

# EuropaCat VIII: “From Theory to Industrial Practice”

## PLATINUM GROUP METALS RETAIN FUNDAMENTAL ROLE IN CATALYSIS

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This biennial European Federation of Catalysis Societies (EFCATS) conference took place on the 26th to 31st August 2007, in the town of Turku on the southwestern coast of Finland, and was hosted by the Nordic Catalysis Society (1). It was attended by 1350 scientists from Asia, the U.S.A. and Europe, of whom 65% were men, with an industrial representation of 40%. The oral presentations included seven plenary lectures, one or more keynote lectures for each session, 180 oral presentations in four parallel sessions and 750 posters. The significance of this conference was highlighted by the fact that there were up to ninety submissions for a session from which only ten presentations could be selected. Presentations were divided into eighteen topic areas:

- Catalysis from first principles
- Nanotechnology in catalysis, novel catalytic materials
- Surface science in catalysis
- New experimental approaches and characterisation under reaction conditions (combinatorial methods included)
- Catalysis for pharma and fine chemistry (homogeneous and heterogeneous catalysis)
- Catalysis by enzymes
- Polymerisation
- Electro-catalysis and catalysis related to fuel cells
- Catalysis in oil refining
- Natural gas conversion (GTL, MTO, methanol, etc.)
- The Hydrogen Society (hydrogen production and storage)
- Catalysis in the conversion of renewable resources (biofuels, catalysis for sustainable developments)
- Catalysis for pollution control (stationary)

- Catalysis for pollution control (mobile)
- Catalysis for bulk and specialty chemicals
- Catalytic reaction engineering (novel reactor systems and novel reaction media included)
- Photocatalysis
- Catalyst deactivation, regeneration and recycling

There was also a workshop entitled “Towards 100% Selectivity in Catalytic Oxidation over Nanostructured Metal Oxides” (VIII European Workshop on Selective Oxidation ISO 2007, hosted by EuropaCat VIII).

Platinum group metals (pgms) featured in most of these sessions, and retain their pivotal roles in fuel cell catalysis, automotive applications, surface science and photocatalysis.

### The Berzelius Lecture

Among the plenary lectures of the conference was the Berzelius Lecture, resurrected by the EuropaCat committee in honour of the Swedish scientist who, in a report in 1836, highlighted the “significance of reactions which take place in the presence of some substance which remains unaffected” (2). This year, this prestigious lecture was given by Nobel Laureate R. H. Grubbs (California Institute of Technology, U.S.A.) after whom is named the homogeneous Grubbs’ catalyst. This catalyst is an efficient, selective catalyst for olefin metathesis which works under mild reaction conditions that tolerate the presence of a range of other functionalities. More than fifty Grubbs’ catalysts have been synthesised. Grubbs demonstrated that, by tuning the *N*-heterocyclic carbene ligands on the ruthenium centre, the catalyst can be made more reactive or more stable, water soluble or enantioselective. Recent work has focused on increasing the barrier to decomposition by hindering the ligand rotation which is the initial

step in this pathway. The consequences of modifying the catalyst ligands by a single methyl group were further illustrated in ethanolysis, in which this structural refinement resulted in a decrease in reaction times from 20 h to 1 h, maintaining the high selectivity. For larger scale applications, a Grubbs' catalyst is being explored for conversion of seed oils – corn and soy bean – into value added chemicals. In these clean, solvent-free reactions, the functionalities already present in the oils are retained at high turnover numbers.

