PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Panel Discussion

G. B. R. Feilden, A. T. Kuhn, D. Pletcher, H. L. Roberts, M. M. Baizer, A. B. Hart, J. P. H. Shaw, R. H. Biddulph, M. Fleischmann, J. B. Goodenough, R. E. Bates, P. J. Boden and G. T. Rogers

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Panel discussion

G. B. R. Feilden, F.R.S. (*British Standards Institution, London, U.K.*). The intention is that this final session might lead to suggestions for strategies to deal with the problems of making new electrochemical applications attractive to users. I have already remarked on the communication barrier that exists; I hope that in this discussion we can deal with the problem of cross-fertilization between different disciplines. First of all, any system has to be made to work from the electrochemical point of view; however, consideration must also be given to the practical aspect of making the engineering work, and several speakers have referred to that. For instance, Dr Steele dealt with the application of new battery systems to personal transport. I should now like to invite contributions from the audience.

A. T. Kuhn (*Bio-materials Science, Institute of Dental Surgery, London, U.K.*). The title of this meeting implies a question, and the answer is something that no one has directly attempted. What prospects are there for industrial electrochemistry? We should try to forecast this by using as many different methods as we can. Let us assume that future prospects depend on the techno-economic framework prevailing say 10 years hence. Specifically, we may include cost of energy, cost of capital, feedstock availability, electrochemical hardware, electrochemical software, human factors, and other factors such as concern for the environment.

This Meeting has not yet considered whether there will be a differential pricing between electrical (nuclear-derived) and fossil energy. There are two clear scenarios here. In one, electricity becomes steadily cheaper than fossil fuel, as the latter runs out. In the other, the traditional pattern of price competition prevails and no one fuel is significantly cheaper than another. This is the first question that I would put to the panel: which scenario do they favour, given a 10–20 year timescale? Secondly, I would ask the panel whether an electrochemical reactor (with associated electrical equipment) is inherently a more expensive unit operation than a non-electrochemical one. A factor that needs clarification is the efficiency of feedstock use. Speakers have referred to selectivity, but in a rather different sense. The electrochemical oxidation of anthracene is nearly 100 % efficient in its use of feedstock. The catalytic route is very much less efficient, and as feedstocks rise in price, this will be important.

Turning to reactors, Professor Goodridge has suggested that a halt be called to further reactor development. He is surely correct in his view that the reactor cost is but a single item in a large overall outlay on buildings, piping, etc., and doubling the efficiency of a reactor might well influence overall costings by only 5–10 %. Would the panel agree that an electrochemical process must offer some special advantage over a conventional process if it is to displace the latter to any significant extent? If so, should we single out for special attention a reactor that, for example, makes *p*-aminophenol from nitrobenzene but with no aniline as by-product, as hinted at by Professor Albery?

My question on 'electrochemical software' is this. Most industrialized or candidate industrial reactions have been known for 50 years or more. Does the panel believe that areas of totally new electrosynthetic reactions may emerge, that is to say reactions that we cannot currently conceive of? Returning to our exercise in forecasting, while electrochemistry develops, so too do the competing non-electrochemical processes. I should like to ask one of the industrialists on the panel if we are competing with technologies that themselves are evolving quite rapidly.

