A quarterly journal of research on the science and technology of the platinum group metals and developments in their application in industry
Contents

Sustainability Reporting and the Platinum Group Metals: A Global Mining Industry Leader? 2
By Gavin M. Mudd

Faraday Discussion 155: Artificial Photosynthesis 20
A conference review by Anthony Harriman

“Iridium Catalysis” 25
A book review by William D. Jones

Recycling the Platinum Group Metals: A European Perspective 29
By Christian Hagemüken

Diesel Emissions Conference India 2011 36
A conference review by Milan Kapoor

Physical Properties and Application Performance of Platinum-Palladium-Rhodium Alloys Modified with Cerium 40
By Xin Hu, Yuantao Ning, Liangwei Chen, Qingnan Shi and Chaoguang Jia

“Platinum 2011 Interim Review” 47

Publications in Brief 49

Abstracts 52

Patents 55

Final Analysis: Opportunities for Platinum Group Metals in Future Emissions Control Technology 58
By Paul J. Millington and Andrew P.E. York

Editorial Team: Jonathan Butler (Publications Manager); Sara Coles (Assistant Editor); Ming Chung (Editorial Assistant); Keith White (Principal Information Scientist)
Platinum Metals Review, Johnson Matthey Plc, Orchard Road, Royston, Hertfordshire SG8 5HE, UK
Email: jmpmr@matthey.com

© 2012 Johnson Matthey
Platinum group metals (pgms) are increasingly used in a wide variety of important environmentally-related technologies (for example, catalytic converters), most of which are expected to grow in demand as the world develops. Over the past decade, the global mining industry has embraced the need to incorporate sustainable development into projects and governance, resulting in a major surge in the use of annual sustainability reporting to demonstrate such performance. The majority of global pgms production is in South Africa, and this paper assesses and analyses the sustainability reporting by the pgms sector. The approach to sustainability reporting is discussed, including an assessment of the extent and detail of reporting by pgms companies, as well as examining the data reported and its relationship to key production aspects such as ore grade and project scale. By analysing trends in water and energy consumption and greenhouse gas emissions, especially in terms of per unit pgms production, critical issues such as life cycle costs can be ascertained. Whilst sustainability includes social, economic and environmental aspects, this paper focuses on environmental aspects only. Overall, the pgms sector certainly appears to be a global leader in the breadth and depth of sustainability reporting, with the continuing evolution providing a valuable basis to understand the major issues facing the industry and allow strategic planning for the future.

1. Introduction

The pgms possess a range of unique chemical and physical properties. They are increasingly finding important uses in a variety of environmentally-related and specialty technologies, such as chemical process catalysts (especially oil refineries), catalytic converters for vehicle exhaust control, fuel cells, electronic components, and a variety of medical uses, amongst others. Given the need to expand almost all of these uses to meet environmental and technological challenges this century, demand growth for pgms can reasonably be expected to be sustained long into the future.
The mining of pgm ores is through conventional underground or open cut techniques. The next stage is grinding and gravity-based separation, followed by flotation to produce a pgm-rich concentrate. The run-of-mine ore grades are typically several grams per tonne (g t⁻¹), while concentrates are some 100s of g t⁻¹ (1). Concentrate is then smelted to produce a pgm-rich nickel-copper matte, with the pgms extracted and purified at a precious metals refinery (including Ni-Cu byproducts). The processing is therefore more analogous to base metals rather than gold, which relies on cyanide leaching and hydrometallurgy. Smelting of concentrates from Ni-Cu mining can also be a moderate source of pgms (for example in Russia and Canada). Further details on pgm ore processing are given by Vermaak (1) and Cabri (2), with a detailed review of resources and production presented by Mudd (3).

Global production of pgms is dominated by South Africa due to their large resources in the Bushveld Complex, while other countries such as Russia, Canada, Zimbabwe and the United States play a lesser but important role. Historical production by country is shown in Figure 1 (4). In South Africa, pgms are produced from the Platreef, Merensky and Upper Group 2 (UG2) reefs in the igneous Bushveld Complex (3).

The global economic reserves are estimated by the United States Geological Survey (USGS) at 66,000 t pgms (5), compared to 2009 production of ~465 t pgms and cumulative production from 1900 to 2008 of ~12,900 t pgms. A recent detailed compilation of reported reserves and resources by project shows ~88,800 t pgms (3). Given the trend of maintaining and expanding economic resources (6), the primary issues for the foreseeable future will not be remaining resources but the complex environmental, economic and social conditions which affect production.

This paper presents a review of the pgms industry, focussing on sustainability reporting and major environmental costs such as water, energy and greenhouse gas emissions (GGEs). The paper presents a distinctive case study for a group of metals which are unique in being largely concentrated in one region of the Earth and pose some intriguing and difficult sustainability issues for the future – yet these challenges also present significant opportunities. The pgm sector is arguably a world leader in the area of sustainability reporting in the mining industry.

2. Assessing the Sustainability of Platinum Group Metals

2.1 Overview

In the past decade, there has been strong growth in annual environmental or sustainability reporting by numerous mining companies (7–10), including many South African and especially pgm companies. In general, sustainability reports cover the environ-
mental, economic and social performance of a company alongside statutory financial reporting. The compilation and analysis of the reported data can provide critical insights into a given mining sector, as well as valuable data for broader analyses of other mineral commodities. This section briefly describes the sustainability context and challenges for mining, and outlines the methodology adopted in this study.

2.2 Sustainability and Mining

At first glance, applying the principles of sustainability to mining seems a simple oxymoron – since mining means to extract a resource which is finite and ‘non-renewable’. The nature of mining is therefore widely considered to be unsustainable, since it is depleting a stock (or ‘natural capital’). The paradox, however, is that the global mining industry is now larger than ever in history, producing minerals and metals at a rate which dwarfs previous generations of mines (11).

While there is evidence to suggest that many mineral commodities have shown growth in known economic resources over recent decades in some countries (for example, Australia (11)) as growing demand has encouraged exploration and developments in extraction technology – it is increasingly clear that the historical patterns of discovery and development of mineral resources cannot simply be assumed to continue unaltered into the future. The primary constraints may vary from social and governance issues in one region, to water or energy resources in another, or GGEs globally.

The application of sustainability principles to mining is therefore complex. The global mining industry, as part of their contribution to the Johannesburg Earth Summit convened by the UN in 2002, released a major report on mining and sustainability. The ‘Mining, Minerals and Sustainable Development’ (MMSD) report (12) was a major shift from arguing the historical case of growing resources over time, to a position where mining can contribute to sustainable development – even if a mining project is only a relatively short to medium term endeavour compared to other industries which are more perpetual in nature (for example, agriculture or tourism).

Sustainability is commonly defined as ensuring the ability of current generations to meet their needs without compromising the ability of future generations to meet their needs (i.e. the Brundtland 1987 definition (13)). In the context of mining, this can be taken to include the availability of resources and a productive environment at former mining or milling sites. The context for sustainable development and mining can therefore be taken back to first principles as balancing the potential environmental, social and economic risks. Further discussion of sustainability and mining are given in (7, 11).

2.3 Sustainability Reporting

An increasingly popular way of demonstrating performance against sustainability objectives is through sustainability reporting. This involves reporting and discussing all aspects of performance for a given year, covering social, economic and environmental aspects. Some mining companies, such as WMC Resources Ltd (now part of BHP Billiton Ltd) and Placer Dome Inc (now part of Barrick Gold Corp), began releasing annual environmental reports in the mid-1990s and these evolved into broader sustainability reports by 2000. Since the 2002 Johannesburg Earth Summit and the release of the MMSD report, numerous mining companies now report sustainability alongside statutory financial performance.

Early methods for reporting used internal company schemes. Due to the need to ensure consistency across companies, industry sectors or other organisations, the Global Reporting Initiative (GRI) was established in 1997 to develop protocols and promote and enhance sustainability reporting. The third edition was released in 2006 (14), with a pilot mining sector supplement in 2005 and the final mining sector supplement released early in 2010 (15). The GRI protocol is now the most common sustainability reporting tool used by mining companies (9).

The GRI itself is voluntary, and can be applied in whole or in part. There are five main sections of reporting, including economic, environmental, labour practices, human rights and social aspects. The qualitative and quantitative indicators used for each area are either core or voluntary. There are 30 environmental indicators in total (16), with some of the most significant examples including:

- EN3/EN4 – direct/indirect energy consumption by primary energy source (core);
- EN8 – total water withdrawal by source (core);
- EN9 – water sources significantly affected by withdrawal of water (voluntary);
- EN10 – percentage and total volume of water recycled and reused (voluntary);
- EN16 – total direct and indirect greenhouse gas emissions by weight (core);
- EN21 – total water discharge by quality and destination (core);
EN22 – total weight of waste by type and disposal method (core).

Overall, the emergence of and continuing improvement in sustainability reporting is providing a valuable basis to assess the environmental sustainability aspects of mining. PGM companies in South Africa are certainly at the forefront in this regard, with Anglo American Platinum perhaps showing the best quality reporting of data and analysis (9).

2.4 Quantifying Sustainability and the Platinum Group Metals

The availability of growing data sets on wastes, energy, water and GGEs from sustainability reporting can be easily combined with normal production statistics from financial performance. In this way it is possible to link aspects such as energy, GGEs and water costs with ore grade, annual throughput or project configuration, providing some useful benchmarks to compare individual site operations and also enable the environmental implications to be understood as pgm production continues to grow to meet rising demand.

The ‘sustainability metrics’ used in this study are unit consumption of energy or water per unit pgm production (GJ kg⁻¹ pgm or m³ kg⁻¹ pgm) with respect to ore grade measured for the four elements platinum, palladium, rhodium and gold (4E g t⁻¹), unit consumption of water or energy per tonne of ore milled (m³ t⁻¹ ore or GJ t⁻¹ ore) with respect to mill throughput (Mt ore year⁻¹), and unit output of GGEs in carbon dioxide equivalents per unit pgm production (t CO₂e kg⁻¹ pgm).

3. Results

3.1 Extent of Sustainability Reporting and GRI Indicators

There are fourteen primary pgm companies, with numerous more at the exploration stage (mostly concentrated in South Africa), plus four diversified mining companies operating Ni-Cu-pgm projects. Of these companies, six of the pgm and all of the Ni-Cu-pgm companies produce an annual sustainability report, with all companies using the GRI as their reporting basis. The extent of reporting against GRI indicators for these ten companies for 2009 is compiled in Table I. For the table, a score of 0 was noted where no information or data is provided, 1 was given for qualitative information or a brief discussion of this indicator, and 2 was given where the data and information is fully compliant with the GRI indicator, giving a maximum score of 60. Although there are many possible assessment approaches (for example, (17)), this system was considered effective to allow a comparison of reporting performance between companies as well as for critical indicators.

The total scores in Table I range from 10 (representing poor reporting performance) to 43 (representing fairly strong reporting performance). Only the energy indicators (EN3 and EN4) were assigned a perfect score for all ten companies. All other indicators varied widely. A major issue which is perhaps not immediately obvious is the lack of site data given by some companies, mainly the larger diversified companies. In order for any data to be materially useful, individual site data is best and should be reported. This is common practice for production.

The two top companies for sustainability reporting were Anglo American Platinum and Vale Inco. These are clearly the leaders in this area for the pgms sector. Anglo American Platinum’s first report was published in 2002 (to coincide with the Johannesburg 2002 Earth Summit), and the content and presentation has continued to evolve over subsequent years. In general, Anglo American Platinum released site data up until year 2007, with the 2008 and 2009 reports giving group totals only (the site data was provided upon request to the present author (18)). Their group energy consumption for 2009 is shown in Figure 2 (19), including the split between mining, milling, smelting and refining as well as sources of energy for each major stage and GGEs by energy source. This is an excellent approach, and allows a quick and substantive interpretation of energy consumption and sources, as well as links to GGEs. Furthermore, in their 2006 and 2007 reports, Anglo American Platinum presented mining, milling and smelting data by site, as well as including site-specific energy intensity targets, shown in Figure 3 (20). This level of detail allows detailed analyses of energy performance, although the 2008 and 2009 reports stopped reporting in this manner. In contrast, Vale Inco have always reported by group totals and, although this allows comparison for Vale’s performance year-on-year, this does not facilitate direct cross-sector evaluation of pgms production (as shown later in this paper). As a reporting model, therefore, Anglo American Platinum’s provides greater depth to facilitate analysis of key factors, trends and issues.

By comparison, Lonmin scored much lower in Table I. However an example of their data is given in Figure 4 (21), showing declining total energy consumption but increasing unit energy consumption.
### Table I

**Sustainability Reporting by GRI Metric (2009 Data)**

| Company                        | Site/Group | EN1 | EN2 | EN3 | EN4 | EN5 | EN6 | EN7 | EN8 | EN9 | EN10 | EN11 | EN12 | EN13 | EN14 | EN15 | EN16 | EN17 | EN18 | EN19 | EN20 | EN21 | EN22 | EN23 | EN24 | EN25 | EN26 | EN27 | EN28 | EN29 | EN30 | Total |
|--------------------------------|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Anglo American Platinum Group  |            | 2   | 0   | 2   | 2   | 1   | 1   | 1   | 1   | 1   | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 0   | 1   | 1   | 1   | 2   | 1   | 1   | 1   | 2   | 1   | 2   | 1   | 2   | 0   | 1   | 40   |
| Impala Platinum Site           |            | 0   | 0   | 2   | 2   | 2   | 1   | 2   | 2   | 1   | 2   | 1   | 1   | 1   | 1   | 2   | 0   | 0   | 2   | 1   | 0   | 2   | 0   | 0   | 0   | 0   | 2   | 0   | 0   | 2   | 9    |
| Northam Platinum Site          |            | 2   | 2   | 2   | 2   | 0   | 1   | 0   | 2   | 0   | 2   | 2   | 2   | 0   | 1   | 2   | 2   | 0   | 0   | 0   | 1   | 0   | 0   | 2   | 0   | 0   | 0   | 2   | 0   | 1   | 28   |
| Lonmin Group                   | Groupb     | 0   | 0   | 2   | 2   | 0   | 0   | 1   | 1   | 0   | 0   | 2   | 2   | 0   | 1   | 2   | 2   | 0   | 0   | 0   | 1   | 0   | 2   | 1   | 2   | 1   | 0   | 0   | 2   | 0   | 0   | 26   |
| Aquarius Platinum Site         | Site       | 0   | 0   | 2   | 2   | 0   | 0   | 0   | 2   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 2   | 2   | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 2   | 2   | 19   |
| Eastern Platinum Site          | Site       | 2   | 0   | 2   | 2   | 0   | 0   | 1   | 1   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 10   |
| Vale Inco Group                |            | 2   | 1   | 2   | 2   | 0   | 0   | 0   | 2   | 0   | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 1   | 2   | 1   | 2   | 2   | 0   | 1   | 2   | 2   | 0   | 2   | 43   |
| Norilsk Nickel Group           | Groupb     | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 2   | 1   | 2   | 1   | 0   | 0   | 1   | 2   | 0   | 0   | 0   | 0   | 2   | 2   | 2   | 0   | 0   | 1   | 2   | 0   | 0   | 2   | 35   |
| BHP Billiton Group             |            | 0   | 0   | 2   | 2   | 0   | 0   | 0   | 2   | 0   | 2   | 2   | 0   | 1   | 0   | 2   | 2   | 0   | 2   | 2   | 1   | 1   | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 2   | 23   |
| African Rainbow Minerals Site  |            | 0   | 0   | 2   | 2   | 0   | 0   | 0   | 1   | 2   | 0   | 2   | 1   | 0   | 0   | 2   | 1   | 0   | 0   | 0   | 0   | 0   | 2   | 1   | 1   | 1   | 1   | 1   | 0   | 1   | 0   | 0   | 18   |

**Number of 0's**
- 5
- 7
- 0
- 7
- 6
- 6
- 0
- 6
- 1
- 2
- 3
- 7
- 2
- 3
- 3
- 6
- 9
- 7
- 3
- 6
- 3
- 6
- 6
- 6
- 7
- 3
- 9
- 4

**Number of 1's**
- 0
- 1
- 0
- 0
- 1
- 3
- 2
- 3
- 4
- 2
- 1
- 3
- 1
- 5
- 2
- 0
- 1
- 0
- 0
- 5
- 3
- 1
- 5
- 1
- 4
- 4
- 0
- 3
- 0
- 2

**Number of 2's**
- 5
- 2
- 10
- 10
- 2
- 1
- 2
- 7
- 0
- 7
- 4
- 2
- 3
- 5
- 7
- 3
- 1
- 3
- 2
- 1
- 6
- 2
- 3
- 0
- 0
- 3
- 4
- 1
- 4

**Average score**
- 1.0
- 0.5
- 2.0
- 2.0
- 0.5
- 0.5
- 0.6
- 1.7
- 0.4
- 1.6
- 1.5
- 1.1
- 0.5
- 1.1
- 1.2
- 1.4
- 0.7
- 0.2
- 0.6
- 0.9
- 0.5
- 1.3
- 0.9
- 0.7
- 0.4
- 0.4
- 0.6
- 1.1
- 0.2
- 1.0
- 27.1

---

*a* Single sites only, hence site is the same as group

*b* Lonmin and Norilsk Nickel generally report as a group (for example, energy, water), but do provide some data by site (for example, CO₂)

Note: Companies who do not produce sustainability reports (or major sustainability sections in annual corporate reporting) are Platinum Australia, Platmin, North American Palladium and Stillwater Mining Company. Xstrata Alloys last released a sustainability report for 2007, which predominantly covers their South African chrome and vanadium operations and only has group data. Although Xstrata took over the Eland pgm project in late 2007, it appears that the group data does not include Eland.
Notes to Table I