## Catalysis from First Principles

J. A. van Bokhoven (ETH Zurich, Switzerland) gave a well-attended and inspirational talk on the ways in which oxide supported nanoparticles of gold are different from bulk metal or crystals. The catalysts discussed were prepared by base deposition precipitation from hydrogen tetrachloroaurate ( $\text{HAuCl}_4$ ) on a range of supports: alumina ( $\text{Al}_2\text{O}_3$ ), silica ( $\text{SiO}_2$ ), ceria ( $\text{CeO}_2$ ), titania ( $\text{TiO}_2$ ), zirconia ( $\text{ZrO}_2$ ) or niobium oxide ( $\text{Nb}_2\text{O}_5$ ). Independent of the support, as the size of Au particles decreases, melting point, coordination number and bond lengths to adjacent atoms all decrease. The reason is that smaller particles have a different electronic structure. This was explained in terms of the fact that the *d*-band narrows and shifts up in energy towards the Fermi level as particle size decreases. The consequence is that the particles are catalytically reactive where the bulk metal is not. Using X-ray techniques – X-ray absorption near edge structure (XANES), extended X-ray absorption fine structure (EXAFS) – and in particular by the use of hard X-rays for high resolution, van Bokhoven showed that nanosized Au interacts with  $\text{H}_2$  and  $\text{O}_2$  and demonstrated that, for the hydrogenation of cinamaldehyde, smaller particles exhibit a higher selectivity. The issue of support effects was raised in the questions; the point was reiterated that, while support effects are clearly important in catalysis on Au, they did not influence the electronic particle properties under discussion.

Novel phenomena related to Au clusters deposited on ultra-thin oxide films were discussed by G. Pacchioni (Università degli Studi di Milano-

Bicocca, Italy). He showed by means of density functional theory (DFT) calculations how oxide thin films may exhibit special properties which differ from the bulk oxide. He considered a system in which a thin layer of magnesium oxide ( $\text{MgO}$ ) is grown on a metal, in this case silver or molybdenum. Subsequently Au particles are deposited on the metal oxide support. The formation of a metal/oxide interface can change the chemical properties of the oxide support and the system work function. When the supporting metal is Mo, what results is the charging of the supported metal atoms and clusters by direct tunneling of electrons from the metal substrate to the supported metal; this is not observed when Ag is used. The reason for this electronic behaviour is that the Fermi level of Ag is lower in energy than the Au 6*s* orbital, so spontaneous electron tunneling is not allowed; in contrast the Fermi level of Mo lies at higher energy than the Au 6*s*.

This fundamental approach to the behaviour of catalytic metal particles was taken further by J. K. Nørskov (Technical University of Denmark) who discussed the reactivity of catalysts in terms of the geometrical and electronic structure of metal nanoparticles. Having discussed the correlations between the energy of *d*-states and the reactivity of a catalyst, he illustrated the practical applications of the theoretical principles in the synthesis of ammonia on 11% Ru on a MgAl spinel. On the Ru nanoparticle surface in this catalyst there are close-packed regions, on which there is a large barrier to dissociation, and steps, where the barrier is much lower and where the catalysis occurs. The question is then how many step sites there are on the nanoparticles, which can be modelled from transmission electron microscope (TEM) images. Around 2–3 nm, the required steps are no longer possible, hence the optimal nanoparticle size is > 3 nm. Although these are simple examples, they serve to illustrate the enormous potential of computational chemistry in predicting useful catalyst structures.

## Surface Science

Investigating the surface science of platinum and palladium, T. Visart de Bocarmé (Université

Libre de Bruxelles, Belgium) illustrated the usefulness of field ion microscopy to elucidate the active sites and chemical species relevant to a catalytic reaction. Observing the reaction between H<sub>2</sub> and NO on a Pt tip showed that an oscillatory reaction occurs with local oxide reduction by H<sub>2</sub> during the oscillating cycles. The reaction occurs on the kink surfaces of the (012) planes where there are [001] zones. For Pd in contrast, there are no plane-specific effects and hysteresis rather than oscillation is observed; here reduction of oxides is only possible at high pressures of H<sub>2</sub>.

Extending the scope of his studies to all the pgms, M. Johansson (Technical University of Denmark) measured splitting coefficients and desorption rates in the hydrogen–deuterium exchange reaction with and without added carbon monoxide on a range of pgms in 1 bar H<sub>2</sub> at temperatures between 40 and 200°C. Surprisingly, in the absence of CO, Ru and Rh proved to have the highest sticking probabilities: the order followed: Ru > Rh >> Pd ~ Pt > Ir. The addition of CO slows the reaction for all the metals, in particular Pt and iridium.

