An improved aluminium conductor

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SYNOPSIS

The paper discusses some factors which are responsible for the widespread use of aluminium in the transmission of electricity. It draws the attention to the limitations and handicaps of aluminium for this purpose and discusses the development of an improved aluminium conductor from the indigenous electric grade aluminium (purity >99·5). The conductor so developed and designated PM-2 is shown to possess better electrical conductivity, higher strength and improved corrosion resistance.

Successful trials on rolling and wire drawing have been completed on the semi-industrial scale at the Indian Cable Company, Jamshedpur.

WHILST aluminium can compete with copper as a conductor of electricity on its own merits, it unfortunately suffers from inferiority complex as it is commonly regarded as a substitute of copper forced upon the electrical industry due to the shortage of indigenously produced copper. Even in countries where import of copper is not a problem, transmission of electricity by aluminium conductor is proving economical and its use is advocated not as a substitute but as a serious competitor of copper on its own merits. The engineering requirements of a conductor material are that it should be (i) plentiful and not too expensive, (ii) an adequate conductor of electricity, (iii) mechanically strong to withstand stresses and strains, (iv) ductile and strong enough to be rolled and drawn into wires and (v) should compare satisfactorily with a copper conductor cable in performance, reliability, durability and cost.

Aluminium meets most of these requirements and is extensively available in India. The Geological Survey of India has placed the reserves of bauxite in the country as follows:

(i) proved 22·4 million tonnes,
(ii) indicated 18·65 million tonnes,
(iii) inferred 131·72 million tonnes.

The production and import of electric grade aluminium is continuously rising (Table I). It is anticipated that almost 50% of the planned aluminium production of 150 000 tonnes in 1970–71 will be used to transmit electricity. Since the policy of the Government has been to grant import licence only for the actual users of the electric grade aluminium, much of the imported aluminium is used for the purpose of manufacture of cables.

TABLE I Indigenous production and import of aluminium

	Indigenous production	Import
	(in tonnes)	
1963–64	55 986	24 532
1964–65	55 742	19 410
1965–66	66 889	20 282
1966–67	74 231	32 862

Figures furnished by DGTD and published in Industrial India 1968, 19, 19–23.

Electrical properties of aluminium

The electrical conductivity of aluminium is second only to that of copper amongst engineering conductor materials. For equal electrical resistance an aluminium conductor has one and a half times the cross sectional area of copper but weighs only half as much. But the conductivity can be made equivalent to that of copper by increasing the conductor size by two gauges. It can normally carry 78% of the load that can be carried by copper conductor of equal cross sectional area for the same rise of the temperature. It is also noted for its non-toxicity, non-magnetic and non-sparking property. Besides, in international market the cost of copper conductor is 3-4 times more than that of equivalent aluminium conductor. Some of its physical properties are compared with those of copper in Table II.

Although aluminium resists corrosion in many atmospheric and chemical enviroments by virtue of its

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TABLE II Properties of aluminium and copper wires used for electrical conductors

Property	Aluminium wire IS:398-1953/61	High conductivity annealed copper wire IS:694(Pt.I)-1964
Density at 20°C (gm/cm²)	2·703	8·89
Weight/cu. ft (lb)	169	555
Coefficient of linear expansion (°C × 10^{-6})	23	17
Melting point °C	659	1083
Specific heat (cal/gm)	0·23	0·092
Thermal conductivity at 0°C (cal/sec./cm²/cm/°C)	0·54	0·92
Standard resistivity at 20°C (microhm-cm)	2·845	1·724
Temperature coefficient of resistance per °C at 20°C	0·004	0·00393
Tensile strength (lb/sq. in)	21 000–27 000*	33 600–35 840
Fatigue endurance limit (ton/in²)	±3·8 approx (5 × 10^8 reversals)	±4·5(10^7 reversals)

*For overhead conductors, aluminium wire is used in the fully hard drawn condition with minimum tensile strength values ranging from 23 000 to 25 600 lb/in² according to wire diameter as compared with the minimum of 21 000 lb/in² for HIE-H.

naturally formed protective oxide film, it corrodes rapidly when exposed to moisture under conditions that exclude air and those having traces of chlorine. Another disadvantage is that it is not as strong as copper. Use of aluminium in electrical transmission calls for the development of an aluminium conductor with high conductivity and adequate strength. These are divergent metallurgical objectives since the conductivity decreases as alloying elements are added to the lattice of aluminium to raise its strength. Upgrading of Indian electric grade aluminium is, therefore, important if the process improves the strength and conductivity simultaneously and imparts better corrosion resistance. The problem of conductivity of Indian aluminium is important as it seems to have forced the Indian Standards Institution to relax in a subtle manner the minimum requirements of conductivity.