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN1</td>
<td>Materials used by weight or volume (core)</td>
</tr>
<tr>
<td>EN2</td>
<td>Percentage of materials used that are recycled input materials (core)</td>
</tr>
<tr>
<td>EN3</td>
<td>Direct energy consumption by primary energy source (core)</td>
</tr>
<tr>
<td>EN4</td>
<td>Indirect energy consumption by primary source (core)</td>
</tr>
<tr>
<td>EN5</td>
<td>Energy saved due to conservation and efficiency improvements (voluntary)</td>
</tr>
<tr>
<td>EN6</td>
<td>Initiatives to provide energy-efficient or renewable energy-based products and services, and reductions in energy requirements as a result of these initiatives (voluntary)</td>
</tr>
<tr>
<td>EN7</td>
<td>Initiatives to reduce indirect energy consumption and reductions achieved (voluntary)</td>
</tr>
<tr>
<td>EN8</td>
<td>Total water withdrawal by source (core)</td>
</tr>
<tr>
<td>EN9</td>
<td>Water sources significantly affected by withdrawal of water (voluntary)</td>
</tr>
<tr>
<td>EN10</td>
<td>Percentage and total volume of water recycled and reused (voluntary)</td>
</tr>
<tr>
<td>EN11</td>
<td>Location and size of land owned, leased, managed in, or adjacent to, protected areas and areas of high biodiversity value outside protected areas (core)</td>
</tr>
<tr>
<td>EN12</td>
<td>Description of significant impacts of activities, products, and services on biodiversity in protected areas and areas of high biodiversity value outside protected areas (core)</td>
</tr>
<tr>
<td>EN13</td>
<td>Habitats protected or restored (voluntary)</td>
</tr>
<tr>
<td>EN14</td>
<td>Strategies, current actions and future plans for managing impacts on biodiversity (voluntary)</td>
</tr>
<tr>
<td>EN15</td>
<td>Number of International Union for Conservation of Nature (IUCN) Red List species and national conservation list species with habitats in areas affected by operations, by level of extinction risk (voluntary)</td>
</tr>
</tbody>
</table>
### Notes to Table Ia (Continued)

<table>
<thead>
<tr>
<th>Term (EN)</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN16</td>
<td>Total direct and indirect greenhouse gas emissions by weight (core)</td>
</tr>
<tr>
<td>EN17</td>
<td>Other relevant indirect greenhouse gas emissions by weight (core)</td>
</tr>
<tr>
<td>EN18</td>
<td>Initiatives to reduce greenhouse gas emissions and reductions achieved (voluntary)</td>
</tr>
<tr>
<td>EN19</td>
<td>Emissions of ozone-depleting substances by weight (core)</td>
</tr>
<tr>
<td>EN20</td>
<td>NOx, SOx, and other significant air emissions by type and weight (core)</td>
</tr>
<tr>
<td>EN21</td>
<td>Total water discharge by quality and destination (core)</td>
</tr>
<tr>
<td>EN22</td>
<td>Total weight of waste by type and disposal method (core)</td>
</tr>
<tr>
<td>EN23</td>
<td>Total number and volume of significant spills (core)</td>
</tr>
<tr>
<td>EN24</td>
<td>Weight of transported, imported, exported or treated waste deemed hazardous under the terms of the Basel Convention Annex I, II, III, and VIII, and percentage of transported waste shipped internationally (voluntary)</td>
</tr>
<tr>
<td>EN25</td>
<td>Identity, size, protected status, and biodiversity value of water bodies and related habitats significantly affected by the reporting organisation’s discharges of water and runoff (voluntary)</td>
</tr>
<tr>
<td>EN26</td>
<td>Initiatives to mitigate environmental impacts of products and services, and extent of impact mitigation (core)</td>
</tr>
<tr>
<td>EN27</td>
<td>Percentage of products sold and their packaging materials that are reclaimed by category (core)</td>
</tr>
<tr>
<td>EN28</td>
<td>Monetary value of significant fines and total number of non-monetary sanctions for non-compliance with environmental laws and regulations (core)</td>
</tr>
<tr>
<td>EN29</td>
<td>Significant environmental impacts of transporting products and other goods and materials used for the organisation’s operations, and transporting members of the workforce (voluntary)</td>
</tr>
<tr>
<td>EN30</td>
<td>Total environmental protection expenditures and investments by type (voluntary)</td>
</tr>
</tbody>
</table>

*From (16)*
Fig. 2. Energy sources and consumption by production stage and greenhouse gas emissions by source for 2009 by Anglo American Platinum (19)

Energy intensity per operation

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>Target 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mines (GJ t⁻¹ broken)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rustenburg section</td>
<td>0.27</td>
<td>0.32</td>
<td>0.27</td>
</tr>
<tr>
<td>Amandelbult section</td>
<td>0.28</td>
<td>0.30</td>
<td>0.29</td>
</tr>
<tr>
<td>Union section</td>
<td>0.34</td>
<td>0.31</td>
<td>0.34</td>
</tr>
<tr>
<td>Lebowa</td>
<td>0.33</td>
<td>0.48</td>
<td>0.32</td>
</tr>
<tr>
<td>Bafokeng-Rasimone</td>
<td>0.23</td>
<td>0.25</td>
<td>0.24</td>
</tr>
<tr>
<td>Twickenham</td>
<td>–</td>
<td>0.08</td>
<td>*</td>
</tr>
<tr>
<td>PPRust</td>
<td>0.02</td>
<td>0.02</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Concentrators (GJ t⁻¹ milled)

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>Target 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rustenburg section</td>
<td>0.15</td>
<td>0.17</td>
<td>0.15</td>
</tr>
<tr>
<td>Amandelbult section</td>
<td>0.16</td>
<td>0.14</td>
<td>0.16</td>
</tr>
<tr>
<td>Union section</td>
<td>0.12</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>Lebowa</td>
<td>0.15</td>
<td>0.16</td>
<td>0.14</td>
</tr>
<tr>
<td>Bafokeng-Rasimone</td>
<td>0.15</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>Mototolo</td>
<td>–</td>
<td>0.17</td>
<td>*</td>
</tr>
<tr>
<td>PPRust</td>
<td>0.21</td>
<td>0.25</td>
<td>0.22</td>
</tr>
<tr>
<td>Western limb tailings retreatment</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Processing plants

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>Target 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterval smelter (GJ t⁻¹ converter matte produced)</td>
<td>91.63</td>
<td>94.47</td>
<td>89.00</td>
</tr>
<tr>
<td>Polokwane smelter (GJ t⁻¹ furnace matte produced)</td>
<td>28.58</td>
<td>31.67</td>
<td>30.00</td>
</tr>
<tr>
<td>Mortimer smelter (GJ t⁻¹ furnace matte produced)</td>
<td>50.54</td>
<td>39.69</td>
<td>53.50</td>
</tr>
<tr>
<td>RBMR (GJ t⁻¹ base metals produced)</td>
<td>58.94</td>
<td>61.12</td>
<td>59.40</td>
</tr>
<tr>
<td>PMR (GJ oz⁻¹ pgms and gold)</td>
<td>0.15</td>
<td>0.16</td>
<td>0.18</td>
</tr>
</tbody>
</table>

* No target set

PPRust = Potgietersrust Platinums; RBMR = Rustenburg Base Metals Refiners; PMR = Precious Metal Refiners

Fig. 3. Site-specific energy consumption and targets by production stage for 2007 by Anglo American Platinum (20)
3.2 Sustainability Metrics

The compiled sustainability metrics are given in Table II, divided by mines and companies where possible.

3.2.1 Water Metrics

The graphs of unit water costs versus throughput or over time, shown in Figure 5, do not show strong evidence of water efficiency gains for most projects. That is, larger project scales do not necessarily lead to higher water efficiency, a common belief in the mining industry. Ore grade does not appear to be a factor in unit water efficiency. Over time, most projects have shown somewhat stagnant water efficiency, with only Bokoni showing strong reductions in total water consumption and unit water costs over time, which also appear to be sustained. Some projects are showing the reverse, however, such as Northam with significantly increasing water costs over time.

3.2.2 Energy Metrics

The various graphs for energy in Figure 6 show no substantive evidence for improved unit energy efficiency at higher throughputs, despite the common perception in the mining industry. There does appear to be a minor negative scale effect for unit energy consumption for stand-alone mine-concentrator-smelter projects with low throughputs (i.e. smaller scales entail higher unit energy costs). Ore grade does appear to be a significant factor for unit energy consumption (correlation coefficient 49.9%, Figure 6). No project studied has shown long term energy efficiency improvements over time, with most showing relatively stable or slightly increasing trends. The Bokoni and Northam projects, however, show substantive increases in energy costs over the past few years – despite both maintaining similar production levels and ore grades.

The low energy cost for mining at Mogalakwena (24.4 MJ t\(^{-1}\) rock) is due to this being an open cut mine, while the deep Northam underground mine (~2 km) has the highest mining energy consumption (1414 MJ t\(^{-1}\) rock). The data in Table II also show that indirect energy (electricity) is the dominant energy input overall, with the majority of energy being used by underground mining. This would be due to the narrow mining techniques used, requiring large areas of development for small returns in ore compared to underground bulk mining techniques. Although a relatively small percentage of Bushveld ore is derived from open cut mines, many pgm producers have planned expansions to incorporate open cut mines in the future. There is a clear energy trade-off between underground and open cut mining (i.e. MJ t\(^{-1}\) rock) and the amount of solid wastes produced, since open cut mining produces large volumes of waste rock (see Section 3.2.4).
Table II  
Sustainability Metrics for PGM Projects and Companies\textsuperscript{a} 

<table>
<thead>
<tr>
<th>Mine &amp; concentrator only</th>
<th>Mining, MJ t(^{-1}) rock</th>
<th>Milling, MJ t(^{-1}) ore</th>
<th>Energy, GJ kg(^{-1}) pgm</th>
<th>Energy, MJ t(^{-1}) ore</th>
<th>Water, m(^3) kg(^{-1}) pgm</th>
<th>Water, m(^3) t(^{-1}) ore</th>
<th>CO(_2)e emissions, t CO(_2)e kg(^{-1}) pgm</th>
</tr>
</thead>
</table>

(Continued)
<table>
<thead>
<tr>
<th>Mine, concentrator, smelter and refinery (full refined production)</th>
<th>Mining, MJ t⁻¹ rock</th>
<th>Milling, MJ t⁻¹ ore</th>
<th>Energy, GJ kg⁻¹ pgm</th>
<th>Energy, MJ t⁻¹ ore</th>
<th>Water, m³ kg⁻¹ pgm</th>
<th>Water, m³ t⁻¹ ore</th>
<th>CO₂e emissions, t CO₂e kg⁻¹ pgm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Company/group totals</th>
<th>Direct energy fraction, %</th>
<th>Indirect energy fraction, %</th>
<th>Energy, GJ kg⁻¹ pgm</th>
<th>Energy, MJ t⁻¹ ore</th>
<th>Water, m³ kg⁻¹ pgm</th>
<th>Water, m³ t⁻¹ ore</th>
<th>CO₂e emissions, t CO₂e kg⁻¹ pgm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northam Platinum</td>
<td>8.0 [6]</td>
<td>92.0 [6]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Anglo American Platinum</td>
<td>23.3 [5]</td>
<td>76.7 [5]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Average values; number of years of data in brackets

**Former name used for consistency with older reporting (Rustenburg Group includes the Bathopele, Khomanani, Thembelani, Khuseleka and Siphumelele mines and Rustenburg mill)**
3.2.3 Greenhouse Gas Emissions Metrics

A moderate relationship is suggested between ore grade and unit GGEs (correlation coefficient 28.6\%, Figure 7), while the correlation between unit energy and unit emissions, surprisingly, yields a correlation coefficient of 39.1\% (Figure 8) – despite South Africa’s electricity supply being dominated by coal (89.7\%) with a small proportion of hydroelectricity (5.0\%) (22). The variability could be due to different estimation methods used by companies, although given the dominance of electricity this should not be the case (recalculation of GGEs based on reported energy consumption also produces consistent results). Most of the values which appear to be unusual (or outliers) are mines which have only reported one or two years of data, or where site activities or conditions were atypical (such as sites undergoing expansions or values reported during the electricity crisis) resulting in lower production and higher metrics. Unit GGEs over time show a slight but gradually increasing trend for all projects included in Figure 7, which could also affect the correlation between energy and emissions intensity.

Since there is some evidence for major pgm producers showing declining ore grades over the past decade (3, 4), the implication is that unit GGEs will increase further if no action is taken. It is worth noting that some companies are now responsible for GGEs of the order of several millions of tonnes per year – and if development and production continue to grow...
at or close to historical rates, this will lead to major increases in total emissions.

Based on the data in Figure 7 and Table II, the growth in GGEs due to production increases is likely to be much greater than the possible savings due to mine, mill or smelter efficiency improvements. To date, it would appear that the energy savings achieved at most sites are relatively modest or are cancelled out by other factors such as operational issues (for example, the South African electricity crisis). By way of illustration, some Anglo American Platinum mines show variation within a typical range (for example, Bafokeng and Union), while others show a gradual increase over time (for example, Bokoni, Mogalakwena, Tumela-Dishaba and Rustenburg Group). In other words, if production doubles there is little evidence that existing mines can reduce energy consumption by half. This means that GGEs will become an increasingly important issue as pgm production grows.

One way to address this issue may be to switch energy production to renewable alternatives. If current coal-derived electricity were changed to baseload solar thermal (i.e. solar thermal plants with heat storage), this could significantly reduce the carbon intensity of pgms production – which, at present, is often trending upwards due to a variety of competing factors.

3.2.4 Mine Wastes – Waste Rock, Tailings and Smelter Slags
The majority of pgm ore is sourced by underground mining, with 2009 production data showing that for the
Bushveld, Great Dyke and Stillwater fields underground mining represents ~83.5% of the ore milled, with ~16.5% by open cut mining.

The two large volume mine wastes, tailings and waste rock, both require active planning and management to prevent major environmental or social impacts such as tailings dam failures (for example, the 1974 Bafokeng tailings disaster (23), acid and metaliferous drainage or other problems (for example, dust and environmental health issues). In addition, slag wastes from smelters are important and are commonly disposed of in tailings dams at pgm mines (or slags can be reprocessed to extract residual pgms).

Given that the ratio of ore to concentrate can be anywhere from 30:1 to 50:1, this means that some 96–98% of the ore becomes tailings. Waste rock to ore ratios are typically high for open cut mining (between 5:1 and 20:1) and the reverse for underground mining (for example, Zimplats reported a ratio of 0.03:1) (24). At present, very little data exists on underground waste rock generation in the Bushveld or other mines, but the ratio could be expected to be ~0.1:1. The waste:ore ratios reported for the Mogalakwena, Kroondal and Marikana Joint Venture open cut mines range from 6.9:1 to 23.7:1, leading to waste rock ranging from 2.6 to 94.6 Mt year⁻¹. During its operation, the Ngezi open cut mine at Zimplats had a ratio of 12.5:1 (24), producing ~150 Mt of waste rock.

At present, it is rare for companies to report total mine wastes under their control and active management.
One exception, however, is Anglo American Platinum, who reported in 2009 that their cumulative mine wastes were 839.1 Mt of tailings, 692.8 Mt of waste rock and 5.2 Mt of smelter slags (19) – demonstrating the large scale and significance of managing these wastes in the surface environment long into the future. Studies by Anglo American Platinum suggest that both Merensky and UG2 tailings have a low acid and metalliferous drainage potential, although potential drainage waters from tailings would still be high in sulfate – meaning tailings still require active environmental management to prevent impacts on water resources. In March 2008, the non-government group ActionAid claimed that there is evidence for local impacts on water resources used by surrounding communities of some Anglo American Platinum operations (especially Mogalakwena) (25). In response, Anglo American Platinum commissioned external studies to assess the extent of water resource impacts, demonstrating that the problems identified by ActionAid were not related to Anglo American Platinum operations (19).

4. Discussion

4.1 Sustainability Metrics: Historical Comparison

In 1955 the Rustenburg and Union mines processed ~1.6 Mt ore and consumed 306,000 GJ of electricity and 2,157,000 m$^3$ of water (26). Assuming all South African production of 11.87 t pgm in 1955 was from these mines, this gives a yield of about 7.42 g t$^{-1}$ (an ore grade of ~9.3 g t$^{-1}$ assuming 80% recovery) and unit energy and water costs of 25.8 GJ kg$^{-1}$ pgm and 182 m$^3$ kg$^{-1}$ pgm, respectively, plus 1.35 m$^3$ t$^{-1}$ ore. Compared to recent values (Table II), this suggests that energy costs have increased over time but water costs have only marginally increased. The increasing energy costs are probably related to the gradually increasing depth of the mines and lower ore grades.

4.2 Sustainability Metrics: Energy

With respect to energy, the data show a moderate negative correlation between ore grade and unit energy costs – as ore grades decline the unit energy costs increase (Figure 6). Although average 4E ore grades in the Bushveld have not declined as dramatically as gold ores elsewhere in South Africa, the current average ore grade of ~3.9 g t$^{-1}$(4E) is marginally below the 2009 average ore grade of Bushveld reserves and resources of ~4.3 g t$^{-1}$(4E) (3). Average ore grade may decline as shallower but lower grade projects (for example, the Platreef or Great Dyke mines) are expanded or developed in preference to deeper Merensky/UG2 projects. Therefore there will be only slight pressure on energy costs from declining grades, and overall, this suggests that total energy consumption will largely be a function of pgm production. Declining grades, however, may still affect individual companies or major projects.

Unlike gold mining, energy in pgm mining and production is dominated by electricity consumption, related to the prevalence of underground mining in the Bushveld region and the more complex processing that is required for pgm extraction. The typical range for unit energy costs is presently 122–319 GJ kg$^{-1}$ pgm, with a production-weighted average of 222 GJ kg$^{-1}$ pgm (based on refined production only). Most projects show variable unit energy costs over time and no clear trend, although 2007 to 2009 are often the highest on record – presumably related to the South African electricity supply crisis affecting production. A recent study of gold mining (7) showed that the typical unit energy costs of gold ranged from 120 to 213 GJ kg$^{-1}$ Au and averaged 143 GJ kg$^{-1}$ Au. The unit energy costs for pgms are clearly higher than those for gold, but not as much as could be expected based on the differences in mining and processing.

Anglo American Platinum’s data show the split in energy costs between mining, milling, smelting and refining (Figures 2 and 3), showing the dominance of the first three of the four major stages in pgms production. In addition, the inclusion from 2006 to 2007 of energy costs split between mining and milling is a rare example of detailed reporting in the global mining industry, and allows improved understanding of the various stages of pgm mining and production. Unfortunately, as individual smelter pgm production statistics are not reported (for example, grade and tonnes of concentrate processed to matte produced), it is not possible to provide a breakdown to unit energy costs (GJ kg$^{-1}$ pgm) for each major stage which could then be expanded into a rigorous, process-based model of pgms production.