Pd was the focus of the talk by W. T. Tysoe (University of Wisconsin-Milwaukee, U.S.A.). He used deuterium-labelling to investigate the reaction mechanism of the industrially significant vinyl acetate monomer (VAM) reaction on, in this case, a Pd(111) surface, in which ethene reacts oxidatively with acetic acid. Using an elegant combination of variable temperature infrared (IR) and temperature-programmed desorption (TPD) spectroscopy, he showed that changing the labelled ethenes – CHD=CHD or CH<sub>2</sub>=CD<sub>2</sub> – gave different rates of reaction. The conclusion that the reaction on Pd proceeds *via* the Samanos pathway (3) was substantiated by DFT, which predicts that the Samanos pathway is energetically more favourable. In the subsequent discussion the possibility was raised that the pathway may be different on a PdAu alloy.

S. Schauer mann (Fritz-Haber-Institut der Max-Planck-Gesellschaft, Germany) demonstrated the active role played by the support iron oxide (Fe<sub>2</sub>O<sub>3</sub>) in the decomposition of methanol. In a model system in which crystalline particles of Pd

were prepared on an Fe<sub>2</sub>O<sub>3</sub> film deposited on a Pt(111) surface, at  $T > 450$  K she showed that O<sub>2</sub> was chemisorbed on metallic Pd. At  $T > 500$  K, layers of PdO formed at the particle–support interface, leading to the coexistence of PdO and Pd metal. At  $T > 600$  K, there was nearly complete oxidation of the particle. The consequences of the decomposition of MeOH are that a reservoir of predissociated methoxy species build up on the Fe<sub>2</sub>O<sub>3</sub> support which spill over onto the Pd particles in order to react. On the theme of reactions of MeOH, R. Blume (Fritz-Haber-Institut der Max-Planck-Gesellschaft, Germany) showed that in the oxidation of MeOH to formaldehyde on oxidic Ru surfaces, different precatalysts evolve into the same catalytically active surface. The amount of transition surface oxide in the first few layers proved to be the parameter which determines which catalytic pathway is followed rather than the amount of RuO<sub>2</sub>.

Alcohols also featured in the investigation of N. Bion (Université de Poitiers, France) into the steam reforming of bioethanol over Rh/MgAl<sub>2</sub>O<sub>4</sub>/Al<sub>2</sub>O<sub>3</sub> to generate H<sub>2</sub>. In crude bioethanol there are a range of impurities which deactivate this reaction. Each impurity was tested individually and it was shown that there is a strong poisoning effect of acetic acid – although there are only low levels of acetic acid in bioethanol – and no inhibition by diethylamine. Of a series of alcohols, the order of poisoning was: branched > linear > other functional groups. This was thought to be due partly to coke deposition and partly influenced by the hydrophobicity of the alcohol, where the C4 and C5 alcohols hinder water activation. Following the ethanol theme, W. Shen (Dalian Institute of Chemical Physics, Chinese Academy of Sciences) proposed an Ir/CeO<sub>2</sub> catalyst for steam reforming of ethanol. He showed that, while there was only limited sintering of Ir during the 60 h test reaction, there was significant growth and morphological changes of the ceria particles, although this did not influence the catalytic activity noticeably.

