



PERSPECTIVE

Catalysis using gold containing materials

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ABSTRACT

This perspective article is based on a plenary lecture delivered by the author at Europacat 2023 in Prague on 29th August in recognition of the Boudart Award of EFCATS in 2021. The article charts the journey taken by the author in the discovery and application of gold catalysts over the preceding 40 years of research. Five topics are discussed. The first three parts describe three facets of monometallic gold catalysts. (1) CO oxidation and the hierarchy of activity of gold species supported on a reducible oxide Fe_2O_3 ; (2) acetylene hydrochlorination for the manufacture of vinyl chloride monomer using highly dispersed gold cations supported on carbon; (3) methane oxidation using molecular oxygen with gold nanoparticles dispersed on the zeolite H-ZSM-5. These first three parts emphasise that the active species of a gold catalyst is dependent on the reaction being catalysed and it is not a one size fits all for this catalysis. The final two parts concern gold palladium bimetallic catalysts. (4) alcohol oxidation and the new Cooperative Redox Enhancement effect (CORE); and (5) the use of *in situ* generation of hydrogen peroxide to enable new oxidative cascade processes. These examples demonstrate the rich tapestry that catalysis by gold can provide to the catalysis community globally, both from an academic and an industrial perspective as well as the societal impact that has been achieved by the commercialisation of gold catalysts.

1. Introduction

Many industrially operated heterogeneous catalysts comprise supported metal nanoparticles. For example Fe and Co nanoparticles catalyse the Fischer Tropsch Synthesis [1,2], Cu nanoparticles supported on ZnO catalyse methanol synthesis [3,4] and these processes have been extensively studied for decades. Fe and Ru catalysts catalyse ammonia synthesis [5,6] while Pd and Pt nanoparticles are integral components of car exhaust catalysts operated globally [7], and Ag nanoparticles catalyse ethene epoxidation [8]. It is clear that gold, element 79 in the periodic table, is surrounded by elements that have found commercial application for decades. Even element 80, namely mercury, has been used commercially on a large scale for the production of vinyl chloride monomer (VCM) [9]. Until relatively recently gold has been ignored as a commercial heterogeneous catalyst; it is interesting to note that had a researcher proposed using gold as a catalyst in a grant application the proposal would certainly have been rejected as it was common knowledge at that time that gold was an immutable element, singularly unreactive and in chemistry textbooks of that era gold demonstrated very limited chemistry and therefore interest for the community. The central problem that was needed to be overcome was how to prepare

stable nanoparticles of gold that could function as an effective catalyst. Typically it was considered that this was too challenging a problem as gold nanoparticles rapidly sintered thereby limiting activity. Yet it was largely forgotten that Faraday had demonstrated the synthesis of colloidal gold nanoparticle in 1857 [10] and therefore there were synthetic routes available to make gold nanoparticles. The major progress in the preparation of gold nanoparticles was made by the seminal work of Haruta who showed it was possible to make stable gold nanoparticles and these were exceptionally active for the oxidation of CO. Indeed these catalysts were shown to be active at temperatures as low as -75°C which being close to the coldest temperature ever recorded on the planet really means that gold is an effective ambient temperature catalyst for CO oxidation anywhere on the planet. These data are reproduced in Fig. 1 from Haruta's second paper on the topic that was published in 1989 [11]. This work was reproduced around the world and the paper [11] is very highly cited and this innovation started the gold rush in catalysis.

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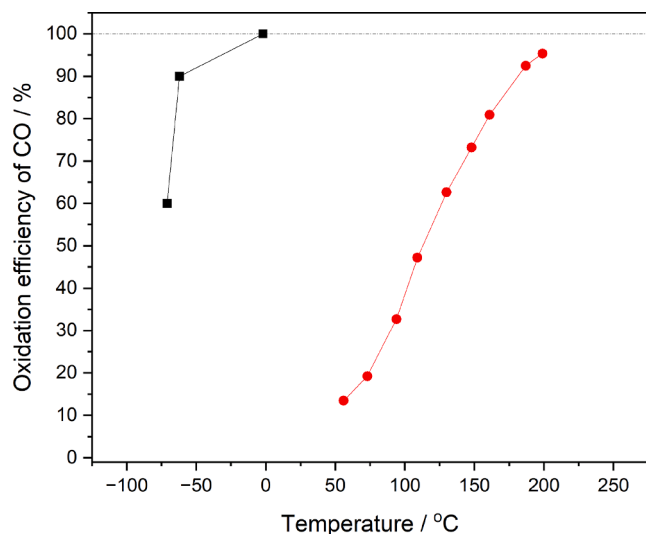


Fig. 1. Oxidation of CO in air; CO conversion as a function of temperature for 5% Au/ α Fe₂O₃. Key: ■ prepared by co-precipitation, ● prepared by impregnation. Redrawn from reference 11.

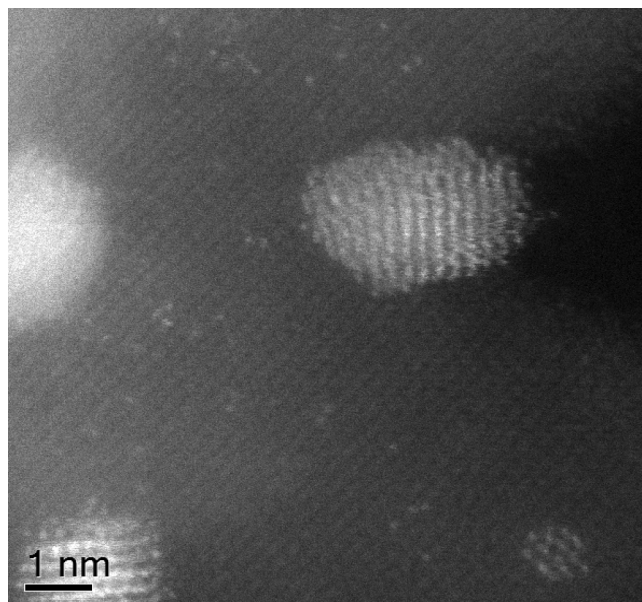


Fig. 2. Aberration-corrected micrograph of Au/Fe₂O₃ showing the presence of Au atoms, clusters and nanoparticles. Reproduced from reference 13.

2. Nature of the active site in gold catalysts for ambient temperature CO oxidation

Following the realisation that supported gold nanoparticles were exceptionally active catalysts for CO oxidation, researchers started to attempt to identify the nature of the active sites in these catalysts. There was a general recognition that reducible oxides were required as supports and that defects adjacent to the gold were important in the overall catalysed reaction [12]. Until the advent of aberration-corrected scanning transmission microscopy (AC-STEM) the prime candidates for the active gold species were nanoparticles in the size range of 2–5 nm, and there was a general correlation between the nanoparticle size and activity with the smallest particles being the most active [12]. However, the application of AC-STEM changed this perception since it was apparent that the most active catalysts not only comprised gold nanoparticles but also gold atoms and small clusters were also present [13]

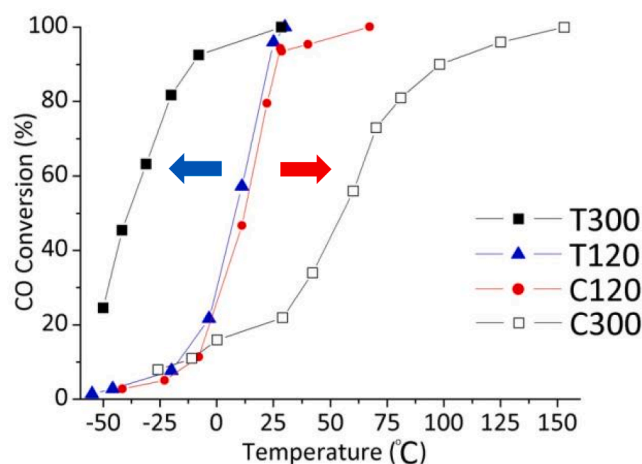


Fig. 3. CO oxidation as a function of temperature for four Au/Fe₂O₃ catalysts prepared by coprecipitation. Key slow preparation denoted T, fast preparation denoted C, the arrows represent the thermal activation behaviour of the catalysts, red arrow C catalysts and blue arrow T catalysts, figure redrawn from reference 14. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 2). So which of these gold species are active? Working with Haruta we addressed this question in a collaborative study between our laboratories in Tokyo, Lehigh and Cardiff and our findings not only provided an answer to this question which had been actively researched since the 1980s but also provided a fascinating insight into the complexities of catalyst synthesis [14].

The highly active catalyst pioneered by Haruta [11] was prepared using a coprecipitation method. However, the method used by Haruta and his team differed significantly from what would be considered as a standard coprecipitation method. In a typical coprecipitation method the dilute aqueous base (Na₂CO₃) is slowly added to a stirred solution of the gold and iron salts (HAuCl₄ and Fe(NO₃)₃) at a maintained temperature. The material is then recovered by filtration, washed until the effluent is free of Na⁺, dried at 120 °C and then calcined at 300 °C. It is therefore a very slow precipitation process. The method used by Haruta was the opposite; the solution of the metal salts was added rapidly to the aqueous base solution causing very fast nucleation and precipitation. The precipitate was collected, washed, dried and calcined in identical manner to the alternative slow process. These two different synthesis methods were used to prepare four catalyst samples that were used for CO oxidation (Fig. 3). Interestingly, the two dried samples gave identical catalyst performance. However, calcining the catalyst that was prepared by the slow acid into base method made the catalyst worse. Whereas calcining the catalyst that was prepared by the fast base into acid method made the catalyst much better; indeed this is the catalyst that exhibits the extremely high activity at sub-ambient temperatures. The reason for this difference was explained using detailed AC-STEM studies [14]. When the Au/Fe₂O₃ catalyst is prepared by the rapid method the very fast nucleation ensure that Au is trapped within the Fe₂O₃ crystallites. On heating this source of Au acts as a reservoir that exsolves from the bulk to the surface providing a new source of the active Au species. In the material prepared by slow coprecipitation no such reservoir of Au is present and on heating the Au species on the surface of the iron oxide simply sinter leading to the observed loss in catalyst activity (Fig. 3).

