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Editorial

Forum on Future Directions in Catalysis

1. Introduction: Professor Y.G. Kim, POSTECH, Korea

The Invited Panel for this Forum comprises eminent researchers from industry and academia, from the Asia Pacific region, from North America and from Europe. The question posed to the Panel is: are the golden days of catalysis over? Catalysis has made enormous contributions to the chemical, petrochemical and pharmaceutical industries. Today, however, the paradigm seems to be shifting towards information technology, biotechnology, and the so-called knowledge based economy. Will manufacturing be pushed aside by information technology? At one time, catalysis attracted some of the brightest and smartest people. Do manufacturing and chemically related industries have a future? Where is catalysis headed in the 21st Century?

In the West, catalysis seems to have reached a mature phase. In the Asia–Pacific region this is not so. Views from this region may be quite different from those of North America or Europe. The Invited Panellists are from all of these regions; their views and comments follow. The Discussion was structured around presentations by three Panellists in turn, followed by questions and comments from the floor and from other panellists. The Panellists in order of their presentation were the following:

Dr. J. Armor, Senior Scientist, Corporate Catalysis Research Centre, Air Products and Chemicals Inc., USA.
Professor W. Keim, Institute fur Technische Chemie und Petrochemie der DWTH, Aachen, Germany.
Professor H. Alper, Vice-Rector for Research, University of Ottawa, Canada.
Professor S. Moon, Seoul National University, Korea.
Dr. J. Rostrup-Nielsen, Research and Development Director, Haldor-Topsoe A/S, Denmark.
Professor I. Wang, National Tsinghua University, Taiwan.
Professor K. Segawa, Sophia University, Japan.
Professor H. van Bekkum, Delft University of Technology, Netherlands, and Ambassador, International Zeolite Association.
Dr. B. Cooper, Vice President for Technology, Johnson Matthey Catalytic Systems Division, USA.

2. Dr. J. Armor, Air Products and Chemicals Inc., USA

The issue of raw materials is a key to many commercial processes, which will be developed, in the next century. There are several approaches to this problem which are the following:

- raw material costs can be reduced by coming up with new reaction pathways;
- the number of steps in a process can be reduced;
- the operating temperature and pressure can be reduced;
- yield, conversion and selectivity can be improved;
- recycle efficiencies can be improved;
- material recovery can be improved.

There are several important areas that deserve attention more than others which are the following:

1. The wider use of oxygen as a selective oxidant: Although oxygen is expensive, it is nevertheless much more desirable than some of the cheaper but more hazardous oxidants. Also, oxygen is cheaper than the alternative “clean oxidants” such as ozone and hydrogen peroxide.

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2. Greater focus on energy efficiency within catalysis: This issue has to be a guiding factor in research we undertake. Exotic processes using an electron accelerator for example are unlikely to be competitive because of their energy consumption.
3. Use of alternative or renewable feedstocks.
4. Catalysis for waste water treatment: Water is a limited and valuable resource. Treating waste water cost effectively to purify it for re-use is difficult, and requires some innovative catalytic approaches.
5. Alkane activation for commodity chemicals: The activation of saturated hydrocarbons for preparation of commodity chemicals is a highly attractive option. Since most commodity chemicals are derived ultimately from alkanes, there is a clear economic incentive to develop more direct routes.
6. Wider use of natural gas as a feedstock: Using natural gas rather than oil as a feedstock to produce some chemicals is a very interesting approach.
7. Enantioselective catalysis: This is an area, which is currently attracting wide interest. Creative opportunities involving homogeneous catalysis are needed. The use of enzymes in processing chemicals is another area where there is not enough catalysis-oriented discussion. Creative people in chemical engineering need to focus on biocatalysis.
8. Photocatalysis with visible light: This is an important area, which needs more attention, particularly in the context of energy conservation.
9. By-product elimination and waste minimisation.
10. Greater use of enzymes in chemical processing.

