Representations of Use and Need in R&D:
The Field of Conducting and 'Intelligent' Polymers

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Comments welcome

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Introduction

This paper provides background for a pilot case study in the examination of representations of use and users in R&D groups. For the pilot study, I have chosen the overlapping fields of conducting polymers (CPs) and 'intelligent' polymers (IPs) and a particular interdisciplinary IP research group.[1] The study involves analysis of documents like published papers discussing the properties and uses of CPs/IPs, research proposals, and records of interactions between the research groups and outsiders, plus interviews with researchers, sponsors and industry partners. A developing discourse on use is mapped onto the historical development of work on particular CPs/IPs and their applications, and onto the structure of relationships among the research group and other interests that may have had an influence on the innovation. The study combines a broad examination of CP/IP activity – including going back to some of the earliest activity to see how they were discussed – with a detailed study of a particular project as it unfolded. For CPs/IPs, the 'user' has to be taken as anyone downstream of the research group and varies according to the application. As with other materials, the first point of contact is typically an intermediary between the researchers and the end user of a device incorporating the polymer: a processor or the manufacturer of the device.

Intelligent polymers

'Intelligent', as one might expect, is a term used increasingly loosely in popular depictions, in the same way that 'smart' is applied to a variety of technologies and materials.[2] For the practitioners, intelligent polymers have properties or behaviour that undergo a reversible change in response to a change in their environment. The change may be in volume, electrical properties like conductivity, optical properties – emission or absorption at specific wavelengths – permeability, mechanical properties like ductility or, for polymer solutions and gels, viscosity. The changes may be in response to electric fields or applied potentials, magnetic fields, pressure, light, temperature, pH or the presence of specific chemicals.

Ideally the notion of 'intelligent' entails a precise and predictable change, and the ideal combination of polymer and application allows automatic and self-powered detection and response. That is, a system of sensing, information processing, energy storage and conversion, and actuation, is embodied in the one material. This integration at a molecular level is contrasted with many 'smart' systems in which these elements are provided in different components. The model intelligent polymer is 'capable of detecting a change in its environment … and actuates an appropriate response … autonomously and [is] self-powered'.[3] The ideal form, as commentator put it, blurs 'the seams between mechanism and material'.[4] Some actual applications arguably achieve this. In others the material combines some of these elements but relies on other components to complete the system.

Conducting polymers

Many of the polymers respond to environmental change by virtue of their electrical conductivity. Intrinsically conducting polymers[5] have been studied intensively over the thirty years since the first synthesis of a reliable conducting form of polyacetylene. Their electrical properties can be tailored through the choice of monomers – and hence the distribution of charge particularly along a conjugated backbone – of substituent side groups or chains, and of 'dopant' counterions.[6] CPs are anticipated to have significant uses in replacing metallic conductors in electrical circuitry, particularly in the manufacture of cheap and flexible printed circuits, but these applications simply make use of their conductivity – and suitable mechanical properties. They have also been used in rechargeable batteries, where the ability of the polymer to undergo repeated electrochemical cycling allows deep discharge without degradation of electrode or electrolyte.[7] The value of conducting polymers in 'intelligent' applications likewise comes from their electroactivity – molecular chains undergoing reversible redox transformations providing stable states with different properties – but here the value is in their ability to sense and respond to changing conditions. In some IPs, though the conductivity of the polymer backbone is still essential, the important function – photoactivity, for example – is embodied in the chosen counterion.

Applications

The applications of CPs/IPs – suggested, under development, and already commercialised – and the domains of application, cover a huge range.[8] The uses are hard to categorise because of overlaps, but the following points should give an indication of their diversity and the ingenuity of their application:

- CPs as a basis for flexible and cheaper microelectronics – 'plastic chips'. CPs can be used straightforwardly as conductors in place of metals, or conductivity can be induced in areas of a suitably doped but otherwise insulating polymer using a masking technique similar to conventional photolithographic methods for semiconductor chip manufacture. Here low cost and mechanical flexibility compensate for relatively poor performance and lifespan. Possible areas of application are relatively simple processing requirements in smart cards.