So what is the active Au species in these catalysts? The data in Fig. 3 shows that the two dried catalysts exhibit identical activities. This led us to expect that the two materials would exhibit similar morphologies when examined by AC-STEM. However, this was not the case; in fact the two materials were totally different, but each comprised a range of morphologies of nanoparticles, clusters and atoms. This was also the

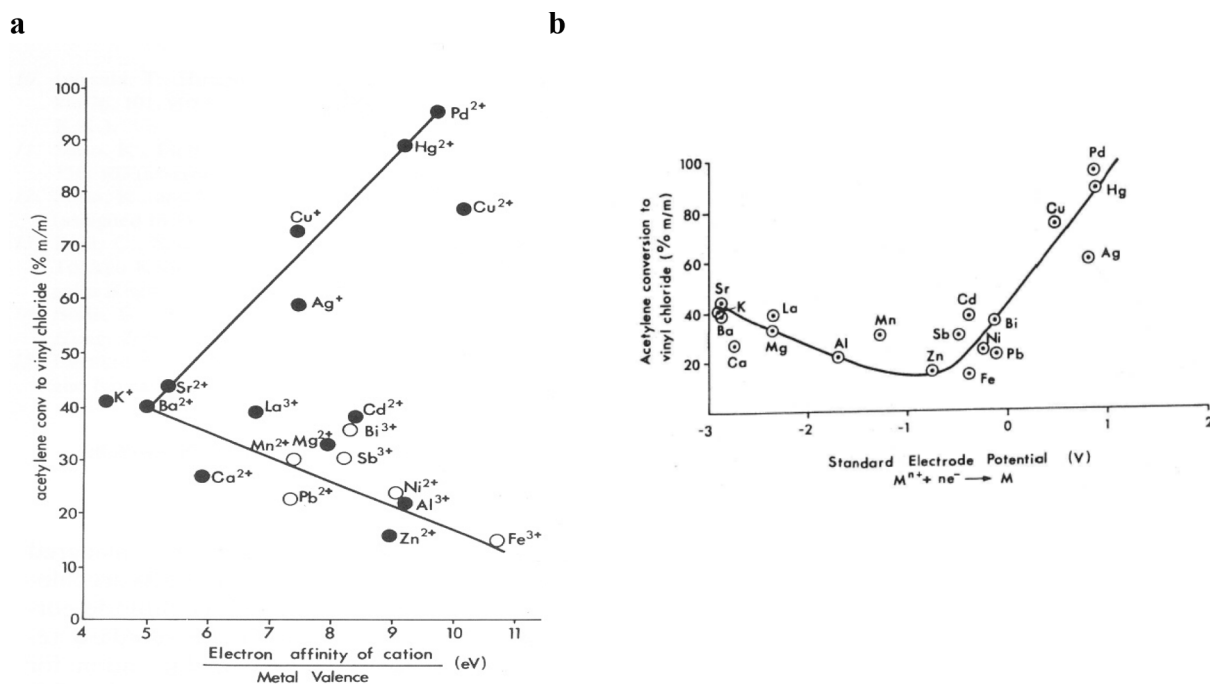


Fig. 4. Acetylene hydrochlorination (a) suggested correlation with the electron affinity of the cation, solid points represent metals that form metastable acetylides; (b) proposed correlation with the standard electrode potential of the cation. Redrawn from reference 19.

same situation for the two calcined catalysts which displayed very different activities. These too also comprised nanoparticles, cluster and atoms. From the extensive AC-STEM study involving thousands of micrographs we could only conclude that there was not one single Au species that was responsible for the very high activity observed with Au/Fe₂O₃ catalysts. We concluded that all the Au species exhibited activity for CO oxidation and that there was a hierarchy of activity. The gold clusters were the most active, then the nanoparticles and the Au atoms exhibited the least activity. Hence the activity displayed by a gold catalyst was made up of the sum of the number densities of these three Au species, and that in turn was determined by the catalyst preparation conditions [14]. Hence, sadly, there is not one unique active Au species supported on a reducible oxide but this hierarchy of active sites which Haruta had previously postulated in his Royal Society of Chemistry Spiers Medal Lecture [15], only now with this detailed study there was comprehensive evidence in support of the proposal.

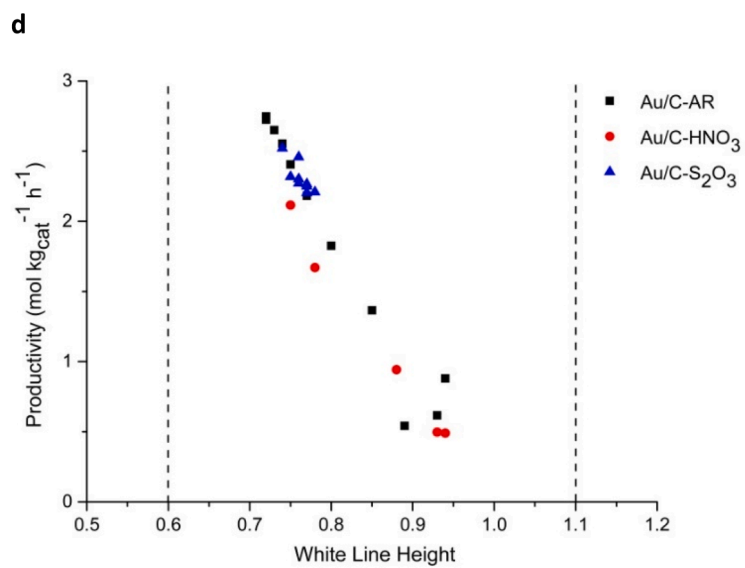
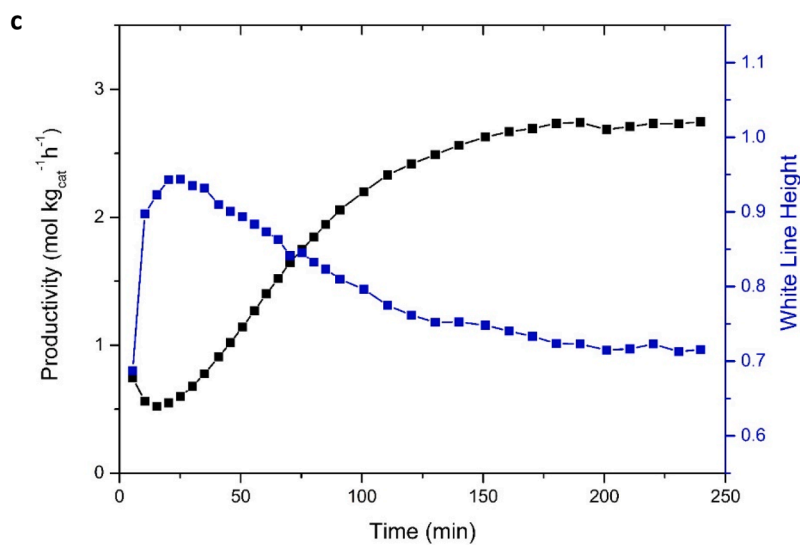
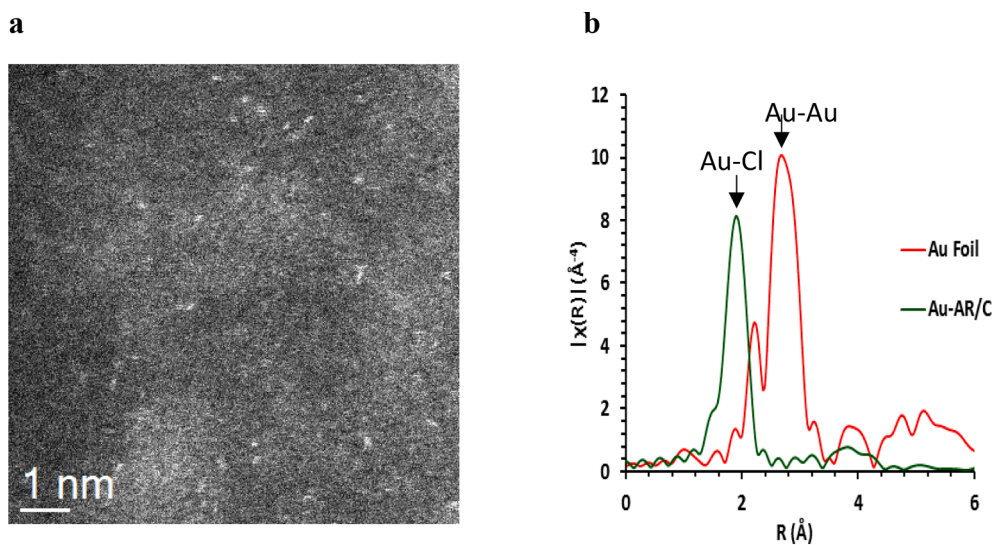
3. Gold catalysts for acetylene hydrochlorination: From discovery to commercialisation

In 1982, when working in African Explosives and Chemical Industries (AECI) in South Africa I was asked to find a better catalyst for acetylene hydrochlorination that is a key reaction to produce vinyl chloride monomer (VCM). AECI had a single production unit that used mercuric chloride as the catalyst comprising 10 wt% HgCl₂ supported on carbon. This catalyst deactivates by loss of HgCl₂ as it sublimes from the carbon support at the reaction temperature and is consequently swept from the fixed bed reactor [9]. HgCl₂ is also reduced to Hg and liquid mercury is found in the pipework downstream of the reactor. Then as today acetylene is mainly produced from coal via calcium carbide; however, acetylene can readily be produced from methane and hence biogas together with renewable energy could enable acetylene to become a new sustainable green carbon chemical intermediate of the future [16], and hence this reaction has great relevance to the chemical industry in a future net zero context.

