first mixer when the input is a periodic. Cross-modulations, except adjacent channel cross-modulation, is unlikely at the third mix on account of the relatively narrow band of the 2 to 3-Mc/sec image filtering, more likely at the second mix on account of its wider band of 1·3 Mc/sec and will occur at the first mixer as a result of any very powerful transmission in any part of the spectrum.

The third mix may therefore be at relatively high level, that is to say, a reasonable gain may be provided from second to third mix although, of course, no amplifier is called for. The first and second mix should, however, work at as low a level as possible. Again very little more than unity should be provided from the first mix to the second mix. This can be simply met as the bandpass filter has a fairly low impedance for the bandpass required and little gain is possible. The r.f. gain should be must sufficient for the r.f. tube noise to over-ride all the following mixers. High mutual-conductance tubes are used for the r.f. stage, which has a gain of about 4, and also for the first and second mix which consequently have relatively low noise levels. The third mixer is a pentagrid.

The equivalent noise resistance of the whole chain is about 2 000 ohms, that of the r.f. tube itself being about 1 200 ohms. Noise figures with the input aperiodic can therefore, with a 400-ohm input, be better than 10 db at all frequencies.

5·5 *R.F. tuned circuits*

Some degree of r.f. pre-selection must be provided for general purpose use on account of cross-modulation and intermodulation effects. Intermodulation products must give rise to the first i.f. of 40 Mc/sec approximately and, in general, the two r.f. frequencies which might cause intermodulation are well removed from each other, except when both are in the region of 20 Mc/sec. A high degree of pre-selection is therefore not necessary on this account, if it can be assumed that field strengths at 20 Mc/sec are rarely excessive.

The difficulty of ganging in pre-selection has been mentioned in Section 3. In the design under discussion a single-stage of pre-selection is provided in the grid of the r.f. amplifier only. This requires no ganging on a second section and consequently can be peaked for maximum performance in much the same way as an aerial trim adjustment. This tuned input also enables the noise figure to be brought near the thermal limit at any suitable input impedance. A noise figure of about 2 or 3 db is achieved at the lower frequencies and about 6 db at the highest.

On account of cross-modulation effects, more pre-selection would perhaps be desirable, although the complication would be increased. The cross - modulation performance of this receiver at frequencies well removed from the main channel is worse than a receiver with more pre-selection, although its performance for near channel cross-modulation is perhaps better than most, as most receivers tend to have excessive r.f. gain at some parts of the band. The problem of cross-modulation can be very troublesome under circumstances where it is essential to work transmitters and receivers in close proximity. This problem often calls for special pre-first stage tuners of involved design. As a precaution against the receiver becoming unworkable in a strong wanted or unwanted field, an aerial attenuator has been included. This is apparently a modern practice. Its use of course will lower the noise figure but this often is of no account when external noise and interference is high or signals are strong.

5·6 *Overall performance of receiver*

The overall performance of the receiver which has been described is as follows :—

Coverage—0 to 30 Mc/sec with the band 0 to 1 Mc/sec included, although the performance on this band is not equal to that on the rest of the coverage.

Stability—From cold to 2 hours after switching on, the drift is not more than 200 cycles/sec at the lower frequencies and 500 cycles/sec at the highest frequency

Stability—Frequency scales linear and setable to 1 kc/sec at any frequency

Spurious signals—Not higher than the internal noise except the breakthrough of the crystal at 1 Mc/sec

Spurious channels—All image channels and other spurious channels down at least 60 to 70 db on the main channel

Sensitivity—10 db or better with the input untuned at an impedance of 400 ohms.

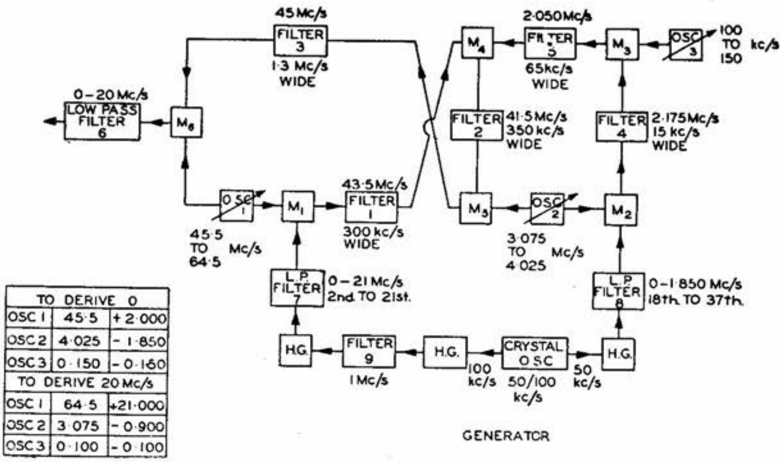
With the input tuned at 70-ohms impedance the sensitivity is 2 to 3 db at the lower frequencies and 6 db or better at the highest frequency.

6. DETAILED CONSIDERATION OF GENERATOR DESIGNS

The design of useful generators for controlling a transmitter or for general purpose use is still being investigated.

One such design has been completed and will be described in detail. It was intended for use as a transmitter drive although it is probably more suitable as a general purpose instrument. A contemplated design for an economical transmitter drive, which should meet the requirements, will also be discussed.