- Chemical detectors and sensors. CPs can be used to detect specific metal ions, or other more complex chemical or biochemical groups, providing an electrical signal, by virtue of a change in capacitance or resistance, or an optical signal through a change in absorbance or refractive index. Sensing relies on a dopant anion or a functional side-group on the polymer chain which has an appropriate reception or recognition site. In some applications the polymer acts as a platform for a bioactive entity such as an enzyme, an antibody or even a living cell; it must preserve the activity of the group and provide a means of signal transmission. Polymers which can change colour in response to changes in their chemical environment might be used in simple diagnostic kits in medicine and environmental health, and in safety clothing which warns its wearer of contamination.[9] One much publicised type of device is the electronic 'nose': the conductivity of the CP depends on the presence of specific vapours; the 'nose' measures a single species or has a variety of CPs to identify the 'fingerprint' of a mixture like a food or a perfume.[10]
- Other sensors – pressure, movement, physical condition. CPs are finding applications in sensing/alerting in machinery maintenance, and as materials for entities that can monitor their own condition and integrity. An athlete's knee sleeve being developed by the group I am studying generates a signal informing the wearer whether they have landed correctly from a jump. Another group is developing a self-diagnosing rope that changes colour when it is failing.[11]
- Electromechanical actuators. In CPs/IPs a useable stress is created by volume changes as ions move in and out of the polymer. The device may be 'active' – that is, it responds to a deliberately applied potential, as in a proposed artificial muscle for medical or robotic applications using CP gel[12] – or 'passive', in that it responds to environmental change. IP fabric in a 'smart bra' is intended to relax or contract in response to changes in stress, providing improved support.[13] The key advantage of CP/IP actuators is their light weight and the possibility of forming small devices operating at low voltages.[14]
- Controlling or triggering chemical reactions. As a substrate, a CP may allow precise control of chemical or biochemical interactions – ion exchange, complexation, hydrophobic interactions, antibody-antigen interactions – on its surface through the application of small electrical potentials. In a one-off action, an electrical signal can

trigger the release of a complexing agent or a precipitating agent from a CP, starting or shutting down a chemical reaction, or in medical applications, an antibody or a drug.[15]

- Physical triggers. One passive application is a temperature-sensitive seed coating: the moisture absorption of the coating increases sharply at a certain temperature, protecting the seed from moisture at low temperatures but allowing later germination.[16]
- Switches. Where the change is required to be reversible between two distinct states the actuators are in effect switches. Here the crucial characteristics for many applications are the switching time and the way the property changes – smoothly varying or a step change.[17]
- Selective membranes. Beyond allowing passive transfer of chemical species as in normal membranes, CP or CP-coated membranes can be stimulated to transfer entities ranging from simple ions to proteins – they are in effect 'pumped' through by repeatedly switching the CP between its oxidation states – or designed with selectivity that changes as conditions change. One IP food wrap regulates the balance of oxygen and carbon dioxide surrounding produce. A drug delivery membrane releases its contents at the correct pH. A thermoresponsive IP membrane changes permeability at critical temperatures.[18] Production of areas of membrane sufficiently large for practical applications is still expensive.
- Other biomedical applications. These include platforms for immobilised biocatalysts, biomimetic actuators, and biocompatible materials. One potential 'passive' actuator using a polymer gel is the subject of research in Japan: an 'artificial pancreatic cell' able to expand or contract in glucose solution according to its concentration, and encapsulate or release insulin in response.[19] In tissue engineering a biodegradable CP could be used as a temporary 'scaffold' for cell attachment and growth stimulation. In prosthetics and neural probes the CP could form an electronics-tissue interface.[20] In discussions of such biocompatible materials, the idea that life consists in large part of polymers communicating with electrical pulses has been invoked to depict CPs as a significant breakthrough in allowing imitation of biological communication and a blurring of boundaries between the biological and the mechanical and the natural and artificial. 'The inherent electronic conduction of these materials permit them to be coupled with conventional electronic devices to provide a line of communication to the molecular world that has hitherto been unavailable.'[21]