Currently acetylene hydrochlorination is operated commercially in China where ca. 18 Mtpa of VCM is produced. Until recently this

production used the mercury catalyst, and this involved over 90 production sites each with up to 100 tubular fixed bed reactors each containing 6–7 tonnes of the 10 wt% HgCl₂/C catalyst, with a total installed catalyst capacity of >15000 tonnes. Each year >1000 tonnes of mercury are lost to the environment representing a major environmental hazard.

Prior to experimentally investigating for an improved acetylene hydrochlorination catalyst I remembered a quote by Frank Westheimer [17] “A month in the laboratory can often save an hour in the library” and so a profitable hour in the library ensued. Shinoda [18] had studied over thirty metal chlorides for this reaction and correlated the observed acetylene conversion with the electron affinity of the cation (Fig. 4a). Considering this plot it is apparent that this is not a strong correlation as three divalent cations from the same triad of the periodic table, namely Zn²⁺, Cd²⁺ and Hg²⁺ span from the worst to the best performance although they all have a similar electron affinity. As most of the metal cations were divalent it was reasoned that the standard electrode potential would be a better correlating parameter. Indeed, reploting the data in Fig. 4a using the standard electrode potential in place of the electron affinity of the cation does lead to a smooth correlation (Fig. 4b) which predicts that supported gold cations would be the best catalyst for acetylene hydrochlorination [19]. Subsequently, this was confirmed experimentally [20]. It should be noted that there was an element of good fortune in this early research of gold catalysis. In our laboratories we did not have access to HAuCl₄·xH₂O, as water soluble salt of gold. Rather, gold metal was used which was dissolved in *aqua regia* to enable catalysts to be prepared by incipient wetness. This method successfully made active catalysts; however, if an aqueous solution of HAuCl₄·xH₂O is used the catalysts are inactive, so it was fortunate that metallic gold had to be used as otherwise the discovery of gold catalysis would not have been made at that time. The reason for the poor activity using HAuCl₄·xH₂O alone is that the carbon reduces the Au³⁺ to Au⁰ which is inactive, but when *aqua regia* is present it reoxidises the Au⁰ back to cationic gold that is the active form. However, the gold catalyst prepared using *aqua regia* was never commercialised as in plant trials the catalyst was deactivated by carbon deposition due to acetylene polymerisation caused by the acid sites on the carbon support induced by the treatment with *aqua regia*.



(caption on next page)

Fig. 5. (a) Representative STEM-HAADF image showing isolated Au species. (b) Fourier transform of k^3 -weighted χ EXAFS *ex situ* data of the sample and a gold-foil reference. Variation in magnitude of Fourier transform is plotted with distance R from the Au absorber, (c) Catalytic performance as a function of time-on-line (black) and the change in normalized white-line intensity (blue) as a function of reaction time, (d) correlation between catalyst productivity and the white line height for catalysts prepared with aqua regia (Au/C-AR), nitric acid (Au/C-HNO₃) and Au thiosulfate (Au/C-S₂O₃); Dashed lines represent the white-line intensities of the Au(I) [AuCl₂]⁻ standard (value of 0.6) and the Au(III) KAuCl₄ standard (value of 1.1). Reproduced from reference 24. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

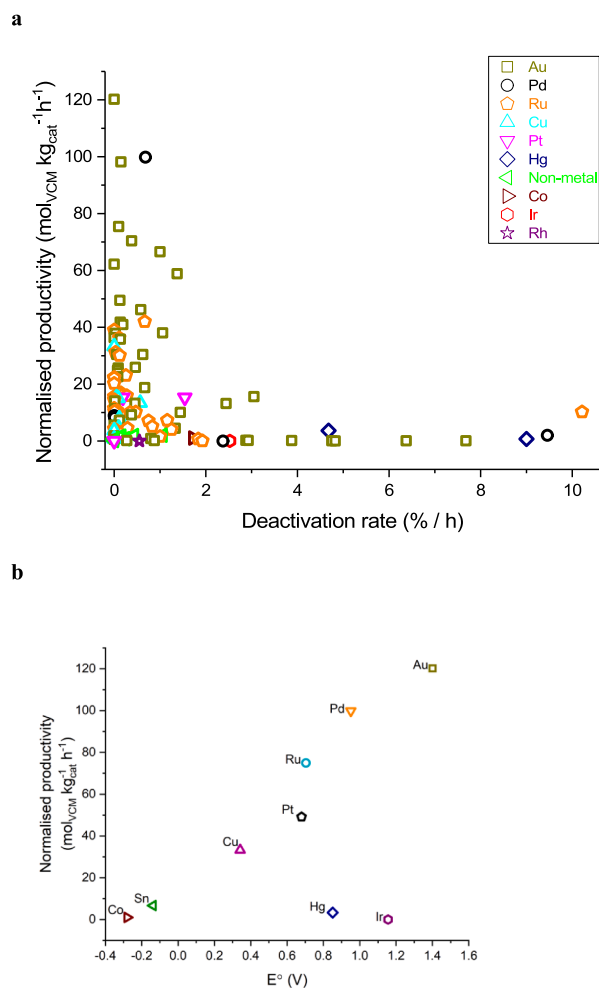


Fig. 6. (a) Normalized vinyl chloride monomer (VCM) productivity versus deactivation rate for a range of catalysts. The active component of the catalysts is shown in the legend; with the exception of the non-metal catalysts, all the catalysts are supported metal catalysts, (b) Correlation between normalized maximum productivity and standard electrode potential for the reaction $M^{2+} + 2e^- \rightarrow M$ or $M^{3+} + 2e^- \rightarrow M^{2+}$; data plotted for best in class for each metal. Redrawn from reference 26.

In 2007 Johnson Matthey acquired the rights to the AECI research and since then Johnson Matthey and Cardiff University have worked together to realise the commercialisation of the gold catalyst for acetylene hydrochlorination [21]. Two problems needed to be successfully addressed. First an aqueous preparation method was required as it would not be possible to produce a gold catalyst at the industrial scale required using *aqua regia* as the solvent. Second the gold concentration needed to be decreased from 2 % used in the AECI work to as low as 0.1 %. Also the new catalyst had to be stable for several thousand hours. Johnston [21] recognised that Au cations are soft whereas Cl⁻ is hard and consequently Au-Cl bonds are weak. In contrast S is a soft ligand and Au-S bonds are strong. Hence the preparation of a catalyst using an aqueous solution of gold thiosulfate gives an exceptionally active catalyst that is stable for required thousands of hours [21]. This catalyst was

initially tested at pilot scale in a single tube (2 kg catalyst, 3 m × 50 mm tube) and subsequently in a full plant scale test (2 tonnes catalyst, 790 3m x 50 mm tubes) and the new gold catalyst easily outperformed the standard mercury catalyst. Johnson Matthey have built a plant in China to produce the gold catalyst at the scale required for the market and it now operates in several plants and continues to be rolled out as its commercialisation in China continues at a pace. In 2015 China ratified the Minimata Convention [22] and in May 2017 Romania, the 50th country, ratified this convention ensuring that the Minimata Convention became international law on 16th August 2017 ensuring that all uses of mercury are not permitted globally by 2022. Hence the discovery and commercialisation of gold as a highly effective catalyst for acetylene hydrochlorination is a key example showing how fundamental scientific research can eradicate the use of a toxic poison from the environment and change international law.

The nature of the active site for the gold acetylene hydrochlorination catalyst was originally predicted to be cationic gold [19]. However, detailed *ex situ* characterisation by X-ray electron spectroscopy and initial transmission electron microscopy always showed that gold nanoparticles were present and these were confirmed to be present by X-ray diffraction [23]. Hence, in these early studies the active site was proposed to be cationic gold species at the interface between the gold nanoparticles and the carbon support. However, it was subsequently found that the methods used in the *ex situ* characterisation reduced the cationic gold to metallic nanoparticles and hence the presence of gold nanoparticles was indeed an artifact of the way the characterisation was carried out. Using *in situ* X-ray absorption spectroscopy coupled with detailed AC-STEM confirmed that the active species was fully dispersed gold cations (Fig. 5a and b). [24] Observing the catalyst performance using *in situ* Extended X-ray Absorption Fine Structure (EXAFS) it is possible to correlate the white line height with the catalyst activity (Fig. 5c) and there is a correlation between the Au⁺/Au³⁺ ratio and the activity (Fig. 5d) and the most active catalysts comprise the highest the concentration of Au⁺. It should be noted that the gold catalyst is very stable under the reaction conditions involving high concentrations of HCl at 180 °C, this is mainly because it is known that halide anions at elevated temperatures can redisperse Au⁰ nanoparticles to form gold cations [25].