In all of these areas it is important to think about not just what we should do, but also how we should go about it. In particular, research efforts should be based on need rather than what are perceived to be exciting areas. Academic research should be focussed on key areas in technology; there needs to be more dialogue between industry and academia to guide the academic research. Industry needs to be providing insight and direction into the selection of projects and the focus that government is going to use for the selection of projects to fund. Greater use should be made of global R&D partnerships in solving major technical problems. Finally, there should be more honesty about what we report and how we report it. There are too many examples of exaggeration and hype in the literature, particularly in the popular press.

3. Professor W. Keim, DWTH Aachen, Germany

Predicting the future is difficult but must be done. Catalysis has three branches: heterogeneous, homogeneous, and biocatalysis. Communicating between these branches is difficult, because of the different backgrounds of people working in these different areas. One message is that these differences must be overcome. By all means hold specialised conferences, but always include general lectures from the other areas of catalysis.

My second message is that the industry is changing rapidly. Companies are merging, divesting, and reducing their catalysis research. This is an excellent opportunity for academia, because companies are increasingly farming out research to universities. Bayer, for example, has initiated 700 research collaborations with academics in the past three years. Degussa has 600 such academic collaborations world wide. Globalisation of companies is occurring; so is globalisation of research.

I wish to consider more specifically the areas of fine chemicals and homogeneous catalysis. What are the advantages of homogeneous catalysis? The understanding of reaction mechanisms is much greater in homogeneous catalysis than in heterogeneous catalysis because there are in-situ tools available, such as NMR, IR, ESR, EXAFS, etc. The shortcoming of homogeneous catalysis is obvious; the problem of catalyst recycle. The answer is heterogenisation. The examples of Ziegler polymerisation of ethylene and metallocene catalysis are well known. Industry now has hundreds of people working on heterogenisation of homogeneous catalysis. What is lacking is understanding of the ligand metal interactions. In broad terms, the support in a heterogenised catalyst is a ligand. A zeolite support is a more uniform ligand than say an amorphous silica–alumina. Selectivity is the greatest virtue of homogeneous catalysis. Regio-, chemo- and enantio- selectivity are challenges for life sciences, pharmaceuticals and agrochemicals. The amount of work being done at present in enantioselective catalysis is I think greater than industry can use. It is necessary to venture into other areas.

Homogeneous catalysis has to date been largely concerned with monodentate ligands. Nature uses multi-dentate ligands. Metalloenzymes use iron, nickel, molybdenum; consider, for example, the possibilities of replacing these metals with other catalytic metals such as platinum or palladium. Take the complicated molecules that nature uses as ligands, and bridge them into homogeneous catalysis.

The role of academia is to provide understanding. Industry would rather farm out fundamental research; this is the opportunity and the challenge for universities.

Finally I consider the question of reactions. Unlike the bulk chemicals market, feedstocks are not a limiting factor in fine chemicals. There are many opportunities for academic researchers in the fine chemicals area to provide the understanding of reactions. Catalysis researchers in universities have the tools to be the bridge between industry and academia.

4. Professor H. Alper, University of Ottawa, Canada

Research and innovation in catalysis has contributed significantly to economic development in a variety of sectors including amongst others the commodities, petrochemicals, pharmaceuticals, agrosciences, materials for automobiles for instance and other applications. Industry practices heterogeneous, homogeneous as well as biphasic processes. The vehicle one uses whether it is heterogeneous, homogeneous or biphasic is not the key issue; what is important is the most economic and efficient road one takes to achieve the desired goal.

What are the new opportunities for the next 20–25 years given the knowledge and experience that we have? One area where I anticipate catalysis will play a significant role is in the synthesis of new materials by metal catalysed polymerisation processes as well as in the modification of polymers. An enormous amount of work has been carried out in metal catalysed polymerisation of simple olefins such as ethylene, propylene and others, as well as copolymerisation reactions. But new classes of functional monomers and novel copolymerisation reactions will lead to some novel materials of very important and broad application. Stereo and enantioselectivity in both the polymerisation and the polymer modification reactions will be important in selected cases.