The circuit arrangement is not a simple extension of the generator of Fig. 4 in so far as the interpolation frequency to the first section is never derived as such but exists only as a difference between the frequencies applied to M_4 and M_5 which are successive mixers in the first section. This system has the same number of mixers and filters as the simpler system, the filter *2* replacing a low-pass filter and M_5 replacing M_2 of Fig. 4. The reason for doing this was to enable the lower harmonics of the 50-kc/sec spectrum to be used. In principle this method can interpolate a difference varying



TO DERIVE 0		
OSC 1	45·5	+ 2·000
OSC 2	4·025	− 1·850
OSC 3	0·150	− 0·160
TO DERIVE 20 Mc/s		
OSC 1	64·5	+21·000
OSC 2	3·075	− 0·900
OSC 3	0·100	− 0·100

Fig. 10

6·1 *Description of generator*

Fig. 10 shows the general arrangement of the generator, excluding incidental amplifiers. It covers the range 0 to 20 Mc/sec and is a two-stage device with three dials. The first selects the harmonics of a 1-Mc/sec spectrum, the second adds to the harmonics of a 50-kc/sec spectrum, while the third controls an interpolation oscillator adding in the variable fraction of 50 kc/sec.

A pentagrid converter runs a crystal oscillator at 100 kc/sec and at the same time counts down two to 50 kc/sec. A harmonic generator and filter produces the 10th harmonic of the 100 kc/sec to give 1 Mc/sec, from which the 1-Mc/sec spectrum is derived as in the receiver. The 50 kc/sec is treated in the same way.

from 0 to 1 Mc/sec, which of course is impossible with the simple system. This was, in fact, done originally and, whilst sound in principle, it was abandoned on account of practical difficulties. This interpolation now covers 1 to 2 Mc/sec in effect.

6·2 *Selection of filtering frequencies*

Filter *3* is made 45 Mc/sec which is more than twice the coverage, to avoid a second harmonic of this filter frequency mixing with the fundamental of oscillator *1*, to give a frequency within the coverage. This is the same problem as arises in an audio best frequency oscillator for the same reason. Higher-order combinations can exist but are very much less troublesome. A lower frequency may be possible with suitable precautions. This will be discussed in the last section.

With an interpolation coverage of 1 to 2 Mc/sec the harmonic filter *1* at 43·5 Mc/sec follows, as does the first oscillator coverage. The harmonic series 2 to 21 Mc/sec is used as a result. This is an advantage of a 1 to 2-Mc/sec interpolation as against a 0 to 1-Mc/sec interpolation, as the first harmonic, which is difficult to separate from the oscillator frequency is avoided. A further advantage is that any given output frequency is derived from a harmonic differing at least 1 Mc/sec from it. Otherwise the output may equal or differ very little from the original harmonic used with possible trouble due to the output leaking into mixer *1* which works at a fairly low level, that is, about 10 millivolts. A further advantage is that it avoids the harmonic-filter frequency lying within the band of filter *3* with possible coupling trouble.

In the second section the harmonic spectrum 18th to 37th of 50 kc/sec is used which, together with the oscillator *3* covering 100 to 150 kc/sec, gives the required interpolation 1 to 2 Mc/sec. The oscillator *3* is made 100 to 150 kc/sec rather than say 50 to 100 kc/sec to avoid any harmonic lying within its span, that is, second harmonic of 50 kc at 100 kc/sec. The mix at mixer *3* is a subtraction to help lower the harmonic order used. Filter *5* is nominally 2 Mc/sec and oscillator *2* nominally 3 to 4 Mc/sec, the small discrepancy arising from incidental causes. The harmonic filter *4* frequency of 2·175 Mc/sec follows from the above. This frequency is as before placed between two harmonics, hence the odd figure and part of the above discrepancy. This harmonic filter frequency is rather close to the top harmonic frequency of 1·850 Mc/sec and consequently the harmonic low-pass filter design is near the limit. The frequency of filter *2* follows.

6·3 *Levels and spurious signals*

The same considerations apply to the level of each spectrum at each harmonic mix as in the case of the receiver. The level of each feed to a mixer which is at a lower frequency than the following filter must not be too high, to avoid harmonics of this feed appearing in the following filter. This applies to oscillator *3* into mixer *3*, filter *5* into mixer *4*, and oscillator *2* into mixer *5*. In all these cases the harmonic order involved is quite high and no great difficulty is experienced in this respect, as long as this possibility is appreciated and also suitable valves are used, for example, pentagrids or similar.

6·4 *Filters and screening*

The screening requirements are not as severe as in the case of the receiver as all circuits work at fairly high level. All filters are screened and are of the nature described in Section 4·2. Harmonic filters consist of six sections and all other filters five sections.

6·5 *Overall performance*

The output of the device with the necessary output amplifier is about 1 volt at 70 ohms. The overall stability equals that of the crystal itself at any frequency above about 1 Mc/sec. It operates quite effectively down to zero frequency and the interpolation scale may be checked by a zero beat with all dials at zero, and also at the other end of the scale at minus fifty and plus fifty on the last two dials.

All scales are linear, the minor divisions being 250 cycles at any frequency. The readability of dials is perhaps 50 or 100 cycles.

Spurious output frequencies are down 60 db on the main signal in respect of all components away from the main signal and 70 db or more on components which may beat with the main signal. The noise level is also some 70 db down, referred to a 10-kc/sec bandpass.

6·6 *Contemplated design*

The above design is somewhat complicated for transmitter drive purposes. A simpler design of a one-stage generator is contemplated of the nature of Fig. 4, in which the coverage is 2 to 5 Mc/sec based on a harmonic spectrum of 100 kc/sec. The stability of such a system could perhaps be very nearly that of the crystal, the interpolation oscillator being 200 to 300 kc/sec. On the grounds of stability it is possibly uneconomic to go further than this, but on the grounds of readability of scales a factor of about 8 would be lost compared with the above generator when deriving a frequency near 20 Mc/sec, that is, the interpolation dial would lose a factor of 2 and a multiplication of 4 would be required in the transmitter.

The harmonic-filtering frequency would be in the region of, say, 7 Mc/sec, with a bandpass of, say, 50 kc/sec. This design is perhaps a bit difficult but modern core materials should ease this difficulty. The possibility of a spurious mix of the second harmonic of the harmonic-filter frequency would have to be taken into account as mentioned in Section 6·2.