In recent years the number of patents and papers on acetylene hydrochlorination have been growing exponentially with patents always outnumbering academic papers demonstrating the commercial significance of this reaction [26]. Cations other than Au⁺ have been explored with authors claiming that all can have higher activities than gold. A detailed review of all these catalysts has been undertaken [26] considering the different reaction conditions and normalising the data. For acetylene hydrochlorination the two most important reaction parameters are the activity and the stability/lifetime. Virtually all catalysts can deliver near 100 % selectivity based on acetylene. It was confirmed that gold is the most active and stable catalyst for this reaction (Fig. 6a) and that the activity of these catalysts correlates with the standard electrode potential (Fig. 6b) thereby confirming the original prediction made in the 1980 s that gold cations are the most active catalyst for this important reaction [19].

4. Methane oxidation using molecular oxygen with gold nanoparticles dispersed on the zeolite H-ZSM-5

The selective oxidation of methane to methanol has been a

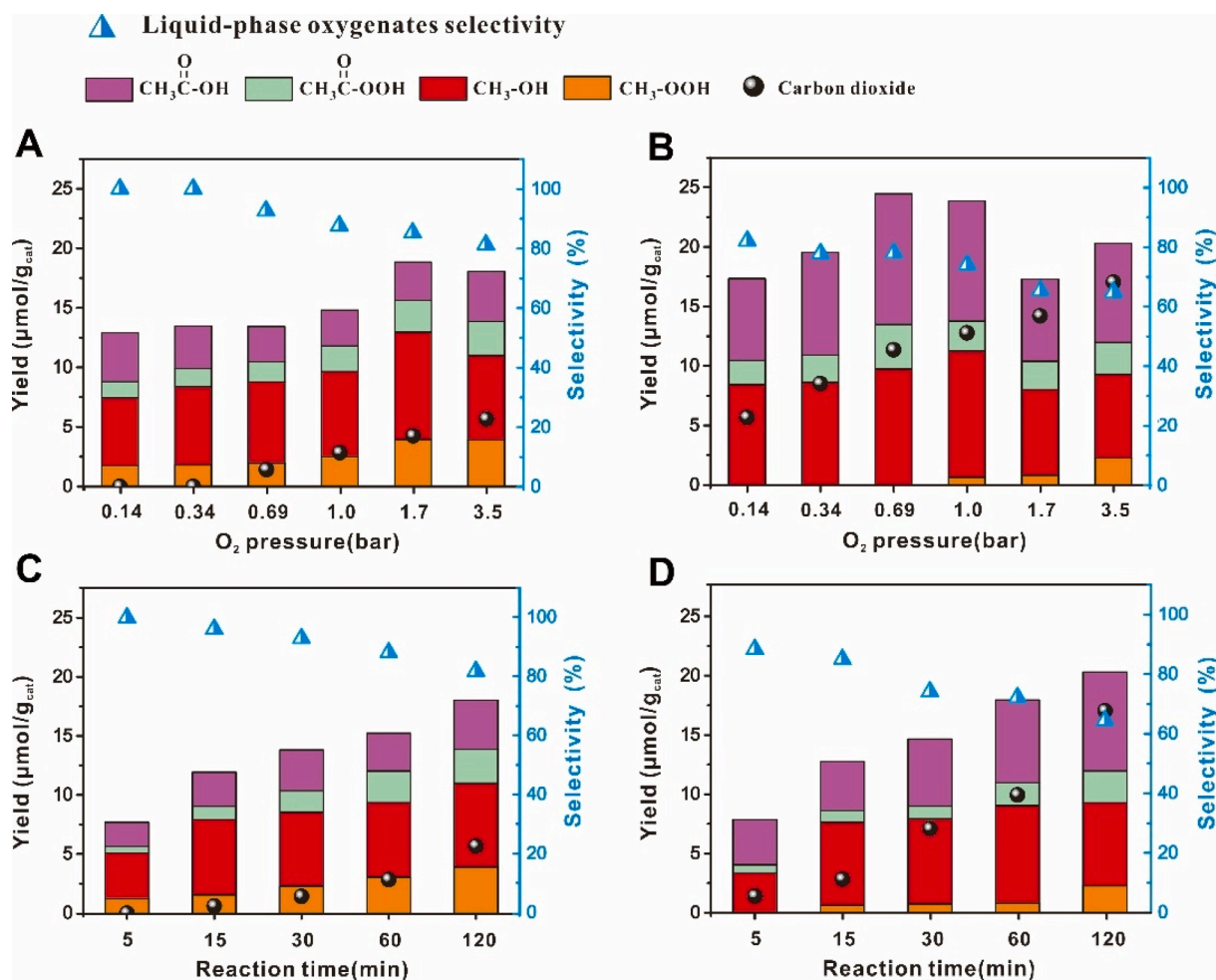


Fig. 7. Effect of O_2 partial pressure (A, B) and reaction time (C, D) on the oxidation of methane Au/ZSM-5 catalysts with 0.25 wt% Au (A and C) and 0.50 wt% Au (B and D). Reaction conditions: catalyst (0.10 g), 240°C , H_2O (15 mL), total pressure 24.2 bar. O_2 . For A, B the partial pressure was changed from 0.14 to 3.5 bar and the reaction time was fixed at 120 min. For C, D the reaction time was varied with CH_4 (20.7 bar) and O_2 (3.5 bar). Reproduced from reference 34.

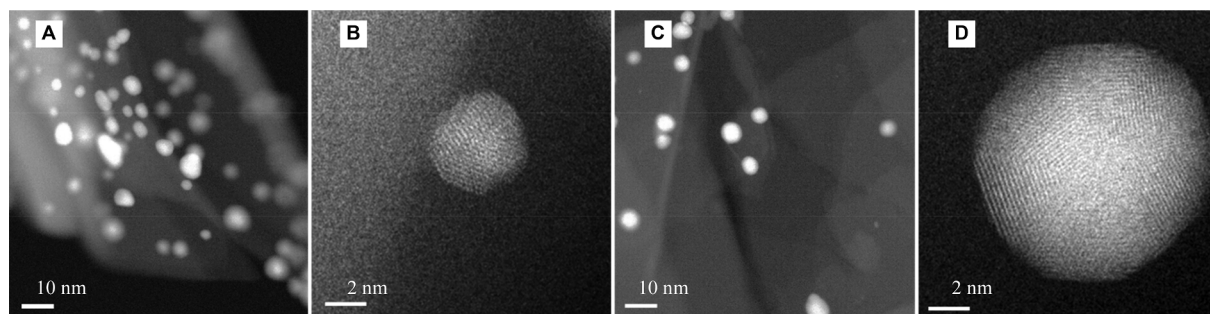


Fig. 8. Representative STEM-HAADF images of (A, B) the fresh 0.5 wt% Au/ZSM-5 catalyst and (C, D) the same catalyst after 2 h of methane oxidation reaction CH_4 (23.2 bar), O_2 (1.0 bar). Reproduced from reference 34.

longstanding subject of research in catalysis. At present methane is functionalised using an indirect process in which methane is reacted with water at high temperature by steam reforming to form synthesis gas ($\text{CO} + \text{H}_2$) which is then reacted further over a copper catalyst to give methanol [3], or with a Co or Fe catalyst using the Fischer Tropsch process to give hydrocarbons [1,2]. These indirect processes have been well established for decades and represent major capital assets for the companies that operate them. Hence at first sight there does not seem to be a pressing need to innovate a brand new process for methanol synthesis based on methane oxidation. However, this is not the case. It is

recognised that about 4 % of global natural gas production (ca. 140 billion m^3/annum) is flared annually [27]. It is flared because CO_2 is a less harmful greenhouse gas when compared to methane; however, this flaring represents a major loss of a valuable resource. In particular, if a selective oxidation catalyst could be identified it would be possible for this to form the basis of small scale methanol synthesis process that could be used at remote locations to liquefy the natural gas thereby making it more feasible for it to be transported and used. However, with the move to net zero carbon over the coming decades it is expected that the use of fossil carbon will be initially minimised and eventually phased