Another technique of value in forecasting is to extrapolate from past progress. Some 10 years ago, a meeting somewhat similar to this one was held at Shell (Thornton, Cheshire). At that time, many brave forecasts were made for the future of electrosynthesis, some of them by people present at this Meeting. Since that time, energy prices have roughly quadrupled, in real terms, and we have additional burdens of environmental legislation. In spite of this, no significant new electrosynthetic processes have emerged, even though there were factors supposedly favouring them. If we argue that electrosynthesis is a 'new and delicate technology', then perhaps it requires support to allow it to emerge; but on the facts that I quote below, I would like to ask the panel whether, in their opinion, it has had such support. At the Electricity Council Research Laboratories, some 150–200 man-years have been devoted to just the subject that we are discussing: the industrialization of electrosynthetic reactions. The cost can be estimated from these figures. Scientists there learnt an important lesson, namely that to achieve credibility with potential industrial users, a small-scale experiment was insufficient. At some cost, they scaled up a number of processes, including benzene oxidation, naphthaquinone oxidation, fluorination, and redox oxidation of aromatics. They offered these processes, fully developed up to and including the pilot stage – and still found no takers. It seems that we must face up to the lessons of this exercise, which culminated in offering one of these processes (iron foil forming) in an advertisement in the *Financial Times*! A similar exercise has been undertaken by a commercial firm (though heavily backed with money from the National Research and Development Corporation) exhibiting at this Meeting. The N.R.D.C. has likewise invested very considerable sums in industrial electrosynthesis or facets of it, again with no known success. These facts must be faced. What conclusions does the panel feel can be drawn from them? Were the wrong processes piloted? Were they piloted in the wrong way? Were there any other reasons? But it must be emphasized that the period in question is so long that economic factors (boom or recession) can hardly be invoked: we have been through several of each in that decade.

Finally, we should record that the N.R.D.C. have spent some £2–5 M on industrial electrochemistry in the past decade. They recently announced their decision to pull out and cease supporting a firm in the North of England, whose representative we heard with interest earlier in this Meeting. [This paper is not included in the published report.] If this is their commercial judgement, I would ask the panel if that does not cast a somewhat gloomy shadow over the proceedings?

In conclusion, I suggest that a clear picture of the short-term to medium-term future is emerging. Sensors and batteries are two areas that have been and promise to be commercially successful, as are metal winning and recovery – but provided the metal is at least as expensive as copper and preferably more valuable still, e.g. silver. Small electrochemical processes (in tonnage, though not necessarily in value) are slowly becoming adopted. There has been little progress with medium-scale processes while with large-scale processes there has been none whatsoever.

If the panel accepts this picture of the last decade, does it have any reasons for thinking that the next 10 years will be any different? I recognize that pessimism is not popular, but if we are being called upon to make a judgement, then we surely owe it to ourselves to make that as honestly as we know how.

G. B. R. Feilden. I shall only add one or two sentences in reply. Dr Kuhn started, quite rightly, on the question of cost of energy, which, somewhat to my surprise, has not yet been considered. It is obviously crucial in comparing electrochemical processes with others. Indeed, in preparing for the meeting, the organizers found, when trying to get some exhibits on electrochemical machining, that there was some reluctance to advocate this process because of the greatly increased cost of energy.

D. Pletcher (*Department of Chemistry, University of Southampton, U.K.*). On the question of energy cost, I think that this is not often significant in organic electrosynthesis. The case for electro-organic processes is much more that electricity is always likely to be available, while other forms of energy may be lacking at some time in the future. Perhaps Dr Kuhn had expectations that were unreasonable 10 years ago. There are probably more processes now than 10 years ago, although maybe only a few more. I expect such small increases to continue, but it is unlikely that we shall be here in 10 years' time announcing 50 new processes.

H. L. Roberts. I wish to make a few comments on the large-scale technical use of electrochemistry. In making products like chlorine, a very large percentage of the final cost is electricity, and therefore if a significant reduction can be made in that, or if a process can be telescoped, as I indicated in my paper, then something of considerable importance has been achieved. In this large-scale electrochemical technology, one is designing something that will be used for a long time on a very dedicated application, so a fairly measured pace is required. If the need for a newly discovered electrochemical reaction were recognized today, it would be 6–8 years before the necessary investment was in being. Inevitably, large-scale industry is slow-moving, and of course there will be developments in other areas of chemistry that will also influence it. I would expect that for large-scale manufacture, people like ourselves can and will, at the research level, investigate four, five or six process routes for every one that we would take to a pilot scale.

In many cases one is looking for something that will specifically enable one to do operations not at present possible. I do not envisage substantial straight substitution as being likely. It is very interesting to look at the report by the Electrochemical Technology Corporation (*Final report on a survey of organic electrolytic processes* (ANL/DEPM-79-5), Argonne National Laboratory (1979)). Their analysis, based only on the energy economy of processes in the literature, showed little economy to be available. This is almost the obvious conclusion from asking a question in that way. Research is about using imagination to see where a decisive step can be made, by eliminating two or three stages or by making a major energy contribution. Such decisive steps are unlikely to be made more than once in a decade. Nearly all of the chemicals that are made today in large tonnages are made with technology that was running in 1970.