- Energy storage. CPs can be used in batteries and capacitors but their uptake has been limited by competition from other emerging technologies. CPs can be used for the electrodes and electrolyte in batteries. In capacitors, a CP film can be charged and discharged rapidly. Again, light weight and high capacity is an advantage in, for example, electric vehicles. CP photovoltaic devices are also being developed using a photosensitive CP film.[22] Again, poor efficiency compared to semiconductor PVs is compensated by low cost, mechanical flexibility and ease of fabrication in large areas. One possibility being explored is photovoltaic fabrics for military applications. Efficiencies are increasing through chemical modification of the polymer.
- Information displays using light-emitting or electrochromic polymers. Again mechanical flexibility and low cost are advantages – in this case over LCDs – and efficiencies and durability are improving. The market for polymer light-emitting diodes is growing rapidly and several major corporations are involved.[23]
- Vibration reduction through magnetostrictive damping. The damping effect of a polymer mount is enhanced by the application of a magnetic field. Proposed applications include improving precision in photolithographic printing of microelectronic circuits and machine tools.[24]
- Corrosion protection. The CP forms a simple coating or is dispersed as an anti-corrosion pigment in paints. The mechanisms of action are not yet well understood.[25]
- Absorption for decontamination. A coating of a CP may have strong adherence and absorption. Some can also be tailored to undergo a colour change in the presence of particular contaminants.[26]
- High volume absorption. Some CP gels can absorb large volumes of liquids and the absorption can be made temperature-dependent to allow capture of liquids as they cool.[27]
- Electrical and magnetic screening, sonar absorption and antistatic materials. Controllable electromagnetic absorptivity has applications in military 'stealth' technologies. A CP coating can guard electronics components against destructive discharges, or reduce electric charge build -up in photolithographic processes to improve precision in microelectronics fabrication.[28]
- Thermoset resins and adhesives. These resins set immediately at a critical temperature, eliminating the curing time associated with conventional resins.[29]

Problems in the field

There have been several major 'reverse salients' in IPs which have hampered successful applications and around which much activity has been focussed.[30] The first centres on processibility – how easily the material can be reformed after initial polymerisation – usually via solution or a colloidal dispersion – particularly for processing in commercially useful quantities. In several applications IPs had to be and still are polymerised chemically or electrochemically *in situ*, directly into the final form required. In the last few years, processibility has improved substantially, particularly through the incorporation of groups enhancing the solubility of polymers in common solvents. Several major corporations, including Monsanto and BASF in the US, plus others in the Netherlands and Japan, entered production in a small number of higher volume processible CPs in the 1990s.[31]

The second key problem remains with many potentially useful IPs: instability and degradation – in air, in aqueous solution, under repeated cycling or through irreversible overoxidation. Some IPs have required inert conditions to operate in, while others have been unable to withstand the elevated temperatures in some applications.

The third limiting aspect is the fundamental understanding of the structure-property relationships in IPs. Though IP advocates make general claims that polymers can be designed with specific properties and for specific purposes – and as I indicate below, the pattern of development does bear out this general trend – there is still a large amount of unpredictability, trial-and-error and adjustment in the synthesis of each new material.[32]

Features of the field and challenges for the study

IPs present several interesting and challenging features as an initial case study for this sort of investigation. In some respects the field forms an easy case. The research and development is, in the terms of Gibbons and colleagues, a typical Mode 2 activity:[33]

- it is carried out by a range of groups in the private and public sectors and there is often close collaboration between industry, academics and government agencies;
- they are interdisciplinary teams – in this case, typically materials scientists and engineers, solid state physicists, chemists, and others depending on the area of application, like biochemists and biomedical researchers;
- the work is problem- or application-focussed and the issues may be short-lived;

- the fundamental science and the applications are developed together and simultaneously, or at least there are constant interactions;
- the teams need to be flexible and offer a quick response;
- the quality of the work is judged not just by peer review but by utility, cost, competitiveness and social acceptability.