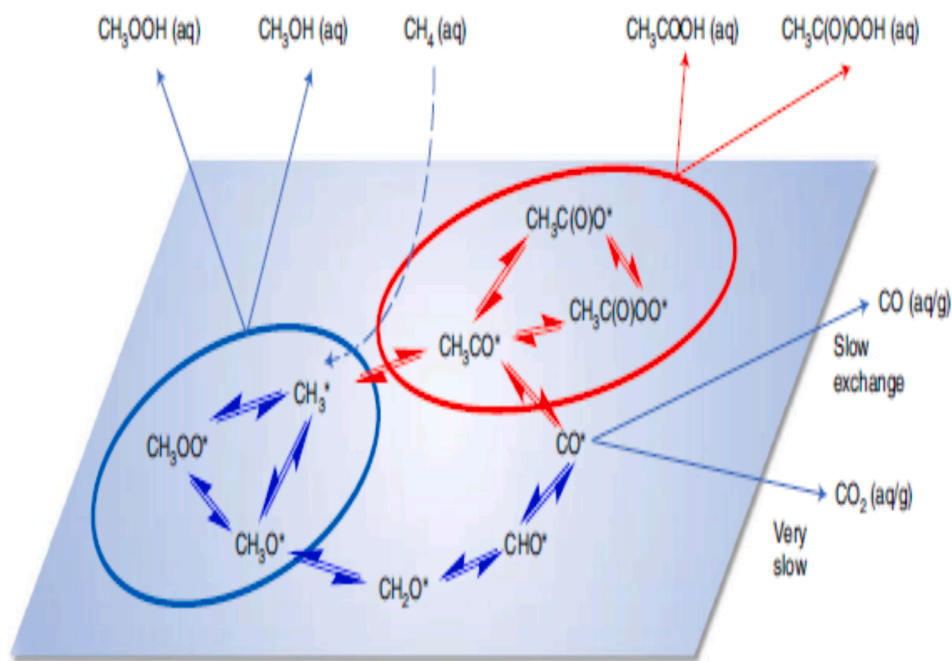
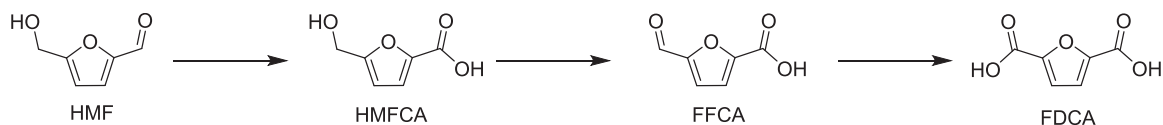


Fig. 9. Schematic illustration of the proposed surface catalysed reactions. Blue arrows and lines are used for C1 intermediates and products, while red arrows and lines are used for C2 intermediates and products. The phase of each product is indicated as aqueous (aq) or partitioned between aqueous and gas phase (aq/g); surface species are labelled with *. The surface species in blue/red ellipses lead to observed partial oxidation products through hydrolysis or hydrogen transfer. Reproduced from reference 34.



Scheme 1.

out. However, we can expect that biogas which contains methane could become a viable feedstock for this new decentralised methanol synthesis process.

There have been many attempts to design a selective methane oxidation catalyst [28]. After all, the nature enzyme methane monooxygenase shows this is possible [29]. Strong acids such as oleum have been used as homogeneous and heterogeneous catalysts as the formation of methyl sulfate can be readily hydrolysed to methanol [30]. However, the hydrolysis step dilutes the acid thereby compromising its activity and these approaches do not lead to closed catalytic cycles.

The subsequent innovation in the quest for a robust catalyst combined acidity with confinement, the latter being a crucial aspect for the operation of methane monooxygenase. Initially, FeCu/ZSM5 was used with H_2O_2 as oxidant; [31] but it is important that molecular oxygen is used at the terminal oxidant. Recent studies using copper zeolites have demonstrated some success, but these catalysts have relatively low activity and often low turnover numbers [32].

One important point to note is that the method to prepare the catalyst for small scale testing must not comprise any adventitious carbon, e. g. using sodium carbonate as a precipitating agent or carbon containing reducing agent or ligands. This is because this can lead to false positive results with the methanol being formed by the catalyst alone [33].

Recently, we have shown that Au nanoparticle dispersed on H-ZSM-5 is an active catalyst for the selective oxidation of methane to methanol [34]. In contrast to copper zeolite catalyst which only produce methanol as the selective product, the gold catalyst produces both C₁ (methanol and methyl hydroperoxide) and C₂ (acetic acid and peroxyacetic acid) products (Fig. 7). The experiments were conducted in an autoclave in

water which is an important reactant. Although the reaction temperature was typically 240 °C, appreciable activity was observed at temperatures as low as 120 °C and by optimising the conditions methane conversions approaching 5 % could be observed with a total oxygenate selectivity of 60 %. Detailed AC-STEM analysis showed that only gold nanoparticles were present, and no Au clusters or atoms/cations were observed. In the fresh catalyst the Au nanoparticles size was ca. 8 nm in diameter (Fig. 8) and hence the active site for this interesting new catalysis comprises the Au nanoparticles supported on the external surface of the H-ZSM-5 crystallites, and there are no Au species within the pore structure of the H-ZSM-5. The acidity of the zeolite is, however, important. On use the Au nanoparticles sinter to ca. 14 nm in diameter (Fig. 8) and the catalyst do lose some activity but after the first reuse they are stable. Detailed theory studies combined with isotopic labelling studies were used to unravel the mechanism for the observed catalysis (Fig. 9). It is proposed that there is a pool of C₁ intermediates on the surface and a surface methyl couples with and oxidised C₁ species. The addition of CO as a reductant leads to an enhancement in activity and using ^{13}C we observed that the C in the methyl group of the C₂ product originated from the CH_4 and the carboxyl group carbon originated from the CO in the isotopic studies, thereby supporting the proposed mechanism. The important observation though is that the Au/H-ZSM-5 catalyst can oxidise methane selectively using molecular oxygen as the terminal oxidant and that a sacrificial reducing agent is not required; something not observed with other zeolite catalysts. However, the amounts of product being produced (μmol) are miniscule and these are heavily diluted in water and so at this stage the catalysis is only of academic interest, but it does offer the promise that more effective

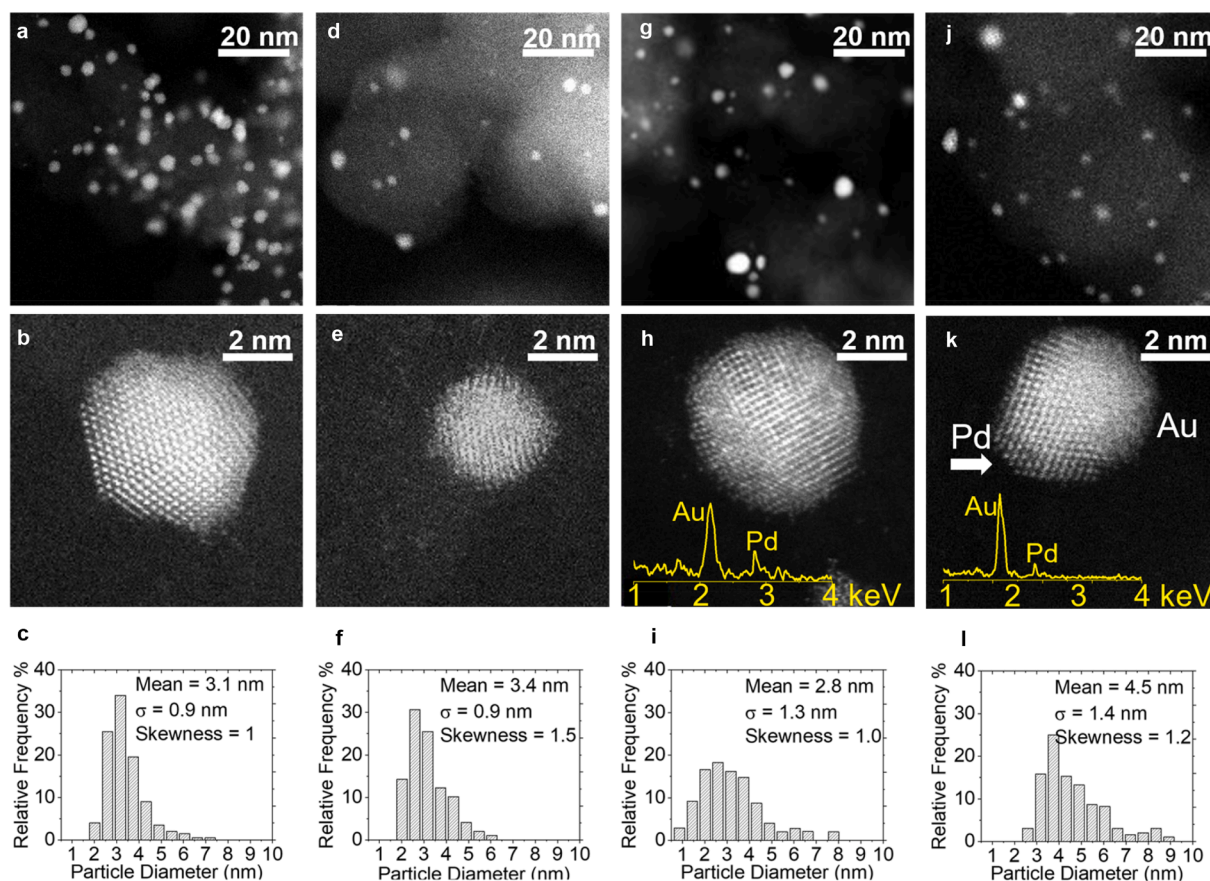


Fig. 10. Representative STEM-HAADF images and the corresponding particle size distribution. a-c, Au/C; d-f, Pd/C; g-i, Au-Pd/C and j-l, Au@Pd/C catalysts. The inset shown in images h and k are the XEDS spectra of the corresponding particle, showing the presence of peaks of Au M (~2.1 keV) and Pd L (~2.8 keV). Image k highlight a Janus-like nanoparticle morphology. The Pd side is highlighted with a white arrow. Reproduced from reference 37.