M. M. Baizer (*School of Engineering and Applied Science, University of California, Los Angeles, U.S.A.*). I think that our estimates show that the electrical energy costs for an electro-organic process are never more than 5–7 % of the total manufacturing cost and are not therefore a determining factor in deciding whether or not to adopt a particular process.

With respect to what Dr Roberts said, most large companies have an electrochemical group but a very much larger catalyst group. It is essential for those working in electrochemistry to keep abreast of work on catalysis; people in each area are working hard to take advantage of their own speciality. In the 20 years or so that I was with Monsanto, the two outstanding technological processes were, I think, the electrochemical adiponitrile process and the catalytic acetic acid process, so electrochemistry has held its own very well.

A. B. Hart (*Central Electricity Research Laboratories*). I think that Dr Kuhn is anxious for the large-scale application of electrochemistry. If, say, by the end of the century there is a substantial amount of base-load nuclear energy, and indeed if the amount of nuclear energy exceeds the base-load demand, there will be strong pressure to store that off-peak nuclear energy, for example in hydroelectric schemes or in underground compressed air. One of the contenders will be in electrochemical devices, including, of course, peoples' battery electric cars. This would be very convenient because the people concerned would mostly provide their own capital for doing so, and that would be an advantage to the Central Electricity Generating Board. After that it would be feasible to consider larger-scale electrochemical storage devices, perhaps for the middle of a city, where it would be inconvenient to store underground and where there would be the advantage of being able to smoothe the transmission and distribution networks. Replacing Bankside power station with a vast battery installation would be of great interest to the London Electricity Board if the cost were not too great. Also, if those who wish to synthesize chemicals could conveniently use off-peak electricity, this is worth considering; however, the cost of the capital equipment usable for only a third of the hours available would probably render this uneconomic. It is nevertheless an idea that has been costed in relation to making hydrogen from water, this hydrogen to be used as a feedstock for industry, to compete with making hydrogen from coal. So hydrogen made electrolytically could be a way of using off-peak electricity from nuclear power. These would be very large-scale processes and the necessary development must be carried out in the near future to satisfy the future needs of industry, which by our calculations could amount to 20 GW of off-peak electricity.

J. P. H. Shaw (*I.C.I. Ltd, Mond Division, Runcorn, Cheshire, U.K.*). In confirmation of Dr Hart's point about cheaper night-time electricity's being of little benefit to high capital cost electrochemical processes, I wish to summarize the position as it affects processes for the production of bulk chemicals.

The present U.K. electricity tariff structure offers lower-price electricity for 7 h each night or 2500 h per year. The enormous capital expenditure involved in the typical production unit necessitates an operating régime of at least 8000 h per year. The cost of continuous base-load electricity in the U.K., however, is significantly greater than the night-time tariff and is the basis on which industry has to plan. It is also an unfortunate fact that in the U.K. high-load factor electricity costs approximately double the price ruling for similar large-scale customers throughout western Europe and North America. Against this competitive background, therefore, it is virtually impossible to expand production capability for the large energy-intensive electrochemical processes. Until or unless this situation is changed, processes such as aluminium production, chlor-alkali electrolysis and other electro-smelting processes cannot be expected to develop in this country. Any process that technically or economically requires a continuous operating régime, and for which electrical energy forms an important part of the variable operating cost, must be associated directly with the provision of cheaper base-load electricity if it is to be competitive in the world scene.

R. H. Biddulph (*Borax Research Limited, Chessington, Surrey, U.K.*). Dr Boden complained about a lack of electrochemists. Would the panel agree with this, or is there really a shortage of electrotechnologists or, for want of a better phrase, electrochemical engineers? Do electrochemists get sufficient practical experience at their universities? As a chemist, I received 5–7 h practical a day with only 2–3 h on Saturday!

