EMISSIONS AND COST SAVINGS WITH AN ALTERNATIVE HIGH-CONDUCTIVITY MATERIAL FOR CURRENT COLLECTION

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SUMMARY

The current collector material presently used in urban railway systems in Australia consists of a bar of high-resistivity carbon-based material with impregnated copper. In this paper we show that using an alternative high-conductivity copper–graphite composite material (CGCM) can reduce arcing and electrical losses at the contact point by about 90%. The conductivity of the present contact material is below 5% IACS (International annealed copper standard) whereas that of CGCM is around 80% IACS. The ratio between conductivity values is about 1:16, indicating that energy savings could be significant.

We assess and quantify energy savings using pantograph bars made of copper–graphite composite material (CGCM) on suburban trains in Melbourne through the use of greenhouse emission balloons. The calculation of CO₂ emissions takes into account that 1 kWh releases 890 g of CO₂, and one black balloon represents 50g of greenhouse gases, and therefore, 1 kWh represents 17.8 balloons. Based on actual data for the annual power consumption of the present Melbourne suburban rail franchisee (MTM) of about 170 million kWh, we assessed the direct environmental benefits of using CGCM to be in the range of 75–105 million black balloons/yr. In addition, there are 2.5%–3.5% cost savings associated with this efficiency gain, or about AUD $0.75–0.85 Million per annum, beside other benefits in reduced arcing, lower wire wear and reduced carbon dust pollution on train roofs.

INTRODUCTION

This paper deals with a copper–graphite composite material (CGCM) for sliding electrical contacts [1]. CGCM exhibits advantages in electrical and tribological properties over materials currently in use [2]. The pursuit of lower carbon emissions is now a global effort and train operators are expected to participate in it by minimizing power consumption and reducing overall operating costs. CGCM presents a viable cost-reducing alternative for current collectors in pantographs. Overhead wire wear, arcing and current consumption are lower with CGCM, and this in turn translates into direct operational cost reduction and actual environmental benefits in the form of carbon emissions balloons.

The contact material currently in use in the train fleet in Melbourne is based on a 1956 British Patent [3] owned by Morgan Crucible. The material in reference [3] is produced by impregnation of halogen-containing polymers, such as polytetrafluoroethylene (PTFE) onto a matrix containing metal powder. The overall resistivity of the product was reported to be in the range 0.7–0.8 × 10⁻¹⁰ ohm cm (1.8–2.0 × 10⁻⁸ ohm cm). In comparison, the resistivity of CGCM is at least about 3 × 10⁻⁶ ohm cm, i.e., about 150 times lower than that of the carbon-based material of reference [3]. This basic difference in reported resistivity values translates into direct environmental and cost benefits, as will be shown.

NOTATION

This section is a brief overview of the relevant properties and their units.

Resistivity

The electrical resistivity (ρ) is the property that describes the ability of the material to resist the flow of current. The electrical resistance (R) of a resistor depends on resistivity and dimensions:

\[ R = \rho \times \frac{L}{A}, \quad (1) \]

where L and A are the length and the cross-sectional area, respectively. In electrical measurements the value of R and dimensions are easily measured, and ρ is determined from these measurements according to eq. (1), as
\[ \rho = \frac{R \times A}{L} \]  
\( (2) \)

The resistance \( R \) is given in ohm (\( \Omega \)) and it follows that the unit of \( \rho \) in SI units is \( \Omega \times \text{m} \) or \( \text{ohm-m} \).

Conductivity

The conductivity (\( \sigma \)) describes the ability of a material to conduct, and is the inverse of \( \rho \) and is calculated as \( 1/\rho \), where \( \rho \) is measured according to eq. (1). The unit of conductivity is ohm\(^{-1}\) (also known as siemens).

For comparison purposes conductivity is commonly expressed as a percentage of the conductivity of annealed commercial-grade copper, and the respective unit is given as a percent of IACS (international annealed copper standard). The conductivity of copper is 100% or 100% IACS on this scale. The corresponding value in SI units is \( 5.80 \times 10^{-8} \text{ ohm}^{-1} \times \text{m}^{-1} \). The IACS value is obtained by dividing the conductivity of the sample to that of copper and multiplying by 100%.

The copper–graphite composite material (CGCM) described in reference [1] has at least 40% IACS, but our more recent products exceed 80% IACS.

1. **BRIEF HISTORY OF CGCM**

CGCM was invented as part of the work on a research project funded by both the Train and Tram divisions of the Public Transport Corporation of Victoria (PTC). In this study—which was performed in the Department of Chemical and Metallurgical Engineering RMIT University—problems of wire wear and wire failure were investigated. The motivation for the project was the realisation that the conductivity of existing current collectors was low and their tribological properties were poor. Overhead wire wear was high and failure occurred relatively often, mainly as a result of temperature surge due to arcing. To address these problems, a new material was invented, which combines the high conductivity of copper with the superior lubrication properties of graphite [2, 4].