Experimental work

In order to impart the Indian electric grade aluminium competitive and exclusive properties, a programme of basic research was undertaken to determine the effect of binary solute additions of silicon, iron, manganese and magnesium, each up to 1%, on its electrical conductivity and strength. It was shown that the conductivity can be improved if the soluble impurities are removed by (i) heat treatment (ii) suitable alloy additions (iii) by both, through precipitation of their intermetallic compounds. Whilst substantial improvement in its conductivity was obtained on prolonged ageing between 350 and 400°C, the tensile strength fell considerably. Significant and simultaneous improvement in both conductivity and tensile strength was obtained only when the soluble impurities were rendered insoluble in the liquid state; any further heat treatment in the solid state was unnecessary and the conductor could retain high strength due to work hardening.

An earlier publication[1] described the upgrading of electric grade aluminium. The PM-2 conductor was successfully rolled and drawn into wires corresponding to the specification of the ACSR conductors. Table III summarises its physical and mechanical properties and shows its superiority over a hard drawn conductor according to Indian Standard 398 : of 1953 and 61.

In order to investigate the influence of silicon and copper on inferior gardes of aluminium containing 0·6–0·9%Fe a number of semi-commercial wirebars, designated PM-7 to PM-16 were cast. The wirebars (30 kg each) were prepared by melting the constituent

TABLE III Electrical and mechanical properties of PM-2 conductor* as compared with different standards for EC grade aluminium

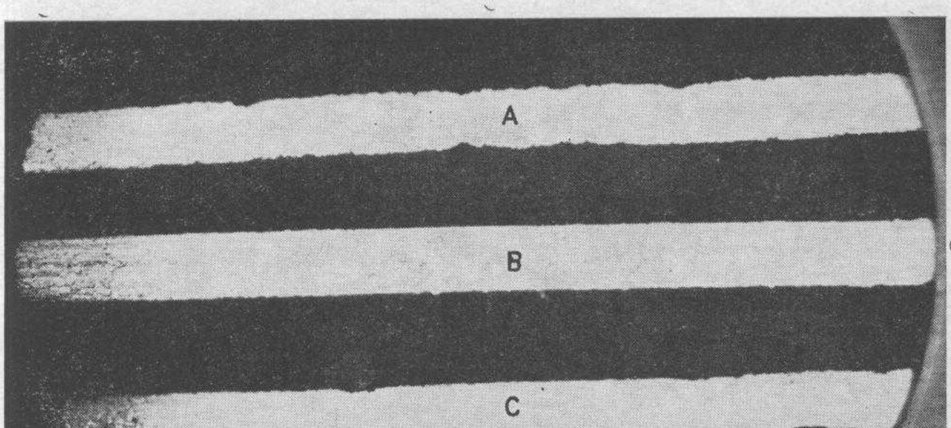
		PM-2	Indian 398–1953/1961	British/Astm 215–1956/B 230–1960
1.	Resistance, ohms/km, at 20°C	4·585	4.654	—
2.	Resistivity at 20°C, microm—cm	2·810	2·873	2·8264/2·8264
3.	Conductivity at 20°C, % IACS	61·4	60·0	61·0/61·0
4.	Tensile strength—Psi	28,400	24,200	24,200/24,500
5.	Improvement in T.S.	15%	—	—
6.	Elongation on 10″ gauge length	3·5%	1·9%	—/1·5
7.	Wrapping test	Passes	6 wrapp round on its own diam.	6 wrapp round on its own diam.

* Test carried out by the Indian Cable Company Ltd., Jamshedpur.

TABLE IV Electrical and mechanical properties of PM-6 to PM-16 conductor wires (2·79 mm. dia.)