D. Pletcher. I think that electrochemistry suffers from two distinctly different problems. First, wherever electrochemistry occurs in industry it occurs mixed with almost everything else, so there is a need for chemists, metallurgists and materials scientists each to have some knowledge of electrochemistry so that when an electrochemist consults them they can talk sensibly. Secondly, I believe that we need a relatively small number of highly trained and specialized electrochemists. The total output of electrochemists is at present extremely small and is normally orientated towards one aspect of electrochemistry because of the supervisors and the facilities available to university departments. To produce people who are really trained in electrochemical engineering, including all the aspects that have been discussed at this Meeting and those that have not (of which there a number), would require a substantial educational effort.

M. Fleischmann (*Department of Chemistry, University of Southampton, U.K.*). I shall add one further point to that. The problems that have been raised, especially by some of the panel members, are clearly very complex. It does not seem feasible to me to give a training in that whole range of backgrounds to a given set of individuals. As we move into a society that is more technologically complex we have the difficulty of setting up groups of people whose minds are sufficiently open that they are ready to talk to each other, so that they can identify the problems they have to act on, and can work together in a sensible way to solve them.

J. B. Goodenough (*Inorganic Chemistry Laboratory, University of Oxford, U.K.*). A university course must emphasize fundamental concepts, develop critical capacities, and prepare the student to analyse and to solve problems in a wide range of disciplines. To train a student in a speciality discipline is to run the risk of forming a technician who, however relevant on the date of graduation, may become obsolete in a relatively few years. In the electronic field, many electrical engineers trained in the 1950s had skills that were obsolete by the mid-1960s, and M.I.T. was forced to develop a retraining programme for engineers in mid-career. The responsibility of a university towards a student is to prepare him for a lifetime professional career and therefore to develop those capacities that permit adaptation to changing responsibilities as well as to rapid developments in a dynamic technology.

As for electrochemistry, I would echo the theme expressed by Dr Steele in the last paper, namely that many of the essential problems in electrochemistry are fundamentally materials problems. In fact, each of the last three speakers illustrated the critical role of materials in battery design, and Professor Baizer has just made the point that electrochemists in a chemical company would do well to keep abreast of developments by their colleagues down the hall working on heterogeneous catalysis. Clearly the development of improved catalytic electrodes requires an understanding of the reaction mechanisms occurring at the solid–liquid interface of an electrode, and the concepts being developed in heterogeneous catalysis are as relevant to electrode development as are electrochemical techniques.

In summary, I would endorse the remarks of Dr Pletcher and Professor Fleischmann. The universities must develop people who are aware of the concepts and techniques of electrochemistry, but within the context of chemistry as a whole. In particular, the innovative electrochemist of tomorrow will be as aware of solid-state and surface chemistry as of the spectroscopy and electrochemistry required to characterize electrodes and their interaction with a particular electrolyte, or of the synthetic chemistry required to modify solid surfaces to achieve novel as well as superior electrode performance. He will be equipped to lead, or at least to work as an equal partner within, interdisciplinary groups of scientists, an ability that in the present context would imply some understanding of the ideas of solid-state science as developed by those working with the electronic and mechanical properties of materials.

H. L. Roberts. I find this kind of statement from the academics extremely reassuring. When I am recruiting, the last type of person that I want is one who is, for example, just an electrochemist or just a solid state chemist. Obviously they will have worked on something for their doctorate, but the chances that they will work on that again for a large proportion of their lifetime are quite small because needs will change: what is wanted are people with open and enquiring minds.

G. B. R. Feilden. I wish to reinforce that point, speaking from my own career. The first job that I was put into at the beginning of World War II, when I left university, was developing jet engines. It will surprise no one that this had not been on the syllabus. We only needed a little electrochemistry, but we had to deal with an immense amount of new metallurgy and many other equally exciting and sometimes very dangerous things. The team working under Whittle all developed a capacity for what is now called lateral thinking, where classical ways of solving a problem had all failed and we had to return to fundamentals and start again. One of the problems that we had was how to achieve the combustion of paraffin at rates (in terms of megajoules per unit volume per hour) much faster than ever before. To solve that meant going right back to the basic processes of combustion.