4.3 Sustainability Metrics: Greenhouse Gas Emissions

The unit GGEs also show a moderate negative correlation to ore grade, similarly to energy – as should be expected given the dominance of coal in South Africa’s electricity mix. The typical range for unit emissions is 25.8–78.3 t CO$_2$e kg$^{-1}$ pgm, with a production-weighted average of 51.2 t CO$_2$e kg$^{-1}$ pgm (based on
reduced production only). The unit GGEs for gold typically range from 10.3 to 16.4 t CO$_2$e kg$^{-1}$ Au and average 11.5 t CO$_2$e kg$^{-1}$ Au (7). The significantly higher unit GGEs for pgm production are influenced by the high proportion of coal-based electricity for Bushveld projects as well as the more intense processing associated with smelting and refining.

The energy and GGEs intensities of Bushveld pgm production give rise to perhaps a unique situation in global mining. Due to the high proportion of electricity used per unit production, it should be possible to examine future low GGE electricity sources, including renewable energy projects like wind power, baseload solar thermal and/or photovoltaics, to progressively replace existing coal-based electricity. This would still allow electricity needs to be met but provide for a significant reduction in emissions. In contrast, gold mining is often dominated by open cut techniques, for which sustainable alternatives to diesel as an energy source appear very limited at present. Although viable energy sources in the Bushveld are outside the scope of this study, it is clear that energy efficiency as well as the choice of energy sources will be critical in determining both the energy and emissions intensities of pgms production.

### 4.4 Sustainability Metrics: Water

The extent of water consumption for pgms is within typical ranges for various metals (8). In terms of water consumed in milling, the range found in this study for processing pgm ore is 0.18–3.39 m$^3$ t$^{-1}$ ore with one project averaging some 15.6 m$^3$ t$^{-1}$ ore. The average of 1.04 m$^3$ t$^{-1}$ ore (excluding the single high value) is similar to gold (1.37), copper-gold (1.22), copper (1.27), lead-zinc-silver (2.67) and nickel (1.01) ore processing (all m$^3$ t$^{-1}$ ore; (8)). Almost all of these ore types undergo grinding and flotation to produce concentrates in a similar manner to pgm ore processing.

A perhaps surprising outcome is the degree to which the Bokoni project has reduced water consumption from a high of 6.07 million m$^3$ in 2004 to just 279,000 m$^3$ in 2009 (18). Most projects, however, have not been successful in this regard, with Anglo American Platinum’s statement on water resource impacts of Mogalakwena versus those of ActionAid, discussed earlier, are an exception in this regard.

### 4.5 Sustainability Metrics: Mine Wastes

The mining industry is the largest annual producer of solid wastes globally (12, 27). The relatively low grade of pgm ores, of the order of a few grams per tonne, means that > 99.99% of the ore becomes solid waste. However, despite numerous major tailings dam failures, riverine or marine disposal of tailings, or ongoing acid and metalliferous drainage at innumerable current and former mine sites around the world (12, 27–29), the GRI still does not mandate that large volume mine wastes be fully and accurately reported. Under the main GRI protocol (14), the core indicator for solid wastes (EN22) is typically taken to refer to putrescible and/or hazardous wastes, such as those sent to landfill, recycled or treated further (for example, chemicals, oils, metals, woods, etc.) (9). The GRI
mining and metals sector supplement (15) proposes that ‘total amounts of overburden, rock, tailings, and sludges and their associated risks’ (p. 33, indicator MM3) should be a core indicator but fails to make it an explicit requirement to report complete data. It is expected that only ‘hazardous’ mine wastes should be reported, effectively leaving the reporting of large volume mine wastes at the discretion of a site ‘risk assessment’ to judge what is ‘hazardous’. This is unfortunate, since it allows an easy escape clause to avoid reporting such wastes. Based on a comprehensive survey of sustainability reporting by many major mining companies, full and accurate reporting of large volume mine wastes is a key strategic weakness across the global mining industry (9).

Within the pgms mining sector, Anglo American Platinum are certainly the leader with respect to reporting mine waste data, although all pgm companies can and need to improve their reporting in this regard. The recent controversy over the perceived water resources impacts at Mogalakwena highlights the importance of proactive management of large tonnage mine wastes, especially where these border large local communities which depend on water resources adjacent to mining projects.

4.6 Sustainability Metrics: Biodiversity

The reporting of biodiversity data and information was highly variable and often poor (indicators EN11 to EN15 and EN25). Given the public prominence of biodiversity issues, legislation and numerous international conventions or treaties and the potential impacts of mining on protected areas and threatened and endangered species, this is rather surprising. For some indicators, a review of International Union for Conservation of Nature (IUCN) information on ‘Red List’ species is all that is required, while other indicators simply require land tenure information and a discussion of protected or high conservation areas relative to land uses and management plans.

The best example of detailed biodiversity reporting was by Vale Inco, who scored perfectly for indicators EN11 to EN15. Vale Inco provide detailed biodiversity data, descriptions of their operations relevant to specific regions or biodiversity values, and detailed discussions of management plans. It is perhaps no coincidence that Vale Inco has been at the forefront of these challenges in their home country Brazil, home of the Amazon rainforest, compared to other companies which are in established agricultural and/or mining provinces where biodiversity issues have not historically been as prominent.

5. Conclusions

This paper has reviewed the ongoing development of sustainability reporting by the pgms mining sector, focussing in particular on the technical basis for environmental aspects and the trends in the reported data. Given the strong expected growth in the long-term demand for pgms to meet the needs of environmental and other technologies, it is critical to understand the existing factors which govern environmental aspects such as carbon intensity, water costs and energy consumption – otherwise known as unit metrics. At present, there appears to be significant upward pressure on these unit metrics, such as t CO$_2$ kg$^{-1}$ pgms or GJ kg$^{-1}$ pgms, due to a variety of complex factors. For example, both the ongoing South African electricity crisis and the current global financial crisis have impacted on production, commonly placing upward pressure on unit metrics. The high proportion of coal in South Africa’s electricity mix is also a crucial factor in the high carbon intensity of pgms, since most pgm ore is sourced from underground mining and is electricity intensive.

In general, the breadth and extent of sustainability reporting by the pgms mining sector is improving over time, especially as companies become more familiar with reporting protocols such as the GRI, as well as the ability to link such reporting to operational performance and targets. Based on the present review, best practice in sustainability reporting involves detailed and complete site data as well as coverage of all GRI indicators, even where only qualitative information is required.

In summary, this paper provides an important insight into sustainability reporting and the pgms sector, which is certainly a global leader in this regard compared to other major mining sectors, allowing a valuable insight into the links between unit metrics, such as carbon intensity, and the issues facing the pgm mining industry such as the choice of electricity source, the development of deeper mines and the challenges of changing ore types and grades.

6. Acknowledgements

This paper builds on previous research by Bonnie Glaisster (Environmental Engineering, Monash University). In addition, various companies have provided data, especially Anglo American Platinum, Northam Platinum and Zimplats. The commitment to sustainability
across the pgm sector is warmly recognised, as they continue to provide a leading example of sustainability leadership and reporting in the global mining sector. Long may this continue and improve!

References
4 B. J. Glaister and G. M. Mudd, Miner. Eng., 2010, 23, (5), 438
5 “Minerals Commodity Summaries”, US Geological Survey (USGS), Reston, Virginia, USA, Years 1999 to 2011
7 G. M. Mudd, Resources Policy, 2007, 32, (1–2), 42
11 G. M. Mudd, “The Sustainability of Mining in Australia: Key Production Trends and Their Environmental Implications for the Future”, Department of Civil Engineering, Monash University and Mineral Policy Institute: Melbourne, Victoria, Australia, October 2007; Revised April 2009, 277 pp
17 A. Fonseca, Corp. Soc. Responsibility Environ. Manage., 2010, 17, (6), 355
18 Anglo American Platinum Ltd, private communications, 9th August 2011 and 12th September 2011
24 Zimplats, private communication
26 Platinum Metals Rev., 1957, 1, (1), 3
27 “Golden Dreams, Poisoned Streams: How Reckless Mining Pollutes America’s Waters, and How We Can Stop It”, eds. C. D. Da Rosa, J. S. Lyon and P. M. Hocker, Mineral Policy Center (MPC), Washington, DC, USA, 1997, 279 pp

The Author
Dr Gavin M. Mudd has been an active researcher and advocate on the environmental impacts and management of mining for over a decade. He has been involved with many aspects of industry with a particular specialty in brown coal wastes, uranium mining and environmental management. He maintains an independent perspective, and has undertaken research for mining companies, community groups and indigenous organisations. With strong qualifications and experience, he has developed a unique understanding of the multidisciplinary nature of the environmental aspects of mining, culminating in a distinctive view on how to quantify an apparent oxymoron – that of ‘sustainable mining’.

© 2012 Johnson Matthey
Faraday Discussion 155: Artificial Photosynthesis

Reviewed by Anthony Harriman
Molecular Photonics Laboratory, School of Chemistry, Newcastle University, Bedson Building, Newcastle upon Tyne NE1 7RU, UK
Email: anthony.harriman@ncl.ac.uk

Faraday Discussions document a long-established series of Faraday Discussion meetings, organised by the Royal Society of Chemistry, which provide a unique international forum for the exchange of views and newly acquired results in developing areas of physical chemistry, biophysical chemistry and chemical physics. The papers presented are published in the Faraday Discussions volume together with a record of the discussion contributions made at the meeting. Faraday Discussions therefore provide an important record of current international knowledge and views in the field concerned.

The latest meeting, FD155, held at the University of Edinburgh, UK, from 5th–7th September 2011, was dedicated to the subject of artificial photosynthesis and to the specific problem of utilising solar energy as a direct supplement to our current energy supplies. The meeting attracted over 120 delegates, mostly academic researchers, from around the world and involved 22 presentations covering many different aspects of artificial photosynthesis (1). Current research follows one of two major routes: loosely speaking these can be considered to involve photo-electrochemical approaches or the construction of bio-inspired molecular devices. Photovoltaic systems, based on either organic or inorganic materials, have the advantage that they actually work under ambient light conditions but they need to be equipped with suitable electrodes in order to use the photo-generated electrical current to split water or reduce carbon dioxide. Molecular systems lag far behind in terms of practical possibilities but are highly attractive in terms of mechanistic insight, intellectual challenge and beautiful synthesis. In both areas, there is a critical need to identify effective catalysts and it is here that the platinum group metals (pgms) play an essential role.

Artificial Photosynthetic Systems

Figure 1 gives a crude indication of the essential features inherent to a bio-inspired artificial photosynthetic unit. Sunlight absorbed by an electron donor (D) causes an electron to transfer to a nearby electron acceptor (A); a reaction that does not occur in the dark. Several concerted electron-transfer reactions are needed to effect water splitting and intermediary elec-
trons and positive holes have to be stored for a few seconds or so at a redox catalyst. Here, we focus on the discussion relating to the use of pgms either as specific catalysts or as photon collectors. It is clear that the pgms offer unrivalled performance as redox catalysts in water splitting or as catalysts for the reduction of CO₂. Additional work relates to designing improved electron donors or acceptors based on pgms.

**Water Oxidation**

Tremendous progress has been made with respect to identifying new homogeneous metal-based catalysts for oxygen evolution from water under ambient conditions. This is a major challenge that must be overcome before effective photosystems can be developed for solar fuel production. A series of mononuclear ruthenium(II) pyridine complexes (Figure 2) has been synthesised by Licheng Sun et al. (Royal Institute of Technology, Stockholm, Sweden) and shown to be excellent water oxidation catalysts. The catalysts operate in acidic solution, under both electrochemical and chemical oxidative conditions, and have been subjected to detailed mechanistic examination. Interestingly, certain complexes of similar structure are poor catalysts, thereby opening the possibility to explore reactivity-structure relationships.

Tom Mallouk and coworkers (The Pennsylvania State University, USA) are following a quite different approach. Here, a photo-electrochemical device has been engineered based on a porous titanium dioxide anodic film equipped with a Ru(II) poly(pyridine) sensitisier that collects photons across much of the visible spectrum. A key feature of this system is the provision of iridium(IV) oxide hydrate (IrO₂ₙH₂O) nanoparticles that function as the catalyst for water oxidation. The quantum yield is low because of fast charge recombination between the primary charges but the system is amenable to detailed mechanistic examination that should assist optimisation of the overall device. At present, this is one of the most effective systems available for artificial photosynthesis. Furthermore, Erwin Reisner (University of Cambridge, UK) has proposed a complementary system wherein a related Ru-based dye is coated onto TiO₂ particles and subsequently equipped with a cobalt-based reduction catalyst. Illumination of the Ru(II)-based dye leads to fast charge injection into the conduction band of the TiO₂. The promoted electron is then trapped at the Co(III)-based catalyst and used to reduce water to molecular hydrogen in neutral solution. Performance of this system is highly promising but it must be noted that hydrogen evolution occurs at the expense of consuming an added organic material.

Several researchers introduced watersplitting photosystems based on the use of a Ru(II) poly(pyridine) complex as the light absorbing unit. This species, apart from collecting incident photons, enters into light-induced electron transfer with added substrates and thereby initiates the oxidation or reduction of water. Thus, Sebastiano Campagna and colleagues (University of Messina, Italy) have used a conventional photochemical reaction to oxidise Ru(II) tris(2,2'-bipyridine) in aqueous solution. The resultant oxidant is used subsequently to oxidise water via a tetra-cobalt(III) cubane cluster: [Co₄O₄(O₂CMe)₄(py)₄] (py = pyridine). The novelty here lies with trying to mimic the oxygen-evolving catalyst found in natural photosynthetic organisms with the Co cluster. Haruo Inoue et al. (Tokyo Metropolitan University, Japan) have considered an alternative oxidative scheme. The idea is to employ a Ru(II) porphyrin, which has superior light-harvesting performance, as a sensitisier for epoxidation of alkenes. The critical feature of this system relates to
using water as the source of the added oxygen. This, in turn, introduces some interesting mechanistic concerns. In many cases, the photochemical reaction occurs in surprisingly high quantum yield and results in formation of a valuable product.

**Photochemical Carbon Dioxide Reduction**

Osamu Ishitani and coworkers (Tokyo Institute of Technology, Japan) have worked for many years on developing photochemical systems capable of the reduction of CO₂. This is an extremely difficult reaction to realise, especially in aqueous solution, and has been a major bottleneck for the successful introduction of an artificial photosynthetic system; hence the focus on production of hydrogen from water as a simpler alternative. The main problem for CO₂ reduction relates to the high overpotential associated with most catalysts. Ishitani et al. have investigated several classes of rhenium(I) complexes as effective CO₂ catalysts. Here, a novel photosystem is introduced whereby a Ru(II) poly(pyridine) sensitisier is covalently linked to a Re(I) complex (Figure 3) to form an integral unit. Illumination into the Ru(II)-based sensitisier results in electron transfer to the nearby Re(I) complex. Transfer of a second electron, fuelled via an added sacrificial reagent, leads to reduction of CO₂ to CO in reasonably high quantum yield. The reaction is carried out in N,N-dimethylformamide, not water, and requires high pressures of CO₂. Nonetheless, this system represents the state of the art in the field.

**Electron Transfer**

Without doubt, the biggest problem associated with the successful development of a bio-inspired form of artificial photosynthesis relates to the need to accumulate multiple charges at a redox site. This situation arises because all photochemical electron-transfer reactions are necessarily single-electron events whereas fuel formation involves a minimum of two electrons. Most systems stop at the one electron stage due to short-circuiting. The bottleneck is removed by the use of sacrificial reagents but this is a very shortsighted approach. Leif Hammarström and colleagues (Uppsala University, Sweden) have searched for ways around the problem and, at FD155, described an interesting series of molecular dyads able to undergo light-induced charge accumulation. Here, a Ru(II) poly(pyridine) sensitisier is covalently linked to an oligo-triarylamine residue (Figure 4). Illumination into the Ru(II)-based sensitisier causes electron transfer from the nearest amine residue but, due to thermodynamic arguments, the resultant positive hole moves to one of the peripheral amines, thereby slowing the rate of charge recombination. Linking the Ru(II)-based chromophore to the surface of TiO₂ allows the promoted electron to be discharged, leaving the accumulated positive holes on the terminal oligo-triarylamine unit. Such research offers promise for the development of multi-electron storage systems.

Two papers of direct interest to pgm chemistry were presented at the follow-on Post Faraday Meeting that
took place immediately after the conclusion of FD155 (2). Etsuko Fujita (Brookhaven National Laboratory, New York, USA) reported detailed mechanistic studies relating to the mode of action of a mononuclear Ru complex (Figure 5) able to bring about the 4-electron oxidation of water to molecular oxygen. Using a battery of sophisticated experimental techniques, aided by quantum chemical calculations, several key intermediates in the redox cycle have been identified. Separately, Oluwafunmilola Ola (University of Nottingham, UK) described her research into pgm-promoted reduction of CO$_2$ on the surface of TiO$_2$ under illumination. Palladium and rhodium appear to be the promising metal deposits for such challenging reduction pro-

![Figure 4: A ruthenium(II) poly(pyridine) sensitizer is covalently linked to an oligo-triarylamine residue](image)

![Figure 5: The mode of action of a mononuclear ruthenium complex able to bring about the 4-electron oxidation of water to molecular oxygen](image)
cesses, although the nature of the TiO₂ host plays a very important role in deciding overall efficiency.

Concluding Remarks
This review has focused on those presentations dealing with the pgms. The remaining presentations demonstrated that considerable research activity has been carried out on the search for cheaper and more plentiful alternatives to the pgms as redox catalysts. Iron and manganese have often been presented as logical replacements for Ru or Ir as catalysts for water oxidation but their performance does not justify such optimism. At present, the pgms are much the better catalysts, especially in terms of reductive chemistry. The challenge for the immediate future, therefore, is to equip these catalysts with high levels of selectivity, as found in natural enzymes.

Copies of all the presentations and the subsequent discussion will be published as Faraday Discussions 155 and may be obtained from the Royal Society of Chemistry (3).