Conductor designation	Composition %			Electrical resistance Ohm/km at 20°C	Electrical conductivity % IACS	Breaking load kg	Wrapping* test
	Si	Fe	Cu				
PM 6 (i)	0·61	1·02	—	4·740	59·6	126	Passes
PM 6 (ii)	0·68	0·82	—	4·774	59·2	124	,,
PM 7 (i)	1·22	0·68	—	4·725	59·8	129	,,
PM 7 (ii)	1·20	0·83	—	4·787	59·04	133	,,
PM 8	0·65	0·80	0·04	4·758	59·4	124	,,
PM 9	0·84	0·80	—	4·761	59·3	123	,,
PM 10	1·39	0·78	—	4·797	58·9	131	,,
PM 11	0·80	0·78	0·02	4·761	59·3	125	,,
PM 12	0·81	0·89	0·04	4·817	58·6	139	,,
PM 13	0·88	0·77	0·02	4·803	58·8	130	,,
PM 14	1·09	0·83	0·035	4·805	58·8	144	,,
PM 15	1·72	1·02	0·02	4·860	58·07	141	,,
PM 16	—	—	—	—	—	—	—

*6 wrapp round on its own diameter.
1. Standard resistance (IS 398 : 1961 at 20°C)—4·654.
2. Minimum breaking load in kg (IS : 398 : 1961) 105.



1 *Shows the comparative surfaces of (A) Imported (B) PM-2 and (C) Indigenous aluminium conductor wires after their exposure to wet chlorine atmosphere for 48 hours (Figure magnified 3·5 times)*

TABLE V (A) Electrical and mechanical properties of PM-6 to PM-16 conductor wires after ageing

	200°C, 2 hours			200°C, 4 hours		
Conductor designation	Resistance at 20°C, ohm/Km	Conductivity at 20°C, % IACS	Maximum stress, Psi	Resistance at 20°C, ohm/Km	Conductivity at 20°C, % IACS	Maximum stress, Psi
PM6 (i)	4·35 4·35	64·97 64·97	14560 16160	4·45 4·29	63·62 65·80	22110 22110
PM6 (ii)	4·24 4·54	66·63 62·22	18000 18400	4·33 4·43	65·30 63·84	22110 23160
PM7 (i)	4·38 4·51	64·53 62·67	19200 18960	4·55 4·54	62·08 62·25	22630 21050
PM7 (ii)	4·95 4·94	66·63 62·22	18400 17200	4·68 4·64	60·38 60·86	23690 24210
PM8	4·61 4·64	61·26 60·86	17360 17920	4·27 4·31	66·27 65·63	22110 22630
PM9	4·51 4·47	62·73 63·21	16800 17600	4·62 4·62	61·21 61·21	22630 22630
PM10	4·59 4·59	61·57 61·57	18400 18000	4·63 4·62	61·03 61·21	22630 21790
PM11	4·56 4·51	61·99 62·67	17840 17600	4·47 4·53	63·15 62·40	21580 22110
PM12	4·60 4·63	61·44 61·05	20240 20800	4·61 4·64	61·31 60·84	25480 25480
PM13	4·57 4·68	61·85 60·40	19200 19200	4·63 4·62	61·00 61·21	24210 24720
PM14	4·50 4·51	62·81 62·67	20800 21120	4·62 4·53	61 25 62·40	25990 26310
PM15	4·64 4·64	60·91 60·91	20480 20400	4·73 4·56	59·76 62·00	25260 26310
PM16	—	—	—	—	—	—

metals in an oil fired furnace, using flux and degasser and were cast without any special precautions for oxide-free metal. Their composition and properties are tabulated in Table IV. Except PM-16, all the alloys were successfully rolled and drawn into wires with the same rolling and drawing sequence as for the electric grade aluminium at the works of M/s Indian Cable Company Ltd., Jamshedpur. Although the wires were superior in respect of mechanical properties, they failed to pass the Indian Standards for resistivity. The effect of heat treatment was investigated in the hope that ageing at 200, 300 and 400°C for 2-4 hours might improve the conductivity with only a slight loss in strength. A summary of the results in Table V shows that conductivity could be improved only at the cost of tensile strength.

The PM-2 conductor

Attention was, therefore, concentrated on the satisfactory development of the PM-2 from electric grade aluminium. Four wire-bars weighing 30 kg each, PM-17 to PM-20, were made in order to study the effect of variation of the nominal PM-2 composition on strength and electrical properties. The wire-bars were also rolled and drawn into ACSR conductors (2·5 mm-dia.) successfully at the Indian Cable Co. Ltd., Jamshedpur and satisfied the Indian Standards as shown in Table VI.

