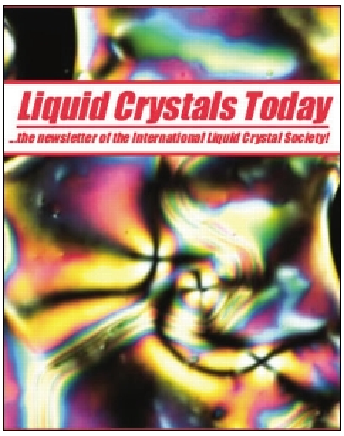

Liquid Crystals Today
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713681230

Industrial Development of Plastic PDLC: Is There a Future?

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To cite this Article Hakemi, H.(1998) 'Industrial Development of Plastic PDLC: Is There a Future?', Liquid Crystals Today, 8: 3, 7 — 12
To link to this Article: DOI: 10.1080/13583149808047713
URL: http://dx.doi.org/10.1080/13583149808047713

but two broad areas emerge marking his earlier work on the synthesis and spectroscopy of organic materials (1961–1990) overlapping with his more recent and finally dominant (1977–1998) research in the field of liquid crystals.

In the earlier period, many firsts in the synthesis of diverse nitrogen heterocycles and compounds of S, Se and Te were achieved by novel methods of synthesis. This research was in parallel with seminal kinetic and mechanistic studies of new photochemical processes, and exacting stereochemical studies of strained carbocycles such as tetrabenzoheptafulvalene, cyclobutane carbonitriles and the diastereoisomers of perhydropyrene, including the one giving the famous 'jumping crystals'.

In the second area, Professor Praefcke's research has been of very great significance in the field of liquid crystals, but in this short review, one can only highlight some of his achievements: the first syntheses of S, Se and Te calamitics and of S-containing discogens; a possible case of atropisomerism in a discogen; extensive studies of inositol systems and other carbohydrates, and the role of hydrogen bonding in building up disc-shaped aggregates determining whether the systems are calamitic or columnar; radial multiynes yielding not only LC hydrocarbons, but also accessible materials forming novel discotic nematic (N_D) and N^*_D phases; fascinating examples of phase induction in TNF doped systems; new metalorganyles and their ability to form induced lyomesophases with TNF and alkanes; an elegant new example of chirality in mixed achiral systems; and imaginative synthetic studies, including work on giganto-heterocycles, directed at biaxial nematics.

On the following day, delegates were treated to a wonderful tour of Berlin during which the history of the city and its academic institutions were expertly explained by Professor Praefcke who acted as guide. On final departure, the view was expressed widely that in retirement some outlet must still be found for the varied talents of this very fine scientist who has added so much to the already strong research reputation of the Technische Universität Berlin.

Contribution from Professor G. W. Gray, CBE, FRS

Industrial Development of Plastic PDLC: Is There A Future?

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The interest in research and development of *plastic* liquid crystal technology originates from the stabilization of liquid crystals with a polymer matrix for manufacturing of large-area flexible electro-optical films which can be used as electrically switchable shutters, panels and privacy windows in the building, residential and transportation sectors, as well as reflective displays. In figure 1, we show typical examples of PDLC applications as electro-optical windows. The display applications of PDLC are not within the scope of the present article.

The first scientific curiosity in PDLC film technology began in the early 1980s, when industrial and commercial activities began at Taliq/Raychem in the USA based on the invention of micro-emulsion (ME) technology by Fergason. This approach has also been known as the Nematic Curvelinear Aligned Phase (NCAP). Following the invention of the phase separation (PS) method at Kent State University in the late 1980s, the industrial activities concerning PDLC entered a new phase of development, and since the beginning of 1990s the PS-based PDLC products began to appear in the worldwide market along with ME-based PDLC. The major industries which have developed and commercialized PDLC films and windows