References


3 Faraday Discuss., 2012, in press

The Reviewer
Anthony Harriman started his career in artificial photosynthesis at the Royal Institution in London in 1974, working under Sir George Porter. He spent a total of 14 years at the Royal Institution, including terms as Dewar Research Fellow, 1977–1988, and Assistant Director of the Davy-Faraday Research Laboratory, 1982–1988. He moved to the University of Texas at Austin in 1988 to become Director of the Center for Fast Kinetics Research. This was followed by a short stay at the Université Louis Pasteur in Strasbourg. In 1999, he took up the position of Professor of Physical Chemistry at Newcastle University. He has maintained a strong interest in artificial photosynthesis. Among his many awards are the Corday-Morgan Medal and Prize, 1984, the first Prix Grammaticakis-Neumann en Photochimie, 1985, and the RSC Chemical Dynamics Award, 2011. He has published more than 400 papers in the areas of molecular photophysics, artificial photosynthesis and electron energy transfer.
“Iridium Catalysis”

Reviewed by William D. Jones

University of Rochester, The College of Arts and Sciences, Department of Chemistry, RC Box 270216, Rochester, New York 14627, USA
Email: jones@chem.rochester.edu

“Iridium Catalysis”, edited by Professor Pher Andersson of Uppsala University, Sweden, is another excellent contribution in the outstanding series, Topics in Organometallic Chemistry. Here for the first time in this series is a collection of modern applications of iridium organometallic complexes for the catalysis of organic reactions. The eight chapters cover a range of types of reactions (described below) that are of strong interest in organic synthesis, and provide extensive up-to-date coverage of both the scope and limitations of the catalysts. This work will be a valuable resource for those who are just entering into the field and want to obtain a thorough overview of how iridium can be used in catalysis.

History of Iridium in Catalysis

The book opens with a chapter by Robert Crabtree (Yale University, USA), in which he presents a personal historical perspective of the development of iridium in catalysis. It is astonishing to realise that early on, iridium found little use in organometallic catalysis, as the more successful rhodium-based Wilkinson’s catalyst (1) was dominating interest in the field. Crabtree takes the reader through the series of step-by-step developments in iridium chemistry, focusing on the contributions that individual researchers have made to propel the field forward, for example, Richard Schrock (Massachusetts Institute of Technology, USA), John Osborn (Laboratoire de Chimie des Métaux de Transition et de Catalyse associé au CNRS, Université Louis Pasteur, Institut Le Bel, Strasbourg, France), Hugh Felkin (CNRS Natural Products Institute, Gif-sur-Yvette, France) and Gilbert Stork (Columbia University, USA). He presents the development of important breakthroughs leading to the widespread use that iridium catalysts enjoy today, including the use of alcohol functionality to selectively direct hydrogenations to only one face of an olefin and the importance of t-butylenylene as a hydrogen acceptor. This chapter was fun to read and is one that I will share with my students to show them how a field develops over time by the successive contributions of individuals.
Iridium-Catalysed Hydrogenation

Chapter 2 by Carmen Claver et al. (Universitat Rovira iVirgili, Tarragona, Spain) describes the broad range of phosphines, both bidentate and monodentate, which have been employed in iridium-based hydrogenations of C–N double bonds. One nice feature of the report is that comparative data are provided with different phosphines. For example, enantioselective imine hydrogenations with BINAP, DIOP (Figure 1), and bis(diphenylphosphino)pentane are presented in tabular form so that one can quickly determine which ligand is best for which type of substrate. About a dozen different chelates are presented and compared, as are several chiral monodentate phosphites and phosphoramidites. Substrates include imines, enamines, quinolines and quinoxalines.

Chapter 3 by David Woodmansee and Andreas Pfaltz. (University of Basel, Switzerland) focuses on enantioselective olefin hydrogenations, in which iridium is ligated by P–N or C–N chelates. In an immediate recognition of the importance of mechanism, the authors highlight the effect of the anionic counter ion on the rate of the cationic iridium catalysts. A large non-coordinating anion such as ‘BArF$^-$‘ ($\text{[B\{3,5-(CF$_3$)$_2$C$_6$H$_3$\}]^-$) is the counter ion of choice in most examples presented. Preferred choices between diastereotopic hydrogenation intermediates are revealed using the PHOX chiral ligand (Figure 2). Many combinations of ligand and substrate are then presented to provide a broad view of the capabilities of these catalysts. Stereocontrol is outlined in the hydrogenation of substrates including trisubstituted olefins, fluorinated olefins, vinylboronates, allylic alcohols, conjugate double bonds, gem-disubstituted olefins and enol ethers.

Hydrogen Transfer Reactions

Chapter 4 by Ourida Saidi and Jonathan Williams (University of Bath, UK) presents iridium-catalysed hydrogen transfer reactions, focusing mainly on ketone/aldehyde exchanges but also including other substrates. First, three distinct mechanisms for metal-based hydrogen transfer are presented and the case is made that each is potentially feasible for the reversible hydrogenation of ketones or aldehydes depending on the nature of the ligands present. Next, extension to other substrates such as $\alpha,\beta$-unsaturated ketones, styrenes and imines is given. Examples of asymmetric hydrogen transfer to these same substrates are presented using ligands that react via the concerted hydrogen transfer mechanism (see Figure 3). Several iridium complexes are shown to be effective for the reverse reaction, alcohol oxidation, and as a result, dynamic kinetic resolution processes have been developed by coupling the reversible step with a second enantioselective enzymatic step. Reversible imine/amine hydrogenation is also shown to permit manipulations of the groups attached to nitrogen.

Chapter 5 by John Bower and Michael Krische (University of Oxford, UK, and University of Texas at Austin, USA) addresses C–C bond formation via iridium-catalysed hydrogenation and transfer hydrogenation. The first part shows how alkynes and allenes can be used to serve as vinyliridium surrogates to allow C–C additions to electrophilic substrates, or to alcohols following dehydrogenation. Examples of iridium-catalysed
reactions in which dienes, alkynes and allylic acetates provide allyliridium intermediates that couple with aldehydes to give homoallylic alcohols, in some cases enantioselectively, are given.

**Functionalisation of C–H Bonds**
Chapter 6 by Jongwook Choi and Alan Goldman (Rutgers, The State University of New Jersey, USA) summarizes iridium-catalysed C–H bond functionalisation. The authors quickly move from the earliest reports of iridium-based alkane transfer dehydrogenation for the production of olefins to the important development of ‘acceptorless’ dehydrogenation. As an example of a tandem reaction involving alkane dehydrogenation by iridium, a second metathesis catalyst takes the olefin formed, scrambles the chain length via olefin metathesis, and the iridium complex then re-hydrogenates the metathesised olefin. The net result is ‘alkane metathesis’. Other types of dehydrogenations using iridium catalysts are also described, allowing formation of enamines from alkylamines. Iridium catalysts have found a broad use in arene borylation, producing the highly valued arylboron reagents for use in Suzuki coupling. These iridium catalysts have found applications in arene silylation using disilane reagents for direct C–H arylation. Iridium catalysts are also reported that have limited use in C–C bond formation, such as alkylation of arenes and biaryl formation.

**Allylic Substitution**
Chapter 7 by John Hartwig and Mark Pouy (University of Illinois, USA) covers iridium-based allylic substitution. As with other chapters, Hartwig and Pouy present a historical overview of nucleophilic attack on iridium-allyl complexes. This proceeds through a survey of ligands used for enantioselective C–C forming reactions using PHOX, PYBOX, DIAPHOX, phosphoramidite, and chiral phosphite ligands. The authors then proceed to discuss recent advances in catalyst design resulting from identification of the catalytic intermediate in the phosphoramidite reaction, in which a C–H activation of the ligand had occurred. Fine tuning of the ligand led to excellent yields and enantiomeric excesses (ees) for enantioselective coupling of amines and soft carbon nucleophiles with allyl carbonate substrates (see Figure 4). The chapter concludes with detailed mechanistic discussion of the intermediates involved in these coupling reactions and the challenges that remain in allylic substitution.

**1,3-Dipolar Cycloadditions**
Chapter 8 by Daniel Carmona and Luis Oro (University of Zaragoza-CSIC, Spain) finishes off the collection by presenting a summary of 1,3-dipolar additions to alkynes using iridium catalysis. For comparison, related reactions with other transition metal complexes (for example, iron or ruthenium), are included. With iridium, the enantioselective dipolar addition of a nitrone to methacrolein is discussed as one of the more studied reactions with iridium. Both the catalytic cycle and the origin of the enantioselectivity are discussed.

**Conclusion**
Overall, “Iridium Catalysis” will serve as a useful up-to-date resource for both those entering the field and those experienced chemists who may not be aware of the advances that have been made. In one location, one has access to a range of organometallic catalysis using the latest ligands and reaction conditions. The only topic that I did not see covered is the industrial uses of iridium catalysis (for example, in the Cativa™ process).
process (2)), but otherwise the book is complete. Many examples of iridium catalysis in enantioselective chemistry are included. The book includes a historical perspective on some of the problems that shows chemistry as a living subject. Readers will be stimulated to find new applications for iridium in catalysis after they examine this book.

References

The Reviewer
William D. Jones received his BS in Chemistry at Massachusetts Institute of Technology, USA, in 1975. He obtained a PhD degree in Chemistry at California Institute of Technology in 1979 with Robert G. Bergman, and moved to the University of Wisconsin as a National Science Foundation (NSF) postdoctoral fellow with Professor Chuck Casey. He began at the University of Rochester in 1980, where he is now the Charles F. Houghton Professor of Chemistry. Jones’ research interests include organometallic research in strong C–X bond cleavage, catalysis, model studies, mechanisms, kinetics, thermodynamics and synthetic applications.
Recycling the Platinum Group Metals: A European Perspective

Effective recycling systems for pgm-containing materials will ensure sustainable supply

By Christian Hagelüken
Umicore AG & Co KG, Rodenbacher Chaussee 4, D-63457 Hanau Wolfgang, Germany
Email: christian.hagelueken@eu.umicore.com

The high technical recyclability of platinum group metals means that over 95% recovery can be achieved once pgm-containing scrap reaches a state-of-the-art refining facility. Technical challenges exist, but the main barriers to recycling pgms lie in ensuring the collection of scrap and in the capacity and technical capabilities of recycling chains around the world. Economic and legislative drivers are also significant. The “seven conditions” for effective recycling and their impact within Europe are discussed in this article; industrial applications are found to lead the way in terms of recycling rates while automotive and particularly electronic areas are currently some way behind. New business models are recommended, to enable precious metal-containing waste to be seen as a valuable resource and ensure the sustainability and security of pgms supply for the future.

Introduction
Platinum group metals (pgms) play a key role in modern society, as they are of specific importance for clean technologies and other high-tech equipment. Important applications beyond the well-known areas of chemical process catalysis and automotive emissions control include information technology (IT), consumer electronics, and sustainable energy production such as photovoltaics (PV) and fuel cells, among others (Table I). Driving forces for the booming use of pgms are their extraordinary and sometimes exclusive properties, which make them essential components in a broad range of applications which can play a part in building a more sustainable society.

Competition between applications leads to increased pressure on supply. One way to ensure adequate supplies is to increase exploration and extraction of geological deposits of the pgms (1, 2). Increasing the efficiencies in the primary supply chain may offer some additional gains and much has been achieved here already, but comprehensive recycling efforts are a vital part of effective life cycle management to enable the increased use of secondary (recycled) metals in the future.
Recycling the Platinum Group Metals

Metals are not consumed. Instead, they are only transferred from one manifestation into another. Metal combinations in products often differ from those in primary deposits, which results in new technological challenges for their efficient recovery.

Mass produced consumer components such as computer motherboards contain around 200–250 grams per tonne (g t⁻¹) of gold and around 80 g t⁻¹ palladium; mobile phone handsets contain up to 350 g t⁻¹ gold and 130 g t⁻¹ palladium; and automotive catalytic converters may contain up to 2000 g t⁻¹ pgm in the ceramic catalyst brick, the active part of the converter. This is significantly higher than the gold or pgm content in primary ores (on average < 10 g t⁻¹). The high intrinsic metal values make recycling attractive from an economic point of view, and due to the much higher concentration compared to mining of ores, it also helps to reduce the environmental burden of metal supply significantly, especially with respect to the impact on climate. Even more valuable for recycling are pgms used in jewellery, as these are typically concentrated at an even higher level.

Technical and Market Challenges

Such challenges exist, especially for complex products such as vehicles and computers. Effective recycling requires a well-tuned recycling chain, consisting of different specialised stakeholders, starting with the collection of old products, followed by sorting/dismantling and pre-processing of relevant fractions, and finally recovery of the metals. The latter requires sophisticated, large-scale metallurgical operations. For example, Umicore, at its integrated smelter-refinery in Antwerp, Belgium (Figure 1), currently recovers and supplies back to the market via its main process route.

Table I

<table>
<thead>
<tr>
<th>Application area</th>
<th>Platinum group metal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Platinum</td>
</tr>
<tr>
<td>Catalysts</td>
<td>✓</td>
</tr>
<tr>
<td>Electronics</td>
<td>✓</td>
</tr>
<tr>
<td>Fuel cells</td>
<td>✓</td>
</tr>
<tr>
<td>Glass, ceramics and pigments</td>
<td>✓</td>
</tr>
<tr>
<td>Medical/dental</td>
<td>✓</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>✓</td>
</tr>
<tr>
<td>Photovoltaics</td>
<td>✓</td>
</tr>
<tr>
<td>Superalloys</td>
<td>✓</td>
</tr>
</tbody>
</table>

Fig. 1. Umicore, at its integrated smelter-refinery in Antwerp, Belgium
seven precious metals as well as ten base and special metals. Further metals are recovered in special processes from rechargeable batteries or high grade photovoltaic residues (3, 4). Johnson Matthey, at its refineries in Brimsdown and Royston, UK, recovers platinum, palladium, iridium, rhodium and ruthenium along with gold and silver from secondary materials using the traditional refining route. It also uses Smopex® to recover other metals where process economics require, or in the cleaning of effluent (5, 6).

Recycling technology has made significant progress (Figure 2) (7–9). Further improvements are constantly being made to increase the yields from the recycling process, as well as to extend the range of metals that can be recycled.

The biggest challenges to overcome are the insufficient collection of consumer goods and inefficient handling within the recycling chain. The life cycle structure for consumer goods differs fundamentally from that of industrial pgm products such as process catalysts. For the latter, ownership usually remains with the industrial user, the product location is well known, and handling throughout the life cycle is conducted in a professional, transparent way. This is known as a “closed loop” recycling system.

In contrast, ownership of consumer items tends to shift frequently, goods such as mobile phones and cars are moved around the globe, manufacturers lose track of their devices and the flow of products becomes impossible to trace. This forms an “open loop” in which recycling cannot be guaranteed. Even after an item reaches the recycling chain, the first steps in particular are not always handled by reputable agencies.

The Seven Conditions for Effective Recycling

For effective recycling of a product, material or metal, seven conditions must be met:

1. **Technical recyclability** of the material or metal combination. All precious metals and many other metals can be recovered from, for example, a printed circuit board if state-of-the-art processes are used.

2. **Accessibility** of the relevant components. An underfloor automotive catalyst or personal computer (PC) motherboard is easily accessible for dismantling, whereas a circuit board used in car electronics (for example, in the engine management system) usually is not. As long as such circuit boards are isolated or dismantled before the car is put through the shredder, the precious metals they contain are easily recyclable.

3. **Economic viability**, whether intrinsically or externally created. A dismantled PC motherboard has a positive net value, therefore recycling is viable by itself. In contrast, a dismantled ultra-thin pgm-coated PC hard disk usually has a negative net value due to the cost of processing it. Recovering the platinum and/or ruthenium from it would currently not be economically viable unless paid for externally or subsidised.

4. **Collection mechanisms** to ensure the product is available for recycling. If collection mechanisms

---

![Fig. 2. PGM recovery/recycling: number of patents in the last ten decades](image-url)
are not in place, items such as old PCs or mobile phones may end up being stored in households or discarded into the waste bin for landfill or municipal incineration. The precious metal they contain would effectively be lost to the recycling chain.

(5) **Entry into the recycling chain** and remaining therein up to the final step. Items such as PC motherboards, mobile phones or cars containing catalysts are often sent (either legally or illegally) to countries without the proper infrastructure for recycling at their end of life. This can also result in precious metals being lost to the recycling chain.

(6) **Optimal technical and organisational** set-up of this recycling chain. Comprehensive recycling chains exist within Europe, though it is important that items such as PCs or mobile phones are not mixed with other low grade electronic waste and channellled into a shredder process without prior removal of the precious metal-containing circuit boards. The same applies to the pgm-containing catalyst in a car or fuel cell.

(7) **Sufficient capacity** along the entire chain to make comprehensive recycling happen. Once Conditions 1–6 are met, the only requirement is to ensure that there is sufficient capacity to process the volume of material available for recycling. Precious metal refiners are willing to invest in building up such capacities provided there is sufficient security of feed later on. Conditions 5 and 6 are thus crucial to trigger timely investments in a principally growing market for (precious) metals recycling.

End of life products and materials will reach various steps in this sequence of conditions; the higher they get, the easier it will be to find appropriate measures to make use of this recycling potential.

**Figure 3** (10) shows a schematic representation of a life cycle for a typical pgm-containing product, highlighting the various points at which losses of precious metal can occur. Each of these provides an opportunity for making an improvement to the process or for adding incentives that encourage recycling to take place.

**Case Studies**
The following case studies briefly illustrate the current recycling rates for pgm materials from industrial,
automotive and consumer electronic applications. All numbers refer to global averages.

Case Study 1: Industrial Applications
Industrial applications such as catalysts used in fine chemicals production or petrochemical processing, and pgm equipment used in the glass industry, are the current benchmark for pgm recycling, with recycling rates of 80–90% (although catalyst lifetimes can reach several years before they enter the recycling chain). Recycling in this case is solely market driven and is an integral part of the product life cycle. Each of the Conditions 1–7 are met, strongly supported by the economic significance of the pgm materials involved. This limits the need for primary metal supply in these industries to covering the small life cycle losses and keeping up with market growth and new applications.

Case Study 2: Automotive Applications
End of life recycling rates for pgms in automotive applications reach a global average of 50–60%. A recent United Nations Environment Programme (UNEP) report (11) shows that this is significantly more than for most other metals, but it still leaves room for improvement compared to the rates of recycling seen in most industrial pgm applications. Automotive pgm recycling within Europe is partly impacted by legislation such as the EU End of Life Vehicles (ELV) Directive (12), but the dominant driver is economic. As for all pgm applications, technical recyclability is not a problem. However, in automotive applications, the pgm-containing catalyst is only a subsystem of a larger product, i.e. the car, which is driven by its own market mechanisms at its end of life. European car catalyst recycling mainly fails at Condition 5 (13). Many old cars are exported to countries outside Europe which lack an appropriate recycling chain, and it is only due to the excellent recyclability and the intrinsic economic value of automotive catalyst recycling that the pgm losses here are not even higher. Better enforcement of transboundary waste shipment rules to limit the export of genuine scrap cars could give a further push to recycling rates within Europe.