Corrosion tests

A number of samples of conductor wires made from

TABLE V (B) Electrical and mechanical properties of PM-6 to PM-16 conductor wires after ageing

Conductor designation	300°C, 2 hours			300°C, 4 hours		
	Resistance at 20°C, ohm/km	Conductivity at 20°C, % IACS	Maximum stress, Psi	Resistance at 20°C, ohm/km	Conductivity at 20°C, % IACS	Maximum stress, Psi
PM6 (i)	4·28	66·04	11040	4·28	66·0	14200
	4·42	63·95	11040	4 28	66·0	14200
PM6 (ii)	4·34	65·13	10800	4·12	68·68	13900
	4·37	64·68	10800	4·39	64·33	14200
PM7 (i)	4·39	64·38	10800	4·46	63·40	14200
	4·33	65·28	10800	4·46	63·40	14200
PM7 (ii)	4·39	64·38	11200	4·57	61·80	14730
	4·43	63·80	11200	4·24	66·57	14730
PM8	4·39	64·38	10800	4·60	61·35	14010
	4·39	64·38	10800	4·59	61·57	14010
PM9	4·35	64·97	10800	4·52	62·47	13690
	4·34	65·13	10800	4·52	62·47	13900
PM10	4·61	61·31	11200	4·65	60·75	14730
	4·59	61·52	11200	4·61	61·31	13900
PM11	4·56	61·98	10720	4·60	61·45	14730
	4·56	61·98	10640	4·60	61 45	13930
PM12	4·63	61·00	15050	4·51	62·70	14930
	4·57	61·80	15260	4·47	63·15	14930
PM13	4·59	61·60	14200	4·60	61·36	14930
	4·56	61·90	14530	4·54	62·0	14200
PM14	4·62	61·21	15790	4·52	62·40	15580
	4·62	61·21	15580	4·42	63·86	15580
PM15	4·69	60·26	15790	4·55	62·0	15580
	4·66	60·67	15790	4·65	60·7	15790
PM16	—	—	—	—	—	—

PM-2, indigenous and imported aluminium were exposed to wet chlorine atmosphere for a period up to 48 hours. Fig. 1 shows that the surface of the conductor wire made from indigenous and imported aluminium was heavily corroded in comparison with that of PM-2. When exposed to sodium hydroxide atmosphere, generated by passing compressed air through a normal solution of sodium hydroxide, PM-2 conductor suffered less corrosion than either of the other two.

Earthing tests

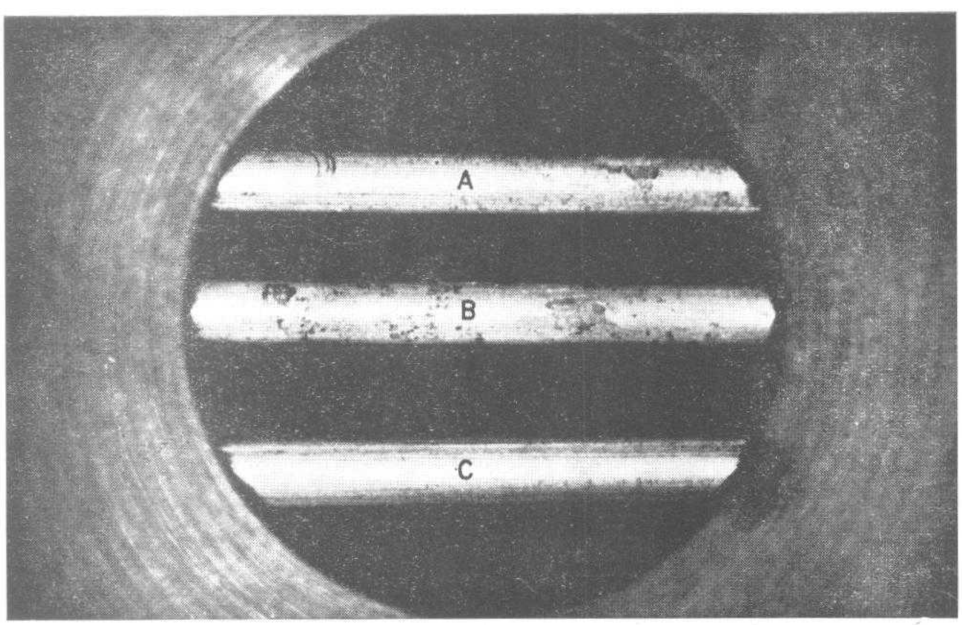
Since several failures of aluminium conductor in earthing wires were mentioned to us by electrical engineers, the corrosion resistance of PM-2 was compared with indigenous and imported aluminium conductors by keeping them in a mixture simulating the earthing conditions, i.e. alternative layers of charcoal and common salt. Fig. 2 shows that pitting had started in indigenous and imported grades of conductor but was substantially less in PM-2.

