Chapter 1 Introduction

1.1 Introduction

The research demonstrates an exploration of the potential of thermochromic dye systems on textiles. There are two principal types of thermochromic systems that undergo reversible transformations: the leuco dye type that change from coloured to colourless and the liquid crystal type that pass through a colour spectrum when subjected to temperature changes. The research highlights the diverse potential of both types of thermochromic dye systems on textiles. The research, although not attempting to define specific applications, demonstrates the flexibility of design systems that could be appropriate for interior applications. The author’s previous experience of thermochromic materials was obtained during MA study at Winchester School of Art, which focused on the idea of change, specifically around light and colour in nature. Natural changing phenomena were translated as printed textiles for interior applications, using thermochromic and photochromic dyes. The MA project was multi-disciplinary and involved a collaborative approach, which brought together a range of techniques and technologies to control and activate colour change. Skills that were shaped and developed through previous experience provided the basis for a higher level of collaborative research. This PhD study has involved a collaborative partnership of science, engineering and design, which has been integral to the investigation of thermochromic dye systems, as documented within this thesis.

Thermochromic systems began to appear from laboratories in the 1960s and have subsequently found use in a range of applications, from digital displays to medical thermometers. Reversible and irreversible thermochromic materials are used in a range of functional products. Irreversible colour-change paints were designed to test the function of combustion engines leaving a heat map on the mechanical parts. The indicator labels market, where colour is used to indicate temperature, is reported to be the largest for thermochromic products. Since the development of microencapsulated thermochromic dye systems, it has been found that they can be applied to a wider range of materials although they were not specifically designed or intended for use on a textile substrate. Some application areas require the thermochromic dye systems to be encapsulated within a polyester film layer, giving them extra protection from UV degradation and added durability. The manufacturing processes for these films are designed for specific products, and the processes and the design of the thermochromic
dye systems are fine tuned for the particular end use. The challenge of this research has been to explore the creative application of these specialist dye systems on textiles, which required an exploration of a range of existing binders for their improved use on textile substrates. Thermochromics have not been designed for textile applications and as such, present difficult technical barriers for designers. Exploitation of the dyes has been limited due to a lack of technical information available to designers, availability of physical samples, and also the relatively high cost of the materials. In spite of these barriers, there are examples of design applications and textile designs employing thermochromic materials and discussion around their potential within textiles continues.

1.2 Research Problem
The problem for textile designers is that there is insufficient information on how thermochromic dyes are applied and on how they visibly change colour on textiles. At present, there is no documented definitive research that designers can access to allow them to employ techniques to create a diverse range of colour-change phenomena using both types of thermochromic dye systems. Currently in the design arena there is more emphasis on the technology used to activate thermochromic materials, than on the potential of the dye systems. The research aims to explore the under-exploited design potential of thermochromic materials on textile substrates and related materials by asking the specific question as to what techniques could be employed to further develop the application and exploit the colour change effects of these dyes.

1.3 Aims and Objectives of the Research
The aims of the research:

• to explore the design potential of thermochromic dye systems on textiles and related materials;
• to investigate electronic devices to activate colour-change on textiles.
• to establish design systems, which demonstrate the capabilities of multi-colour change on textiles;

The objectives of the research:

• to explore application methods including screen-printing, and coating of thermochromic dye systems to textiles and related materials;
• to design and develop heat-profiling circuits to be used as a methodological tool to activate and control colour and pattern change;
to develop transitional colour-change effects and exploit the aesthetic qualities and creative potential of thermochromic dye systems for textile applications.

1.4 Design Research Methods

The research was practice-led and drew upon methodology centred on theories of ‘design thinking’. Kimbell (2009) analyses the concept of design thinking based on findings proposes theories which go beyond trying to understand what individual designers do/think during the creative process. Designs-in-practice is a theory put forward by Kimbell (2009) that can be related to the design thinking (methods) used within this body of research. The term as is understood refers to the evolving nature of design outcomes through the process of practice. It describes a theory that extends designs beyond the designer and to the many stakeholders out with the designs production. The users or stakeholders as Kimbell describes are involved over time in constituting what the design is.

In terms of the research described designs-in-practice has resonance as the design decisions evolved through developing an understanding of thermochromics. The process of research enabled designs to be produced. The stakeholders in this case are other disciplines and methodological tools, such as the electronics that allowed visualisation of surface effects that could be applied to design products. The design process within this research was focused on what aesthetic surface effects were achievable with colour-change. The surface effects were recorded in a range of possibilities and ultimately presented through workshops and exhibition enabling thermochromic surface qualities to be explored in particular design contexts. The combination of technologies extends the design process, for example, the printed circuit boards that are used to activate the thermochromic fabrics change the possible surface design continually and over time.