R. E. Bates (*Saft* (*U.K.*) *Ltd*, *Hampton*, *Middx*, *U.K.*). Some mention was made, earlier in the Meeting, of conversion of radiation into electricity. Would the panel comment on the prospects for direct power generation from radiation?

A. B. Hart (*C.E.G.B.*, *Research Laboratories*, *Leatherhead*, *Surrey*, *U.K.*). If by this is meant solar energy, there certainly are prospects for that. Most of the solar radiation falling on an area of roof or land can be collected and the energy converted into electric current, which may then be used to produce hydrogen. It is much more difficult to convert nuclear radiation into an electric current. It is of course possible to use nuclear radiation to raise the temperature of some working substance, but this leads us back to a Carnot cycle, which is no doubt what Mr Bates is trying to avoid!

J. B. Goodenough. Nuclear energy represents a constant point source of heat that must service a variable energy demand. Nuclear engineering has addressed itself to the problem of converting the heat from nuclear energy to electricity. This concern is adequate so long as nuclear energy supplies less than the base-load requirements for electrical energy. However, in an economy where nuclear power is called on to supply a major fraction of the total energy demand, including that for transport and for domestic use as well as industrial heat, much of the electricity generated from nuclear power must be stored as portable chemical energy. Some of this stored energy will be in the form of chemical feedstock or of value-added products, some will be used as fuel either to provide heat or mechanical power or to be reconverted – in a secondary battery or a fuel cell – into electricity. Therefore, the development of nuclear power beyond the relatively modest requirements of base-load electric power will depend critically on developments in electrochemistry. Electrolysis-fuel cells, electrosynthesis cells, and secondary batteries all have potential markets of extraordinary size.

By radiation, I assume that solar radiation is meant. This, with wind and wave power, is a long-term, abundant energy source, but they all are variable and of low density. They are therefore plagued by two fundamental problems: conversion/concentration and storage. Concentration is generally more feasible after conversion, although concentration of direct sunlight by mirrors before conversion will have limited application. Concentration of electric power can be expected to be cheaper than the concentration of chemicals, but the longer-distance transport of chemical energy is cheaper than the transport of electric power. Heat, on the other hand, can only be used locally. Therefore I foresee two important markets for solar energy: local conversion to low-temperature heat for domestic purposes (including air conditioning and refrigeration) and the production of chemical energy from solar-generated electric power, chemical energy being the most versatile form of energy storage.

Wind and wave power are converted directly to electric power, solar radiant energy may also be converted in a photovoltaic cell. Conversion of at least some of this electricity to chemical energy is a necessary adjunct to the development of these energy sources. Therefore the demand for secondary batteries, for electrosynthesis and for electrolysis cells, particularly for the electrolysis of water, will increase. Chemical energy can also be produced directly from radiant solar energy. Nature does it by photosynthesis. The industrialist would be happy with just one step of this process, namely the photocatalytic splitting of water into hydrogen and oxygen. This conference has studiously avoided photoelectrochemistry, presumably because there are no systems under study that have yet shown any promise for commercialization. However, several speakers have alluded to semiconductor electrodes, and there is considerable fascination in the scientific community with the photoelectrochemical properties of the semiconductor–electrolyte interface. A photoelectrode must provide in a single material the photovoltaic function of a photovoltaic cell as well as the catalytic function of the electrode of an electrolysis cell. Even with the solution of this formidable problem, the concentration of the chemical products must compete with the concentration of electricity from a photovoltaic cell preceding a conventional electrolysis cell. Therefore, if I were an industrialist, I would concentrate my attention on electrolysis–fuel cells and on secondary batteries.

P. J. Boden. I should like to redress the balance of the discussion so far and bring the topic back to electroplating. Statistics are hard to come by, but it seems that electroplating is about 25 % of all electrochemistry-based industry and adds more to the gross national product that any other activity discussed in this session. It is suffering: the electroplating industry is being depressed in this country. Our share of the output for Europe is 17 % compared with, say, Germany's 25 %, France's 25 % and Italy's about 20 %. I wish to ask the panel what advice they would give to the electroplating industry to reverse this trend. I should like to couple this with corrosion protection. As many government surveys have shown, we are not applying the knowledge that we have already, for example on cathodic protection. Have the panel any advice to the industry about this?