Case Study 3: Electronic Applications
Recycling rates are currently only 5–10% for pgms in electronic applications. The main driver for recycling is legislation such as the EU Waste Electrical and Electronic Equipment (WEEE) Directive (14). The largest use of pgms in electronics is palladium used in circuit boards, and market mechanisms at the end of life of products such as PCs, TVs, mobile phones, car electronics etc. play an important role in the rates of collection and recycling of the circuit boards they contain. As in the case of automotive catalysts, a big challenge occurs at Condition 5 when end of life electronics are exported out of Europe, but Condition 4 in which items are stored by consumers or disposed of through municipal waste collection is also significant. Conditions 2 and 3, the accessibility and economic viability of components for recycling, can be an issue in some cases, as can Condition 6, inappropriate handling within the recycling chain.

Legislation such as the EU WEEE Directive helps to stimulate recycling of electrical and electronic products but its enforcement is currently weak. More transparency and better monitoring of end of life chains would improve the rates of recycling of these products. And, most importantly, a shift of focus of the current legislation away from mass and towards a more pragmatic approach to the introduction of treatment standards and a certification system along the recycling chain would help to increase the recycling rates of pgms and other metals which are present in low amounts.

Differences in Recycling Rates
The main reason for the differences in recycling rates in these three case studies is less a question of market vs. legislative drivers, and more connected to which step a product reaches in the sequence of conditions listed above. It is important to note that in all applications the technical recyclability is not an issue, as yields of well over 95% can be achieved if the product or the pgm-containing component therein (for example, a circuit board) reaches a state-of-the-art precious metals refinery. Hence, neither pgm product manufacturers nor pgm refiners can act to improve the situation; it is the life cycle system as a whole and the interactions of the stakeholders within that system which will make the difference.

Recommendations for the Future
The potential for recycling precious metal-containing waste can be thought of as an “urban mine”, and can complement the primary source of pgm supply from mining. However, in order to fully utilise this potential source of secondary supply, the following changes will need to take place:

• **Attitudes** need to change from “waste management” to “resource management” to ensure the collection and appropriate treatment of end of
life products and encourage the enforcement of legislation. This is particularly important where economic or environmental drivers are currently absent.

• **Targets** need to be adapted accordingly, with emphasis on the quality and efficiency of recycling processes and the recovery of precious and other critical metals, rather than on the overall mass of materials such as plastics or steel.

• **Recycling practice** needs to reflect the new requirements. In place of the traditional structures of a scrap business, high-tech recycling can sit alongside clean-tech manufacturing and renewable energy generation in terms of company structures, appearance and stakeholder cooperation, with increased emphasis on transparency and business ethics.

• **The manufacturers’ vision** needs to change. Rather than a burden imposed by legislation, recycling can be seen as an opportunity for manufacturers to sustainably increase access to the raw materials needed for their future production.

To close the recycling loop for consumer products there will need to be a gradual shift towards more industrial style practices, which means that new business models will need to be introduced to provide strong incentives for returning products at their end of life. This may include deposit fees on new products; product service systems, such as leasing; or other means. This may include deposit fees on new products; product service systems, such as leasing; or other approaches. For emerging technologies (such as fuel cells (15) and photovoltaics), setting up “closed loop structures” from the beginning will be essential, and manufacturers that put successful models in place can secure their supply of pgms for the future.

**Conclusions**

Efficiently recycling our end of life products today is insurance for the future. Effective recycling systems would thus make a significant contribution to conserve natural resources of metals and secure sufficient supply of pgms and other scarce metals for future generations. It would further mitigate metal price volatility and limit the climatic impacts of metal production, which is energy intensive, especially in the case of (precious) metals mined from ores containing low concentrations of the desired metals.

The technical recyclability of the pgms combined with the structures in place within the pgm industry as a whole means that it has reached a leading position in terms of sustainable metals management and recycling, thanks in part to the high value of the pgms. In some areas further room for improvement exists, and this can be put into practice by involving all stakeholders and with appropriate political support for the relevant legislation.

**References**


**The Author**

Dr Christian Hagelüken is a director for EU Government affairs at Umicore. He has over 20 years' experience in (precious) metals recycling, covering various working fields from automotive and chemical catalysts to electronic scrap and fuel cell recycling.
Diesel Emissions Conference India 2011

Highlights from the latest Diesel Emissions Conference, held in Delhi

Reviewed by Milan Kapoor

Johnson Matthey India Pvt Ltd, Plot 12, Sector 3, IMT Manesar, 122050, Haryana, Gurgaon, India
Email: kapoorm@mattheyasia.com

Introduction

The 2nd Diesel Emissions Conference India 2011, held in Delhi on 5th–7th September 2011 (1), brought together over 200 leading stakeholders from India and beyond to discuss the industry's progress in meeting the Bharat Stage III and IV legislation which also applies to commercial vehicle diesel applications over 3.5 tonnes (2). The conference also showcased the latest emissions reduction technologies being used in India and across the world, and acted as a platform for networking among Indian diesel emission industry delegates. There were 27 presentations given over three days which included topics such as:

• Government strategy for supplying Bharat Stage IV (BS IV) diesel fuel;
• The crucial development of AUS 32 (aqueous urea solution, 32.5%, also known as AdBlue®) supply infrastructure and AUS 32 price analysis in India;
• New fuel economy standards in India and their impact on the automotive industry;
• Emissions control for on- and off-road vehicles in India to further improve air quality;
• Case study on the implementation of Euro IV in China and lessons for the Indian market.

This review focuses on the use of selective catalytic reduction (SCR) technology for controlling diesel nitrogen oxides (NOx) emissions and the development of the AUS 32 market in India. Papers can be purchased from the Diesel Emissions Conference website (1).

Selective Catalytic Reduction Technology

Original equipment manufacturers (OEMs) in India are choosing between an SCR or an exhaust gas recirculation (EGR) route for controlling NOx emissions. EGR works by recirculating some of the exhaust gas back into the engine. This lowers the temperature of combustion and reduces the amount of NOx formed.

SCR is a very effective alternative NOx emission control technology. It provides a means of converting NOx to nitrogen gas (N₂) and water (H₂O) (3). Ammonia in the form of AUS 32 is typically added to the exhaust stream to act as reductant. An accurate ammonia con-
trol system is required to inject the ammonia at an appropriate rate. The operation of an SCR system is shown in Figure 1. Ammonia SCR does not deal with hydrocarbon (HC), carbon monoxide (CO) or particulate matter (PM) emissions. These may be removed by a diesel oxidation catalyst (DOC) and/or a diesel particulate filter (DPF). While SCR typically uses base metal/zeolite-based catalysts, the DOC uses a platinum group metal (pgm) catalyst and DPFs may also be catalysed by pgms to aid regeneration. Platinum can also be used to control ammonia slip – preventing emissions of unreacted NH₃.

Cummins Emission Solutions, India, showcased why the market trend, in their experience, is towards the use of SCR systems (4). Following are the salient points given on why SCR is preferred over EGR for the Euro IV and V markets:

- Improvement in overall system efficiency;
- Robustness to variation in fuels quality;
- Fuel economy improvement;
- Increased power density and lower heat rejection;
- Service interval improvement (oil drain – low soot);
- Low maintenance cost;
- Technology path to Euro V.

The presentation described Cummins’ global experience of SCR, with approximately 9 billion km on-road experience in Europe and 24 million km in the USA. Some pros and cons of both EGR and SCR were also presented, of which the most important was fuel economy. This is 5%–8% better with SCR compared to EGR. Challenges for the adoption of SCR technology include the packaging, dosing strategy and cost of AUS 32 (3).

### AUS 32 Demands and Forecast in India

After the launch of BS IV in India, around 17% of total diesel and 27% of total motor gasoline consumption was of BS IV quality in 2010–2011. The percentage of vehicles using BS IV fuel is expected to increase in the next few years as BS IV fuel becomes available in 50 cities. This will allow more vehicles to be fitted with an exhaust aftertreatment system which meets the BS IV standards. To achieve the BS IV standards for the commercial vehicle segment in India, OEMs are developing systems based on SCR and DOC plus DPF options. Figure 2 shows diesel emissions control technologies which can be found in the Indian market to achieve the BS IV and V standards.

The current scenario in the Indian commercial vehicle market is summarised in Table I. Current penetration of SCR in the Indian commercial vehicle market is negligible but is expected to reach 60% by 2015–2016. Currently the Indian commercial vehicle market is dominated by the DOC plus DPF option, but this may come down to 37% of market share once SCR and the availability of automotive quality AUS 32 are established.

Gulf Oil Corporation Ltd, India, shared a presentation on different modes of distribution of AUS 32 in India and the impact of its price on the SCR market in India. Presently the mode of distribution is mainly in drums (200 litres). In the next 3 years as demand...
grows; a bulk dispenser option will also come in along with small packs (10 litres and 20 litres). Figure 3 shows the expected demand projection of Adblue® (AUS 32) in BS IV cities for the buses which are more than 12 tonnes.

The price of AUS 32 will also play a key role in making SCR popular among Indian OEMs (5). Presently the price in India is approximately US$1 per litre (plus taxes). The speaker indicated that it will be essential to bring down the price to be equivalent to that of diesel, which is US$0.82 per litre in Delhi at the time of writing. It will then be necessary to further reduce the price to two thirds of the diesel price to make it commercially viable for customers. AUS 32 is a subsidised commodity in India and its pricing and availability will remain a critical point of discussion in Government corridors.

Conclusion
India is moving ahead with stringent emissions standards for commercial vehicle applications. It has already implemented Bharat IV, equivalent to Euro IV, in thirteen cities and the number of cities will increase in future. OEMs have opted for either an SCR or an EGR route to achieve these standards. During the three day course of the conference and panel discussions, there was much discussion of the advantages and disadvantages of the SCR route for NOx control. To what extent SCR will be used by OEMs in India will also depend upon the availability of AUS 32 in India. Good infrastructure and easy availability of AUS 32 at a reasonable price are a few points which the Indian government needs to look into in the future.

Presently in the heavy duty diesel segment the majority of OEMs are ready with either DOC only or DOC + partial filter (uncoated) or SCR as exhaust aftertreatment systems on different platforms to meet the stricter emission standards. The major volume share is currently DOC or DOC + partial filter systems. However, we envisage that the use of SCR technology will increase as the BS IV standards are implemented across India.

Table I
Classes of Diesel Commercial Vehicles in the Indian Market, with the Dominant Types of Emissions Control in 2011

<table>
<thead>
<tr>
<th>Class</th>
<th>Size, tonnes</th>
<th>Different emissions control technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light commercial vehicles (LCV)</td>
<td>3.5 to 7.5</td>
<td>EGR or EGR + DOC or EGR + DOC + DPF</td>
</tr>
<tr>
<td>Medium commercial vehicles (MCV)</td>
<td>7.5 to 12</td>
<td>Mostly EGR or EGR + DOC, EGR + DOC + DPF, some SCR</td>
</tr>
<tr>
<td>Heavy commercial vehicles (HCV)</td>
<td>&gt; 12</td>
<td>Mostly SCR</td>
</tr>
</tbody>
</table>

Fig. 2. Diesel emissions control regulation limits in India, and the technologies currently found in the Indian market to achieve them. Note: the Bharat II, III, IV and V emissions limits are equivalent to the Euro II, III, IV and V limits, respectively
References


The Reviewer

Milan Kapoor is Senior Application Engineer for Johnson Matthey Catalysts, India. He is responsible for giving technical support to Indian OEMs and helps to develop new business.
Physical Properties and Application Performance of Platinum-Palladium-Rhodium Alloys Modified with Cerium

http://dx.doi.org/10.1595/147106711X615749

By Xin Hu
School of Materials Science and Engineering, Kunming University of Science and Technology, Kunming, Yunnan 650093, China; and Faculty of Metallurgy and Material, Kunming Metallurgy College, Kunming, Yunnan 650033, China

Yuantao Ning
Kunming Institute of Precious Metals, Kunming, Yunnan 650106, China

Liangwei Chen* and Qingnan Shi
School of Materials Science and Engineering, Kunming University of Science and Technology, Kunming, Yunnan 650093, China
*Email: lwchen1968@yahoo.com.cn

Chaoguang Jia
Faculty of Metallurgy and Material, Kunming Metallurgy College, Kunming, Yunnan 650033, China

The physical properties and some application performance parameters of a platinum-palladium-rhodium-cerium alloy (Pt-4Pd-3.5Rh-0.1Ce) (wt%) are reported. This alloy possesses finer grain size, higher recrystallisation temperature and better mechanical properties, including tensile strength, lasting strength and creep resistance, than traditional Pt-10Rh and Pt-4Pd-3.5Rh catalytic alloys. Catalytic gauzes made of the Pt-4Pd-3.5Rh-0.1Ce alloy also show a higher conversion rate of ammonia to oxides of nitrogen, lower Pt loss rate, improved resistance to corrosion, adhesion and poisoning, and longer service lifetime for nitric acid production than gauzes made of the traditional alloys.

1. Introduction
Nitric acid (HNO₃) is produced by ammonia (NH₃) oxidation through catalytic gauzes under pressures of 0.1–0.9 MPa and temperatures of 800–900°C. Pure Pt was originally selected as the catalyst due to its high catalytic activity and chemical stability (1). The operating life of catalytic gauzes strongly depends on the mechanical properties and grain size stability of the material from which they are made. The performance, lifetime and efficiency of gauzes used in the process of NH₃ oxidation are also determined by the rate of inactive surface growth which impedes the flow of gases through the gauzes, the methods used to process the alloys into wires and gauzes, the structural stability of the alloys and the stability of parameters of the NH₃ oxidation process (2, 3).

In order to improve the mechanical properties of Pt catalytic gauzes, Pt-Rh alloys with various Rh contents in the range 5–20 wt% Rh were developed. In the 1940s DuPont patented a Pt-Rh alloy containing 92.5–93% Pt and 7.0–7.5% Rh (4). In the 1950s the former USSR developed a Pt-4Pd-3.5Rh alloy catalyst by partial substitution of Pd for Rh in the formulation (5). After 25 years, another new catalyst alloy, consisting of 81% Pt, 15% Pd, 3.5% Rh and 0.5% Ru, was developed (5). Currently, Pt-Rh and Pt-Pd-Rh alloys are the
main catalyst materials used for production of HNO₃ through NH₃ oxidation. Attempts have been made to improve the properties of these alloys by further modifications. A Pt-10Rh alloy modified with boron was found to have lower grain growth and similar catalytic properties to a ‘classical’ Pt-10Rh alloy. Its application in the nitric industry would enable the temperature of NH₃ oxidation to be increased, with subsequent improvements in process efficiency, while significantly reducing the emission of harmful nitrous oxide (N₂O) to the atmosphere and maintaining the operating lifetime of the gauzes (6). Iridium, zirconium, vanadium and rhenium may also be added to modify the alloy. The properties of Pt-5Rh-1Ir-0.1Zr, Pt-5Rh-1Ir-0.01V and Pt-5Rh-1Re alloys were found to be similar to those of Pt-10Rh (7, 8).

Research on the strengthening effect of rare earth (RE) metals on Pt and its alloys was performed at Kunming Institute of Precious Metals (KIPM) in China (9–11). As a result of this work, new Pt-Pd-Rh-RE catalytic alloys, containing 0–15 wt% Pd, 0–10 wt% Rh, 0–1.0 wt% single or mixed RE and the balance Pt, were developed and patented by KIPM (12). The present paper reviews the main properties of Pt-Pd-Rh catalytic alloys modified by Ce additions and their application in the production of HNO₃ in China.

2. Microstructure of the Alloys

In order to compare the Pt-10Rh binary alloy (‘PR-1’) and the Pt-4Pd-3.5Rh ternary alloy (‘PR-2’) with the Pt-4Pd-3.5Rh-0.1Ce quaternary alloy (‘PR-3’), a parallel study was carried out (13). X-Ray diffraction (XRD) patterns indicated that the three alloys are single solid solution structures (14). The microstructures of the PR-2 and PR-3 alloys annealed at 900ºC for 30 min are shown in Figure 1. It can be seen that the PR-3 alloy (Figure 1(b)) has a much finer grain size than the PR-2 alloy (Figure 1(a)). The recrystallisation softening curves of the PR-2 and PR-3 alloys are shown in Figure 2, indicating that the recrystallisation temperature of the PR-3 alloy is about 120ºC higher than that of the PR-2 alloy.

3. Physical Properties of the Alloys

3.1 Mechanical Properties

The mechanical properties of the three alloys after annealing at 900ºC for 1 h and after annealing continuously at 1000ºC at a rate of about 20 m min⁻¹ are indicated in Table I. Mechanical tests were carried out at room temperature. The tensile strength (σₚ) of the PR-3 alloy was significantly higher than those of the PR-1 and PR-2 alloys under both sets of annealing conditions. The tensile elongation (δ) in 100 mm of the PR-3 alloy was similar to those of the PR-1 and PR-2 alloys (13).

The tensile strengths, stress-rupture curves and creep rupture times of the PR-1, PR-2 and PR-3 alloys at high temperature are shown in Figures 3–5. The tensile strength of the PR-3 alloy was higher than those of the PR-1 and PR-2 alloys even at high temperatures. The tensile strength of the PR-3 alloy at 1100ºC was similar to that of the PR-1 alloy and about 40% higher than that of the PR-2 alloy (see Figure 3), the lasting strength (defined as the stress to produce failure at a specified time and temperature) of the PR-3 alloy at 900ºC for 100 h was 1.7 times higher than that of the PR-1 alloy and about 3.5 times higher than that of the PR-2 alloy, respectively, and creep-rupture
time of the PR-3 alloy was longer than those of both the PR-1 and PR-2 alloys (see Figure 4). The creep-rupture time of the PR-3 alloy at 900ºC with a stress of 40 MPa was over 3 times longer than that of the PR-1 alloy and 10 times longer than that of the PR-2 alloy (see Figure 5).

### 3.2 Oxidation and Volatilisation of the Alloys

The volatilisation losses caused by oxidation of the three alloys during isothermal heating at 900ºC in pure flowing oxygen were studied (15). The relationship between the weight loss per unit area (\(\Delta W/S\)) and the heating time (\(t\)) shown in Figure 6 can be approximately expressed as in Equation (i):

\[
\Delta W/S = K_1 t^{2/3}
\]

Here \(K_1\) is the weight loss rate constant for the alloy samples. The difference in \(K_1\) is due to the effects of the Rh, Pd and RE components in the alloys on the formation rate of platinum oxide (PtO\(_2\)), as determined by Rubel et al. (16, 17). It can be seen from Figure 6 that the PR-3 alloy had the smallest \(K_1\) value of the three alloys studied.