Without the institutionalised division between fundamental and applied research, much of the discussion of applications and users is therefore explicit and appears before a project even starts.

The field of CPs/IPs, however, shows interesting features and raises its own set of questions, not least concerning the many useful properties, the huge variety of potential applications and domains, and the possibility of design for specific applications.

The field follows a general trend in materials science and technology in general over the last few decades: instead of developers creating a material and then revealing its properties and finding applications – or having at most only limited scope for modifying it – materials are to varying extents designed for particular properties. In metallurgy the polycrystalline structure has long been tailored through alloying and heat treatment, with reasonably predictable and through the twentieth century increasingly well understood effects. In conventional polymers the choice of monomers and synthesis conditions – and hence the molecular weight, the distribution of crystalline and amorphous regions, chain alignment and cross-linking obtained – plus plasticisers and fillers, can all be varied to provide more or less consistent, reproducible and predictable properties. Similarly in IPs now, all these variables, plus the choice of oxidant and other dopant ions at synthesis, plus the possibilities of combinations with other materials in composites, allow the properties to be manipulated over a wide range and with increasing precision.

The use of conducting polymers for their electrical conductivity alone, and also in energy storage and conversion functions, has already met problems in competing with established materials. It tends to rely on low cost or desirable mechanical properties compensating for poorer electrical or electrochemical performance and shorter lifetimes. 'Intelligent' applications, however, are typically not displacing existing materials. Rather it is their unique properties that are being exploited, so that their uses have often not even been contemplated before.[34] Thus we can expect the promise-requirement cycle[35] to be different from that where one material is replacing another – where the existing material comes to be seen as inferior to the promised properties of its replacement. Here the promise is typically of a new functionality and new uses altogether. The competition for IPs is accordingly often limited or non-existent. What competition there is for particular applications comes, for example, from smart composite materials or structures in which the detection and response are produced by different components.[36]

The wide range of potential applications – such that advocates depict them as 'limited only by imagination and our ability to engineer these inherently dynamic materials into consistent products'[37] – raises the question of how researchers become aware of needs or potential uses. I have found the question a difficult one to explore in interviews with IP researchers, and it remains to be seen how reliable are their recollections of the sources of ideas. Personal experience and background knowledge, discussions within the interdisciplinary team, with other teams and potential project sponsors, diverse other contacts and chance conversations, and latterly industry-specific conferences to brainstorm ideas, appear to have played roles in different cases.[38] Not only for an outsider but for even for researchers themselves if the application is in a field with which they have no familiarity, many of the applications in the IPs literature are highly specialised and stunningly obscure – even if potentially economically significant.[39] Explanations of the origins of the ideas, of course, might lead to important practical lessons: ways in which the fertilisation of ideas might be structured and facilitated and made less serendipitous.

Clearly the increasing use of 'smart' systems for control in a variety of domains – for example, in industrial machinery, vehicles, weapons and household technologies – provides a form of demand to which developers of CPs/IPs can respond. That is, developers of these systems require improved sensors and actuators, and the possibility of combining some or all functions in 'smart' materials should provide significant advantages. That possibility also opens up opportunities in – provides a demand from, and indicates a convergence with – developments in the miniaturisation of devices: in micro- and nano-technologies. The same point can be made about developments in 'smart' structures and 'smart' composite materials in building and civil engineering, though the scale of materials use and the severity of conditions may present problems in using IPs.

Embedded assumptions about use and value

Beyond explicit discussion on uses, a number of other forms of discourse on IPs are evident which impinge on the question of use. It is in these that I hope to be able to find lessons, and develop concepts and methods for investigation, for areas in which assumptions about use and need are predominantly and more subtly embedded in research practices and discourse.