G. T. Rogers (*A.E.R.E., Harwell, Oxon., U.K.*). Dr Boden is quite right to ask what should be done, given the situation that he states. My short answer is that we must return to Dr Feilden's comments about communication. In this case we can point out to the engineers the things that we can do, for example that we can put a coating onto a cheap substrate to protect it against an adverse environment, to modify its frictional or wear properties, or to improve its looks, which is very important in selling a product. Electroplating is the only way of putting a thin coating of a generally expensive material onto the surface of a cheap substrate at near ambient temperature. This makes much better use of materials, which is a point that has not, perhaps, been made as clearly as it might have been at this Meeting. We really must conserve materials: electroplating provides the opportunity to put a surface coating where it is needed, while getting strength and other bulk properties from something much cheaper and more plentiful. Electromachining gives us machining in the ordinary sense of the word but without swarf losses or dust, and without wearing the tool away and so losing tolerances. Electrochemists have probably been remiss in not being aggressive enough in going out and telling engineers what we can do, and then doing it and showing them that we can do it in a way that is attractive to them. That means making electroplating, electrochemical machining 'machines' that can be operated and treated like a lathe or a milling machine, because that is what our engineer customer wants and has to do in his business.

J. B. Goodenough. I would not go to the engineer first, but to the customer. In this case I would go to the customer who has a need for reliability and long life and who is willing to pay for quality components. Surely the Department of Defence, British Rail, and Rolls-Royce are customers who need reliability and longevity of mechanical components, and they should be prepared to purchase quality. I would go to such customers to discover their perceived needs, to obtain engineering specifications for tomorrow's advanced products. Only then would I go to my own Research and Development department or engineers to find out how to produce these components at a competitive cost.

But such a response begs a critical problem in all this process, namely *communication*. If the engineer is able to design a product that meets the customer's specifications, all goes well. However, if he cannot, what then is the response? Unless the engineer is willing to confront the scientists with his problem and the scientist is capable of translating the engineering perception of the problem into the laboratory variables that he commands, then there can be no progress.

It has been my experience that British industry tends to be too secretive about its problems, thus failing to bring the engineering perception of a problem and its potential importance to the scientific community. And the scientists, in turn, tend to have too little experience with the task of translation from the language of engineering to that of science. Therefore, I am particularly pleased to participate in this conference, which has brought practising engineers together with academic scientists. It reminds me of the early conferences on magnetism and magnetic materials that were first organized in the early 1950s. The engineers and metallurgists had been working for years on improving magnetic alloys for transformers. But in the early 1950s the need for magnetic insulators in such high-frequency devices as television antennae, microwave components, and digital-computer memories had introduced the vast new world of magnetic oxides. Today, the electrochemist is no longer restricting himself to conventional metal electrodes: he has discovered metallic oxides, semiconductor electrodes and modified electrodes. He has also discovered that fast ionic transport in solids may provide practical solid electrolytes and insertion-compound electrodes. These materials options and the energy crisis offer tremendous scope for the engineer and the scientist to come together to create an era of innovation in electrochemistry that could approach in scope the electronics revolution of the last three decades. The challenge is there, and I hope we can muster the will to meet it. I sincerely believe that our civilization depends on it.

G. B. R. Feilden. Evidently our discussion could continue for some time, but as we have now reached the time set for the ending of our Meeting I must regretfully bring it to a close. We have ranged widely from energy costs to the stimulation of microbiological processes by electrochemical means. Several speakers have referred to the problems of interdisciplinary communication, particularly those between electrochemists and engineers. To me this is a prime example of the need for broadly based education for all scientists and technologists. Education of this type will leave future generations of graduates, irrespective of their discipline, with a sufficiently open approach to the challenges of the future.

Finally, I should like to thank my co-organizers, our speakers and contributors to the discussion sessions for all they have done to make this meeting as useful and informative as it has been.

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