The setting accuracy could be allowed for in the following manner. An auxiliary interpolation oscillator of no great stability could be switched into circuit in place of the interpolation oscillator, while the output of the whole device is used to set the frequency of the main interpolation oscillator on, say, the tenth harmonic of the latter. For example, to set up, say, 3·456 700 Mc/sec, the interpolation oscillator must be set to 256 700 kc/sec. If the whole instrument with the aid of the auxiliary oscillator be set to generate 2·567 Mc/sec, the zero beat with the tenth harmonic of 256 700 kc/sec may be used to set the main interpolation oscillator with the aid of a build-in detector and phone jack. The main interpolation oscillator is then switched back and the first dial set to 3·4 Mc/sec. This system would of course be of no assistance in checking the frequency while the transmitter is running but could be done at any time the transmitter is idle.

7. CONCLUSION

Problems of adequate frequency control of flexible equipment to meet modern requirements are continually confronting the radio engineer to-day. The methods described are capable of easing these problems, although the exact form in which they should be applied to any particular requirement requires further investigation. The technique is not easy but none of the associated problems are insuperable. Equipment employing these methods can be mechanically simple and robust and are extremely simple to operate efficiently. The difficulties of their design they share with all other methods directed to the same ends.

8. ACKNOWLEDGMENT

The author wishes to thank the Council for Scientific and Industrial Research for permission to present this paper and to demonstrate the equipment.

9. REFERENCE

1. Impulse governed oscillator. *Philips Transmission*, Century House, Shaftesbury Avenue, London.

DISCUSSION

A. Birrell (Associate Member): The application of the principles described by Mr Wadley makes possible the design of a receiver which possesses ideal characteristics for communication purposes :—

a High accuracy of frequency setting
b High stability (virtually crystal stability)
c Continuous frequency coverage without bandswitching
d Constant calibrated bandspread of 1 Mc/sec.

Other receivers are available in which these characteristics are obtained by the use of multiple crystals and considerable mechanical and electrical complexity. The simplicity of Mr Wadley's receiver from a manufacturing and maintenance point of view compared to such receivers is a revelation.

For the specialized diversity receivers employed on commercial radio telephony and telegraphy circuits it is felt that the application of the frequency generator as the first heterodyning oscillator of the receiver, is preferable to the application of the principles outlined, directly to the receiver.

It is in the application to transmitter frequency control, as a frequency generator that these principles are likely to be most valuable. The international frequency tolerance generally applicable to services operating between 4 000 and 30 000 kc/sec is $\pm$ 30 parts in 10^6 While stability much greater than this can be achieved by the use of crystal control the difficulty of producing crystals whose specified frequency is well within this tolerance (say, $\pm$ 15 parts in the 10^6) is difficult and expensive.

Some interesting monitoring records compiled during 1950 and 1951 by the British Post Office revealed that in 1950, 46·9 per cent of all stations checked showed departures greater than $\pm$ 30 parts in 10^6 from nominal frequency, and that for 1951 this was 43·7 per cent.

The required bandwidth for teleprinter operation on frequency shift keying at 20 Mc/sec using a deviation of 425 c/sec is 1 870 c/sec plus the tolerance of 1 200 c/sec. It is probable that in the future a further decrease in tolerances is likely for the efficient utilization of the frequency spectrum. This would require still more accurate control of transmitter and receiver frequency stabilities.

Modern transmitters are usually self-contained with crystal oscillators having ten switch-selected crystal frequencies. This is very inflexible on a large station, and with the present scramble for frequencies it is essential that when a clear frequency has been found by monitoring, it should be immediately occupied. This is not possible with fixed crystal control. In an attempt to solve the first difficulty, the British Post Office have developed an extremely simple aperiodic crystal oscillator, which uses crystals produced to a very rigid specification and which without temperature control can meet a tolerance of $\pm$ 15 parts in 10^6. These oscillators are provided in centralized banks on the basis of one per registered station frequency and are fed by coaxial cable to any desired transmitter. The second problem of a variable oscillator of high stability is under consideration by the British Post Office. A prototype generator requires common equipment producing some 37, frequently oddly related frequencies from a standard source of 100 kc/sec. These frequencies are fed into five modulators to produce any integral multiple of 4 kc/sec between 3 and 7 Mc/sec with interpolation of 4 kc/sec provided by a variable oscillator. The disadvantages of this system are—

a physical size and complexity of the equipment

b the fact that the frequencies are not built up according to a simple system, and require the use of decade switches which are set up to indicate the desired frequency, and indicate the mixing frequency inputs to the various modulators on a lamp display panel. These frequencies are then fed into the five modulators for the synthesis of the desired frequency. The interpolation oscillator is set up to interpolate the final 4 kc/sec.

A commercially available variable oscillator uses twelve crystals and an interpolation oscillator covering 150 kc/sec to give a continuous coverage from 3·45 to 6·9 Mc/sec by using the upper and lower side bands generated with each crystal frequency.

Other systems of frequency synthesis exist, but generally suffer from complexity, and the fact that the setting up procedure is not direct.

The essential simplicity of a frequency generator operating on the principles outlined by Mr Wadley, and covering from 2 to 7 Mc/sec with a first 100 kc/sec harmonic selection dial and a second dial interpolating 100 kc/sec is obvious when compared with the systems mentioned above. Adequate stability could be obtained by ovening the interpolation oscillator and using a high-stability 100 kc/sec master frequency for the whole station. The setting-up accuracy could be ingeniously obtained as outlined in the paper, without necessity for high calibration accuracy of the interpolation oscillator, or by the use of a separate frequency generator to check the tenth harmonic of the interpolation oscillator. The latter method would seem to be preferable for a large station as it would also allow for the checking of the frequency during operation. Such an oscillator could also be readily applied to the control of commercial diversity receivers. The restriction of the range to 7 Mc/sec which is approaching the design limit for a 100-kc/sec harmonic series would be no disadvantage, as frequency doubling and quadrupling is common in such receivers, and also in most transmitters, to restrict the crystal frequency range when crystal frequency control is employed.