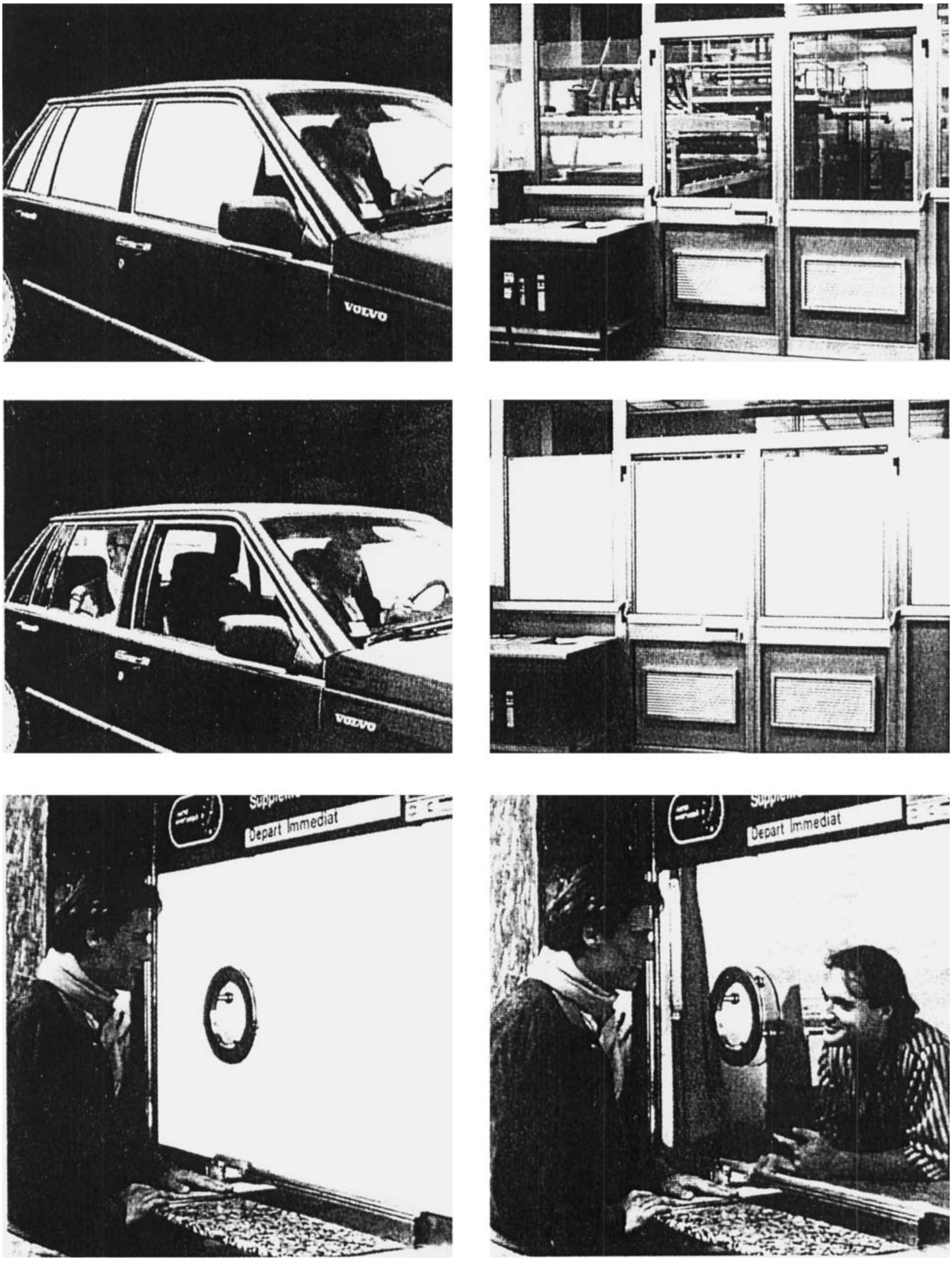

Figure 1. Examples of the applications of plastic PDLC as large-area electro-optic windows.