The design methodology/thinking is described throughout the thesis at the beginning of the relevant chapters in the introduction section and highlights decisions made through the process of design that influenced the outcomes of the research.
1.5 Overview of Chapters

Chapter 2

The chapter, based mainly on literature review, provides an overview of current design practice, technology and science, and presents definitions and appropriate information specific to this area of design research. The chapter is divided into seven sections. The first section introduces the broad range of chromic materials. The second section introduces both types of thermochromic systems, leuco dye systems and liquid crystal dye systems. The third section reviews previously reported design work using thermochromics from an historical context, as well as current practice within the art and design arena. The fourth section highlights the use of chromic materials in art and design and the fifth the use of other related colour-change and illumination technology. The sixth section provides an overview of conductive materials and current design practice that combines the technologies. The final section discusses significant observations from the literature review.

Chapter 3

This chapter highlights the application mechanisms employed for designing with thermochromics on textiles. The chapter is divided into four sections that present the methods used for preparing specific thermochromic fabrics for testing in combination with heat-profiling circuits. The first section introduces the chapter and specific objectives. The second section describes the fabric selection for use in the research. The third section presents the leuco thermochromic dye systems prepared for application to the selected fabrics and related materials and describes the application method. The fourth section presents the liquid crystal dye systems prepared for application to the selected fabrics and related materials and describes the appropriate application methods.
Chapter 4

The chapter presents the research on the development of heat-profiling electronic systems to be used in combination with thermochromic fabric samples. The chapter is divided into seven sections. The first section introduces the chapter and objectives of the research. The second section discusses the heat-sink technology concept as a tool to activate change on the thermochromic fabric samples. The third section describes the design, development and optimisation of the heat-sink circuit technology. The fourth section describes the development of a prototype exploiting heat-sink circuit technology. The fifth section describes a workshop scenario in which textile designers exploit heat-sink circuit technology. The sixth section describes the design of track resistors for comparison of the heating effect achievable using this technology. The seventh section describes other circuit experiments relevant to the research.

Chapter 5

The chapter describes the design development and is divided into four sections that include design inspiration and final design concepts. The first section introduces the chapter and the objectives. The second section describes exploration of pattern to enhance the thermochromic fabrics. The third section describes key inspiration areas that informed the design process. The fourth section presents the final designs produced that have been informed by key research findings.

Chapter 6

The chapter presents the main conclusions drawn from the design research findings and presents a series of recommendations for future work.
Chapter 2 Literature Review

This chapter provides an overview of the context and current art and design practice in the use of thermochromic dye systems and related technology. It also presents definitions and appropriate information specifically required for developing the technology and science for the use and activation of thermochromic dye systems on textiles and related materials.

2.1 Chromic Materials

Chromic materials generally refer to materials which give rise to a change in colour because of an induction process caused by external stimuli. There is a wide range of such materials as shown in Table 2.1, which offer the potential for exploitation within a design context. The range of chromic materials can be classified depending on the stimuli that cause the colour change as illustrated in Table 2.1:

Table 2.1 Chromic materials

<table>
<thead>
<tr>
<th>Chromism</th>
<th>External energy stimulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermochromic</td>
<td>Temperature</td>
</tr>
<tr>
<td>Photochromic</td>
<td>Light</td>
</tr>
<tr>
<td>Electrochromic</td>
<td>Electricity</td>
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<tr>
<td>Piezorochromic</td>
<td>Pressure</td>
</tr>
<tr>
<td>Hydrochromic</td>
<td>Liquid</td>
</tr>
<tr>
<td>Carsolchromic</td>
<td>Electron beam</td>
</tr>
<tr>
<td>Chemochromic</td>
<td>Chemical</td>
</tr>
</tbody>
</table>

These responsive chromic materials can be in an ever-changing non-constant state, and can be categorised as ‘smart’. Defined by Tao (2001) smart materials and structures can be described as ‘materials and structures that sense and react to environmental conditions and stimuli, such as those from mechanical, thermal, chemical, electrical, magnetic or other sources. According to the manner of reaction, they can be divided into passive smart, active smart and very smart materials. Passive materials can sense environmental change or stimulus, active smart will sense and react to change or
external stimulus, and very smart materials can sense, react, and adapt to external stimulus.’ (pp. 2-3)

Chromic materials fit within the area of smart materials because of their inherent responsive nature. Addington & Schodek (2005) describe the principle of this type of smart material in that ‘they are designed to change with the input of external energy. The external input energy produces an altered molecular structure or orientation of substance on the surface of the material. When the external stimulus disappears, the structure reverts back to its original state’ (p.84)

It appears that smart materials started to be recognised for their potential over 10 years ago. Ball (1997) highlights that ‘smart materials represent the epitome of the new paradigm of materials science, where functional materials are superseding structural materials’ (p.104). Ball (1997) suggests that in the past a change in a material’s properties (such as its elasticity, its volume, or its colour) in response to a change in its environment would have been generally considered a problem. Devices with functions such as switching or relaying a signal are commonly made up of many components that are stable and do not change. There are ranges of smart materials today that can be categorised as smart at the simplest level in that they respond to their environment (within which chromic materials fit), suggesting they could replace more stable materials in design products (p.104).