A duplicate of the prototype receiver constructed at the Telecommunications Research Laboratories by a post office engineer under Mr Wadley's supervision, has been in use for about two years. This receiver with its high setting accuracy compared to conventional receivers, has proved invaluable on our commercial services as a check receiver, and we consider that such receivers would be extremely useful for monitoring services.

A three-dial frequency generator constructed by Mr Wadley has been in use on one of the Post Office transmitters for several months. The generator frequency is doubled in the transmitter and setting accuracies of the order of $\pm$ 200 c/sec on the final frequency can be obtained without reference to frequency measurement. The internal crystal and the interpolation oscillator in this generator are un-ovened but after warm up, stabilities of the order of $\pm$ 20 c/sec are obtained. This generator in its present form more than meets the stability requirements for international services, but the calibration and setting accuracy is too low at the lower frequencies. This could be overcome very simply by the setting-up procedure outlined in the paper, but it is felt that it would be highly desirable if a calibration and setting up accuracy of $\pm$ 20 c/sec could be obtained in the interpolation oscillator, to allow direct setting up to within tolerance at any frequency.

The Post Office as a result of tests on this generator, has decided to employ frequency generators operating on these principles for the drives to all transmitters which will be installed at the new International transmitting station at Olifantsfontein. The principles may later be extended to receiver control at the International receiving station at Derdepoort, instead of using crystal control on spot frequencies with its attendant disadvantages. The total requirements of both stations would be in the order of 50 units. It is proposed that these generators will be produced by the Post Office, after the development and testing of a prototype.

The general adoption of these principles would undoubtedly lead to improved utilization of the frequency spectrum and considerable economies in outlay on crystals, which would only be used on fixed frequency transmitters.

Mr Wadley is to be congratulated on the contribution which his development of these principles makes to the art of frequency control in radio equipment.

B. J. Stevens : I should like to congratulate Mr Wadley on his excellent paper, and even more on the development which forms its subject.

Communications engineers have been trying for many years to develop a variable-frequency oscillator which would attain the stability of a reasonably good crystal-controlled instrument, and which could be used to control the frequency of transmitters.

While inductance-capacity types of variable frequency oscillators have been developed which would be sufficiently stable for most applications, there are certain instances where the conventional *L.C.* oscillators, cannot meet stability figures of better than 1 part in 100 000. I refer particularly to the need for a variable-frequency-drive oscillator for use with short-wave transmitters in the high-frequency broadcast bands. These bands are now so congested that it has become almost impossible to find a clear channel, and it is becoming more and more necessary to resort to shared frequency working.

An analysis of the results of monitoring by Commonwealth countries of the 6, 7 and 9 Mc/s international h.f. broadcasting bands between 16·00 and 20·00 G.M.T. for the month of January 1953, reveals that in the 6-Mc/s band, which is 250 kc/sec wide, 56 stations were identified in Zone 1, and 61 stations in Zone 3. In addition, some 24 stations were identified outside the band. The maximum number of h.f. broadcasting stations identified in any zone was thus of the order of 85, which gives a spectrum space of under 3 kc/sec per transmission, a very unsatisfactory state of affairs when at least 10 kc/sec is required for music transmissions.

In the 7-Mc/s band, which is 200 kc/s wide, 49 stations were identified in Zone 1 and 56 in Zone 3, with some 30 additional stations identified outside the band. The maximum number of transmission identified in Zone 3 was of the order of 86, which again gives a spectrum width per transmission of approximately 2·3 kc/sec.

The 9 Mc/s band, 275 kc/s wide, contained 49 identified transmissions in Zone 1, 55 in Zone 3 with 20 additional transmissions outside the band. The maximum number of stations identified in any zone was thus 75, which gives a spectrum space of under 3·7 kc/s per transmission.

The South African Broadcasting Corporation (S.A.B.C.) in establishing its proposed new short-wave centre at Bloemfontein, is thus faced with the choice of either trying to find a number of clear channels for operation (an almost impossible task) or of operating on the same frequencies as those used by distant stations. The latter solution, while open to many objections, is the only alternative. However, this method of finding spectrum space by frequency sharing requires that our transmitter carrier frequencies be adjusted to the same values as those of the distant stations, which necessitates the use of variable-frequency drive oscillators. An additional requirement is that our carrier frequencies be sufficiently stable as to remain within a few cycles per second of the other stations, otherwise the transmissions would be marred by low-frequency heterodynes. Since most h.f. broadcast transmitters to-day are controlled by relatively stable drive oscillators (usually) crystal controlled—it should be possible to operate under these conditions fairly satisfactorily—provided that the S.A.B.C.'s drive oscillators are capable of being set to the required frequencies and that they will have a short-time stability of at least one part in a million.

These requirements of relatively high stability, together with an ability to be set to any particular frequency, cannot be met by the conventional *L.C.* oscillator, and the S.A.B.C. was at a loss for a satisfactory solution to the problem when Mr Wadley came to our aid with his radically new design, which should prove completely satisfactory for the purpose.

I must therefore thank Mr Wadley and the Telecommunications Research Laboratory, not only for an excellent paper, but for the development of a piece of equipment which will be of great assistance to us in establishing the proposed S.A.B.C. short-wave centre at Bloemfontein.