Table 1 Worldwide activities on plastic PDLC in 1980s–1990s

Company	Product	Trade mark
3M / Viracon (USA)	film & window	'Priva-view'
Polytronix (USA)	film	'Polyvision'
Raychem (Taliq) (USA)	film	'Varylite'
Ajinomoto (Japan)	film	'ACT'
Asahi Glass (Japan)	film & window	'ViewTech'
Nippon Sheet Glass (Japan)	film & window	'UMU'
Saint Gobain (Europe)	window	'Priva-lite'
Isodima (Europe)	window	'Varilite'
Snia BPD (Europe)	film	n.a.

are listed in table 1. A number of other large and small industries, not included in the table, have only carried out research and development programmes.

Since the invention of PDLC, related scientific and technical publications have grown to over a thousand, with more than three hundred patent filings. In spite of these intense activities, however, little has appeared on the industrial development of *plastic* PDLC in the open literature. This shortcoming is particularly due to the fact that the use of plastic coating and lamination, which is the backbone technology of *plastic* PDLC films, has been safe-guarded by industries and has never become the subject of academic inquiries.

The industrial processing of large-area plastic PDLC involves a rather complex technology and is based on a proper integration of the two individual processing technologies, i.e. the PDLC processing (phase separation or micro-emulsion) and the roll-to-roll film coating and lamination (C&L) processing. Such an industrial challenge requires the following systematic manufacturing innovation steps:

- Development of PDLC processing (PS or ME) at large scale.
- Development of *plastic* C&L adapted to PDLC processing.
- Integration of *plastic* C&L and PDLC processings into a unified technology.
- Manufacturing of a high quality and cost-effective *plastic* PDLC product.

At the industrial level, the processing of large-area (m^2 scale) PDLC requires the necessary coupling of PS with plastic C&L technology. The passage from the laboratory-scale to industrial-scale, which is beyond the scope of mainstream academic research, is not straightforward and requires a full-fledged development of a new process engineering and hardware system.

Phase separation of PDLC

The well-documented phase separation of PDLC process is based on *in situ* separation of liquid crystal microdroplets from a homogenous and refractive index-matched mixture of liquid crystal and prepolymer (or polymer) matrix according to one of the following three techniques: PIPS (Polymerization Induced Phase Separation); SIPS (Solvent Induced Phase Separation) or TIPS (Thermally Induced Phase Separation).

The phase separation of PDLC usually depends on the nature of the polymer matrix and the curing process. Among the commercially available materials, there is a vast choice of liquid crystal mixtures, prepolymers (i.e. UV-curable adhesives and epoxy resins) and polymers (thermoplastics) for processing by one of the three PS methods. Such materials and processing methods are extensively utilized in both academic research and industrial development of PDLC.

Coating and lamination of PDLC

Continuous roll-to-roll coating and lamination (C&L) is a well known and mature technology in many plastic and film industries, and is an essential and integral part of plastic PDLC manufacturing. In contrast to the conventional C&L techniques, the production of PDLC film requires rather different C&L processing conditions (i.e. very slow production speed of 0.5–1.0 m min^{-1}), as well as very expensive raw materials (i.e. liquid crystals and ITO-PET film). These two unconventional factors alone are sufficient to introduce further complications in design, engineering, process control and production scheme and manufacturing cost of PDLC.

Conventionally, the roll-to-roll film C&L is done by *dry* (solventless) or *wet* (solvent-based) techniques. For the production of PDLC, the choice of either of these techniques depends on the type of PS method. The *dry* C&L is utilized in production of PDLC by PIPS or TIPS method, whereas the *wet* C&L technique is used in case of SIPS processing. In figure 2, we present examples of manufacturing schemes for processing of *plastic* PDLC by these two C&L techniques. These processing schemes show not only the integration of PS and C&L techniques, but also demonstrate the possibility of PDLC production