What can be predicted with confidence is the valuable role that catalysis will play in rapidly evolving areas including photonics where it already is making dramatic contributions in the last two years. Telecommunications and Internet based industries are now employing chemistry graduates. Finally, I note the potential for racemic and chiral water soluble polymer metal complexes as catalysts to improve existing chemistry as well as in the invention of new reactions. I believe that the next quarter century really belongs to that of the life sciences. This will provide new challenges to researchers in catalysis. Chemists, chemical engineers with skill set in the biomedical sector and life scientists must seize the opportunities, which arise. Whether we are talking about materials for devices such as an artificial heart or stem cell research or chiral synthesis of new bio-pharmaceuticals catalysis can be, and must be, at the forefront. Selectivity is the key word for this research. New classes of chiral ligands including some natural systems will be required in addition to the arsenal of existing chiral species to address the new science. Another sector where catalysis may grow in importance is the agroscience business area. Of particular note is the marked progress in the area of GMOs (genetically modified organisms). With this progress has come considerable controversy much of which may prove to be unfounded, but in addressing this controversy and the concerns which arise alternate strategies to GMOs may emerge involving catalysis as a significant contributor.

What techniques will support the future of catalysis? One that has attracted attention recently is the use of high throughput screening methods also known as combinatorial chemistry. While the initial work in this area focused on the pharmaceutical sector there is and will be major progress in the use of combinatorial methods for a wide range of catalytic processes. That has already been realised in a number of sectors dealing with heterogeneous catalysis based systems. A number of companies now employ combinatorial techniques and some recent appointees as assistant professors around the world are pursuing research in this area.

Crucial to success in multi-disciplinary research is the need for partnerships and collaborations. Researchers in science, engineering and medicine must, where justified, form strategic alliances to make the collaboration a genuine success. Added to this is the need to nurture, as was said before, meaningful university industry partnerships. Not only can university industry synergy accentuate progress in research, it has important fringe benefits to the training of highly qualified personnel, to the sensitisation of students and post doctoral fellows to the nature, philosophy and time lines for industrial research, and in the broadening of the perspective of industrial scientists. Industry in addition to working with university, on occasion, works just as well with government and other industries in various partnerships and ventures. In conclusion, considering the various issues I have raised I believe the future of catalysis is really bright and by being creative and imaginative researchers in catalysis can significantly contribute to the advancement of science and innovation for the benefit of society.

Question: Professor Suresh Bhargava, RMIT, Australia

Academic research is focussed on transferring knowledge to colleagues and to the scientific literature, whereas industry is more confidential and focussed on outcomes rather than fundamental understanding. How can these two apparently conflicting areas be married together?

Comment: Dr. John Armor

The answer is to find areas that lend themselves to collaboration without jeopardising trade secrets. More and more companies are relying on academics to do the fundamental work. This can be a more cost-effective way for companies to do the research. The danger is that universities then think they should own the research. This stifles any discussion or dialogue. It is essential to negotiate a reasonable settlement of this issue, and not become preoccupied with the ownership issue. It is also important to avoid making outrageous claims on what can be done; this is not the way to encourage contract research with industry.

Comment: Professor W. Keim

70% of the funding in my institute comes from industry. Industry has two types of projects; those that are totally free, in an area of interest to the company, and those that are much closer to a particular product or pilot plant. In that case, a patent is usually filed, and once that is done you are free to publish. So, I have never encountered difficulties.

Comment: Professor H. Alper

I personally have never encountered problems in carrying out research funded by five different companies. On the issue of intellectual property, it is essential to be flexible. My experience in Canada has been that it is sometimes more difficult to work with government than with the corporate sector.

Question: Professor J. Vedrine, University of Liverpool

I have a specific question about combinatorial chemistry. Many people are working on this in industry. What is the role of academics in this domain, particularly for homogeneous catalysis?

Answer: Professor H. Alper

There has been a rapid development of combinatorial work in the area of heterogeneous catalysis in the past 18 months. The role of universities may be to provide probes for new catalysts and new methods. My personal view is, however, that combinatorial chemistry does not require by itself a great deal of creativity. It is a tool to enable new things to happen; it is not by itself going to change the world.