Conclusions

The upgraded PM-2 conductor claims the following :

TABLE V (C) Electrical and mechanical properties of PM-6 to PM-16 conductor wires after ageing

Conductor designation	400°C, 2 hours Resistance at 20°C, ohm/km	Conductivity at 20°C, % IACS	Maximum stress Psi	400°C, 4 hours Resistance at 20°C, ohm/km	Conductivity at 20°C, % IACS	Maximum stress Psi
PM6 (i)	4·29 4·24	65·80 66·57	14200 14200	4·26 4·20	66·31 67·35	14200 14200
PM6 (ii)	4·37 4·08	64·57 69·24	14200 14200	4·44 4·27	63·62 66·00	14200 14200
PM7 (i)	4·42 4·41	63·84 64·00	14200 14200	4·47 4·40	63·15 64·38	13690 13690
PM7 (ii)	4·41 4·45	64·00 63·38	14200 14200	4·41 4·36	64·00 64·81	14200 14200
PM8	4·49 4·44	62·92 63·62	14200 14200	4·46 4·41	63·40 64·00	14200 14200
PM9	4·43 4·37	63·84 64·57	14200 14200	4·49 4·56	62·92 62·00	14200 13900
PM10	4·48 4·52	63·15 62·47	14200 14200	4·56 4·57	62·00 61·80	14200 14200
PM11	4·27 4·27	66·00 66·00	14010 14010	4·23 4·23	66·82 66·82	13690 13690
PM12	4·42 4·39	63·84 64·33	14730 14850	4·49 4·63	62·92 61·14	14730 14730
PM13	4·55 4·57	62·00 61·80	14200 14200	4·51 4·51	62·70 62·70	14200 14200
PM14	4·56 4·60	61·90 61·35	15260 15260	4·56 4·56	62·00 62·00	14930 14930
PM15	4·57 4·55	61·80 62·00	15260 15260	4·50 4·57	62·70 61·80	14930 14730
PM16	—	—	—	—	—	—



2 *Shows the comparative degree of pitting in (A) Imported, (B) Indigenous and (C) PM-2 Aluminium conductor wires after keeping them in a mixture simulating earthing conditions (Figure magnified 3·5 times)*

TABLE VI Electrical resistance and breaking load values for aluminium conductors*

Conductor designation	Dia. of wire drawn (inches)	Resistance of HD wire at 20°C, ohm/km	Breaking load of the wire (kg)	Wrapping test (6 round wrap on its own diam.)
PM 17	0·0981	5·776	84	Passes
	0·0982	5·723	89	
PM 18	0·098	5·735	105	,,
	0·098	5·735	98	
PM 19	0·0982	5·715	102	,,
	0·098	5·710	104	
PM 20	0·0982	5·760	103	,,
	0·098	5·710	105	
PM 2 (i)	0·0982	5·776	90	,,
	0·0982	5·710	90	
PM 2 (ii)	0·0982	5·785	90	,,
	0·0982	5·800	94	
PM 2 (iii)	0·098	5·800	102	,,
	0·0981	5·776	100	
Indigenous (A)	0·0983	5·800	84	,,
	0·0983	5·785	85	
Indigenous (B)	0·0983	5·776	92	,,
	0·0981	5·800	94	

*IS : 398/1961 specifications :
Standard resistance at 20°C – 5·802 ohm/km
Minimum breaking load (kg)—84·6.

(i) practically no additional cost
(ii) mechanically strong and capable of being rolled and drawn into wires without change in existing machinery.
(iii) superior electrical properties, 15% higher strength and improved ductility than specified in the Indian Standards.
(iv) better corrosion resistance.

The superior anti-corrosion and electrical properties of PM-2 additionally suggest its use for the screening cables. Its replacing the ordinary electric grade aluminium for overhead conductors manufactured by the process involving hot rolling, would be advantageous in view of the general industrial experience that the tensile properties of the conductors from electric grade aluminium are not adequate for the specifications.