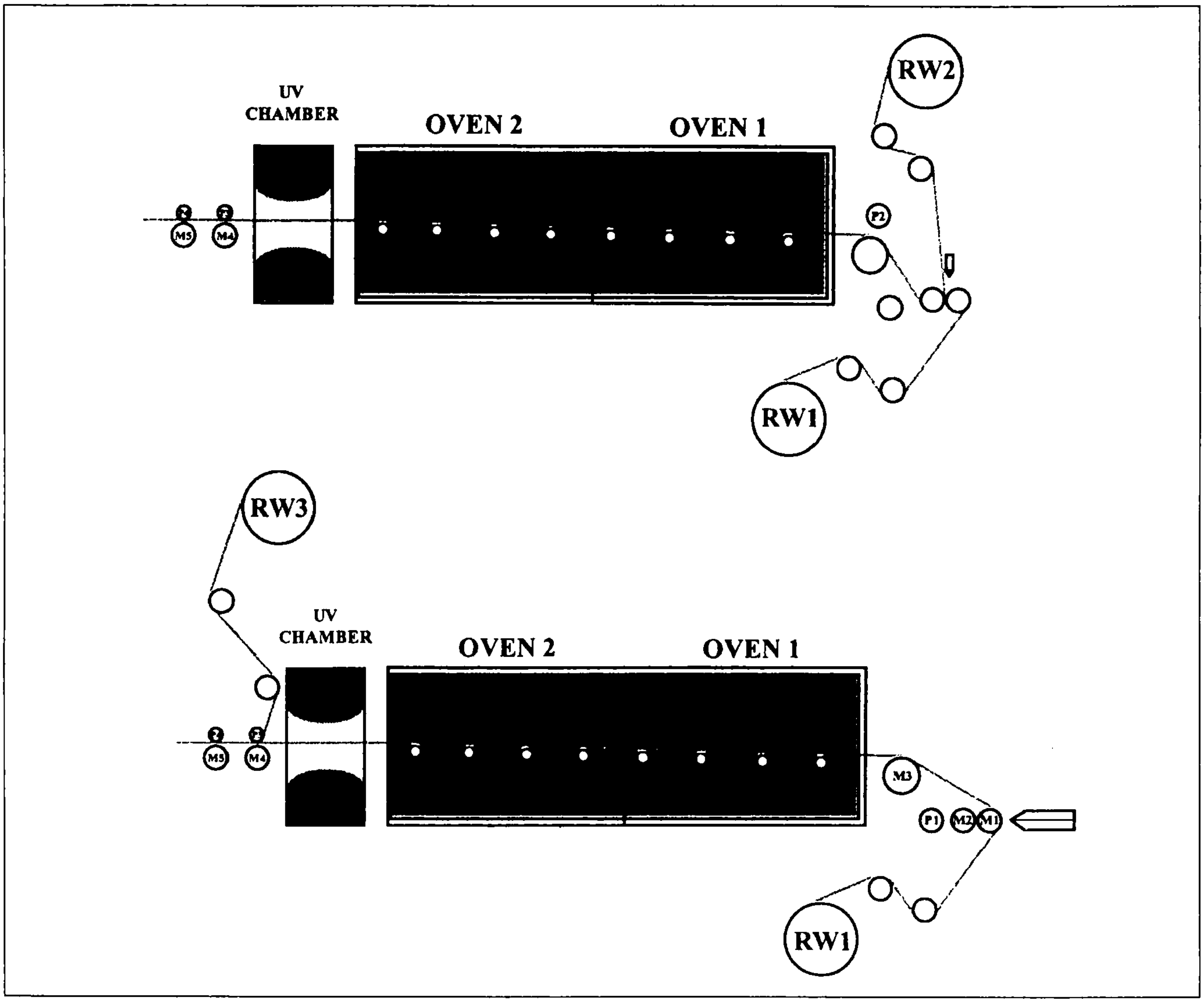

Figure 2. Plastic coating and lamination processes with dry (top) and wet (bottom) techniques.