Answer: Professor W. Keim

Combinatorial chemistry is not new. Trial and error was part of catalysis at the turn of the last century. There are new tools available today, but combinatorial chemistry will not advance our understanding of catalysis. I am not downgrading it; I think it is needed, but in the academic world I would only do it in collaboration with a partner in industry.

5. Professor S. Moon, Seoul National University, Korea

I focus in my remarks on two questions: how does catalysis impact on the Asia–Pacific region and the economies in it, and what is the research cycle in this area as opposed to North America or Europe?

The Asia–Pacific region is at a different industrial stage. Korea, for example, has brought processes and is running plants based on imported technologies. But there are still opportunities for improving or modifying these processes. Also, we are in some cases using different raw materials. For example, oil is the major energy source in the world, but coal consumption is increasing rapidly in this region. Australia is the largest exporter of coal in the world (followed by the USA); Japan and Korea are the biggest importers of coal. Catalysis research related to coal utilisation should therefore be a very important thing to consider.

Coal combustion is thought of as easy technology, but here are still many innovations possible in technology, particularly involving catalysis. Catalytic combustion requires refractory support materials. Removal of sulphur is another important issue in coal utilisation. Sulphur dioxide removal from flue gas has been achieved successfully in Korea by recycling sulphur dioxide remaining in the flue gas after the Claus process through a reduction step to hydrogen sulphide, using cobalt molybdenum sulphide catalysts. This kind of effort to solve local problems, particularly in relation to local raw materials, should be an important part of catalysis research in this region.

6. Dr. J. Rostrup-Nielsen, Haldor-Topsoe A.S., Denmark

I want to consider the future of industrial catalysis from the viewpoint of an industrialist, and from the viewpoint of research policy. I will do this in terms of a SWOT analysis: strengths, weaknesses, opportunities and threats.

The opportunities will be dominated more and more by society pull rather than technology push. There are plenty of opportunities dictated increasingly by societal needs rather than by what is invented in the laboratory. It has become more and more difficult to introduce new technology to industry for a number of reasons. First, the plants have become larger and larger, so that the risk associated with new technology is very high. If an advantage of say 30% internal rate of return cannot be provided, there is little chance. Most developments in industry involve gradual improvements in existing technologies approaching maturity. The second problem in introducing new technology is that chemical plants are becoming more and more integrated. Optimising one section may be to the detriment of another.

Industry in the western world is dominated increasingly by shareholders; it is not technology driven any more. The cheapest solution is brought to fix the present situation, not a long-term solution. Another threat is that society requires collaboration between legislation, industry and research. This collaboration is only as strong as the weakest link, the politicians. Industry, instead of being proactive, will wait to respond to regulation. Of course, large industries may be able to influence this process through political lobbyists. Politicians are not interested however in arguments that say catalysis is great, give us more money.

What are the strengths of catalysis? The experimental tools are well known. Presently, combinatorial chemistry becomes popular. I consider this in some way catalysis attempting to borrow the flavour of biotechnology and thus attract more funding. It is very important not to follow after trends. Catalyst development must be linked with an understanding of the phenomena. There is sufficient strength in catalysis that it can be a learning process and not just a blind empirical search after gold.

What are the weaknesses of the field? Industrial catalysis is characterised by being multi-disciplinary. It ranges from surface physics through surface chemistry, kinetics and chemical process engineering. This is an enormous strength if the effort is carried out in an integrated way. But it can also be a weakness if the integration is not properly achieved. Individual researchers may focus on one small part of the problem and forget to collaborate with their neighbours. This is a serious problem.

In industry also the situation is bad. Many industries have cut down on their basic research because technology is something you buy when you need it. Many industrial laboratories that have tried to take an integrated approach have fallen below the critical mass that is essential in a multi-disciplinary field. There is a limit, however, to what can be outsourced to universities. If a company does not have the strength and the competence to integrate what they have outsourced, they will lose. It is long term research however that will create the opportunities for companies to choose.