### 3.3 Performance of the Platinum Alloy Catalytic Gauzes

Parallel industrial experiments for HNO\(_3\) production were carried out (18). Catalytic gauzes made from the PR-2 and PR-3 alloys were tested in an atmospheric pressure reactor, with an operating pressure of 0.1 MPa and temperatures of 820–840ºC. Catalytic gauzes made from the PR-1, PR-2 and PR-3 alloys were tested in a medium pressure reactor, at an operating pressure of 0.5 MPa and temperatures of 860–880ºC. The conversion rate of NH\(_3\) to oxides of nitrogen, the weight loss rate of Pt and other parameters were determined in the same HNO\(_3\) production plant.

#### 4.1 Oxidation and Volatilisation of the Catalytic Gauzes

The rates of Pt loss from catalytic gauzes made from each of the three alloys were determined during parallel industrial experiments over a period of two years in an atmospheric pressure reactor (18). The relationship between the parameter \(\psi\) (\(\psi = \Delta W/W \times t\)), which is the sum of the relative Pt loss per day for the PR-2 and PR-3 alloy gauzes, and the running time (\(t\)) is shown in Figure 7. It can be approximately written as Equation (ii):

\[
\psi = K_2 t^{2/3}
\]

Here \(K_2\) is the platinum loss rate constant for the Pt alloy catalytic gauzes. \(K_2\) was \(3.95 \times 10^{-2}\) d\(^{-1}\) for the PR-2 alloy gauze and \(2.95 \times 10^{-2}\) d\(^{-1}\) for the PR-3 alloy gauze over the period studied. The Pt loss rate con-
stant of the PR-3 alloy gauze was 25% lower than that of the PR-2 alloy gauze.

It should be noted that Equation (ii) has the same form as Equation (i) because the same mechanism of Pt loss applies.

4.2 Conversion Rate of Ammonia to Oxides of Nitrogen
The mechanism of NH₃ oxidation over Pt, Pd and Rh wires has been reported (19). The overall reaction pathways to N₂O, nitrogen monoxide and nitrogen are equivalent on each of the three platinum group metals. NO is a primary reaction product, while N₂ and N₂O originate from consecutive NO transformations. The extent of the secondary reactions determines the net NO selectivity. Rh is the most active catalyst for the unwanted reduction of NO by NH₃, while Pt shows the lowest activity. This explains the superior NO selectivity attained over Pt. NO selectivity approaching 100% at complete NH₃ conversion can be equivalently attained over Pt, Pd and Rh by increasing the oxygen content in the feed. For a feed of O₂/NH₃ = 10, both N₂O and N₂ production are suppressed due to the impeded NO dissociation and favoured NO desorption at high O₂ coverage.

The conversion rate of NH₃ to oxides of nitrogen is one of the main performance indexes for catalytic gauzes. In an atmospheric pressure reactor, an NH₃ conversion rate of 96% or above is required for optimal operating efficiency. The average NH₃ conversion rate for the PR-2 alloy gauze in an atmospheric pressure reactor over a period of two years was 97%, and for the PR-3 alloy gauze it was 98.5%. In a medium pressure reactor, the NH₃ conversion rate for the PR-2 alloy gauze was about 1.0–1.5% higher than that of the PR-1 alloy gauze. This was attributed to the contribution of the Pd component (4). The NH₃ conversion rate for the PR-3 alloy gauze was about 1.0–2.0% higher than those of the PR-1 or PR-2 alloy.
gauzes. These results suggest that the addition of Ce to Pt-Pd-Rh alloys can further increase the conversion rate of NH$_3$ to oxides of nitrogen.

The catalytic activity of Pt alloys is related to the O$_2$ adsorptivity of Pt. High-resolution electron energy loss spectroscopy (HREELS) revealed two characteristic peaks at 700 cm$^{-1}$ and 870 cm$^{-1}$ due to O$_2$ adsorbed on Pt (111) at 92 K. This suggests that molecular oxygen may be attached on the surface of the Pt atoms. At higher temperatures, a dissociatively adsorbed O atom has a loss peak at 470 cm$^{-1}$, which may be assigned to a Pt-O stretching vibrational mode (4). This mode may promote the formation of active compounds and speed the NH$_3$ oxidation reaction. Pd metal has intrinsic catalytic activity for the NH$_3$ oxidation reaction, and the Pd component in the Pt alloy can also help to reduce PtO$_2$ to Pt and to prevent the formation of rhodium(III) oxide (Rh$_2$O$_3$) (20). Therefore adding or increasing the content of Pd in a Pt-Rh or Pt-Pd-Rh alloy would be expected to increase the NH$_3$ conversion rate.

The unfilled 4$f$ electron shells of RE metals, especially elements such as cerium, lanthanum and praseodymium which have a variable valence, may be responsible for their catalytic activity. Under the conditions of the NH$_3$ oxidation reaction, Ce metal is oxidised to CeO$_2$ or Ce$_2$O$_3$ in a reversible oxidation-reduction reaction, Equation (iii):

$$2\text{CeO}_2 \rightleftharpoons \text{Ce}_2\text{O}_3 + 1/2\text{O}_2$$  (iii)

The Ce component has a large oxygen storage capacity. If the alloy has a Pd component, CeO$_2$ may be reduced and attached to Pd crystal surfaces (11). This can increase the oxygen storage capacity of the Pd lattice, and new active sites for NH$_3$ oxidation may be formed at the lattice interfaces between Pd atoms. This may explain the high NH$_3$ conversion rate of 98.5% observed for the PR-3 alloy catalyst in the atmospheric pressure reactor.

4.3 Platinum-Loss Rate of the Platinum Alloy Gauzes

During production of HNO$_3$, Pt is lost from catalytic gauzes, mainly due to PtO$_2$ volatilisation. The Pt loss rate can be measured as the weight loss of the catalytic gauze per tonne HNO$_3$ produced, and directly affects the production cost of HNO$_3$. The Pt loss rates for catalytic gauzes made from each of the three alloys were determined. The Pt loss rates for the PR-2 and PR-3 alloy gauzes running for 337 days in atmospheric pressure reactors are listed in Table II. The total Pt loss from the PR-3 alloy gauze was 861 g, and the Pt loss rate was 0.043 g Pt per tonne HNO$_3$. This was about 28% lower than that of the PR-2 alloy gauze.

It should be noted that these results may contain errors due to ignoring the increased weight of CeO$_2$. It is difficult to measure the CeO$_2$ weight increase, and as the alloy contains less than 0.1 wt% Ce evenly distributed throughout the alloy, only the small amount of Ce at the surface would become oxidised. Therefore this weight increase was ignored.

4.4 Corrosion Resistance of the Platinum Alloy Gauzes

The smooth surfaces of the original gauzes gradually became roughened during operation. It has been suggested that between 286ºC and 374ºC, adsorbate-enhanced surface diffusion of Pt can cause surface restructuring, well below the temperatures reported for significant Pt transport through the gas phase via volatile PtO$_3$ (21). Pt atoms, or rather PtO$_2$ particles, evaporating from a wire surface can lead to catalytic NH$_3$ oxidation taking place close to, but not at, the

### Table II

<table>
<thead>
<tr>
<th>Alloy gauge</th>
<th>Amount of Pt loss, g</th>
<th>Pt loss rate, g Pt t$^{-1}$ HNO$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR-2</td>
<td>1192</td>
<td>0.060</td>
</tr>
<tr>
<td>PR-3</td>
<td>861</td>
<td>0.043</td>
</tr>
</tbody>
</table>

Fig. 7. The curves of the sum of the relative Pt loss per day and running times for the PR-2 and PR-3 alloy gauzes.
gauze wire surface itself. Pt is then deposited on catalyst or catchment gauzes, forming deposits known as ‘Brussels sprouts’ or ‘cauliflowers’. These deposits have little catalytic activity. The Pt deposits on catalyst and catchment gauzes have a dense structure, with crystal-oriented flat subgrain walls (22, 23).

During the NH$_3$ oxidation process, each sheet of catalytic gauze becomes etched along the grain boundaries and defects of the alloys. A large number of corrosive pits, etching facets and cauliflower-like structures appear on the surfaces, causing surface structural reconstruction (24). The surface morphology of the PR-2 and PR-3 alloy catalytic gauzes after 6 months’ service in parallel atmospheric pressure reactors is shown in Figure 8. Cauliflower-like structures can be seen in the PR-2 alloy gauzes (Figure 8(a)); however, the PR-3 alloy gauzes (Figure 8(b)) do not show these cauliflower-like structures. It may be concluded that the PR-3 alloy gauzes showed less etching and therefore better corrosion resistance than the PR-2 alloy gauzes.

In addition, the PR-3 alloy gauzes showed higher resistance to adhesion and poisoning than the PR-2 alloy gauzes during service. The service lifetime of the PR-3 alloy gauzes was found to be about 1.5 to 2 times as long as those of the PR-1 and PR-2 alloy gauzes in atmospheric and medium pressure reactors (13). At 0.1 MPa, the service lifetime was 12 months for the PR-1 and PR-2 alloy gauzes, and 18 months for the PR-3 alloy gauze. At 0.5 MPa the service lifetimes were 3 months for the PR-2 alloy gauze and 6 months for the PR-3 alloy gauze.

5. Conclusions
The Pt-4Pd-3.5Rh-0.1Ce alloy has a finer grain size in both the as-cast and annealed form, higher recrystallisation temperature, greater tensile and lasting strengths, longer creep-rupture time at high temperature, and lower weight-loss rate constants than the traditional binary Pt-10Rh alloy and ternary Pt-4Pd-3.5Rh alloy. Catalytic gauzes manufactured from the quaternary Pt-4Pd-3.5Rh-0.1Ce alloy demonstrate a higher conversion rate for the oxidation of NH$_3$ to oxides of nitrogen, a lower Pt loss rate, better resistance to corrosion, adhesion and poisoning, and longer service life for the production of HNO$_3$ in industrial atmospheric and medium pressure reactors.

References
9 Y. Ning, Guijinshu (Chin.), 1994, 15, (2), 61
10 C. Hu, H. He and F. Chen, Guijinshu (Chin.), 1998, 19, (1), 1
11 Y. Ning and X. Hu, Platinum Metals Rev., 2003, 47, (3), 111
12 Y. Ning and J. Wang, Kunming Rare Metal Institute, ‘Platinum Alloy for Ammonia Oxidation Catalyst’, Chinese Patent 1,071, 602; 1993
13 Y. Ning, Guijinshu (Chin.), 2011, 32, (1), 7
14 Y. Ning, H. Dai, F. Wen, Y. Li, X. Hu, Q. Zhou and G. Guo, Guijinshu (Chin.), 1997, 18, (2), 1

Fig. 8. Surface of: (a) PR-2 alloy and (b) PR-3 alloy catalyst gauzes after 6 months’ service in parallel atmospheric pressure reactors (magnification × 200)
16 M. Rubel, M. Pszonicka and W. Palczewska, *J. Mater. Sci.*, 1985, **20**, (10), 3639

**The Authors**

Xin Hu is a Senior Engineer at Kunming Metallurgy College, and a PhD student at Kunming University of Science and Technology in China. His research interests are mainly in developing and producing new materials based on precious metals for industrial application. He has published several papers and won national prizes for his work.

Professor Yuan Tao Ning is a Professor of Physical Metallurgy at Kunming Institute of Precious Metals in China. His main research interests are related to principles of alloying and new materials based on precious metals, particularly platinum group metals and their alloys, including those modified by the rare earth metals. He has published around 200 papers in national and international periodicals and won national prizes for his scientific achievements.

Professor Dr. Liangwei Chen works at Kunming University of Science and Technology in China, where he carries out X-ray diffraction and scanning electron microscopy (SEM) analysis. He has released 48 X-ray powder diffraction patterns to the International Centre for Diffraction Data® (ICDD®). His main fields of research include alloys of the platinum group metals as well as zinc- and titanium-based alloys.

Professor Qingnan Shi is the Director of Educational Administration at Kunming University of Science and Technology in China. He has carried out important studies on nanomaterials by severe plastic deformation, mainly copper-, aluminium- and titanium-based alloys. He advises several research groups on topics including platinum-based superalloys, alloys for high-temperature applications and materials analysis.

Chaoguang Jia is a Senior Engineer at Kunming Metallurgy College in China. He has been engaged in editing, proofing and publishing of the Journal of Kunming Metallurgy College, and in collecting information on the platinum group metals.

Platinum Market Forecast to Be in Small Surplus in 2011
Gross demand for platinum was predicted to increase by 175,000 oz to 8.08 million oz, the highest level for four years. All sectors apart from investment were expected to show year-on-year growth.

Global supplies of platinum were anticipated to rise by 6% to 6.4 million oz and the recovery of platinum from recycling was set to increase by 3% to 1.88 million oz. Continuing strong demand was expected to be more than matched by growth in supplies and higher recycling, therefore the platinum market was forecast to move to a small surplus of 195,000 oz in 2011.

Growth of Autocatalyst Demand to Continue
Demand for platinum in autocatalysts was expected to rise by 3% to 3.16 million oz in 2011, due to increased production of heavy-duty diesel vehicles particularly in North America. The Japanese earthquake in March 2011 affected the demand for platinum by domestic manufacturers in Japan and in Japanese car plants overseas. As platinum continues to be substituted by palladium in light-duty diesel autocatalyst formulations, platinum demand in Europe was expected to weaken by 15,000 oz to 1.48 million oz.

Industrial Demand to Reach a New Record
Strong growth in the petroleum refining and glass manufacturing sectors was expected to increase demand for platinum in industrial applications by 12% to reach a new record high of 1.96 million oz. Platinum demand was expected to rise by 13% to 435,000 oz in the glass sector while in the petroleum industry, demand was predicted to increase by 24% to 210,000 oz. Purchasing of platinum in the chemical sector was anticipated to grow by 40,000 oz. Electrical demand was also estimated to be strong.

Platinum Purchasing by the Jewellery Sector to Increase Modestly
Gross platinum demand in the global jewellery sector was predicted to increase by 2% to 2.47 million oz in 2011. This was mostly driven by growth in the Chinese market where the purchasing of platinum was set to rise by 35,000 oz to 1.69 million oz. European demand was expected to soften. In Japan and North America, demand was expected to remain robust.

The recycling of platinum from the jewellery sector was set to fall by 6% to 690,000 oz, mainly due to a reduction in recycling in China of 20% from previously high levels.

Palladium Market to Be in Surplus in 2011
The palladium market was forecast to be in surplus by 725,000 oz in 2011 due to anticipated shipments of Russian state stocks. Supplies of newly refined palladium were expected to rise by 5% to 6.67 million oz and be supplemented by sales from Russian state stocks of 750,000 oz. Therefore, total supplies of 7.42 million oz were forecast, which is a similar level to those in 2010. Recycling of palladium was forecast to increase by 19% to 2.2 million oz. Gross palladium demand was predicted to fall by 9% to 8.89 million oz due to net negative investment demand for palladium.

Automotive Palladium Demand Set to Rise to Record Levels
In the first half of 2011, growth in vehicle production in Europe and North America helped drive palladium demand in emissions control to a new record high of 5.92 million oz, a 6% increase compared with 2010. Stricter emissions standards came into force in Europe, resulting in higher palladium demand in gasoline autocatalysts.

Weaker Demand for Palladium Jewellery
Gross demand for palladium jewellery was expected to fall by 8% to 545,000 oz. The Chinese market remains the largest, although consumer demand fell due to high prices which resulted in lower manufacturing. In Europe, demand was
expected to remain flat at 65,000 oz. In North America, gross demand was predicted to fall by 20,000 oz to 45,000 oz.

**Industrial Demand to Reach a Six-Year High**

Industrial palladium demand was forecast to strengthen by 7% to reach pre-recession levels of 2.65 million oz. Demand in the electrical sector was forecast to increase by 5% to 1.49 million oz. The need for upgrading computer hardware was the driving force for higher production of electronics. Palladium demand in the chemical industry was expected to rise by 23% to 455,000 oz in 2011 due to capacity expansions driven by downstream consumer demand.

**Other Platinum Group Metals**

The supply and demand data for rhodium was briefly discussed and the net demand for ruthenium and iridium was mentioned. Gross rhodium demand was predicted to rise by 18,000 oz to 905,000 oz in 2011 due to high purchasing levels in the glass sector and new physical investment demand. Rhodium supplies were expected to increase by 5% to 768,000 oz and recycling of rhodium from spent autocatalysts was set to increase by 8% to 260,000 oz. Therefore, the market was forecast to remain in surplus by 123,000 oz as growth in supplies and recycling counteracted the rise in gross demand.

In 2011, ruthenium demand was estimated to fall by 14% to 811,000 oz due to lower levels of purchasing by the electrical sector, mainly in the hard disk sector.

Demand for iridium was set to remain strong at 342,000 oz, an increase of 4000 oz compared with 2010 due to the continued strong purchasing of crucibles in the electrical sector.

**Special Feature**

Emissions control for non-road mobile machinery (NRMM) was covered in this edition's Special Feature. NRMM can be described as any transportable industrial equipment or vehicle which has an internal combustion engine and is not intended for the use of passenger or goods transport on the road, for example, agricultural, construction and industrial equipment.

Future pgm demand is very promising in this area. Regulations on engine emissions from NRMM have been in place since the late 1990s, however, these rules were generally not sufficiently strict to require pgm aftertreatment. New regulations were introduced in 2011, such as Stage IIIB legislation in Europe and Tier 4 Interim in the USA, which requires the use of pgm aftertreatment in certain engine categories and applications. Demand for pgms in all non-road sectors was predicted to reach a total of 130,000 oz in 2011. As non-road emissions legislation is increasingly implemented in Europe, Japan and North America and is tightened, pgm demand in NRMM is predicted to grow over the next few years.

**Availability of “Platinum 2011 Interim Review”**

The book is available to download free of charge, as a PDF file in English, Chinese, Japanese or Russian by visiting the Platinum Today website at: http://www.platinum.matthey.com/publications/pgm-market-reviews/archive/platinum-2011-interim-review/. Alternatively the English version can be ordered in hard copy, by filling in the form at: http://www.platinum.matthey.com/publications/pgm-market-reviews/request-a-copy/, by sending a request to the email address: ptbook@matthey.com, or by writing to: Johnson Matthey, Precious Metals Marketing, Orchard Road, Royston, Hertfordshire, SG8 5HE, UK.
**Publications in Brief**

**BOOKS**

**“Green Approaches to Asymmetric Catalytic Synthesis”**

The importance of chirality in molecular recognition processes and the biological activity of many chiral pharmaceutical drugs and agrochemicals is well accepted. There is a need for new synthetic methods leading to single or enriched enantiomers. This book describes the development of ‘greener’ asymmetric reactions which preserve stereoselectivity. The topics covered are as follows:
(a) The search for alternative catalysts;
(b) Alternative solvents;
(c) Alternative synthetic strategies and processes.