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The authors would like to record their thanks to M/s Indian Cable Company Ltd., for giving them extensive facilities at their Jamshedpur works and in particular to their Production Manager Shri K. P. Ganapathy for his keen interest and stimulating discussion. Thanks are also due to Dr T. Banerjee, Scientist-in-Charge, National Metallurgical Laboratory, for his interest in this project and to the Mechanical Metallurgy Division of the NML for carrying out the mechanical test on the specimens.

Reference

1. Kumar, R. and Singh, M. : Electrical Conductivity of Some Aluminium Alloys, NML. Symp. on Metallurgy of Substitute Ferrous and Non-ferrous Metals, 1966.

Discussions

Mr **V. K. Agrawal** (Hindustan Aluminium Corpn. Renukoot) : The author has compared the maximum tensile and electrical properties obtained in PM-2 conductor with minimum properties given in IS-398 for drawn EC wire. We have observed that in actual practice if the purity of the EC grade metal used for the casting of wire bars is high i.e. silicon-0·10% max., Ti+V+Mn+Cr 0·015% max., it is possible to get over 62% IACS conductivity in 3/8″ dia. rolled rods and above 61·4% IACS conductivity in drawn wires. Further, by using a proper sequence of wire drawing operation, it is possible to attain about 10-15% higher tensile strength in the drawn wires than what is mentioned in IS-398. In the international standards for drawn EC wires for conductors (B.S. 215/ASTM B-230) the minimum electrical conductivity requirments is 61% IACS and not 60% IACS as given in IS-398. This is probably because in the year 1961 when this IS standard was drafted, the purity of the EC grade metal available in the country was not as good and so the conductivity standard was lowered. The purity as well as the availability of the EC grade metal in the country now has improved considerably as compared to what it was in the year 1961 and it is possible to get the higher electrical and mechanical properties in the drawn EC wires (comparable to PM-2 conductor) as indicated above.

It is mentioned that sometimes it is not possible to meet the tensile strength requirement in drawn EC wires as per IS-398 when the starting material used is the wire bar. This may be true, but the problem can be overcome either by using ½″ dia. rolled rod instead of 3/8″ dia. as the starting material for wire drawing or by using small amount of copper say 0·02% in EC grade metal to give the additional strength.

In the development of the PM-2 conductor, EC grade metal from two indigenous primary metal producers has been used as the starting material, but the melt has not been analysed for the minor impurities like Ti, V, Mn, Cr, etc. which have a very marked effect on lowering the electrical conductivity. I assume that these impurities must have been very low, since EC grade metal has been used but I wonder whether it will be possible to attain the properties claimed in PM-2 conductor when these impurities are on the higher side, especially manganese content.

The laboratory scale corrosion studies made for PM-2 conductor are really very interesting and more work should be done to investigate the mechanism of passivity attained in chlorine and sodium hydroxide atmospheres.

If the techniques used by the authors for upgrading of EC grade (99·5% Al) metal could be applied to the upgrading of commercial grade Al i.e. Al of 99% purity with silicon above 0·15% and harmful impurities like Mn, Ti, V, Cr, etc. above 0·10%, it will be a very significant contribution and the availability of conductor grade metal in the country will be substantially increased.

Dr **R. Kumar** (Author) : I am thankful to Sri V. K. Agrawal for his elaborate comments on our paper. However, it is not correct to say that the electrical properties of the PM-2 conductor have been compared with the minimum properties of the IS-398 for drawn EC wires; both the standard and the maximum permissible values of the resistivity have been stated. There is no doubt that if the purity of the electric grade metal is high, a higher conductivity results. The novel feature of our investigation is that it upgrades aluminium of lower purity, which is not otherwise capable of yielding the conductivity value of 61% IACS and can be made to do so as in the case of PM-2 conductor.

We appreciate the point that the requirement of tensile strength in the drawn EC wires, (IS-398), when the starting material is used as a wire bar, can be met by cold drawing from ½″ dia. instead of 3/8″ dia. as is the general practice. This question must, however, be examined in relation to the increased power requirement in the wire drawing operation.

The improvement claimed in the paper relates to the electric grade metal where the associated impurities are naturally low in content. Our work has shown that aluminium of purity less than 99·5% can also be upgraded if a heat treatment cycle is incorporated in between the hot rolling and drawing operations.