H. Dainty: I would like to make a few comments regarding some of the practical problems encountered during the course of constructing receivers to Mr Wadley's design, and based on a prototype provided by the Telecommunications Research Laboratory of the C.S.I.R. As a matter of interest, I will also give a brief description of the latest prototype made, and which is exhibited here to-night.

In the first place, the prototype receiver provided was duplicated without difficulty. The layout of the following receivers was then radically altered in order to make for ease of production. Ordinarily during the normal process of evolving a production sample, one expects to make changes until the final stage is reached. During the development of the conventional type of receiver, radical changes are made without difficulty, but in the case of the Wadley receiver, major changes have to be carefully considered.

The reason for this may have been gathered from Mr Wadley's paper—the necessity for very careful screening and isolation between certain sections of the receiver. This is of paramount importance, if proper performance without the presence of spurious signals is to be secured. Spurious signals can be eliminated to the point where they are inaudible, provided the right technique is employed. This technique, if I may say so, is somewhat foreign to those of us more used to handling and thinking in terms of the conventional type of receiver. However, once a proper appreciation of the design problems of the Wadley-type receiver is arrived at, and the right technique employed, the solution follows.

During the course of the development of the latest model Wadley receiver, the difficulties encountered with spurious signals proved to be extremely frustrating. It was found that the spurious signals present were due to ineffective screening and by-passing, r.f. leaks via power connections to shield compartments, and the generation of spurious responses in the second mixer due to the application of an unnecessarily high harmonic level.

The combination of all these faults at one time proved to be harrowing experience to the unitiated—once the causes had been traced step by step the technique for their prevention and elimination was soon acquired. These points are mentioned, because while the application of Mr Wadley's principles to receiver construction does present some problems, the ease by which they may be surmounted depends on experience. The problems mentioned are peculiar to the designer and manufacturer and will not recur to plague the serviceman.

In spite of the apparent complexity of the Wadley receiver, it is quite easy to manufacture. The more or less complete absence of the usual multiplicity of r.f. tuning inductors and associated switch decks, padders, trimmers, etc., goes a long way towards making for easy production. Apart from the filters, the r.f. inductors which do exist in the receiver are the five simple tapped coils in the r.f. stage grid circuit and the three coils associated with the input of the 2/3 Mc/sec interpolation section of the receiver. The filters are easily constructed. The fact that the receiver is divided into units which may be assembled and wired separately, is also an advantage. The amount of metal fabrication involved is somewhat more than normally required, but this does not represent a production problem. Cast-aluminium compartments and chassis with built-in filter boxes may be employed in the future.

The receiver exhibited is easy to service—all sections are easy to get at and components are conventional. Adjustments are perfectly straightforward, most of them being required in the 2/3-Mc/sec interpolation section which to all intents and purposes is a straightforward superheterodyne, with mixer/oscillator, two 456-kc/sec i.f. stages, detector and two-stage audio amplifier. The signal and harmonic image filters are not adjustable, and the 40-Mc/sec i.f. and 37·5-Mc/sec harmonic filters are slug tuned. It is not anticipated that these filters will need adjustment in the normal course of events. The performance of the harmonic generator chain starting from the 1-Mc/sec crystal stage through to the output at the second mixer grid, can be checked with the aid of an r.f. voltmeter. The use of a crystal diode in series with the test leads of the usual 20 000-ohm per volt test meter serves admirably for this purpose.

The first oscillator in the receiver covers the range 40·5/69·5 Mc/sec, the tuning of which is controlled by the megacycle dial. The required stability of this circuit is easily attained without any special treatment. In any event the overall receiver calibration accuracy is not dependent on this section of the circuit. The tuning of the megacycle dial is quite broad and is merely peaked for noise or signal at the required megacycle point, either by ear or with the aid of the signal-level meter.

The calibration accuracy of the receiver is dependent on the 2/3 Mc/sec interpolation section of the receiver, the tuned input circuits of which are controlled by the kilocycle dial. These circuits are easy to stabilize and calibrate accurately because of the narrow tuning range. The calibration accuracy claimed for this receiver is within 1 kc/sec at any frequency, and stability within 500 cycles per secnd from switch on, after any period and at any frequency.

It will be appreciated that such performance is most uncommon, and can be realized in the conventional receiver only at very considerable expense. In this connection, while final cost and selling figures for the Wadley receiver are not yet available, indications are that these figures will be very modest for a receiver of its class, and will certainly be quite well below imported types with anything like comparative performance.

The latest type Wadley receiver exhibited has seventeen tubes of the miniature B7G base series, and one octal base rectifier. Six of the tubes are associated with the harmonic generator, the balance being accounted for by the r.f. stage, first mixer, first oscillator, second mixer, third mixer, 2/465-kc/sec i.f. stages, diode detector/a.g.c. rectifier/noise limiter, b.f.o. and two stages of audio. No attempt has been made to provide an elaborate audio system the output of the audio amplifier being of the order of 1 watt to the built-in speaker.

Apart from the tuning dials, the following controls are provided :—r.f. input attenuator r.f. trimmer and associated switch for selecting broad band or tuned input, i.f. and audio gain controls, b.f.o. pitch control and on/off switch, a.g.c. and automatic noise limiter switches, and variable selectivity control.

The signal level indicator is a microammeter in series with the diode detector load. It provides a ready means for reading signal level, and incidentally, also serves as a built-in means for checking overall receiver performance. For example, with no antenna connected and full i.f. gain 10 microamps is registered with untuned input and about 25 microamps with tuned input. As most of the noise in the receiver emanates from the r.f. stage, these figures will not be attained if all sections of the receiver are not performing satisfactorily. As a matter of further interest 0·6 of a microvolt input at 15·5 Mc/sec will result in 25 microamps of detector current (about 16·5 volts across the diode load).