## New Experimental Approaches

*In situ* techniques, which can be used to study the structural modification of catalysts under real-

life reaction conditions, are of critical importance to any scientist who is trying to understand how a catalyst really behaves. J.-D. Grunwaldt (ETH Zurich, Switzerland) presented 2D mapping of supported pgm catalysts under operational conditions in order to investigate the variation of the catalyst structure that can occur inside a catalytic reactor as a result of prominent temperature or concentration gradients. The catalytic systems studied were alumina supported pgms (Rh/Al<sub>2</sub>O<sub>3</sub>, Pt-Rh/Al<sub>2</sub>O<sub>3</sub>, Pt/Al<sub>2</sub>O<sub>3</sub>, Pt-Ru/Al<sub>2</sub>O<sub>3</sub>, Pd/Al<sub>2</sub>O<sub>3</sub>) prepared by flame-spray pyrolysis and the reaction studied was the total oxidation of methane. X-Ray absorption spectroscopy (XAS), recorded with a micro-focused beam scanning over the sample coupled with a 2D-area detector, is particularly effective for *in situ* studies since it requires shorter acquisition times. The temperature profile was analysed using an IR thermography camera and the catalytic performance by means of mass spectrometry. It was shown that the structure of a catalyst during partial oxidation of methane varies strongly along the axial coordinate of a tubular catalytic microreactor. There are considerable structural differences between the pgm particles of less than 100 μm diameter, and a strong dependence on the reaction conditions (temperature, space velocity). This talk highlighted the importance of 2D-spectroscopic studies under operational reaction conditions.

A. Tompos (Chemical Research Center, Institute of Surface Chemistry and Catalysis, Hungarian Academy of Sciences) used catalysts combinatorially designed for methane total oxidation in order to understand the role of Pt and Au on the performance of trimetallic Pt-Pd-Au/CeO<sub>2</sub> catalysts. Ceria was obtained by the urea precipitation route and subsequently impregnated with the three metals. By X-ray photoelectron spectroscopy, *in situ* Fourier transform infrared (FTIR) spectroscopy, TPD of H<sub>2</sub> and CO chemisorption measurements, direct evidence was found for alloying of Pt with Pd. The conclusion was that the improved catalytic properties of multimetallic Pt-Pd-Au/CeO<sub>2</sub> catalysts over the monometallic Pd analogues are due to: (a) the increase of the number of Pd(0)–PdO dual-type active sites,

(b) stronger methane adsorption at the Pd(0)–PdO boundary, (c) a higher accessible metallic area in the working catalyst, (d) suppression of the reduction of Ce(IV), and (e) suppression of the concentration of ionic Pd(II).

## Novel Catalytic Materials

The pgms are the first port of call for scientists in search of new catalytic materials. Pd featured in the talk by G. L. Chiarello (Università degli Studi di Milano, Italy). He compared 0.5% Pd/LaCoO<sub>3</sub> catalysts made by flame-spray pyrolysis with more conventional catalysts prepared by impregnation in the reaction in which small amounts of H<sub>2</sub> in exhaust gases are used to reduce NO. In the flame-made catalyst, the Pd(II) partially replaces Co in the perovskite structure. When this catalyst is calcined at 800°C and reduced at 300°C in 5% H<sub>2</sub>/He, Pd segregates to the catalyst surface. In contrast, reduction at 600°C leads to the formation of a PdCo alloy. A further feature of the flame-made catalyst is that at temperatures over 500°C, EXAFS evidence suggested that the Pd redissolves in the perovskite framework instead of sintering, putting this in the class of so-called ‘intelligent catalysts’ which redisperse following sintering. The flame-based preparation route gave a clear advantage in catalyst performance over the impregnation method; the catalyst yielded 100% conversion at 160°C along with 78% selectivity to nitrogen and after 100 h there was no deactivation of the flame-made catalyst.

Encapsulated pgm nanoparticles are the novel approach to preventing sintering described by M. Paul (Max-Planck-Institute for Coal Research, Germany). He proposed encapsulating Au or Pt nanoparticles in hollow metal oxide spheres. In this way the nanoparticles are physically separate and sintering is prevented at high temperatures. By this method a colloidal nanoparticle is encapsulated in a silica shell, which is then coated with zirconia or titania and calcined at 900°C. Subsequently the silica core is leached out by treatment with sodium hydroxide. TEM images showed the effective encapsulation. Using the CO oxidation reaction, it was shown that hollow sphere encapsulation does stabilise the catalyst

against sintering while causing no mass-transfer limitation and thus retaining catalytic activity.