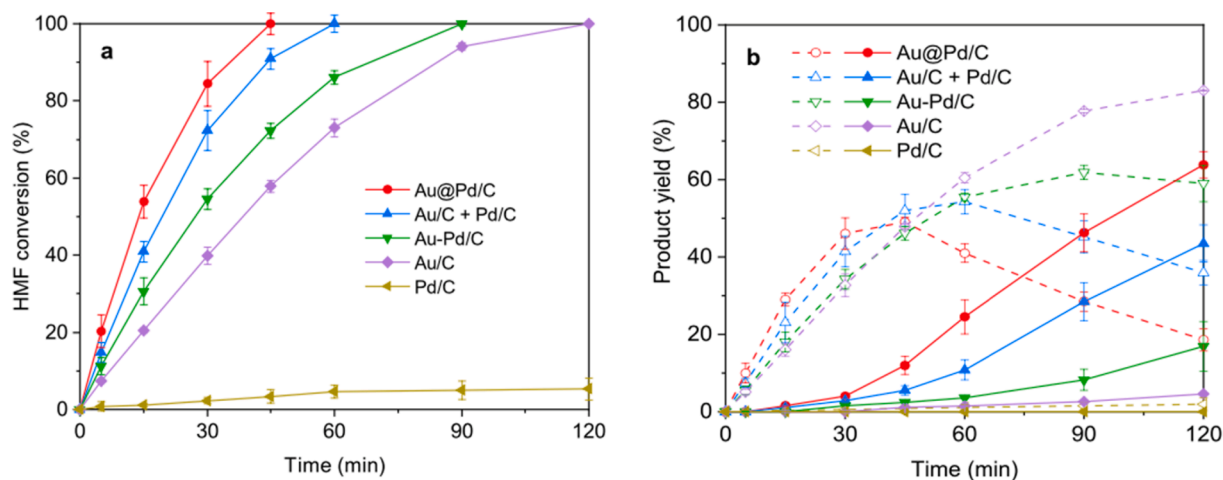


Fig. 11. Catalytic performance for aqueous HMF oxidation. a, HMF conversion and b, product yield of HMFCA (dashed line) and FDCA (solid line) as a function of time over a series of catalytic formulations. Reaction conditions: HMF (0.1 M); NaHCO_3 (0.4 M); H_2O (16 mL); 80 °C; $p\text{O}_2 = 3$ bar; catalyst amounts for Au@Pd/C, Au/C + Pd/C and Au-Pd/C: 143.1 mg; Au/C: 72.1 mg; Pd/C: 71 mg. For each reaction, the moles of Au and Pd used are always constant (Au/Pd = 4 (mol/mol)). Associated error bars correspond to mean \pm SD (N = 5). Reproduced from reference 37.

catalysts could be designed.

5. Comments on the nature of active sites for gold catalysts

In the early days of catalysis by gold there was always a debate about the nature of the active site. [12] In this paper three different gold

catalysts have been introduced and it is clear that there is not a single active site for a gold catalyst as it depends heavily on the reaction being catalysed. Indeed, for the Au/ Fe_2O_3 catalyst for CO oxidation the nanoclusters, the nanoparticles and the Au atoms all have activity and there is a hierarchy of activity (Fig. 2). The Au/C catalyst for VCM synthesis comprises fully dispersed Au⁺ cations (Fig. 5b) whereas for the

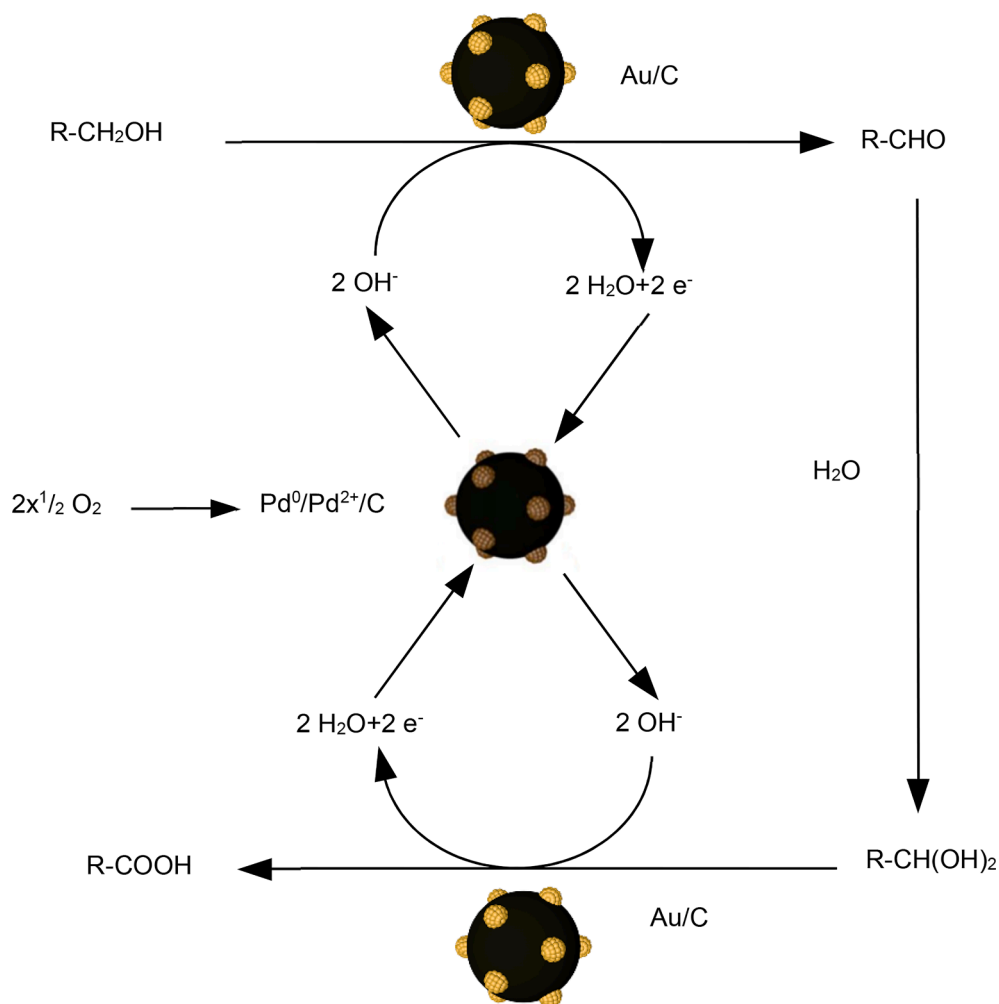


Fig. 12. Proposed reaction scheme for the aqueous phase oxidation of alcohols and formyls over a physical mixture of Au/C and Pd/C. A cooperative redox enhancement effect is facilitated by the ORR reaction taking place on Pd sites. Reproduced from reference 37.

Au/H-ZSM-5 catalyst the active Au species are large Au nanoparticles (Fig. 8b). However, in all these cases the support plays an equally important role to the gold species and, indeed, alternative supporting matrices are less effective. Hence, it is the metal species combined with the supporting matrix that must always be considered as a whole.

6. Alcohol oxidation and the new Cooperative redox enhancement effect (CORE)

In 2006 we showed that while Au/TiO₂ and Pd/TiO₂ monometallic catalysts were effective for benzyl alcohol oxidation when alloyed as AuPd/TiO₂ they were far more effective for this reaction. [35] At that time we referred to this enhancement effect as synergy and many subsequent studies have tried to unravel the origin of this effect. In 2010 Davis and co-workers [36] studied glycerol oxidation using O₂ as oxidant and proposed monometallic Au catalyses both the oxidative dehydrogenation (ODH) reaction and the oxygen reduction reaction (ORR) simultaneously in alcohol oxidation. Hence, it is OH⁻ anions that are the effective species involved in the initial ODH of glycerol and O₂ plays an indirect but important role in regenerating the OH⁻ via ORR. We were interested if the hypothesis proposed by Davis could be extended to bimetallic catalysts so that one metal could catalyse the ORR reaction and the other metal the ODH reaction. [37] For this study we chose the oxidation of hydroxymethylfurfural (HMF) as a model reaction to study. Our motivation for selecting this reaction was that HMF oxidation is very commonly investigated and hence there is an

abundance of literature to which reference can be made. HMF contains two oxidizable functional groups (formyl and alcohol) and the final product 2,5-furandicarboxylic acid is of commercial interest. The reaction is a six electron oxidation via 5-hydroxymethyl-2-furoic acid (HMFA) and 5-formyl-2-furancarboxylic acid (FFCA) as intermediates (Scheme 1).