A resume of the receiver performance and features is as follows :—

Frequency range—1·30 Mc/sec. The band 0 to 1 Mc/sec is included and is useful over at least portion of this range.

The frequency scale of the dials is directly calibrated, is bandspread over an equivalent of 37 ft, and is linear with frequency. Calibration accuracy is within 1 kc/sec

Stability—Within 500 cycles per second after switch on, for any period and at any frequency

Sensitivity—10db or less at 400 ohm untuned, and 6 db tuned

S.F. bandpass—5 kc/sec normal, 3 kc/sec at broad crystal and continuously variable down to 160 cycles/sec at narrow crystal position

Image channels—Down 60 db or more.

As may be imagined, the receiver described has a character (if one can describe it so) all of its own. Its appeal grows with use, and I predict that it is a receiver which will become a firm favourite with operators. To those not accustomed to operating a receiver with such a high degree of accuracy, the unfailing performance in this respect will be a revelation. It has other uses, for example it makes a very useful laboratory tool.

In conclusion I would like to pay tribute to the S.A. Council for Scientific and Industrial Research for making the design of the T.R.L. crystal-controlled receiver available for manufacture by South African industry and to pay tribute to Mr Wadley for his extremely valuable contribution to the State of the art.

T. C. B. VLOK (Associate Member): It gives me great pleasure to contribute to the discussion on Mr Wadley's fine effort. I have handled a receiver based on the principle demonstrated to-night and can say that the frequency selection is somewhat startling to one who is accustomed to main dial plus vernier (and its calibration). My only criticism is that, for receiver application, the final stage still depends on the frequency stability of an *L.C.* oscillator, but over a band of 1 Mc/sec as the width specification frequency stability is only a mild problem. I hope members will agree that much publicity must be given to this new technique so that the application can become widespread and become a useful tool in the practice of radio.

The Defence Department were sufficiently impressed with this new departure that it has sponsored the production of six prototypes.

T. G. E. COCKBAIN (Associate): I have been fortunate enough to have had the opportunity of conducting some tests with a receiver using the Wadley principle. These tests were conducted mainly in the field, using the receiver in a mobile radio station. For this reason I shall confine my remarks to the application of the principle to receivers.

The receiver under test was produced by a South African commercial firm for prototype trials, and as it was one of the first, was not perhaps as elegant in appearance as the later models, which look very impressive. Its true worth became apparent as soon as we started to use it for communications, however, and the following points became clear :—

a The apparatus is easy to use
b The excellent frequency accuracy, and consequent re-setability of the receiver simplified operating procedure, and saved time and temper, particularly when conditions were poor
c The absence of tricky setting-up procedures to ensure accuracy of the tuning scales was very welcome, particularly after some sad experiences with three other types of high-accuracy receivers
d The stability of the receiver, even from cold, was outstanding.

In amplification of the above remarks, let me say that a side-by-side test was conducted with the Wadley receiver and one of the very expensive American receivers which makes a special point of its extremely accurate calibration. This receiver covers the normal communications band in steps the r.f. stage, these figures will not be attained if all sections of the receiver are not performing satisfactorily. As a matter of further interest 0·6 of a microvolt input at 15·5 Mc/sec will result in 25 microamps of detector current (about 16·5 volts across the diode load).

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In amplification of the above remarks, let me say that a side-by-side test was conducted with the Wadley receiver and one of the very expensive American receivers which makes a special point of its extremely accurate calibration. This receiver covers the normal communications band in steps of one megacycle, switched by successive half-turns of a conventional bandswitch. A slide-rule type dial covers the first interpolation, and an engraved scale showing integral kc/sec is attached to the main tuning knob, being read against an adjustable pointer. This pointer is set by calibrating the tuning dial against a built-in 100-kc/sec crystal oscillator.

In practice, the Wadley receiver, in spite of the fact that its dial calibrations are spaced 5 kc/sec apart, proved at least equal to this comparison receiver in accuracy, and every bit as good in sensitivity. The short-term and long-term stability of the Wadley appeared to be superior especially from cold. Once the slight differences in operating technique required for the Wadley were mastered by the operators, they expressed a preference for it, and used it normally for schedule operating. The Wadley proved a lot easier and more consistent in its frequency accuracy, due in part to the fact that the comparison receiver gave a certain amount of trouble in setting up, due to crystal oscillator drift and b.f.o. setting. Thus it is fairly safe to say that the practical accuracy to be expected from the Wadley would be better than that of the comparison receiver. Only one really noticeable defect was present in the Wadley receiver tested, namely, that a frequency shift could be noticed due to loading of the input, when a nearby transmitter was keyed. (It should be mentioned that the transmitter was not supplied off the same power as the Wadley). This took the form of a slow chirp, continuing for more than a second, until a new stable operating point was reached. The magnitude of this frequency shift was of the order of 250 cycles per second. The comparison receiver did not suffer a similar shift. I am informed that this trouble will be ironed out in the later models.

The delightful mechanical simplicity of the Wadley receiver compares favourably with other high-precision receivers, in particular with the very complex mechanical arrangements on the comparison receiver used. In addition, no large batch of crystals is required to provide the precision megacycle bands, and simplified controls render it an easy receiver to use. For these reasons, the Wadley appears to be a much cheaper receiver to produce, especially in quantity. Maintenance would probably be considerably simpler and less costly, while the apparent stability of the calibration leads one to believe that it could be run for long periods without much attention. The ease with which this design lends itself to adaptation to panoramic reception, makes it quite attractive as a military receiver. On balance, therefore, the application of the Wadley principle to communications receivers has everything to recommend it, and I hope that some enterprise will produce these receivers in quantity. The only factor militating against such a happy development, as I see it, may be the lack of a quantity market in this country, and therefore I hope that some steps will be taken to enable the overseas market to be exploited.