Assumptions about IP applications and their value are embedded in the selection and presentation of properties, functions and behaviours,[40] and in discussions and judgements of efficacy and usefulness.[41] These may involve a scalar measure, such as conductivity, or a dichotomy – that the material does or does not perform. Here my focus is not so much on negotiation over *whether* it does or does not perform, or judgements on how well it performs, as in sociological work on testing,[42] but on what dimension is chosen as relevant and how it is defined – like biocompatibility.

Similarly, ideas of use and value are entailed in assumptions about trajectories of improvement and the identification of reverse salients. For example, the relatively long switching time and poor operating life in electrochromic display devices has directed activity towards increased purity and homogeniety, adjustments to molecular structure particularly to improve carrier mobility, and nature of the solvent and electrolyte used with the CP electrode in the system. Similar problems of slow response and short lifetime affect some actuators.[43]

While much of the discussion about uses is explicit, then, and many papers in even specialist journals speculate about potential applications when reporting a new 'synthesis and characterisation', much of the literature discusses specific properties, and improvements in them, which are simply assumed to be useful or desirable. Taking the absence of those properties, or inadequate versions of them in earlier polymers, as problems worth working on, itself makes assumptions about usefulness. There does appear to have been a shift in the IP and CP literature towards properties as a focus rather than simply the problem-solving capabilities of their applications.[44] This appears to be both a strategic rhetorical move by IP advocates, to create an impression of a universally applicable class of materials with limitless uses, and a reflection to some extent of a change in the organisation of development-application matching from one-to-one co-production to a mapping of a general capability onto a class of problem or use. It remains to be investigated, however, how much this shift is wishful thinking. To the extent that the discussion does move to general properties, of course, treatment of the materials probably becomes more separated from that of the social and political implications of their uses.

The depiction of general capabilities, though, is in tension with the acknowledgement among practitioners that each development is task-specific – the molecular structure and characteristics of an IP have to be tailored for a particular application. The picture from market observers is of niche markets, intensive and costly development for each, and small volume production – not of readily transferable off-the-shelf solutions for generic problems.[45]

Conclusion

The IPs case offers rich material for examining discourses on need and use. The study presents the usual methodological problems first of any discourse analysis and second of any recent historical reconstruction, where participants have already started to create a coherent narrative, selecting particular influences for emphasis and rationalising away the messiness of the events. Assuming the pilot is productive, the intention is to extend the study to groups in other fields: in areas like IPs in which application is overtly and intimately linked to fundamental research, and in others more like the Mode 1 model of basic research.[46]

The focus on IPs has also opened up other questions for investigation which I see as common to a general sociology of materials drawing on insights from the social shaping of technology, something that with notable exceptions appears to have been neglected so far.[47] This broader endeavour is probably amenable to any of the frameworks and focusses that have been developed over the past couple of decades in SST. Similar questions around users selecting and appropriating technologies, and the articulation of production and use, suggest themselves. We could, for example, examine the strategies of developers, users and intermediaries in shaping the locus and control of innovation in materials. To what extent do developers seek to accommodate their work to a notion of existing requirements, or can they attempt to inscribe particular practices and patterns of use in materials? To what extent do they try to force a reworking of production techniques to suit their new material, or try to fit the material to existing techniques? To what extent are anticipated changes to production and use procedures a criterion for judging or selecting that material? What goes on in the process of getting a material 'to work'?[48] For the extension and development of SST analyses I see a wealth of material in materials.

References and notes

1 The pilot work was supported by a University of Wollongong Small Grant. I thank Jasmin Sydee for her work in reviewing the applications of intelligent polymers, and Geoff Spinks for his help in getting me orientated in the field.

2 The use of the term in discourses on materials would itself form an interesting study. Other 'smart' materials include shape memory alloys and piezoelectric ceramics.