In conclusion, there is some optimism for industrial catalysis. Firstly, there is pressure on academic research to be relevant, whether through research contracts from industry, or through following political fashion. It is very essential however that universities continue to do exploratory research and do not just follow short-term relevance. Industry is now dominated by short-term value to shareholders. There must be more collaboration within universities and between universities, between universities and industry, and between industries. Catalysis centres such as those established in parts of the US and Europe are one outcome of such collaboration. Government schemes for promoting industry–university collaborations also exist in many countries. Ultimately, knowledge centres created in the West, in Asia, and around the Pacific Rim provide the way forward for catalysis.

7. Professor I. Wang, National Tsinghua University, Taiwan

My theme is more specific, the potential and future application of zeolites in catalysis. Four areas of relevance can be identified: reducing production costs, meeting new environmental product specifications, developing clean processes, and fine chemical applications.

Historically, zeolites have had a big impact. The introduction of zeolite FCC catalysts, for example, increased gasoline yields almost 50%. The high para-selectivity achieved in BTX plants using zeolite catalysts has dramatically reduced energy consumption. The use of TS-1 titanosilicate zeolites in oxidation catalysis greatly simplifies oxidation processes, with particular relevance to fine chemicals production.

The 21st century will see a continuation of the success of zeolite catalysts. The fine chemicals industry, in particular, has some special characteristics. There are many steps in most processes, and a lot of waste. Processes using HF in homogeneous acid catalysed reactions may be able to use a zeolite such as mordenite, for example. In our laboratory, this is being done to alkylate long chain olefins to benzene. MCM-22 is another zeolite with some unique characteristics. With appropriate adjustment of the acidity, it may be possible to produce caprolactam over this catalyst. MCM-41 based oxidation catalysts are now being used to produce intermediates in the synthesis of vitamin E. Finally, what about the possibility of combining shape selective concepts with oxidation catalysis in TS-1 type catalysts? These are all examples with potential applications in the fine chemicals area.

Question: Dr. S. Derouane-Abd Hamid, University of Liverpool

A question for Professor Moon. What are the prospects for universities and research and development centres in the Asia Pacific region to develop their own process licences using their own raw materials?

Answer: Professor S. Moon

I will give some examples. Singapore has a large petro-chemical complex. Singapore sees many opportunities for further development in this area, even though the technology is considered mature in the US and Europe. These opportunities lie in different environmental requirements, and in different patterns of product consumption. By-products may be used as raw materials for further processes. Similar ideas are being implemented in Korea. Countries such as Malaysia have different raw materials, such as palm oil. It is my belief that in the Asia–Pacific region we should emphasise these conventional or mature areas.

Comment: Professor D. Trimm, University of New South Wales, Australia

It is clear that in the future we as catalytic scientists have to educate the people who are the sources of research funding better than we have done in the past, if the integrated approach espoused by Dr. Rostrup-Nielsen is to work.

Comment: Professor H. Alper

I agree with Professor Trimm. It is essential for all of us working in catalysis to work with governments in a constructive way to educate them. We should talk to politicians in a positive way; talk about the opportunities that investing in research and innovation will provide for the country.

Comment: Professor A. Masters, University of Sydney, Australia

There have been three messages that have come through in this discussion: the need for collaboration, the need for understanding, and the importance of looking at the strengths and weaknesses of our own area. A conference such as APCAT provides opportunities for communication and collaboration in a way that larger and/or more specialised conferences do not.

Comment: Dr. J. Rostrup-Nielsen

A comment on the danger of focussing exclusively on local needs. The biggest danger facing industrial catalysis is falling below the critical mass; we have to collaborate world wide in confronting the important issues.

Comment: Professor W. Keim

We must advertise the importance of catalysis research. Government has an obligation ahead of industry to support research. Why not regard research in a developing region as foreign aid? We could form a group of prominent professors to promote this view.

Comment: Dr. J. Rostrup-Nielsen

I am afraid that would not work. The most persuasive argument to government is that it has the responsibility to fund long-term exploratory research as the basis for training the personnel needed for industry.

Comment: Professor H. Alper

I believe you have to convince government of the importance of what you do. That is, the university role in education and research supervision; teaching students to address and solve problems, because that will make them valuable to the corporate sector, to government and to the universities. Governments will invest in this way, but they will not necessarily invest in fashionable trends. The Canadian government, for example, has just announced a program of funding 2000 new research chairs in universities, which will contribute immensely to the status and importance that society places on universities in general, and research in particular.