2. **PRINCIPLES OF CGCM OPERATION**

The principle of CGCM operation is not new in itself. The heat generated in the contact area, \( \Delta H \), is the electric loss in the contact area multiplied by a constant and is given by

\[ P = V \times I \]  
\( (3) \)

\[ \Delta H = \alpha \ V \times I = \alpha \ I^2 \times R, \]  
\( (4) \)

where \( I \) is the current, \( R \) the resistance, \( \alpha \) is Faraday's constant and \( P \) is the actual power loss in W. A lower wire temperature could be achieved by reducing the resistance at the contact point. The addition of carbon to improve friction has been common practice in contact brushes, but usually the added carbon is not added as graphite, which is very lubricious, but in some other state, with hard particles embedded. Cu an C are considered to be immiscible (see the C–Cu phase diagram (Fig. 1)) [5].

![Figure 1](http://resource.npl.co.uk/mtdata/phdiagrams/ccu.htm)

**Figure 1.** The C–Cu phase diagram showing lack of mutual solubility of these elements (Source: http://resource.npl.co.uk/mtdata/phdiagrams/ccu.htm (accessed 15-02-12))

The novelty in CGCM consists in the fact that despite the lack of mutual miscibility between Cu and graphite, islands of graphite could be successfully embedded in a matrix of pure copper, thus achieving a combination of properties that maximise electrical efficiency together with optimized wear delivered by the tribological properties of carbon in graphitic form. A typical micrograph of the material is given in Fig. 2.

![Figure 2](http://example.com/cgcm_micrograph.png)

**Figure 2.** Micrograph of CGCM showing islands of graphite embedded in a matrix of high-purity copper. The composition of this sample was 92% Cu, 7% graphite, 0.5% Si and 0.5% MoS\(_2\). Magnification × 50.

During sliding of the CGCM contact strip along the trolley wire, this microstructure forms a lubricating carbonaceous layer at the contact interface, producing a very low friction coefficient and very low wire wear [2]. CGCM samples were tested in...
sliding over contact wires in the lab and no wear could be measured after travelling 100,000 km at about 60 km/h.

3. ARCING

The superior electrical properties of CGCM were demonstrated in an arcing test in which a sample made of CGCM took part in a trial in which the arcing properties of a number of contact materials used for current collection on the bullet trains (Shinkansen) in Japan were compared.

The arcing experiment was performed at the laboratories of Japan Rail (JR), at the Railway Technical Research Institute (RTRI) in Tokyo, Japan, courtesy of Drs Hiroki Nagasawa and Shunichi Kubo. In the experiment, arcing was induced between the copper wire and a sample of the material tested, and the intensity and duration of the arc were measured. A schematic diagram of the apparatus is shown in Fig. 3 and the results are shown in Fig. 4. The operating voltage was 120 V and the current was 31 A. The composition and properties of the materials used for comparison with CGCM are given in Tables 1 and 2. From the results it appeared that CGCM behaved almost like copper, with its arcing duration within a fraction of a second of that of Cu, reinforcing the fact that its conducting properties are close to those of copper.

![Figure 3. Schematic diagram of the arcing test facility.](image)

![Figure 4. Arcing behaviour of copper, CGCM and other contact materials used in the Japanese rail system.](image)

<p>| Table 1 Composition of contact materials used in the JR system and compared with CGCM |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Element</th>
<th>Cu</th>
<th>Sn/Zn</th>
<th>Fe</th>
<th>Cr</th>
<th>Mo</th>
<th>Fe-Mo</th>
<th>P</th>
<th>C</th>
<th>Si</th>
<th>FeS/CuS</th>
<th>Pb</th>
<th>Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR1</td>
<td>Bal.</td>
<td>4-6/</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12-15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3-5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PC78A</td>
<td>42-54</td>
<td>&lt;0.5/</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Bal.</td>
<td>&lt;1.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TF5A</td>
<td>-</td>
<td>-</td>
<td>Bal.</td>
<td>10-16</td>
<td>1.2-4.2</td>
<td>-</td>
<td>&lt;0.2</td>
<td>-</td>
<td>0.8-2.8</td>
<td>2-10</td>
<td>&lt;1</td>
<td></td>
</tr>
<tr>
<td>CGCM</td>
<td>87</td>
<td>/1.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
4. ESTIMATION OF POWER LOSSES

4.1 The Effect of Improved IACS Values

Losses are inherent to electricity use. They cannot be eliminated, but they can be minimized. One of the major known losses in trains equipped with pantograph current collectors occurs at the contact point and is attributed to two main reasons: heat losses in the strip and discontinuity in the current flow. The use of CGCM could reduce both these losses significantly, because less heat is generated in the strip and also the discontinuity in material conductivity is reduced.