with all three PS methods with a single manufacturing unit. In figure 2 (top), the production scheme of plastic PDLC with the integrated *dry* C&L/PIPS (or TIPS) technique consists of simultaneous coating and lamination of a PDLC layer between two ITO-PET film rolls (RW1 and RW2) travelling from right to left. This '*in situ*' C&L process is followed by thermal (ovens 1 and 2) or radiation (UV chamber) curing, product collection (sheeting or rewinding), inspection and quality control of the product. The *dry* C&L process is similar in both PIPS and TIPS methods. The *wet* C&L/SIPS technique, as shown in figure 2 (bottom), is carried out by coating of a solvent-based mixture onto a first plastic roll (RW1) by 'slot die' or a similar method. After the solvent evaporation (oven 1) and phase separation of PDLC (oven 2), the open-face PDLC layer is laminated with the second plastic support (RW3), followed by product collection, inspection and quality control.

The evolution of PDLC

In the past decade and despite a consistent growth in basic research, the industrial evolution of PDLC has witnessed cycles of progress and setbacks. Until the early 1990s, the technology experienced substantial industrial progress, mainly in the US and Japan. In the mid-1990s, Taliq/Raychem, Asahi Glass and Ajinomoto suspended their commercial activities, while 3M and Snia focused on the development of plastic PDLC for the architectural windows market. The current leading manufacturers of PDLC films are 3M (USA) and Nippon Sheet Glass (Japan). In the meantime, other small films and windows manufacturers like Polytronix (USA) have been continuing to produce PDLC film on a modest scale. The main producers of PDLC windows include 3M/Viracon in the USA, Nippon Sheet Glass in Japan, as well as Saint Roch (Saint Gobain) in Europe. Also in Europe, other smaller industries, such as Isoclima (Italy) and Romag (UK), have been commercializing the PDLC windows on a small scale.

Aside from the type or method of production, the performance of all present-day commercial PDLC products are similar, and the data presented in table 2 define the current worldwide industrial state-of-art for this technology.

Despite industrial surveys forcasting a large potential market of over 100 000 m^2, the actual exisiting worldwide PDLC market for architectural window applications hardly exceeds 8000 m^2/year volume. The market share of such modest sales is approximately equally shared between the USA, Japan and Europe. Whereas it is not the scope of this article to give a detailed account of the history and evolution of PDLC technology, we may indentify three factors of *price*, *performance* and *patenting*, as being the major influences on the commercialization of PDLC technology.

The high *price* of PDLC film and window is a result of costly production, arising from the use of expensive raw materials and the high cost of film and glazing production. The current quoted price range of PDLC products in the worldwide market is around \$200–500 m^{-2} for films and \$1000–1500 m^{-2} for windows. As such high prices are prohibitive for many applications at the large-volume end of the market, the PDLC producers are struggling to reduce the price of the windows to the target range of \$300–350 m^{-2}. However, as long as the price of raw materials and production costs of PDLC film and, particularly, windows remain above this target range, the *price* issue will be a major barrier to the growth of the PDLC market.

Table 2 Performance of commercial plastic PDLC

Performance	Value
ITO-PET Thickness	50–175 (mμ)
PDLC Thickness	10–30 (mμ)
PDLC Film Width	90–99 (cm)
Transparency	65–80 (%)
Opacity	0.1–1.0 (%)
Normal Haze	5–10 (%)
Off-Angle Haze	10–20 (%)
Operating Voltage	40–120 (V)
Rise Time	1–5 (ms)
Decay Time	5–40 (ms)
Power Consumption	10–50 (W m^{-2})
Min. Operating Temperature	−20/−10 (°C)
Max. Operating Temperature	70/105 (°C)
Average Microdroplet Sizes	0.3–3.0 (mμ)

The *performance* criterion of PDLC has also been the subject of many concerns and criticisms. Due to its large area, a PDLC film or window is susceptible to many unexpected problems that arise in production and post-production phases. The most frequently debated performance problems of PDLC are the off-axis haze, the power consumption, cosmetic defects, and product stability. These challenging issues are a subject of extensive concern and investigation by both PDLC film and windows producers.