8. Professor K. Segawa, Sophia University, Japan

The chemical industry, manufacturing, petrochemicals and polymers, has evolved significantly in recent times. Through enormous effort, most of the environmental problems caused by emissions of toxic chemicals have been solved. A recent report indicated that waste output has been decreased by 90% during the 1990s, although chemical production as a whole increased by 10% during this time. On the other hand, NO_x, CO_2, CFCs and dioxin related materials are still regarded as central environmental issues, and technical efforts to solve these problems are a major endeavour. Growing public concerns about environmental protection are having a significant impact on political and economic activity. How can commercial products and industrial waste materials be made more environmentally benign?

There is not yet an international consensus on the definition of green chemistry. For industrialised countries, however, green chemistry is accepted as chemistry designed for pollution prevention, as opposed to waste treatment and control, or the analysis and characterisation of pollutants. The Green Chemistry revolution is just beginning, and this is an exciting time with new challenges for catalysis.

What are environmentally benign processes? The items that must be evaluated in any chemical process are atomic efficiency, energy efficiency, environmental friendliness, and engineering efficiency. However, the weighting on each factor is not the same, depending on the type or purpose of the process.

In terms of green catalysis, in the area of bulk chemicals oxidation processes can be significantly improved. Catalysis for the partial oxidation of alkanes is an important key technology to be developed for reducing the burden on the environment. Various possible processes for partial oxidation of alkanes can be evaluated using carbon dioxide emissions as an index. In this calculation the heats of combustion of raw materials and additional materials used in the process are converted to the equivalent amount of carbon dioxide released if they were burned. Likewise, steam and electricity used in the process are converted to the amount of carbon dioxide produced in the power plant generating the utilities.

For example, the production of maleic anhydride through partial oxidation of butane can be compared with maleic anhydride production from benzene. We conclude from such a comparison that producing maleic anhydride from butane decreases the total carbon dioxide emission to 30% of that obtained using benzene as the feedstock. This result is perhaps predictable. On the other hand, we have also compared the production of acrylic acid from propane with that from propene. Propane might be regarded as the greener of these two feedstocks. However, until now the total carbon dioxide emission per tonne of acrylic acid produced is much larger using propane than propene. This is of course because of the much lower partial oxidation selectivity achieved with propane. Here is a challenge for catalysis.

A similar calculation comparing carbon dioxide emissions in the production of acrylonitrile from propane versus propene concludes that there is no particular advantage in using propane. In this case, the carbon dioxide emissions resulting during ammonia production are the largest contributing factor, and these are common to both hydrocarbon feedstocks.

In conclusion, in considering the environmental impact of chemical processes and the possible roles for catalysis in reducing environmental impacts, it is necessary to take account of all of the factors involved. However, selectivity enhancement can be singled out as one of the major challenges for catalysis in the 21st century.

9. Professor H. van Bekkum, Delft University of Technology, the Netherlands

A second area of Green Chemistry is the use of products and processes based on renewable materials. The lifetime of existing energy sources oil, gas and coal, are all very short in the long-term. Solar energy, on the other hand, has an indefinite lifetime. The solar radiation reaching the earth's surface would account for 3000 times the projected total energy requirements for the year 2040. Suppose we consider the question of the hydrogen economy. Making certain assumptions that 1% of the available sunlight is captured by solar cells, that these convert solar energy to electricity with 15% efficiency, and that electrolysis of water is 80% efficient, we can conclude that hydrogen production by this route could amount to three times the total projected energy demand in 2040. There is no doubt that the hydrogen economy is close to realisation. Hydrogen fuel cell driven cars will be appearing by 2004; the only question is whether these will use hydrogen directly as a primary fuel, or will generate hydrogen on-board from hydrogen precursors such as methanol, methane or gasoline.