Equations (3) and (4) indicate that for a given current the losses are determined by the value of R. In the following calculations we used the notations \( R_c \) and \( IACS_c \) for the resistance and conductance (in IACS) of the carbons currently in use and \( R_{CGCM} \) and \( IACS_{CGCM} \) for our strips, respectively.

Assuming that the supply current flowing to strips of similar dimensions in train operation remains approximately the same, the ratio between power losses using existing strips versus using CGCM is given by:

\[
\frac{P_c}{P_{CGCM}} = \frac{(I^2 \times Rc)}{(I^2 \times R_{CGCM})} \quad (5)
\]

Assuming that the current \( I \) is the same, this becomes

\[
\frac{P_c}{P_{CGCM}} = \frac{R_c}{R_{CGCM}} \quad (6)
\]

The ratio between resistance values is the inverse of the ratio of IACS values, therefore:

\[
\frac{P_c}{P_{CGCM}} = \frac{R_c}{R_{CGCM}} = \frac{IACS_{CGCM}}{IACS_c} \quad (7)
\]

The power losses are directly proportional to the IACS ratio. The IACS value of a typical CGCM strip made recently is 80–85. The carbons currently in use have a IACS value of less than 3%, but for the sake of this comparison we assumed better conductivity values of 5~50%. From eq. (7), the losses in the pantograph strip will be reduced by a factor of 80 / 5 = 16.

In other words, the improved conductivity of CGCM reduces the losses at the contact point by a factor of at least 16.

4.2 Losses at the Contact Point

Even before discussing greenhouse gas emissions, and without considering any other beneficial effects on the environment, such as savings in copper wire wear and reduction in the amounts of carbon dust that wears off from the present carbons, the energy loss with a CGCM strip would be only 6.25% of that lost with the carbons currently used.

Assuming an optimistic scenario in which the losses in the system amount to only about 5%~6%, about one third to one half of the electrical losses occur at the point of contact, i.e. 2%~3% of the entire energy bill is wasted at the interface between pantograph and wire. Using CGCM, this particular loss component would be reduced by a factor of 16 to 6.2% of its value, i.e. for each $1 lost at the point of contact more than 93 cents would be saved by using CGCM. Overall, the total electric losses would reduce from about 6% to about 3.19% (taking into account that ~50% of the 6% losses occur in the rest of the circuit, and these do not vary with changing the contact material). This concept was also the driving force for developing this invention.

4.3 Emission Balloons and Realistic Cost Savings

To calculate CO₂ emissions we took into account that 1 kWh releases 890 g of CO₂, and one black balloon represents 50 g of greenhouse gasses, and therefore, 1 kWh represents 17.8 balloons. Based on actual consumption data, the annual energy consumption of the present Melbourne suburban rail franchisee (MTM) is about 170 million kWh. The direct environmental benefits of using CGCM can be assessed using these data to be in the range of 75–105 million black balloons/yr from train operation only.

In addition, there are 2.5%~3% cost savings associated with this efficiency gain, or about AUD $0.75–0.85 Million per annum, beside other benefits in reduced arcing, lower wire wear (which is very difficult to assess) and reduced carbon dust pollution on train roofs.

It goes without saying that the amounts mentioned here were estimates only, but actually these calculations were based on very modest assumptions. For example, we assumed a IACS
value of 5% for the product currently used, when it is probably closer to 3%, which means that the loss at the contact point could be actually reduced by a factor much larger than 16, probably closer to 25. In any case, assuming that CGCM strips do not cost more than carbon strips, in terms of dollars these amounts could be directly saved from the operational budget, with no technical changes required, and as such these savings are very realistic.

CONCLUSION

This paper was intended to show the potential cost and possible carbon emission gains in adopting CGCM as the pantograph current collector. This is a contact material that was invented in Australia with the specific purpose of improving the electrical current collection and wire wear in suburban rail. The self-lubricating mechanism of CGCM reduces arcing and wire wear and would overall improve current collection in rail systems in more aspects than just cost savings. As shown in this paper, in addition to direct cost benefits there are expected environmental benefits in reducing carbon emissions.

REFERENCES


3. Coad, BC, Impregnated electric current collecting brushes and electric contacts, British Patent 811,390 (1956)