In addition to the *price* and *performance* barrier, PDLC technology has also witnessed another unprecedented set-back due to the *patent* issues. In the early 1990s, the Fergason (ME-PDLC) patent applications came under a series of oppositions in Japan and Europe, but in 1994, contrary to many expectations, the Fergason patents were finally granted in both Japan and Europe. This event had a drastic effect on worldwide industrial activities in PDLC, among which were the suspension of PDLC film and windows production by Asahi Glass and Ajinomoto in Japan. Curiously enough, the situation in the USA took a different turn, where after the closure of Taliq in 1993, the 3M/Viracon venture began a large commercial campaign on PDLC windows.

One may view the complex evolution of PDLC technology to be rather peculiar. Despite the persisting challenges, industrial development showed consistent progress until the mid 1990s, followed by an impass which persists to this date.

The future of PDLC

Industrial activities in PDLC require traditional as well as non-traditional disciplines. In recent years, while basic and industrial research activities have been growing, the commercial efforts of the technology have not been able to satisfy the anticipated growth. The short history and the ups and downs of PDLC technology confront us with a difficult question: is there a future? The answer is not an easy one and places us in the domain of speculation.

Although we believe that *price–performance– patenting* issues are formidable barriers to overcome the current impass, future progress requires fresh ideas within the concepts of 'strategic alliance' and 'product innovation'.

It may be helpful to both industrialists and academics to make some points about these important concepts. A *strategic alliance* between the active industries would be advantageous for many reasons. For example it allows the patent and licensing issues to be settled, the reduction of production costs and the product price, the improvement of performance, the development of new products and application, the expansion of the market and above all, the verticalization of the technology to facilitate its transformation to end-users. The concept of strategic alliance is being pursued by some industries, where the film suppliers and end-users are attempting to consolidate a coherent effort to expand the future market of PDLC for the architectural windows applications.

Despite the inevitable needs for product improvement, the history of PDLC technology has shown that the product flexibility and diversification is another key issue for market acceptance of the PDLC product. Consequently, the 'single-product' approach is an inadequate development strategy pursued by many industries. In other words, the concept of 'PDLC for all seasons' is proven to be an unsuccessful product strategy. In this respect, some industries are begining to realize and implement the 'multi-product' strategy to overcome this shortcoming. A capability and flexibility for product development and fine-tuning for different applications would allow the PDLC industries access to vast and far-reaching applications and end-use markets.

Last but not least, the *plastic* PDLC technology for large-area applications has been solely developed in industry, almost without academic participation. The short history of PDLC reveals that, while the industries have been struggling to develop plastic PDLC for large-area applications, the basic research has been developing in various areas of displays. The exclusion of academia from research on plastic PDLC is a result of the complex history of this technology and will not be discussed here. It is sufficient to point out that the lack of such vital industrial–academic interactions not only created a divergence of interest and research activities, but has also prevented industries accessing fundamental understanding, and resolving the technical problems impeding technological innovations. Through a framework of active industrial–academic collaboration it would be possible to introduce the *plastic* PDLC technology into the main stream of basic research and, in return, to resolve the existing problems, efficiently and cost effectively. Such collaborations will provide far-reaching opportunities for future innovations in industrial development of this technology.

In conclusion, we believe that the current impass in *plastic* PDLC technology is only a temporary one. There are already indications that industries are making substantial revisions of their development strategies. Such revisions incorporate the concepts of alliance, multi-product approach and academic collaborations. In this way, not only the progress of *plastic* PDLC will be guaranteed, but also there will be ample opportunities for development of liquid crystal film technologies as a whole, in other areas of innovation and device application.

PRODUCT NEWS

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- LCD display materials
- thermotropic surfactants
- metallomesogens
- polymers
- NLO compounds with mesogenic structures

The in-house database LiqCryst 3.1 has further data with enhanced search and manipulation functions on around 75 000 compounds and about 200 000 properties. The data have been extracted from journals, patents, dissertations, conference absracts and books.

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