The renewable material that is most readily available both as an energy source and as a source of organic chemicals is biomass. If the total available arable land on the earth's surface is taken as 2.8×10^9 ha, about 1.8×10^9 ha of this is needed to feed a population of nine billion people. This leaves 10^9 ha available in principle for carbon farming, enough to deliver a carbon yield of 20×10^9 t per annum.

In thinking about biomass as a provider of organic chemicals, there are two approaches to take. One is simply to gasify and produce a synthesis gas which can then feed into existing technologies (or to liquefy to a kind of biocrude). New catalytic upgrading techniques are required here. The alternative is to convert natural compounds or materials directly into the required products in one or more process steps.

Consider fibres, for example. Total production of cotton (95% cellulose) at present amounts to 20×10^6 t per annum, which is about the same as the total amount of synthetic fibres produced. Could biomass be used to produce synthetic polyester fibres? Bio based routes to terephthalic acid via terpenes or fructose can be considered. The polymer of 1,3-propanediol has many of the characteristics of nylon. Shell has announced a new process to make propanediol from ethylene oxide and synthesis gas; the ethylene oxide could in principle be produced from biomass. Glycerol was formerly made in a complex multi-step process; the alternative single step hydrolysis of triglycerides is much more attractive and is now dominating. Recently, Du Pont announced a biocatalytic process to make 1,3-propanediol from glucose.

Lactic acid is often regarded as a sleeping giant around which an entire chemical network could be built. Production of lactic acid from fossil fuels is a multi-step route via acetaldehyde and lactonitrile, producing only 15 000 t per annum. Direct conversion of sucrose and glucose to lactic acid could increase this production to more than 250 000 t per annum, and has the advantage of producing a single enantiomer rather than a racemic mixture. Dow and Cargill have announced large-scale production of poly-lactate.

Non-ionic surfactants based on alkylated mono- or di-saccharides are an attractive alternative to the present petroleum derived fatty alcohol–ethylene oxide molecules. Catalytic processes for the oxidation of polysaccharides need to be developed. Methanol is a key commodity presently made from petroleum or natural gas that lends itself also to production from biomass. Ethanol is another key chemical already made on a large-scale from biomass. I mention also recent work at the University of Michigan in which glucose is reacted with carbon dioxide to yield succinic acid, using biocatalysis.

So, in conclusion, there is no reason for pessimism. Given the availability of solar radiation, biomass can be not only a source of food but will also contribute more and more to energy and chemicals. A mix of conventional catalysis and biocatalysis will be needed to address these problems; there are many challenges ahead.

10. Dr. B. Cooper, Johnson-Matthey, USA

The product of automobile exhaust catalysis is clean air, which arguably means that the issues faced are different from those in other areas of catalysis. The first point I would like to make is that despite the success of current emission control technology, there are still many vehicles around the world which predate that technology, which are producing high levels of pollution. The challenge, particularly for the developing regions of the world, is to develop cheap catalysts that can be retrofitted to old vehicles.

The second point is that the industry has changed. Exhaust control catalysis is now an integrated part of vehicle management and no longer an add-on. This is an area where legislation is the driver; without government initiatives to produce the demand for clean air, nothing happens. Parts of the US have probably the toughest emission standards at present, but legislation is still limited by the test procedures available. Projections of population growth and increases in vehicle numbers means that NO_x levels in the atmosphere will continue to rise unless even more stringent legislation is put in place. This is particularly true in Asia. There is thus a need for further development of catalyst technology.

Why is the drive for clean air continuing? It is based on health concerns related to generation of ground level ozone. The California Air Resources Board has recently declared diesel particulates to be toxic, because of the link between inhalation of diesel particulates and lung disease. Of course, there is also the challenge of carbon dioxide production.

What are the challenges? One is to produce exhaust treatment technology that will work in all kinds of different environments, for the lifetime of the vehicle. Materials science has an important role to play here in the production of robust and efficient catalysts. Low temperature particulate combustion is not only an issue for diesel powered vehicles, but also for the new generation of low CO_2 high fuel efficiency gasoline engines. Integration of the emission control problem across different parts of the automobile industry needs to be more effective. There is the on-going issue of the sulphur conundrum: do we develop more sulphur resistant emission control catalysts, or do we desulphurise more effectively the fuels being used? The answer in this case will be a compromise, where improvements are made in both areas. Finally, the industry is still looking for a real breakthrough in the area of lean-burning NO_x control; introduction of more efficient engines requires a solution to this problem that does not yet exist.