As a catalytic element, Au has proved a particularly popular subject of study since Haruta's work in the 1980s (4). In this meeting, S. Carrettin (Instituto de Tecnología Química, CSIC, Spain) gave a pioneering example of a heterogeneous Au catalyst used for a carbon-carbon bond formation, namely the isomerisation of  $\omega$ -alkynylfurans to phenols. The 1.8% Au on ceria catalyst was prepared using  $\text{HAuCl}_4$  and nanocrystalline ceria. The nanocrystalline support seems to stabilise the cationic species Au(I) and Au(III): the presence of these species on the surface was established by observing CO probe molecules by FTIR spectroscopy. The hypothesis that the Au cationic species is the active site was challenged during the discussion, and the question remained as to whether FTIR is a sufficiently sensitive technique to allow Au(I) and Au(III) differentiation.

Well known in the field of Au catalysis, G. J. Hutchings (Cardiff University, U.K.) presented a new synthetic approach to supports for highly active oxidation catalysts. Au supported on ceria prepared using supercritical antisolvent ( $\text{scCO}_2$ ) precipitation was demonstrably more active and more stable for CO oxidation than comparable nanoparticles supported on conventional ceria derived from the direct calcination of cerium(III) acetylacetonate. In search of new industrial uses for Au catalysts J. McPherson (Project AuTEK, South Africa) deposited Au on hopcalite with the aim of improving the stability of this filter material to water. Despite extremely efficient deposition of Au, Au/ZnO and Au/TiO<sub>2</sub> proved more active for aspirator applications.

## Automotive Catalysis

As ever, pgms played a starring role in the section on automotive catalysis. In the section on NOx traps E. C. Corbos (Université de Poitiers, France) elegantly illustrated the redispersion of Pt on ceria-containing supports at temperatures greater than 800°C in an oxidising atmosphere. The techniques used were *in situ* time-resolved turbo XAS in fluorescence mode and *in situ* TEM. In a cycling regime of 3% H<sub>2</sub>/He (60 s) followed

by 20% O<sub>2</sub>/He (60 s), the particles which start at 7 nm decrease in size to 5 nm within 30 s and to 3 nm within 1000 s. The hypothesis was that the oxidised atoms migrate. In the discussion the question was raised concerning the influence of water on these process, which is yet to be studied.

H. Grönbeck (Chalmers University of Technology, Sweden) approached NOx storage from a computational perspective, using super-cell calculations to examine the adsorption of NO<sub>2</sub> on layers of barium oxide(100) on Pt(100). The adsorption energy of BaO ( $E_a = 1.04$ ) is enhanced by a factor of 2 ( $E_a = 2.38$ ) when two layers of BaO are arranged on the Pt surface and there is a noticeable effect even up to 5 layers, 16 Å, of BaO between the Pt and the NO<sub>2</sub>. It was proposed that a similarly substantial effect would be observed on Pt supported MgO(100) ( $E_a = 1.65$ ) with charging of the NO<sub>2</sub> molecule induced by the Pt-MgO interaction.

The theme of the talk by R. Burch (University of Belfast, Northern Ireland) was the importance of scientific rigour, in particular in not theorising beyond the available data. This is particularly important in studying non-steady state processes. In order to study NOx storage on 1% Pt/17.5% Ba/ $\gamma$ -alumina, Burch uses fast transient kinetics apparatus with very short residence times and a full gas mixture. The conclusion was that NH<sub>3</sub> is only observed in large quantities over a Pt catalyst when H<sub>2</sub> alone is used as the reductant. With the typical 3:1 CO:H<sub>2</sub> mixture, CO inhibits the formation (release) of NH<sub>3</sub>.