The catalysts used in this study were prepared by sol-immobilisation [37] a method that leads to the formation of well-dispersed, reduced metal particles; no thermal reductive treatment is required and hence this limits sintering. The reducing agent we used was sodium borohydride and polyvinyl alcohol was used as a stabiliser to control nanoparticle aggregation so that mean particle size distributions of ca. 2–5 nm could be maintained across a series of different metal and metal combinations. For this study [37] we selected supported Au and Pd catalysts using HAuCl₄ and PdCl₂ as the precursors and we used XC72R carbon as the support as this is highly conducting and is used in fuel cell applications. We constructed five samples for investigation (a) monometallic Au denoted Au/C, (b) monometallic Pd denoted Pd/C, (c) a physical mixture of the Au/C and Pd/C denoted Au/C + Pd/C, (d) a homogeneous AuPd alloy prepared by reducing a solution of the combined Au and Pd precursors denoted AuPd/C, and (e) a Janus type bimetallic, prepared by reducing separate solutions of the metal precursors and then combining the two sols prior to immobilisation on the XC72R, denoted as Au@Pd/C. For the initial tests the molar ratio of the two metals in the bimetallic catalysts was fixed at Au:Pd = 4:1 M. Electron microscopy confirmed that the particle size distributions of the

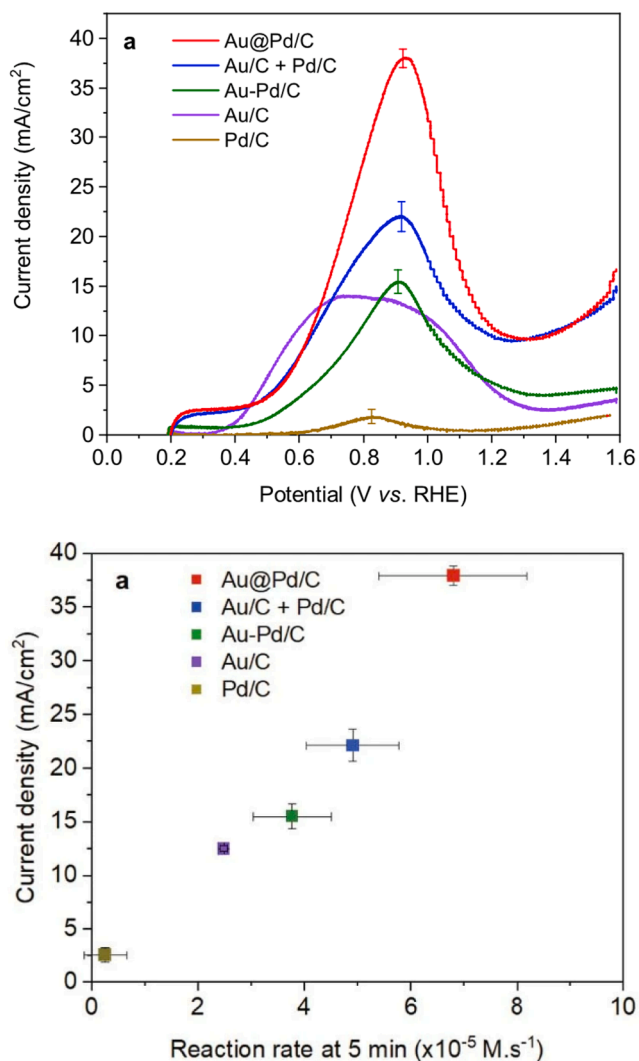
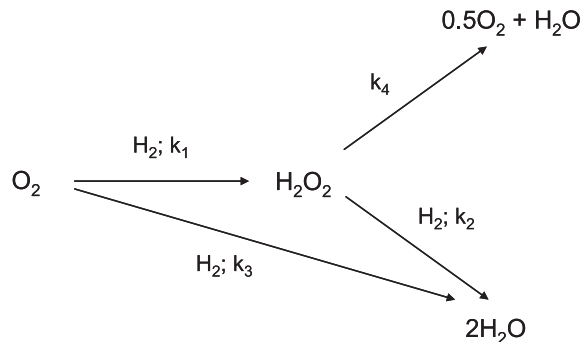


Fig. 13. (a) Electrochemical performance. Cyclic voltammetry (anodic scan) of half-cell with HMF solution. Net current density is the difference between anodic-scan current density and blank current density (0.1 M NaOH only). Reaction conditions: 0.1 M NaOH; 0.02 M HMF; 50 mL H₂O; 25 °C; scan rate 50 mV·s⁻¹; N₂ flow: 50 mL/min. (b) Relationship between the maximum current density in (a) and the reaction rate measured at 5 min for HMF oxidation under reaction conditions in Fig. 11a. Reproduced from reference 37.



Scheme 2.

nanoparticles were broadly similar as well as the confirmation of the homogeneous alloy and the Janus nanoparticles (Fig. 10).

The oxidation of HMF under aqueous alkaline conditions using the

five catalysts showed that spatial separation of the Au and Pd gave enhanced conversion of HMF and, in particular, increased the yield of the final FDCA product by a factor of 10 for the Au/C + Pd/C physical mixture as compared to the Au/C monometallic catalyst (Fig. 11). [37] The Pd/C catalyst was not particularly active for this reaction and although alloying Au with the Pd gave an increase in activity that was higher than the sum of the two monometallic catalysts tested separately, it was the spatial separation of the two metals (Au/C + Pd/C and Au@Pd/C) that gave the highest promotional effect. This enhancement through spatial separation of the Au and Pd was observed for a wide range of alcohols (Fig. 11). We have named this catalytic observation the Cooperative Redox Enhancement Effect (CORE) and the mechanism by which it operates is that Au catalyses the ODH of the alcohol and Pd catalyses the ORR reaction using the electrons released from the ODH reaction to convert O₂ to 2OH⁻ (Fig. 12). The reason that the spatial separation leads to the observed enhancement in rate as compared to alloying the Au and Pd is that alloying inhibits the cycling between Pd²⁺ and Pd⁰, that is essential for the catalysis to proceed. As the redox reaction proceeds by transfer of electrons we have demonstrated that the enhancement can be observed in the electrocatalytic oxidation of alcohols using cyclic voltammetry (Fig. 13a) and furthermore plotting the initial thermocatalytic rate for HMF conversion versus the maximum current density observed in the cyclic voltammograms leads to a linear plot (Fig. 13b) confirming the overall consistency between the thermocatalytic and electrocatalytic alcohol oxidation in the observation of the new CORE effect. We have also shown that the effect can be observed over a range of Au:Pd molar ratios and also that CORE is not observed just with Au and Pd and other metal combinations, notably Au and Ir and Pd and Ir, demonstrate CORE [38].

In our initial paper in 2006 [35] we demonstrated that alloying Au with Pd led to a significant enhancement in the activity for alcohol oxidation. However, although this initial study sparked an enormous amount of interest in alloy catalysts it was clearly not the full story as spatially separating the Au and Pd on a conducting support leads to an even higher enhancement in activity. The Janus type nanoparticle Au@Pd/C, indeed, demonstrates the highest activity enhancement as would be expected as the two metals are in close contact. Unfortunately, the Janus type particles are not stable and on use these nanoparticles gradually form AuPd alloys and the activity is consequently decreased [37]. We so, however, consider that this new CORE effect will enable improved catalysts to be designed across a broad range of redox reactions.

7. Chemo-enzyme cascade reactions using *in situ* hydrogen peroxide

The direct synthesis of hydrogen peroxide from oxygen and hydrogen can be considered to be a dream reaction as, in principle, it can be 100 % atom efficient. However, there are three competing reactions (Scheme 2) that can limit the selectivity of the reaction; namely hydrogenation, combustion and decomposition.

The reaction involves the catalytic hydrogenation of O₂ (k₁) but catalysts that can typically hydrogenate O₂ can also hydrogenate H₂O₂ (k₂). H₂O₂ can be catalytically decomposed (k₄) or O₂ and H₂ can combust (k₃) and both processes can be explosive. Hence care is needed in conducting the direct synthesis of hydrogen peroxide and typically the reaction is conducted with dilute gases below the lower explosion limit of hydrogen.

We have researched the direct synthesis reaction extensively for over twenty years [39] and we have designed catalysts that can give 100 % specificity to H₂O₂, i.e the three competing reactions occur at negligible rates with these catalysts; namely AuPd alloy nanoparticles supported on acid pretreated carbon, [40] or heat treated PdSn/TiO₂ [41]. AuPd catalysts can also produce H₂O₂ at a rate required for commercial application [40]. However, one remaining problem has yet to be overcome and that is the requirement to produce H₂O₂ at a concentration

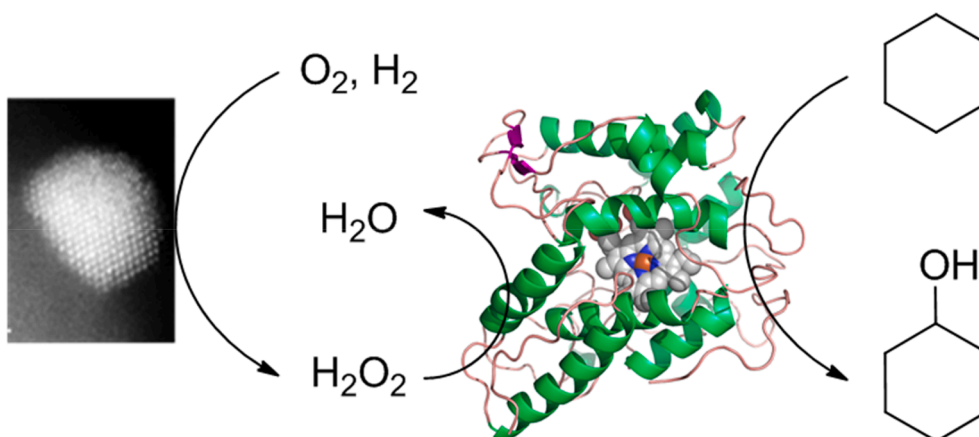


Fig. 14. Schematic representation of a chemo-catalyst (AuPd/TiO₂) generating H₂O₂ that is used by the UPO enzyme to oxidise cyclohexane to cyclohexanol. Reproduced from reference 42.