The partnership issue is an important one here. Talk to the industry before setting up research projects; make sure the problems you tackle are the ones that are most important to the industry, and that the issues involved are well understood.

Comment: Dr. P. Selvam, Indian Institute of Technology, India

On the issue of hydrogen fuel cells, generation of hydrogen from fossil fuel sources is not a long-term solution. A sustainable hydrogen economy will require hydrogen to be generated from water directly, rather than via electrolysis; this is a major challenge.

Question: Professor D. Trimm

It is interesting to consider that almost none of the issues discussed here would have been raised at catalysis conferences held say 25 or 50 years ago. My question for the panel: what is the long-term solution to the transportation problem, once fossil fuels have run out?

Answer: Dr. B. Cooper

The key challenge in alternative power plants is energy density. The advantage of the gasoline and diesel engines over the available alternatives today is the power output per unit weight. There have to be many further developments in fuel cell vehicles before they are competitive on an energy density basis.

Question: Dr. K. Ahmed, Ceramic Fuel Cells Ltd., Australia

When talking about the hydrogen economy, it is important also to talk about capacity of fuel cells. Does the panel have any feeling for what might become an economically viable technology for hydrogen generation on a small-scale in the near term?

Answer: Dr. J. Rostrup-Nielsen

The cheapest way of making hydrogen today is from natural gas. My answer would be an air blown natural gas reformer. There are two conglomerates of car and fuel cell manufacturers working on this at the moment; one argues for natural gas, and the other for petroleum as the source of hydrogen. Another issue here is hydrogen storage; there are many developments going on at the moment.

I agree with Dr. Cooper that the diesel engine has a very high energy density that cannot be beaten by fuel cells in a car. Fuel cells as stationary power sources are a different issue. Fossil fuels should be used for transportation, using high energy density devices. There are sufficient fossil fuels, including coal, for this purpose.

The big challenge is to find other routes for power generation that do not use fossil fuels.

Question: Professor S. Moon

A question for Professor van Bekkum on use of biomass as a source of chemicals. In a northern country like Korea the availability of biomass is limited; I had always believed that there was insufficiency to use them as a chemical feedstock. How do you estimate the availability of biomass?

Answer: Professor H. van Bekkum

It is a combination of all the things provided by agriculture. We will go for total crop use. The concept is that you extract the valuable chemicals and materials from biomass and then subject the remainder to a process of hydrothermal upgrading for fuelling power generation. In Holland there is currently a biomass power plant working effectively, consuming 200 000 t of waste wood per year.

Question: Dr. S. Derouane Abd Hamid

I would like to return to the issue of technology development in the Asia Pacific region. At the moment in south east Asia processes are licensed without effective transfer of knowledge. Are there any moves for developed countries to collaborate with academic research and development centres in the Asia–Pacific region in a meaningful manner?

Answer: Dr. J. Rostrup-Nielsen

My company now does $<20\%$ of the engineering associated with a new plant; the remainder is carried out by engineering companies in the countries where the plant is built. I see no problem with building up international alliances in this way. We still do the basic research, since we consider we need to understand the processes that we license, but we make a lot of effort to collaborate with knowledge centres around the world, including in this region.

Question: Dr. R. Rhee, Seoul National University, Korea

There has been a lot of discussion about collaboration between the universities and the private sector, but only 10% of the delegates at this conference are from industry. What can be done to increase industry participation in these kinds of meetings.

Answer: Professor W. Keim

Invite industrial speakers, in particular senior management people to give general talks. It is very difficult to get industrial research workers to talk in detail about their work.

Answer: Professor H. Alper

I agree, but there are success stories. The Gordon research conferences in the US attract up to 60% industrial participants. It is crucial to invite industrial people to participate; that should be done for the next APCAT meeting.

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