3 G Spinks, *Smart Polymers: a Case Study in University / Industry Collaboration*, State Science Briefing, IPRI, University of Wollongong, Wollongong, 2001.

4 I Amato, 'Animating the Material World', *Science 255*, 1992, 284-286. I am not particularly concerned to establish a precise demarcation, though the use of the term 'intelligent' and its role in projecting IP/CP scenarios is itself an interesting aspect.

5 Notably polyacetylene, polyaniline, polyphenylene, polypyrrole, poly(phenylene vinylene), polythiophene, polyfluorene, polypyridine. The distinction is from composites in which the conductivity comes from conventional metal or carbon conductors embedded in otherwise insulating polymers. Many of the basic polymers had been synthesised decades earlier. Spinks *et al.* trace the dramatic growth in the number of papers and patents on CPs in Chemical Abstracts since 1975: GM Spinks *et al.*, 'Current State and Future Directions of Research and Development in Conducting Polymers', *Materials Forum 24*, 2000, 125-166, fig. 7.

6 The term doping was borrowed from semiconductor treatment, but is misleading: the process is reduction or (more commonly) oxidation of the polymer backbone by chemical or electrochemical means; the counterion is incorporated to balance the developing charge in the polymer backbone during synthesis. In some cases, synthesis is also possible by photochemical means or using enzymes as catalysts. *ibid.*

7 AG MacDiarmid & RB Kaner, 'Electrochemistry of Polyacetylene: Application to Rechargeable Batteries', in A Skotheim (ed.), *Handbook of Conducting Polymers 1*, Marcel Dekker, New York, 1986, 689-727.

8 Some early CP devices, particularly in energy storage, have already been withdrawn after failing to make inroads into markets against competing materials. Many of the following applications, and explanations of their operation, are examined in Spinks *et al.*, *op. cit.*; this summary draws heavily on that review. See also the lists as at 1993 of 'proposed applications' and 'feasibility-demonstrated applications' in JS Miller, 'Conducting Polymers: Materials of Commerce', *Advanced Materials 5*(7/8), 1993, 587-589, tables 2 & 5.

9 T Moore, 'Smart Materials for the Power Industry', *EPRI Journal 23*(4), 1998, 26; JH Holtz & SA Asher, 'Polymerized Colloidal Crystal Hydrogen Films as Intelligent Chemical Sensing Materials', *Nature 389* (6653), 1997, 829-832.

10 e.g. teams at Warwick and Southampton Universities in the UK, and Wollongong University in Australia, have developed electronic noses for foodstuffs. Cranfield has worked on a nose for diagnosing respiratory diseases such as TB from analysis of sputum. R Stella *et al.*, 'Characterisation of Olive Oil by an Electronic Nose Based on Conducting Polymer Sensors', *Sensors and Actuators 63* (1/2), 2000, 1-9; BBC News Online, 'Electronic Nose Sniffs out TB', 15 Aug 2001, http://news.bbc.co.uk/hi/english/health/newsid_1492000/1492338.stm; R Marsili, 'Food Production Design: The Electronic Nose', 1995, http://www.foodproductdesign.com/archive/1995/0695QA.html

11 Amato, *op.cit.*

12 e.g. RH Baughman, 'Conducting Polymer Artificial Muscles', *Synthetic Metals 78*(3), 1996, 339; G Wallace, 'Artificial Muscles: Stronger Than Steel', *Australasian Science 22*(5), 2001, 36-37; Worldwide Electroactive Polymer Actuators: Artificial Muscles, 2001, http://ndeaa.jpl.nasa-nde/lommas/eap/EAP-web.htm.

13 'Smart Bra to Give Support Where It Is Needed', *ABC Science Online*, 26 May 2000, http://abc.net.au/science/news/stories/s131388.htm.