Among the talks devoted to catalytic combustion, A. Baylet (Université de Poitiers, France) and P. Gélin (Université de Lyon, France) shared a theme of catalytic combustion of natural gas over supported PdO. Since metallic Pd is much less reactive than its oxide, and reoxidation of Pd may be the rate limiting step in the reaction, different approaches were taken to increase the PdO:Pd ratio. A. Baylet doped highly thermally stable hexaaluminate supports ( $\text{La}_{0.2}\text{Sr}_{0.3}\text{Ba}_{0.5}(\text{MnAl}_{11})\text{O}_{19}$  with 1% Pd; the most effective catalyst proved to be a hexaaluminate/alumina mixture. The approach of P. Gélin was to vary the support in order to increase the PdO-Pd transition temperature,

achieving the highest activity on Pd/YSZ in the absence of sulfur. Only Pd/Al<sub>2</sub>O<sub>3</sub> was not poisoned by sulfur.

The theme of catalytic combustion was continued by A. de Lucas-Consuegra (Universidad de Castilla-La Mancha, Spain) who discussed the use of solid electrolytes to make conducting electroactive catalyst supports for use in the catalytic combustion of hydrocarbons, exemplified by propane. Promoting 1% Pt/ $\beta$ -Al<sub>2</sub>O<sub>3</sub> with potassium ions gives a catalyst that operates, both in near-stoichiometric and O<sub>2</sub> rich conditions, at lower temperatures – around 200°C – well within the 190–310°C working exhaust temperature.

## Fuel Cells

For some time a lot of scientific effort has been devoted to decreasing the amount of pgm required for efficient operation of a fuel cell. M. Tada (University of Tokyo, Japan) used an impressive range of *in situ* XAS techniques to study the mechanism of the O<sub>2</sub> reduction reaction at the cathode on a Pt/C catalyst under realistic operating conditions. Two *in situ* time-resolved techniques were used: time-gated EXAFS (TG-EXAFS), with a time resolution of 1 s and *in situ* time-resolved energy-dispersive EXAFS (DXANES), with a resolution of 4 ms. Having estimated all kinetic parameters for the reaction, she concluded that there are eight elementary steps involved, and there is a significant time lag between electron transfer and structural changes in the Pt catalyst. Since the Pt–Pt bond dissociation rate and the PtO bond formation rate constants are similar, it was shown that at higher potentials than the open circuit voltage oxygen atoms break in to the sub-surface of the Pt nanoparticles.

N. Tsiouvaras (Universidad de la Laguna, Spain) gave a controversial presentation on ternary catalysts for direct methanol fuel cells in which Mo had been introduced to PtRu/C at loadings of between 2 and 12 wt.% for an overall 30% metal loading. Pt crystallite sizes of 2–5 nm were observed; there was no evidence of alloying. Although the catalyst displayed high metal losses on electrochemical cycling – mostly of Mo – the CO stripping potentials were lower than the com-

mercial 30% PtRu/C standard. Using differential electrochemical mass spectrometry, the gases produced during electrochemical processes were analysed demonstrating that the onset of CO<sub>2</sub> production was at lower potentials than observed for commercial catalysts. Similarly, by carrying out *in situ* FTIR on the electrochemical cell, it appeared that qualitatively a small quantity of CO poisoned the ternary catalyst surface. Finally, tests for activity in MeOH oxidation again gave higher current densities than the commercial standard.

## Photocatalysis

A. Kudo (Tokyo University of Science, Japan) demonstrated an exciting system for solar H<sub>2</sub> production from water. Ru/SiTiO<sub>3</sub> doped with Rh was the catalyst for H<sub>2</sub> generation; this proved better than the Pt analogue because the presence of Ru effectively suppresses the back reaction. By preparing the catalyst by a hydrothermal rather than solid state route, an improvement in quantum yield to 3.9% from 0.3% resulted. The improvement was thought to be due to the better crystallinity, smaller particle size and decrease in grain boundaries in the hydrothermally prepared catalyst, providing fewer sites where recombination could occur. The optimal system combined Ru/SiTiO<sub>3</sub>:Rh for H<sub>2</sub> generation with BiVO<sub>4</sub> for O<sub>2</sub> generation, using Fe(III) as the couple mediator, and gave a system responsive up to 520 nm.