that can be utilised in a short reaction time. Although we continue to research this fascinating reaction, we decided to solve this remaining problem by using the H₂O₂ *in situ* as it is formed in a second cascade process. Our initial approach to this was to combine the AuPd/TiO₂ chemo-catalyst with an enzyme capable of using the H₂O₂ for a coupled oxidation reaction [42]. The enzyme we selected was an unspecific peroxidase (UPO) which have only recently been isolated in 2004. UPOs catalyse the insertion of an oxygen atom from H₂O₂ into the C-H bonds a wide variety of substrates including hydrocarbons. In contrast to mono-oxygenases UPOs do not require the presence of cofactors (e.g. NADH) and so are ideal for the type of cascade reaction proposed. In this study we use an evolved UPO, named PADA1 which is recombinantly expressed and isolated from fungi – in this case *Pichia Pastoris*. Our initial aim was to couple the chemo-catalyst and the UPO for the oxidation of cyclohexane to cyclohexanol (Fig. 14). However, there is an important consideration, and this is the “conditions gap”. Reaction conditions that are used for the direct synthesis of H₂O₂ typically require high reaction pressures, low sub-ambient temperature and high stirring speeds. Whereas enzyme reactions prefer ambient pressure and temperature and they are shaken not stirred in a buffered solution to maintain the pH in the desired range. Hence, we needed to adjust the reaction conditions for the AuPd/TiO₂ catalyst to determine if it could operate under the conditions required by the enzyme. We were, however, very fortunate that the enzyme only requires a low steady concentration of H₂O₂ for the oxidation reaction and we found that the steady supply of 20 ppm H₂O₂ was sufficient for PADA1, and this could be achieved with a low stirring speed using H₂ and O₂ mixtures above the higher explosive limit at atmospheric temperature and pressure. Also we were fortunate that the enzyme could tolerate slow stirring speeds without too high a detrimental effect. The combination of the chemo-catalyst AuPd/TiO₂ and PADA1 proved to be very successful and cyclohexane could be oxidized selectively to cyclohexanol [42] and we demonstrated that very high turnover numbers of several hundred thousand could be achieved [43]. This combination of chemo-catalyst and enzyme was successfully used for several substrates (Table 1) and in all cases the expected regio- and enantio-selectivity of the enzyme was retained. As such this approach represents that an easily scalable supply of low levels of H₂O₂ to UPO reactions as no additional enzymes and co factors needed; or, indeed the approach does not require specialist equipment that would be challenging to scale up.

Recently, we have used the approach of using H₂O₂ *in situ* as it is synthesised in other reactions. Most notably for the ammoxidation of cyclohexanone at 80 °C in the presence of ammonia using *in situ* H₂O₂ [44].

8. Concluding reflections

It is clear that supported gold catalysts and gold-containing catalysts are very effective for a range of reactions. Indeed, the catalyst comprising gold cations fully dispersed on carbon has been commercialised for acetylene hydrochlorination.

In this paper it is demonstrated that the method of catalyst preparation is very important. It is very easy to make a poor gold catalyst given the propensity of gold to sinter. Indeed, it was the facile nature of sintering for gold catalysts that probably led to the late development of this exciting field of catalysis. A key observation is that the active sites for gold catalysts can vary with the reaction being studied. Furthermore, the support is an integral part of the catalyst matrix and hence the preparation strategy needs to take into account these factors.

When considering bimetallic catalysts, previously it was considered that certain alloys were efficacious, but we now know that spatial separation of the two metals can be highly advantageous and this has led to the discovery of the new CORE effect. This unexpected discovery can be expected to underpin future catalyst design for redox reactions.

In the final part it is shown that the *in situ* generation of H₂O₂ can be effectively coupled with an enzyme that can use the H₂O₂ effectively. It is a positive finding that the chemo-catalyst can operate efficiently under the reaction conditions dictated by the enzyme. This approach to oxidation catalysis can be expected to open up new avenues of exploration.

CRediT authorship contribution statement

Graham J. Hutchings: Writing – review & editing, Writing – original draft.

Declaration of competing interest

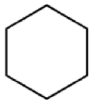
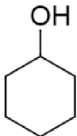
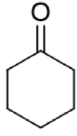
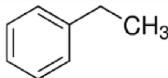
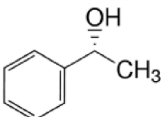
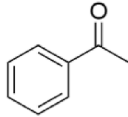
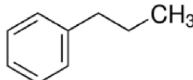
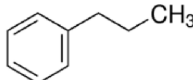
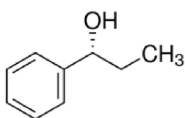
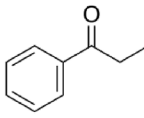
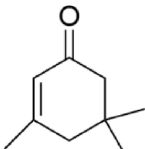
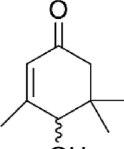
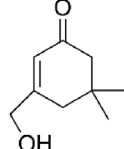
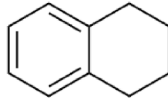
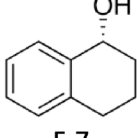
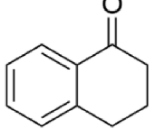
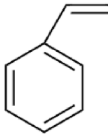
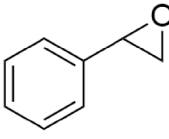
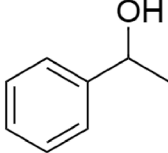
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Data availability

Data will be made available on request.

Table 1

Substrate Scope of Tandem Heterogeneous and Biocatalytic System using *in situ* generated H₂O₂ [42].

Substrate	Reaction Time / h	Product Concentration / mM		TTN x10 ³ (a) (Yield / %) (b)
	16	 8.7	 0.3	25.3 (87%)
 (20 mM)	16	 8 (e.e. ~98%)	 1.2	25.9 (80%)
 (20 mM)	16	13.1 (e.e. ~98%)	2.9	47.0 (65%)
	8	 2.9 (e.e. >99%)	 0	8.2 (29%)
 (30 mM)	8	 11.2	 11.2	63.1 (75%)
	24	 5.7 (e.e. >99%)	 0.2	16.6 (57%)
	2	 2.12 (e.e. 6%)	 2.04 (e.e. ~98%)	11.7 (21% epoxide)

Reaction conditions: PaDa-I (15 U ml_{RM}⁻¹) was coupled with *in situ* H₂O₂ generation by 0.5 % Au-0.5 % Pd/TiO₂ (0.1 mg ml_{RM}⁻¹) using a gas mixture of 80 % H₂ in air in a sealed system under 2 bar total pressure. Substrate concentration was 10 mM unless otherwise stated. ^a Total turnover number of C-H activation reaction accounting for secondary oxidation products, ^b to major (primary) hydroxylated products.

- disparate catalytic sites drives thermochemical rate enhancement, ACS Catal. 13 (2023) 14189–14198, <https://doi.org/10.1021/acscatal.3c03364>.
- [39] J.K. Edwards, S.J. Freakly, A.F. Carley, C.J. Kiely, G.J. Hutchings, Strategies for designing supported gold-palladium bimetallic catalysts for the direct synthesis of hydrogen peroxide, Acc. Chem. Res. 47 (2014) 845–854, <https://doi.org/10.1021/ar400177c>.
- [40] J.K. Edwards, B. Solsona, E.N. Ntainjua, A.F. Carley, A.A. Herzing, C.J. Kiely, G. J. Hutchings, Switching off hydrogen peroxide hydrogenation in the direct synthesis process, Science 323 (2009) 1037–1041, <https://doi.org/10.1126/science.1168980>.
- [41] S.J. Freakley, Q. He, J.H. Harry, D.A. Crole, D.J. Morgan, E.N. Ntainjua, J. K. Edwards, A.F. Carley, A.Y. Borisevich, C.J. Kiely, G.J. Hutchings, Palladium-tin catalysts for the direct synthesis of H₂O₂ with high selectivity, Science 351 (2016) 965–968, <https://doi.org/10.1126/science.aad5705>.
- [42] S.J. Freakley, S. Kochius, J. van Marwijk, C. Fenner, R.J. Lewis, K. Baldenius, S. S. Marais, D.J. Opperman, S.T.L. Harrison, M. Alcalde, M.S. Smit, G.J. Hutchings, chemo-enzymatic oxidation cascade to activate C-H bonds with *in situ* generated H₂O₂, Nature Commun. 10 (2019) 4178, <https://doi.org/10.1038/s41467-019-12120-w>.
- [43] D. Wilbers, J. Brehm, R.J. Lewis, J. van Marwijk, T.E. Davies, D.J. Morgan, D. J. Opperman, M.S. Smit, M. Alcalde, A. Kotsiopoulos, S.T.L. Harrison, G. J. Hutchings, S.J. Freakly, Controlling product selectivity with nanoparticle composition in tandem chemo-biocatalytic styrene oxidation, Green Chem. 23 (2021) 4170–4180, <https://doi.org/10.1039/D0GC04320F>.
- [44] R.J. Lewis, K. Ueura, X. Liu, Y. Fukuta, T.E. Davies, D.J. Morgan, L. Chen, J. Qi, J. Singleton, J.K. Edwards, S.J. Freakley, C.J. Kiely, Y. Yamamoto, G.J. Hutchings, Highly efficient catalytic production of oximes from ketones using *in situ*-generated H₂O₂, Science 376 (2022) 615–620, <https://doi.org/10.1126/science.abi4822>.