With the advent of this reasonably cheap high-accuracy, high stability receiver, I should like to see some effort put into the development of an adaptor for frequency-shift reception, employing straightforward filters, thereby eliminating the present complex discriminator-type adaptors.

PROFESSOR G. R. BOZZOLI (Vice-President): The Institute is fortunate in having been given the opportunity of first making public the details of this remarkable receiver and Mr Wadley deserves no little praise for his achievement. There is little doubt that both his receiver, and its offspring, the continuously variable signal generator of crystal stability will find many uses both in laboratories and in communications. As a laboratory instrument, the signal generator has no equal. Any of us who have used signal generators both of the cheaper general purpose type and of the more expensive specialized type have felt the lack of adequate calibrated bandspread and the shortfall in stability of frequency, both long and short term. This instrument will probably fall between the two in price and far surpass the more expensive in performance. It will place within the reach of University laboratories a secondary standard of frequency of great versatility.

The success of the device, whether a receiver or a generator, clearly lies in the care taken over filtering and shielding. Owing to the high frequencies normally involved, capacitances used are often of the same order as valve stray capacitances. This immediately raises the question of servicing and valve replacement. The author has not discussed servicing although he has dealt fully with spurious responses and I would be very interested to know with what ease service could be carried out. It would seem to me that should a fault manifest itself by the appearance of an unwanted signal or heterodyne whistle, the serviceman might find considerable difficulty in locating the cause and removing it. Has the author considered the advisability of drawing up comprehensive instructions for the location of such defects? Such instructions would probably need to be a small treatise on the combination frequencies possible. The serviceman would also probably have to include in his kit, suitable frequency-measuring equipment.

V. R. Krause (Associate Member): I should like to add my congratulations to Mr Wadley for his remarkable, original and even historic contribution to the art.

I feel that the full benefits and repercussions of his contribution cannot at present be appreciated. It is impossible to foresee all the possible applications for this valuable new tool. The idea is so different from the usual that, as in the case of the transistor, we are required to think along different lines from the conventional and to use new thought approaches, to fully appreciate the potentialities of the system.

With regard to the application of the system to receivers, which was the main application discussed in the paper, Mr Wadley's development has given us an ideal method of setting the frequency of the receiver to the required incoming signal. In eliminating the wave change system common to more conventional systems we are presented with a very real advantage. However, in a really first class communications receiver of the general coverage type, it is a considerable advantage, for obvious reasons, such as noise considerations, to have one or possibly two stages of pre-selection. The tuning of the preselector stages over such wide ranges as required in a general coverage receiver must, at present, be done by conventional *L.C.* circuits which bring us back to the wave-change switch. It is a pity that we have not a parallel development to Mr Wadley's wide-band oscillator system, which could be applied effectively to the tuning of the input signals.

These remarks, of course, do not apply when the receiver is to be used for fixed frequency point-to-point service, for example in diversity applications. In this case wide bands of frequency coverage are not usually required and r.f. pre-amplification is a relatively simple matter. The problem arises when high performance is required under the flexible conditions usually imposed upon general coverage communications receivers.

With regard to spurious responses and beat troubles which are common to multiple heterodyne systems, it is desired to draw attention to the Mixer Harmonic Chart, by Thomas T. Brown, published in the mid-June 1953 issue of *Electronics*. This chart simplifies the identification of beats produced by the various harmonic combinations of two frequencies. No doubt a similar form of chart or charts could be developed in a reasonably short time to be especially applicable to the present problem. Such a chart would probably prove of considerable value in identifying quickly any spurious response, particularly during development. It might prove helpful with one of the problems described by Prof Bozzoli in connection with servicing.

In the case of the system being applied to generators for the primary control of the frequency of large transmitters, a possible difficulty is foreseen. Under these circumstances the generator will probably be operating in a field of high intensity (and complexity) caused by the transmitters. Should the output frequencies of the transmitters be of the same order as the frequency of any of the signals within the various oscillator-mixer chains, then difficulties might arise. The careful shielding and filtering used within the equipment to adequately control the spurious responses generated within the various sections of the equipment, while proving adequate for that purpose, might not be capable of dealing with the intense external fields.

This type of trouble, it is felt, will be encountered only occasionally as it will often be the case that the frequencies of the transmitters will not be sufficiently near oscillator or mixer frequencies to form new and undesirable signals. It is felt, however, that a very real and serious problem may be presented under some circumstances.

G. ff. Bellairs (Associate Member): This paper describes the successful outcome of a remarkable piece of original research. Mr Wadley's technique has solved the old problem of the communcations engineer, which may be described as the development of a 'rubber crystal' which could be squeezed to provide a number of alternative frequencies, each, however, having full crystal stability. The author has achieved an equivalent result in a neat and practical manner, and I think that his technique is likely to become standard practice in the construction of communication type receivers in the future.

I must confess that I am not too happy when I read of a new development unless I can form a mental picture of the processes involved. I was not able to do this while reading the paper as presented by the author, and I feel that there may be others present who also have experienced some difficulty in visualizing exactly what takes place in this ingenious receiver. I have, therefore, drawn out a frequency diagram, using the symbolism generally employed in depicting the frequency translations of a carrier telephone system. In the diagram the frequencies are shown on the horizontal scale, and the rest of the diagram shows the various frequency spectra occurring in the receiver of Fig. 5 in the paper. Part A of Fig. A shows the frequency spectrum of the 1-Mc/sec crystal X accompanied by the harmonic series spaced at megacycle intervals extending up about 32 Mc/sec beyond which point the low-pass filter has suppressed all higher harmonics. This may be regarded as a 'fence-post' spectrum. Part B of the figure shows the frequency S of the signal to be received, the frequency V of the variable valve oscillator and the sum and difference products $V + S$ and $V - S$. The pass-band of the first i.f. filter is also shown and it will be observed that V must be positioned very roughly so that $V - S$ falls within the band of this filter. Part C of the figure shows the result of inter-