**“Micro Reaction Technology in Organic Synthesis”**

Though continuous processes have found widespread application within chemical production, the advantages associated with these have not always been acknowledged. Chemists still favour batch reactions. With the range of commercially available flow reaction platforms now available, it is the aim of this book to highlight the current state of the technology in order to encourage more synthetic chemists to start flow chemistry research programmes; facilitating the identification of novel and interesting synthetic methodologies that possess the potential to be scaled to production.

**“Polymeric Chiral Catalyst Design and Chiral Polymer Synthesis”**
Edited by S. Itsuno (Toyoashi University of Technology, Japan), John Wiley & Sons, Hoboken, New Jersey, USA, 2011, 528 pages, ISBN: 978-0-470-56820-0, £100.00, €120.00, US$149.95

This book reviews chiral polymer synthesis and its application to asymmetric catalysis. It features the design and use of polymer-immobilised catalysts and methods for their design and synthesis. It collects recent advances in this important field of polymer and organic chemistry.

**“Theory and Practice of Metal Electrodeposition”**
Y. D. Gamburg (Russian Academy of Sciences, A. N. Frumkin Institute of Physical Chemistry and Electrochemistry, Moscow, Russia) and G. Zangari (University of Virginia, Department of Materials Science and Engineering, Charlottesville, Virginia, USA), Springer, New York, USA, 2011, 378 pages, ISBN: 978-1-4419-9668-8, £117.00, €139.05, US$179.00

The theory covered in this book largely focuses on the electrochemistry of metals. Details on the practice discuss the selection and use of metal coatings, the technology of deposition of metals and alloys, including individual peculiarities, properties and structure of coatings, control and investigations. Relevant chapters for pgm deposition include: ‘Technologies for the Electrodeposition of Metals and Alloys’ and ‘Technologies for the Electrodeposition of Metals and Alloys: Electrolytes and Processes’.

**“Writing Chemistry Patents and Intellectual Property: A Practical Guide”**

Based on a short course Dr Francis Waller gives for the American Chemical Society, the book teaches how to structure a literature search, to educate the patent examiner on your work, to prepare an application that can be easily duplicated, and to understand what goes on during
the patent examining process. The book provides applicable examples.

**JOURNALS**

**Current Opinion in Chemical Engineering**

Editor-in-Chief: K. K. Sirkar (Department of Chemical Engineering, New Jersey Institute of Technology, USA); Elsevier; ISSN: 2211-3398

A new journal in the Current Opinion Series, *Current Opinion in Chemical Engineering* will be commissioning short and focused review articles written by experts on current advances in chemical engineering. It will initially consist of four issues per year covering the following eight sections, each of which is reviewed once a year: nanotechnology; energy and environmental engineering; biotechnology and bioprocess engineering; biological engineering; separation engineering; materials engineering; process systems engineering; and reaction engineering and catalysis.

**Light: Science & Applications**

Editor-in-Chief: J. Cao (Ministry of Science and Technology of China, China); Nature Publishing Group and Changchun Institute of Optics, Fine Mechanics and Physics; ISSN: 2047-7538

Nature Publishing Group is to introduce a new open access journal focusing on research in optics and photonics. *Light: Science & Applications (LSA)* seeks to promote research from all aspects of optics and photonics, including basic, applied and engineering research and applications. LSA will publish new research and reviews in cutting-edge and emerging areas.

**Special Issue: 100th Anniversary of the Fritz Haber Institute of the Max Planck Society**


This special issue to mark the 100th anniversary of the Fritz Haber Institute (FHI) and dedicated to Professor Gerhard Ertl on the occasion of his 75th birthday contains essays outlining the history of the FHI, and an account of Fritz Haber’s career. Other specially commissioned articles include a review on carbon monoxide oxidation as a prototypical reaction for heterogeneous processes co-authored by the Directors of the FHI: Hans-Joachim Freund, Gerard Meijer, Matthias Scheffler, Robert Schlögl and Martin Wolf. Articles involving pgms include: ‘High-Sensitivity Hydrogen Detection: Hydrogen-Induced Swelling of Multiple Cracked Palladium Films on Compliant Substrates’, ‘Role of Surface Iron in Enhanced Activity for the Oxygen Reduction Reaction on a Pd$_2$Fe(111) Single-Crystal Alloy’ and ‘Titania-Supported Iridium Subnanoclusters as an Efficient Heterogeneous Catalyst for Direct Synthesis of Quinolines from Nitroarenes and Aliphatic Alcohols’.

**Special Issue: Controlling Photophysical Properties of Metal Complexes: Towards Molecular Photonics**


Photochemistry and photophysics is represented in a European collaboration programme COST Action D35 “From Molecules to Molecular Devices: Control of Electronic, Photonic, Magnetic and Spintronic Behaviour”. This special issue includes invited articles and selected contributions presented at a COST meeting “Controlling photophysical properties of metal complexes: Toward molecular photonics” held on 17th–19th May 2010 at the J. Heyrovský Institute of Physical Chemistry in Prague, Czech Republic. An overview of the important role metal complexes play in molecular photonics was attempted. This is confirmed for Pt, Ir and Ru by a selection of contributions including: ‘Light-Emitting Devices Based on Organometallic Platinum Complexes as Emitters’, ‘Sensory Luminescent Iridium(III) and Platinum(II) Complexes for Cation Recognition’ and ‘A Computational Approach to the Electronic and Optical Properties of Ru(II) and Ir(III) Polypyridyl Complexes: Applications to DSC, OLED and NLO’.

**Themed Issue: Cross Coupling Reactions in Organic Synthesis**


This themed issue covering various state-of-the-art palladium-catalysed cross-coupling reactions is devoted to the three chemistry Nobel Prize winners of 2010: Professors Richard F Heck, Ei-ichi Negishi...
and Akira Suzuki. Based on their pioneering work, organic synthesis has been changed in recent decades and has become significantly more efficient. Guest editor Matthias Beller introduces this themed issue. Interesting items include: 'Cross-Coupling in Flow', 'Microwave-Assisted C–C Bond Forming Cross-Coupling Reactions: an Overview', 'Nanocatalysts for Suzuki Cross-Coupling Reactions', and '35 Years of Palladium-Catalyzed Cross-Coupling with Grignard Reagents: How Far Have We Come?'.

**ON THE WEB**

**Hydrogen Storage Materials Database**

The US Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) has launched a hydrogen storage materials database to collect and disseminate materials data and accelerate advanced materials research and development. The new database includes information from the DOE/IEA Hydpark databases, Hydrogen Storage Material Centers of Excellence, and the Fuel Cell Technologies Program. The database has hundreds of material property listings and references including properties such as synthesis conditions, sorption, release conditions and impurities formed during release reactions, etc.

Find this at: http://hydrogenmaterialssearch.govtools.us/search.aspx
Abstracts

CATALYSIS – APPLIED AND PHYSICAL ASPECTS

Studies on the Catalytic Ability of Palladium Wire, Foil and Sponge in the Suzuki–Miyaura Cross-Coupling
Different forms of metallic Pd were evaluated in the Suzuki-Miyaura cross-coupling reaction. All samples were found to be catalytically active for both electron-poor and electron-rich aryl bromides combined with a variety of arylboronic acids. Pd wire was recycled six times without decrease of catalytic activity. A series of poisoning experiments demonstrated that the true catalyst is a soluble form of Pd arising from a leaching process.

Investigation of Heterogeneous Asymmetric Dihydroxylation over OsO₄–(QN)₂PHAL Catalysts of Functionalized Bimodal Mesoporous Silica with Ionic Liquid
1-Methyl-3-(trimethoxysilyl)propylimidazolium chloride was grafted onto the surface of bimodal mesoporous silicas (BMMs), and then 1,4-bis(9-O-quininyl)-phthalazine ((QN)₂-PHAL) and K₂Os(OH)₄·2H₂O were immobilised onto the resulting functionalised bimodal mesoporous silica with ionic liquid (FBMMs) by adsorption or ionic exchange. The mesoporous ordering degree of the bimodal mesoporous silica decreased after functionalisation and immobilisation of OsO₄–(QN)₂-PHAL. The solid catalyst was effective in asymmetric dihydroxylation with high yield and enantioselectivity and could be recycled for five times.

CATALYSIS – REACTIONS

A Continuous-Flow Approach to Palladium-Catalyzed Alkoxycarbonylation Reactions
Using a continuous-flow approach, alkoxycarbonylations of aryl iodides were performed using Pd(OAc)₂ (0.5 mol%) as catalyst with no additional ligand. Optimised reactor design allowed for adequate mixing of the gaseous and liquid reagents. Reactions were performed at rates of ~3 ml min⁻¹ and at concentrations of 1 M, allowing for significant volumes to be processed per unit time.

Borrowing Hydrogen Methodology for Amine Synthesis under Solvent-Free Microwave Conditions
Microwave heating was applied to the ‘borrowing hydrogen strategy’ to form C–N bonds from alcohols and amines, removing the need for solvent and reducing reaction times. For example, DPEphos, [Ru(p-cymene)Cl]₂, benzyl alcohol and morpholine were added to a microwave vial containing a stirrer bar.

EMISSIONS CONTROL

Photocatalytic Membrane Contactors for Water Treatment
Commercial TiO₂ particles (P25 and ST01) were deposited on porous ceramic materials. Pt was then deposited from a H₂PtCl₆ aqueous solution onto TiO₂ by the photoreduction method. The activity of the resulting three-phase photocatalytic membrane contactor (CMC) was studied for the removal of model contaminants such as formic, oxalic and humic acids from water. The highest degradation rate was observed under UV irradiation with simultaneous O₂ supply. The catalytic activity was maintained during several months of testing and several months of storage in air.
FUEL CELLS

A Study of the Methane Tolerance of LSCM–YSZ Composite Anodes with Pt, Ni, Pd and Ceria Catalysts

The performance of SOFC anodes based on composites of LSCM and YSZ containing 0.5 wt% metal catalyst was studied. Electrodes containing Pt were stable in CH4 but C deposits with granular or filamentous morphologies were found with electrodes containing either 0.5 wt% Pd or Ni. C deposition with both Pd and Ni was suppressed by the addition of 10 wt% ceria as a cocatalyst.

Activity, Stability, and Degradation Mechanisms of Dealloyed PtCu3 and PtCo3 Nanoparticle Fuel Cell Catalysts

A stability and activity study of supported dealloyed PtCu3 and PtCo3 NP catalysts for the ORR was carried out. PtCu3 and PtCo3 were subjected to two voltage cycling tests: a ‘lifetime’ regime (10,000 cycles, 0.5–1.0 V vs. RHE, 50 mV s–1) and a corrosive ‘start-up’ regime (2000 cycles, 0.5–1.5 V vs. RHE, 50 mV s–1). Significant activity and stability benefits were demonstrated for dealloyed PtCu3 and PtCo3 for the ORR compared with those of pure Pt. After testing in the ‘lifetime’ regime, the Pt-surface-area-based activity of the Pt alloy catalysts was still twice as high as that of pure Pt.

Pt–Ru Alloyed Fuel Cell Catalysts Sputtered from a Single Alloyed Target

Pt1–xRu0 x NPs with compositions from Pt0.32Ru0.68 to Pt0.95Ru0.05 were sputtered from a single alloyed target to deposit on the surface of a C matrix support. The control of parameters such as sputter gas type, sputter gas concentration, deposition pressure, sputter power, and sputter type (RF or DC) resulted in a low metal loading catalyst, ~30 wt%, with a MeOH oxidation reaction onset potential of <300 mV vs. RHE and peak current of >200 µA cm–2. The optimised catalysts outperformed commercially available catalysts at DMFC operating potentials.

METALLURGY AND MATERIALS

Surface Geometry of Pure Iridium Oxidized at 1373 K in Air

The surface microstructure of a polished Ir sample during isothermal heat treatment at 1373 K in air exhibited triangular pits and terraces, ‘pyramid’-like plateaus and striated edges. The changes in surface geometry were dependent on the original grain orientation. Most grains were confirmed to possess or partly exhibit a geometric configuration of {1 1 1} faceting habit, while periodic bond chain vectors played an important role in determining the ultimate surface morphology.

Effect of Ruthenium on High-Temperature Creep Rupture Life of a Single Crystal Nickel-Based Superalloy

The addition of 3 wt% Ru improved the creep rupture lives of a single crystal Ni-based superalloy at 1100°C/150 MPa and 1000°C/310 MPa. The change of γ/γ’ lattice misfit in the initial microstructure is believed to be the key role of Ru on the high-temperature creep deformation. The larger negative lattice misfit caused by the addition of Ru induces smaller and more regular γ’ particles in the initial state, as well as denser dislocation networks at the γ/γ’ interface during creep.

CHEMISTRY

Hydrogenolysis of Palladium(II) Hydroxide, Phenoxide, and Alkoxide Complexes

(8hPCP)Pd(II)–OR (8hPCP = 2,6-bis(CH2P(8h)2)C6H3; R = H,CH3,CH2CH2C(CH3)3,CH2CH2F,CH2CHF2 or CH2CF3) pincer complexes were synthesised. Hydrogenolysis of the Pd hydroxide complex to generate the Pd hydride complex and H2O was inhibited by formation of a water-bridged H-bonded Pd(II) hydroxide dimer. The Pd alkoxide and aryloxide complexes exhibited reactivity dependent on the –OR ligand (steric bulk, electron-donating ability, and/or the presence of β-hydrogen atoms). Full selectivity for hydrogenolysis was observed with the Pd(II) 2-fluoroethoxide complex.
ELECTRICAL AND ELECTRONICS

Optimization of L10-FePt/MgO/CrRu Thin Films for Next-Generation Magnetic Recording Media
L10-FePt thin films were deposited on Si substrates with the structure Si/CrRu/MgO/FePt. The magnetic and microstructural properties were optimised by varying the FePt sputter pressure and temperature, as well as the thicknesses of all three layers. High coercivity thin films greater than 1.8 T were obtained when the FePt sputter pressure was 1.33 Pa with a thickness of 4 nm, on CrRu and MgO underlayers of 10 nm and 2 nm, respectively.

MEDICAL AND DENTAL

Organometallic Iridium(III) Cyclopentadienyl Anticancer Complexes Containing C,N-Chelating Ligands
\[n^5\text{Cp}^*\text{Ir(CN}^\text{N})\text{Cl}] \quad \text{(Cp}^*=\text{Cp}^*\text{, C}^\text{N}=2-(\text{p-tolyl})\text{pyridine} \text{(1)}, \text{2-phenylnquinoline} \text{(2)}, \text{2-(2,4-difluorophenyl)pyridine} \text{(3)}; \text{Cp}^*=\text{tetramethyl(phenyl)cyclopentadienyl} \text{(Cp}^\text{tmb})\text{, C}^\text{N}=2\text{-phenylpyridine} \text{(4)}; \text{and Cp}^*=\text{tetramethyl(biphenyl)cyclopentadienyl} \text{(Cp}^{\text{tmbk})}, \text{C}^\text{N}=2\text{-phenylpyridine} \text{(5)) have been synthesised and characterised. 2 and 5 have typical ‘piano-stool’ geometry. All the complexes hydrolysed rapidly in aqueous solution (<5 min). All the complexes showed potent cytotoxicity with IC_{50} values from 6.5 to 0.7 μM toward A2780 human ovarian cancer cells. Potency increased with additional phenyl substitution on Cp^*: Cp^{abiph} > Cp^{ph} > Cp^* . Cp^{abiph} with 5 exhibited submicromolar activity (twice as active as cisplatin).

\[\text{cis}[\text{Ru(bpy)}_2(5\text{-cyanouracil})]^{2+}\text{ as a Potential Light-Activated Dual-Action Therapeutic Agent}\]
cis-[Ru(bpy)\text{2}(5\text{-CN}U)\text{2}]^{2+} (5\text{CNU}=5\text{-cyanouracil}) was shown to undergo efficient photoinduced 5CNU ligand exchange for solvent H_2O molecules, thus simultaneously releasing biologically active 5CNU and generating [Ru(bpy)_2(H_2O)_2]^{2+}. The latter binds covalently to double-stranded DNA, such that photolysis results in the generation of 3 equiv. of potential therapeutic agents from a single molecule.

NANOTECHNOLOGY

Patchy Multishell Segregation in Pd–Pt Alloy Nanoparticles
Chemical ordering in fcc-like PdPt NPs consisting of 38–201 atoms was studied via DFT calculations combined with a symmetry orbit approach. It was found that for larger particles in the Pd-rich regime, Pt atoms could segregate at the centre of the NP (111) surface facets, in contrast with extended systems in which Pd is known to segregate at the surface of alloy planar surfaces. In a range of compositions around 1:1, a novel multishell chemical ordering pattern was favoured, in which each shell is a patchwork of islands of atoms of the two elements, but the order of the patchwork was reversed in the alternating shells.
**CATALYSIS – APPLIED AND PHYSICAL ASPECTS**

### Producing Iridium-Containing Catalysts


A catalyst comprising of Ir dispersed on a support is prepared by: (a) treating a SiO₂-containing support with one Ir compound and one organic compound (e.g. triethanolamine) to form a treated support consisting of an organic Ir complex on the support; (b) heating the treated support in an oxidising atmosphere at ~325–450ºC to form a partially decomposed organic Ir complex (this retains 10–95 wt% of the dry weight attributed to the complex before partial decomposition); and (c) heating the treated support in a reducing atmosphere at ~350–500ºC to convert the partially decomposed organic Ir complex into the Ir component. The partially decomposed organic Ir complex has one or more IR absorption bands between 2100--2200 cm⁻¹ which were not present in the original organic complex.