14 The voltages required are orders of magnitude less than for piezoelectric polymers. Spinks *et al.*, *op. cit.*

15 G Wallace, 'Conductive, Electroactive Polymers: Providing the Basis of Intelligent Material Development', paper to 21st Engineering Conference of the IEAust Illawarra Group, *Materials for the Nineties*, University of Wollongong, 1990.

16 Landec Corporation, 2001, http://www.landec.com/busi_prod/bp2.html.

17 e.g. H He *et al.*, 'A Conducting Polymer Nanojunction Switch', *Journal of the American Chemical Society 123*(31), 2001, 7730-7731

18 IY Galaev & B Mattiasson, '"Smart" Polymers and What They Could Do in Biotechnology and Medicine', *Trends in Biotechnology 17*(8), 1999, 335-340.

19 R Dagani, 'Intelligent Gels', *Chemical and Engineering News 75*(23), 1997, 26-37; A Coghlan, 'Smart Way to Treat Materials', *New Scientist 135* (1828), 1992, 26

20 *ibid.*; TJ Rivers, TW Hudson & CE Schmidt, 'Synthesis of a Novel, Biodegradable Electrically Conducting Polymer for Biomedical Applications', *Advanced Functional Materials 12*(1), 2002, 33-37. Rivers and colleagues claim '[t]he next generation of implantable biomaterials will be interactive and programmable, and thus capable of seamless communication with surrounding tissues.'

21 W Lewis & GG Wallace, 'Communicative Polymers: the Basis for Development of Intelligent Materials', *Journal of Chemical Education 74*(6), 1997, 703-708.

22 P Dastoor *et al.*, 'Conjugated Polymers: New Materials for Photovoltaics', *Chemical Innovation*, 2000, 15-22.

23 D Collier, 'Polymers Devise a Bright Future', *Chemistry & Industry*, 18 Jun 2001, 373-376; P Skabara, 'Polymers Trip the Light Fantastic', *Chemistry & Industry*, 18 Jun 2001, 371-372.

24 Mide Technology Corp., 'Smart Materials and Motorless Actuators', 2000, http://www.mide.com/expertise/materials.html;

Sandia, 'Smart Materials and Structures at Sandia', 2001,

http://endo.sandia.gov/9234/smas.html.

25 Here the application has been developed well ahead of the explanation of the mechanism, Spinks *et al.*, *op. cit.*, so the case forms an interesting one for my purposes.

26 HN Gray *et al.*, 'Smart Polymeric Coatings for Surface Decontamination', *Industrial and Engineering Chemistry Research 40*(16), 2001, 3540-3546.

27 F Buchholz, 'Absorbing Work for Smart Polymers', *Chemistry & Industry* (2), 1999, 56-61.

28 Spinks *et al.*, *op. cit.*

29 Landec Corporation, *op. cit.*

30 TP Hughes, 'Reverse Salients and Critical Problems', paper to conference *Technology and Social Change*, Edinburgh, Jun 1986.

31 Spinks *et al.*, 2000, *op. cit.*

32 In particular, conditions such as the solvents and pH in chemical oxidation processes crucially affect the structure and properties of the polymer molecules. The stereoregularity in the molecules, defects in the form of irregular branching, and the meso-level order – the arrangement of polymer molecules obtained in synthesis or by post-polymerisation processing with secondary dopants – also have profound effects on the electrical and other properties. The number of variables provides both unpredictability and the possibility of obtaining additional functionality. *ibid.*

33 M Gibbons *et al.*, *The New Production of Knowledge*, Sage, London, 1994

34 JC Scott, 'Conducting Polymers: From Novel Science to New Technology', *Science 278* (5346), 1997, 2071

35 H van Lente, *Promising Technology: the Dynamics of Expectations in Technological Developments*, Eburon, Delft, 1993; H van Lente, 'Forceful Futures: From Promise to Requirement', in N Brown, B Rappert & A Webster (eds.), *Contested Futures: a Sociology of Prospective Techno-Science*, Ashgate, Aldershot, 2001, 43-63

36 With CPs used for their electrical properties, the picture is different. The use of metal or carbon inserts or coatings with conventional polymers, for example, seriously limits the application of CPs as simple electrical conductors.