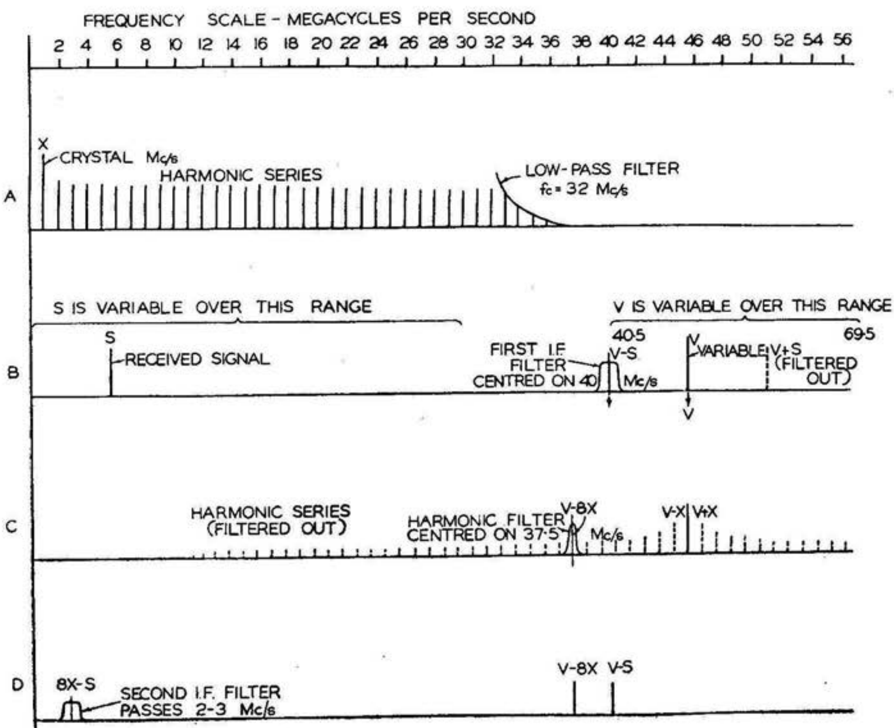

Fig. A

modulating the valve oscillator frequency V with the 'fence-post' spectrum of Part A. The result is a double 'fence-post' spectrum centred on the frequency V. In this figure is also shown the pass-band of the harmonic filter centred on 37·5 Mc/sec. It will be noticed that in the example chosen, one of the lines of the 'fence-post' spectrum (namely that corresponding to $V - 8X$) falls within the pass-band of this filter. All the remaining lines in the spectrum are filtered out and suppressed. Part D of Fig. A shows that the object of the foregoing manoeuvres is the production of the two difference frequencies $V - S$ and $V - 8X$ respectively. These two are intermodulated and, disregarding the sum product which is filtered out, we are left with the difference product which is $8X - S$. V does not enter into this result and it will, therefore, be noticed that the effect has been to move S in frequency by an integral number of megacycles. The product $8X - S$ passes through the second i.f. filter to the interpolation receiver, where it is treated in the ordinary way.

I must confess that the operation of the generator shown in Fig. 10 proved too much for my powers of mental appreciation! I feel it would be very helpful if the author could produce some form of frequency diagram for this generator, possibly on the lines employed in Fig. A.

T. L. Wadley (*in reply*) : The possibility of intense fields from transmitters causing trouble within a generator is a very real one which must be taken into account in the design of the screening of the equipment.

Trouble in this respect is anticipated only at the input of the harmonic mixer, as all other circuits are at relatively high level. In the case of a generator covering up to 7 Mc/sec at present under development, the harmonic filtering is performed at 8·250 Mc/sec, and a powerful field within 50 kc/sec of this might cause trouble. The leakage signal at the harmonic mixer input would have to be not more than about 10 to 30 microvolts. It should be possible with suitable screening to keep below this level.

In the case of an individual transmitter interfering with itself, the difficulty could be overcome by a shift of this filtering frequency by re-adjustment.

RULES AND REGULATIONS FOR THE ADMINISTRATION OF THE BURSARY SCHEME OF THE INSTITUTE

OBJECTS

The Education and Bursary Fund shall be utilised in the first place for awards as outlined below, the nature and extent of the awards to be reviewed from time to time with regard to the amount standing to the credit of the fund.

One of the initial objects of the scheme is to aid Student Members of the South African Institute of Electrical Engineers in their technical education by giving them financial assistance in the purchase of books, instruments etc. The basis of selection of a candidate for a bursary shall be the progress made by him in his studies, and his financial position.

NUMBER AND VALUE OF BURSARIES

Bursaries of a minimum of £20 0s 0d each, tenable for one calendar year, will be awarded annually; the number and value of the bursaries will depend on the number and merit of the applicants and the amount of money available in the Bursary Fund. One or more bursaries may be awarded to students at any one institution.

ELIGIBILITY OF CANDIDATES

(i) Candidates must be Student Members of the South African Institute of Electrical Engineers.

(ii) Candidates must be attending an educational engineering institution, taking correspondence courses with such institution or be engaged in private technical study.

(iii) Awards may be made to a student at any stage of his studies.

(iv) The receipt of a bursary shall not debar a student from re-applying in any subsequent year.

SELECTION OF CANDIDATES

(i) Students will be advised annually when and how to apply for bursaries.

(ii) On completion, the application forms will be forwarded to the Secretary of the Institute. Where applicable these forms will be submitted by the Institute to the Heads of Departments of the institutions concerned for report to the Education and Bursary Fund Committee which will make recommendations to Council.