### Preparation of Tris(dibenzylidenacetone)-dipalladium (chloroform)


The catalyst Pd₂(dba)₃∙CHCl₃ is prepared in two steps: (a) a Pd(II) complex (selected from Pd(Hal)₂, Pd(diolefin)(Hal)₂ and Pd(CH₃CN)(Hal)₂) is reacted with an alkali metal halide (Li, Na, or K halide) in an alcohol solvent at ~20–50ºC; (b) the product obtained from step (a) is reacted with a mixture comprising dba, CHCl₃ and alkali metal acetate over 60 minutes at ~49--53ºC to form Pd₂(dba)₃∙CHCl₃. The molar ratio of Pd(II) complex:dba is preferably 2:3.20.

### Ruthenium-Based Carbene Catalyst


A method for preparing a Hoveyda-type Ru-based carbene catalyst with chelating alkylidene ligands by reacting a Ru alkylidene complex (for example, Ru indenyldiene or Ru benzylidene) with an olefin derivate in a cross metathesis reaction in the presence of a polymers-supported cation exchange resin is claimed. The reaction temperature is 20–120ºC, preferably in the range of 20–100ºC and the reaction time is 0.5–4 h, preferably 0.5–2 h. After the reaction, the solvent(s) are removed, the remaining residues are suspended in a non-polar hydrocarbon solvent, and the precipitated catalyst is separated and dried.

### Thermo-Neutral Reforming of Hydrocarbon Fuel

Saudi Arabian Oil Co, *US Patent* 8,008,226; 2011

A multicomponent catalyst consisting of Ni, Ce₂O₃, La₂O₃, Pt, ZrO₂, Rh and Re is used in a thermo-neutral reforming process to produce a H₂-rich synthesis gas from a petroleum-based fuel. The fuel mixture, O₂-rich gas and steam are introduced into a reactor which has a catalyst bed (combined combustion, steam and/or CO₂ reforming catalyst). This mixture is preheated to ~380–450ºC and brought into contact with the catalyst bed at GHSV of ~30,000–70,000 h⁻¹ which results in an exothermic reaction (the temperature is raised to ~800–900ºC) and causes an endothermic steam reforming reaction for a period of time sufficient to reform the liquid fuel to yield a H₂-rich synthesis gas. The wt% of each constituent of the catalyst is: 0.5–15 Ni; 0.5–10 Ce₂O₃; 0.5–5 La₂O₃; 0.1–2 Pt; 0.5–3 ZrO₂; 0.1–2 Rh; and 0.1–2 Re.

### Platinum-Palladium in Exhaust System

Johnson Matthey Plc, *US Appl*. 2011/0,214,412

An exhaust gas aftertreatment system for a diesel vehicle consists of an NSC followed in a downstream direction by a CSF which has a wall flow filter containing inlet and outlet channels and comprises an oxidative catalyst with an OSC containing CeO₂ or CeO₂-ZrO₂ and a Pd-rich mixture of Pt and Pd. The Pt:Pd weight ratio is < 1:10. The OSC of the oxidative catalyst is 20–50 wt%. A Pt-based oxidative catalyst is situated on the inlet channels and the Pd-rich Pt:Pd oxidative catalyst is located on the outlet channels.

### Two Washcoat Layers on a Three-Way Catalyst

BASF Catalysts LLC, *US Appl*. 2011/0,217,216

A catalyst capable of effectively reducing CO in exhaust gas from an internal combustion engine consists of two washcoat layers: (a) a layer comprising of Pd impregnated on a CeO₂-free OSC (for example, ZrO₂-PrO₂) and Pt impregnated on a refractory metal oxide (for example, Al₂O₃); (b) another layer comprising of Pt and Rh impregnated on a CeO₂-containing OSC. The layers consist of 1–90 g ft⁻³ Pt; 1–90 g ft⁻³ Pd and 1–30 g ft⁻³ Rh.

---

**CATALYSIS – REACTIONS**

### Thermo-Neutral Reforming of Hydrocarbon Fuel

Saudi Arabian Oil Co, *US Patent* 8,008,226; 2011

A multicomponent catalyst consisting of Ni, Ce₂O₃, La₂O₃, Pt, ZrO₂, Rh and Re is used in a thermo-neutral reforming process to produce a H₂-rich synthesis gas from a petroleum-based fuel. The fuel mixture, O₂-rich gas and steam are introduced into a reactor which has a catalyst bed (combined combustion, steam and/or CO₂ reforming catalyst). This mixture is preheated to ~380–450ºC and brought into contact with the catalyst bed at GHSV of ~30,000–70,000 h⁻¹ which results in an exothermic reaction (the temperature is raised to ~800–900ºC) and causes an endothermic steam reforming reaction for a period of time sufficient to reform the liquid fuel to yield a H₂-rich synthesis gas. The wt% of each constituent of the catalyst is: 0.5–15 Ni; 0.5–10 Ce₂O₃; 0.5–5 La₂O₃; 0.1–2 Pt; 0.5–3 ZrO₂; 0.1–2 Rh; and 0.1–2 Re.

### Platinum-Palladium in Exhaust System

Johnson Matthey Plc, *US Appl*. 2011/0,214,412

An exhaust gas aftertreatment system for a diesel vehicle consists of a NSC followed in a downstream direction by a CSF which has a wall flow filter containing inlet and outlet channels and comprises an oxidative catalyst with an OSC containing CeO₂ or CeO₂-ZrO₂ and a Pd-rich mixture of Pt and Pd. The Pt:Pd weight ratio is < 1:10. The OSC of the oxidative catalyst is 20–50 wt%. A Pt-based oxidative catalyst is situated on the inlet channels and the Pd-rich Pt:Pd oxidative catalyst is located on the outlet channels.

### Two Washcoat Layers on a Three-Way Catalyst

BASF Catalysts LLC, *US Appl*. 2011/0,217,216

A catalyst capable of effectively reducing CO in exhaust gas from an internal combustion engine consists of two washcoat layers: (a) a layer comprising of Pd impregnated on a CeO₂-free OSC (for example, ZrO₂-PrO₂) and Pt impregnated on a refractory metal oxide (for example, Al₂O₃); (b) another layer comprising of Pt and Rh impregnated on a CeO₂-containing OSC. The layers consist of 1–90 g ft⁻³ Pt; 1–90 g ft⁻³ Pd and 1–30 g ft⁻³ Rh.

---

http://dx.doi.org/10.1595/147106711X620653 • *Platinum Metals Rev.*, 2012, **56**, (1), 55–57•
FUEL CELLS

Palladium-Bismuth Catalyst
Univ. Southampton, British Appl. 2,478,981; 2011

A catalyst with the composition Pd\textsubscript{x}Bi\textsubscript{y}M\textsubscript{z} is used in the anode of a fuel cell and optionally the cathode. M is a metal selected from Pt, Rh, Ir, Os, Ru, Re, Ni, Ag and Au or a combination; \(x = 0.1–0.7\); \(y = 0.3–0.9\); \(z < 0.1\); and \(x + y + z = 1\).

Hydrogen Production Apparatus
JX Nippon Oil & Energy Corp, Japanese Appl. 2011-088,778

A H\textsubscript{2} production apparatus includes a reforming section which carries out steam reforming of raw materials needed for H\textsubscript{2} production. This part consists of a catalyst comprising of Pt, Pd and Rh on an Al\textsubscript{2}O\textsubscript{3}-containing support. The ratio of pgm on the support is 0.3–5.100 wt%. The Al\textsubscript{2}O\textsubscript{3}-containing support comprises of \(\alpha\)-Al\textsubscript{2}O\textsubscript{3} which has a pore volume of \(\geq 50\) nm and the diameter is 0.2–1.0 ml g\textsuperscript{–1}, carrying 2–25 wt\% of rare earth oxides and 0.1–15 wt\% of alkaline earth oxides.

METALLURGY AND MATERIALS

Osmium in a Series of Penetrator Rods
J. Wisotzki, US Appl. 2011/0,189,325

A single crystal rod is made of an alloy of 40 wt\% W, 40 wt\% Ti and 20 wt\% Os and is grown to the final usable shape in a support-free float zoning process. The internal arrangement and control of the support-free float zoning process consists of producing single crystal rods in a serial process; necking the intervals between each grown rod down to a diameter of 1.0 mm and separating the grown rods from each other. Compressed rods can be produced by obtaining a powder of high purity W, Ti and Os and compressing this with a die to reduce the O\textsubscript{2} content between the granules of the powder. The single crystal penetrator rods do not break upon impact on a target and enable a size and weight reduction as no material is lost upon impact on the target.

APPARATUS AND TECHNIQUE

Surface-Enhanced Raman Scattering Substrate
Instytut Chemii Organicznej, European Appl. 2,369,327; 2011

A substrate for SERS consists of a semiconductor surface (GaN) containing whiskers which are coated with metal or alloy selected from Pt, Ag, Au or Cu. Each whisker contains a linear defect which may be a dislocation or an inversion domain and are connected with each other through terminals, forming conical bunches. The film thickness is 50–150 nm, length of the whiskers range from 0.2–2.0 \(\mu\)m, preferably 0.5–1.5 \(\mu\)m and the diameter ranges from 40–150 nm, preferably 50–70 nm.

MEDICAL AND DENTAL

Osmium(II) Arene Azo Anticancer Complexes
Univ. Warwick, World Appl. 2011/131,925

The Os-containing complexes, 1–3, can be used as cytotoxic agents, especially as anticancer or immunosuppression agents. Ar is an arene moiety; X is a halo or a donor ligand; Y represents a cyclic or bicyclic ring structure such as a 3, 4, 5, 6, 7 or 8 membered saturated or unsaturated heterocyclic ring; Z is N or CR\textsuperscript{’} (R\textsuperscript{’} = H, CN, N\textsubscript{3}, C\textsubscript{1}–C\textsubscript{10} alkyl or aryl); R is a substituted or unsubstituted cyclic or heterocyclic ring; R\textsubscript{1} is H, C\textsubscript{1}–C\textsubscript{4} alkyl, OH, amino or substituted amino; Q is an ion which may be present or absent; and m and n are
charges. In 3, Y is absent or is a C(R')(R'') group. These compounds can be prepared by reacting [ArOsX2]2 with an azo or imino containing ligand such as azopyridine or iminopyridine.

**Palladium-Based Dental Alloy**
DeguDent GmbH, US Appl. 2011/0,236,254

A Pd dominated dental alloy comprises of Au, Pd and Ag, one grain-growth inhibitor (Ru) and a grain-refinement control element (Ta, Nb or a mixture). The dental alloy contains (in wt%): 30–45 Au; 35–50 Pd; 10–25 Ag; 6–10 Sn; 0.03–1.0 Ru; and 0.03–2.0 grain-refinement control element.

**PHOTOCONVERSION**

**Bridged Ring Metal Complexes**
Sumitomo Chemical Co Ltd, British Appl. 2,478,450; 2011

An electroluminescent metal complex, 1, where X1 = C and X2 = C or N; M = Pt, Pd, Rh, Ir, Os or Ru; and A represents a group such as an amine or silyl group is claimed. Z1 and Z2 represent an optionally substituted aromatic hydrocarbon or heteroaromatic ring. The sum of squares of orbital coefficients of the outermost d orbital of M is ≥ 33.3%. The dihedral angle is 9–16º. The complex can be used in a light-emitting device or solar battery.

**REFINING AND RECOVERY**

**Purification of Rhodium-Containing Solutions**
Mitsubishi Mater. Corp, Japanese Appl. 2011-093,748

The purification of Rh-containing solution (which also contains NH4+ ions) involves adding NO2– to form a solution containing Rh nitrite complex. The purification process involves: (a) changing the pH to ≥ 1 by adding the NO2– salt and stirring the solution for ≥ 1 hour at 40°C and pH ≤ 7 for gradually generating Rh nitrite complex ions and decomposing NH4+ ions; (b) heating the solutions to ≥ 70°C and stirring for ≥ 1 h; and (c) solid-liquid separation to recover the precipitated free Rh nitrite complex ion solutions. (NH4)3Rh(NO2)6 may be generated by the addition of NH4+ salts to the recovered Rh nitrite complex ion solution. Rh recovery yield is improved using this process.
Opportunities for Platinum Group Metals in Future Emissions Control Technology

Platinum group metals (pgms) have been a key component in automotive emissions control catalysts and systems since their conception in the first decade of the twentieth century. In 1909 an audience in London was introduced to the idea that a supported platinum catalyst in the exhaust box or silencer could remove the products of incomplete combustion from a gasoline engine (1). This presentation by the French chemist Michel Frenkel, entitled ‘Deodorisation of the Exhaust Gases in Motor Vehicles’, was remarkable as it was only a couple of years after the Model T Ford (Figure 1) went into production.

The Development of Autocatalysts

A century after this first announcement, with the accumulation of over 30 years’ practical experience since the first use of catalysts in the 1970s, commercial catalysts are today applied to most motor vehicles across the globe. There has been a continual striving to improve the catalyst performance and function, but also to reduce, or thrift, the amount of pgms applied to the catalyst. Frenkel suggested 30 g of platinum would be sufficient for the 25 horsepower motor vehicles of his time; today, combinations of platinum, palladium and rhodium are used on much more powerful vehicles. For example, the gasoline three-way catalyst

Fig. 1. Model T Ford © conceptcarz.com
(TWC), which can remove carbon monoxide, hydrocarbons and nitrogen oxides (nitric oxide (NO) and nitrogen dioxide (NO₂), or NOx) simultaneously, contains less than 10 g of pgm and can produce tailpipe exhaust emissions that are cleaner than the air drawn into the engine!

But what of the role of pgms in the future of emissions control? What are likely to be the major challenges?

The Future of Emissions Control Technology

An increasing emphasis on greenhouse gas emissions, combined with a need to meet NOx and particulate emissions legislation, means that engine and vehicle manufacturers are forced to improve engine designs and power trains. This means engines will get smaller and new designs will be encountered, for example, hybrids combining an advanced internal combustion engine with a battery (Figure 2). One of the consequences of improved fuel economy is decreasing engine out temperatures. This is often coupled with increased levels of pollutants such as CO, hydrocarbons and particulates. The pgm-containing catalysts of the future will need to be more active, work at lower temperatures, respond rapidly to the change in operating mode of the vehicle, and remove pollutants as soon as the engine is switched on.

For many aftertreatment solutions we are approaching the stage where catalyst performance is not limited purely by catalyst activity. For example, the low temperature performance of a selective catalytic reduction (SCR) catalyst is limited by the temperature at which the urea solution can be injected into the exhaust, and this is governed by urea hydrolysis and the need to avoid the formation of deposits in the exhaust system.

Oxidation catalysts are pgm-based. Their low temperature activity is limited not by activity for CO oxidation but by inhibition by hydrocarbons, NOx and water. Therefore, the use of zeolites to trap hydrocarbons until the catalyst temperature is high enough to burn them will increase. NOx adsorbers, based on pgm, will also be required to hold NOx until the downstream SCR or NOx trap catalysts are warm enough to remove it.

Low exhaust temperatures also pose a problem to components that need periodic regenerations. These include the desulfation of diesel oxidation catalyst (DOC), NOx trap and SCR catalysts and the cleaning of soot from particulate filters. Exhaust systems may require active engineering solutions to modify the exhaust configuration and bypass thermally sensitive catalysts during high temperature regeneration events.

A method that has been practically demonstrated for improving engine efficiency in diesel and gasoline engines is to introduce some hydrogen into the engine alongside the fuel. This helps combustion, and can also reduce emissions of NOx and particulate matter (PM) (2). The hydrogen would be produced by converting some of the fuel into CO, carbon dioxide and hydrogen in a process known as reforming. Typical reformer catalysts will contain pgms, such as rhodium, and to drive the reaction the whole system will need to be integrated with the engine so that waste heat from the engine can be used.

Emissions Legislation and Fuel Choice

Worldwide legislation will continue to tighten and encompass new vehicle types and pollutants. For example, in Europe CO₂ emissions regulations will be phased in over the next few years, and nitrous oxide (N₂O), which is 300 times more effective than CO₂ as a greenhouse gas, will be regulated from 2014 in the
USA. Therefore, catalyst chemists and engineers must continue to improve catalysts and systems to produce N₂O in amounts as close to zero as possible. Particulate number will also be controlled in Europe from 2014, and improved systems to control PM will be required in the future as the legislation tightens further.

Legislation will also extend to other vehicle types, including ships, trains and stationary engines, and the pgm systems will need to meet the specific challenges of these applications. For example, currently ships use fuel with high sulfur levels, but in-harbour legislation may require them to carry low sulfur fuels for use in port. Also, stationary engines can be very large, and therefore so will be the catalyst which, if pgms are needed, necessitates very efficient use of the pgm to bring the cost as low as possible.

Another future challenge for emissions control catalysts could be the range of fuels available. It is already possible to buy many of the ‘new’ fuels, and it will be necessary for the catalysts to work no matter what fuel is used in the engine; some new vehicles and ships already use dual fuel engines. Fuels that may be encountered include synthetic fuels, such as those derived from coal or biomass; hydrogen; biofuels such as fatty acid methylesters or ethanol; methanol; compressed natural gas; and blends of these.

Conclusion
Lower temperatures and the continuing presence of poisons will continue to restrict the use of base metal catalysts and necessitate the use of pgm catalysts. But even in the event that base metal catalysts find a greater role in emissions control technologies, for example in SCR catalysts, these are significantly promoted by upstream pgm catalysts for NO₂ generation. Thrifting of the pgms will continue to be important while the catalysts still need to operate efficiently and overcome all the challenges outlined. To address all these issues an integrated approach is required, involving fuel suppliers, engine and vehicle manufacturers, and catalyst chemists and technologists. Without a doubt, with all these new challenges, many opportunities for pgm-containing emissions control catalysts and adsorbers remain as we look to the future.

This article is based on and updated from an item written for the Royal Society of Chemistry’s journal Education in Chemistry (3).

PAUL J. MILLINGTON AND ANDREW P. E. YORK*
Johnson Matthey Technology Centre,
Blounts Court, Sonning Common,
Reading RG4 9NH, UK
*Email: ayork@matthey.com

References

The Authors
Dr Paul Millington originally joined Johnson Matthey in the Emission Control Research group in 1995. After a short break in the automotive industry he rejoined in 2001. He currently works on all forms of pgm-containing aftertreatment in the Emission Control Research group at the Johnson Matthey Technology Centre, Sonning Common.

Dr Andy York joined Johnson Matthey in 2000, initially in the Emission Control Research group, he is currently on secondment at the Department of Chemical Engineering and Biotechnology at the University of Cambridge working on a range of academic and business related projects involving catalysis and engineering.
Platinum Metals Review is Johnson Matthey’s quarterly journal of research on the science and technology of the platinum group metals and developments in their application in industry.

http://www.platinummetalsreview.com/