37 JN Barisci *et al.*, 'Conducting Polymers as a Basis for Responsive Materials Systems', *Journal of Intelligent Material Systems and Structures 9* (9), 1998, 723-731

38 See also the experiment in generating applications in 'Smart Ideas for Smart Materials', *New Scientist 134* (1822), 1992, 4.

39 To take an application of CPs at random: conducting polymer coatings with a graduated conductivity can reduce voltage stress at the edges of capacitors, inhibiting partial discharge and extending the life of the components. 'Conductive Polymers Spark New Ideas', *Machine Design 64* (21), 1992, 161.

40 On the importance of the distinctions, see the discussion in RUN Working Paper 1, 20-21, and MA Rosenman & JS Gero, 'Purpose and Function in Design: from the Socio-Cultural to the Techno-Physical', *Design Studies 19*, 1998, 178-180.

41 See e.g. Miller, *op. cit.*, table 1 'Anticipated Attributes of Conducting Polymers', reproduced here as an appendix.

42 e.g. D MacKenzie, 'From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy', in D Gooding, TJ Pinch & S Schaffer (eds.), *The Uses of Experiment: Studies in the Natural Sciences*, Cambridge University Press, Cambridge, 1989, 409-36; T Pinch, '"Testing – One, Two, Three ... Testing!": Toward a Sociology of Testing', *Science, Technology and Human Values 18*(1), 1993, 25-41.

43 G Tourillon, 'Polythiophene and Its Derivatives', 293-350, and M Gazard, 'Application of Polyheterocycles to Electrochromic Display Devices', 673-687, in A Skotheim (ed.), *Handbook of Conducting Polymers 1*, Marcel Dekker, New York, 1986.

44 cf. H van Lente & A Rip, 'The Rise of Membrane Technology: from Rhetorics to Social Reality', *Social Studies of Science 28*, 1998, 225-226

45 e.g. JR Ellis, 'Commercial Applications of Intrinsically Conducting Polymers', in A Skotheim (ed.), *Handbook of Conducting Polymers 1*, Marcel Dekker, New York, 1986, 489-499.

46 Gibbons *et al.*, *op. cit.*

47 But see Bijker on Bakelite and earlier plastics: WE Bijker, 'The Social Construction of Bakelite: Towards a Theory of Invention', in WE Bijker, TP Hughes & TJ Pinch (eds.), *The Social Construction of Technological Systems*, MIT, Cambridge, MA, 1987, 159-187; W Bijker, *Of Bicycles, Bakelite and Bulbs: Towards a Theory of Sociotechnical Change,* MIT Press, Cambridge MA, 1995; and H Bodewitz, G de Vries & P Weeder, 'Toward a Cognitive Model for Technology-Oriented R&D Processes', *Research Policy 17*, 1988, 213-224

48 By analogy with analyses of the appropriation of other technologies, presumably processes like: trying to reproduce or preserve the required properties as the material is manipulated; creating the right conditions for working with the material; dealing with the waste and by-products of processing or manufacture; dealing with public or regulators' responses to the use of the material and any environmental and health effects.

Appendix: Anticipated attributes of conducting polymers

reproduced from JS Miller, 'Conducting Polymers: Materials of Commerce', *Advanced Materials 5*(7/8), 1993, 587.

High, metal-like electrical conductivity
Semiconductivity
Large polarizabilities
Bistability ($\geq$2 'stable' states)
Low density
Flexibility
Film and/or fibre formation
Processibility
Transparaency
Solubility/dispersibility
Low environmental contamination
Biocompatibility
Compatibility with other polymers for composites
High strength
Modulation/tuning of properties via organic chemistry
Thermoelectric power
Redox active
Optical changes (linear and non-linear)
Fast optical response
High threshold for optical damage