## Selective Oxidation

A. Pashkova (DECHEMA, Germany) presented a new approach for the synthesis of hydrogen peroxide directly from H<sub>2</sub> and O<sub>2</sub>. Single channel asymmetric membranes were used as the support for the active Pd or Pd-Ag alloy species. The selectivity for H<sub>2</sub>O<sub>2</sub> could be increased from 20% to 80% by changing the concentration profiles of O<sub>2</sub> and H<sub>2</sub> from countercurrent to equicurrent profiles.

The selective generation of propylene oxide by epoxidation of propylene was the subject of a paper by N. Mimura (Research Institute for Innovation in Sustainable Chemistry, Japan). The epoxidation was carried out using a mixture of H<sub>2</sub> and O<sub>2</sub> over titania supported Au nanoparticles

prepared by deposition precipitation. Characterisation showed that the nanoparticles had deposited only on the four-coordinate titanium sites. The problem of the explosion limit was solved by feeding in H<sub>2</sub> and O<sub>2</sub> in two separate streams and using a membrane in the catalyst area. Similarly good performances were obtained with Au on titanium silicalite-1 (TS-1) and with Mo oxide on silica for epoxidation by molecular O<sub>2</sub>.

## Conclusion

EuropaCat VIII proved to be a key conference for any researcher studying the behaviour and characterisation of catalysts. An impressive selection of oral and written presentations generated what was certainly high quality if occasionally somewhat heated discussion both in and out of the conference venue. The high industrial representa-

tion attested to the significance of the conference to the wider commercial world. It was clear that pgms retain their fundamental role in many branches of catalysis and, despite or perhaps as a result of all efforts at substitution and thrifting, will continue to be the focus of considerable catalyst research activity for the foreseeable future.

EuropaCat IX: "Catalysis for a Sustainable World" will take place in Salamanca, Spain, from 30th August to 4th September 2009 (5).

## References

- 1 EuropaCat VIII: <http://www.europacat.org/>
- 2 Berzelius, *Ann. Chim. Phys. (Paris)*, 1836, 61, 146
- 3 B. Samanos, P. Boutry and R. Montarnal, *J. Catal.*, 1971, 23, (1), 19
- 4 M. Haruta, T. Kobayashi, H. Sano and N. Yamada, *Chem. Lett.*, 1987, 16, (2), 405
- 5 EuropaCat IX: <http://www.europacat2009.eu/>

### The Reviewers



After her Ph.D. in Coordination Chemistry in Basel, Switzerland (1999), Emma Schofield spent two years as a post-doctoral researcher in Strasbourg, France, before taking up a Lectureship in Inorganic Chemistry at Trinity College in Dublin, Ireland. In 2004 she moved to Johnson Matthey in the U.K. where she specialises in developing new synthetic routes to heterogeneous catalysts.



After specialising in heterogeneous catalysis applied to environmental technology at the Universidad Complutense de Madrid, Spain, and graduating from the Università di Urbino, Italy, Nadia Acerbi started her Ph.D. with Johnson Matthey in the framework of the Marie Curie Actions and in collaboration with the University of Oxford, U.K. Her research is focused on 'Novel Nano-Coated Catalysts for Selective Oxidation of Hydrocarbons'.



Cristian Spadoni graduated from the Facoltà di Chimica Industriale, Università di Bologna, Italy, with a specialisation in heterogeneous catalysis. He started his Ph.D. in Chemical Engineering with Johnson Matthey in the framework of the Marie Curie Actions and in collaboration with the University of Bath, U.K. His research has been focused on 'Direct Synthesis of Hydrogen Peroxide from Oxygen and Hydrogen'.