2.2 Thermochromic Dye Systems

Traditionally these specialist materials have very specific uses in a commercial context. These commercial uses for thermochromic materials include, medical thermometers, thermal labels, and food hygiene products. There are relatively few manufacturers of thermochromics. Major manufacturers include LCR Hallcrest, UK, Gem’Innov, France, Color Change Corporation, USA, Matsui, Japan, and Americos, India (Christie et al, 2007).

LCR Hallcrest has 40 years of experience in the field of manufacturing temperature measuring devices (LCR Hallcrest, accessed March 2010). The information that follows was documented through personal communication with Russell Booth (November 2006) to gain an insight into the company, products and adaptations of thermochromic materials applicable to textiles. The business was originated in the production of irreversible thermochromic paints used in thermal surveys of mechanical parts; these products are still produced by the company. The company has diversified over 40 years
into other markets and also specialises in the microencapsulation of liquid crystals and leuco thermochromic dye systems and the development of temperature responsive indicator labels. The production of these temperature indicating devices requires that the thermochromic systems are sandwiched between a polyester film and a backing according to the application, the films can be screen printed and the finished films are die-cut into label shapes. These materials and manufacturing processes have been developed to fit certain application areas and were not developed with a textile application in mind. Thermochromic dye systems have not been designed for use on textiles (although there are leuco thermochromic dye systems and a specific binder that are recommended for use on fabric). Solutions for developing thermochromic systems for use on textiles were discussed, among these, the application of liquid crystal thermochromic systems on textiles. It was suggested in this discussion that the expense of the materials could be one of the main factors to restrict textile designers working with these materials and therefore their development for textile application has not been exploited (Booth, 2006). The principle that the design of the materials restricts their growth in the textile market is acknowledged by Towns (1999) stating ‘the textile sector generally lags behind other markets in the exploitation of thermochromic materials and ongoing research in the chemistry and technology of the dyes will be important to expand the range of materials available and to improve their performance’ (pp.196-99). It appears that the fundamental reason that the textile design field has not more readily exploited these specialist materials is that they were not developed for use on textiles. This would suggest the use of thermochromic dyes systems on textiles needs to be approached differently. They cannot be used in the same way as traditional dyes and pigments are used on textiles. Worbin (2006) highlights the need to design differently with these materials treating the whole design process differently.

Christie et al (2007) highlight that the dyes may also show limited stability in certain environments, leading to questionable longevity of design products. Another factor, which may have restricted exploitation in textiles, is the ingrained memory of their use in the past for novelty effects, presenting a psychological barrier to more intelligent and creative use in complex design systems.

2.2.1 Leuco and liquid crystal dye systems

The following section introduces the fundamental characteristics of thermochromic dye systems and the underlying science to inform potential design directions for experimentation with the materials. A feature of both thermochromic systems that have
been applied to textiles is the need for encapsulation that is essential to ensure that the materials are contained and to provide some protection against their environment, to which the materials may be sensitive (Bamfield and Hutchings, 2010, p.54).

(a) Leuco encapsulated thermochromic dye system

Leuco thermochromic dye systems are encapsulated systems that undergo a reversible change from coloured to colourless in a change that is stimulated by raising the temperature. The encapsulated particles contain a colour former, an acid and a low melting solvent. Increasing the temperature melts the solvent and this induces the chemical conversion, which causes the colour change inside the particle. Leuco thermochromic dye systems can be intermixed with traditional pigment inks, and this colour mixing can produce a colour change from one colour to another (Bamfield and Hutchings, 2010, pp. 54-57). A range of products with standard transition temperatures is commercially available in a variety of colours from 15°C, 29°C, 31°C and 47°C. Dyes with custom-made temperature thresholds are also available that range from -10°C to +69°C and these can be provided in special colours (Chromazone, accessed March 2010).

Research at Heriot-Watt University, School of Textiles and Design has evaluated the colour-change properties of thermochromic pigment-printed textiles using a unique system developed in the laboratories to measure colour as a function of temperature (Bryant, 1997). Christie et al (2007) suggest that this methodology potentially provides a unique tool for designers to establish the exact nature of the thermochromic colour changes and the temperatures at which these changes occur. The technique could for example be applied usefully to determine the temperature range over which leuco dye thermochromics change colour. The interpretation is relatively straightforward as it involves a simple interchange between two colours. Leuco thermochromic dyes, that are reported by the manufacturers as having similar temperature change ranges, have shown clearly that there are differences possibly due to differences in rates of change, or indeed to batch variation in the commercial samples. This variation may result in a multi colour-change effect, or a graduated colour change effect. It is common for designers to discover effects serendipitously, but the colour measurement method offers the facility to predict such effects for use as a design tool (p.6)
Makow (1991) describes a liquid crystal as ‘a substance in an intermediate state between a crystalline solid and a liquid, and, depending on the temperature, the substance may appear in any one of these states’ (p.126). A crystal is solid and has a structure that can be described as having positional and directional order, which is referred to as an anisotropic solid. An isotropic liquid has a structure that has lost its positional and directional order while a liquid crystal has a structure that has lost its positional order but has retained directional order. The fact that the molecules have directional order means they are oriented and in certain specific cases can reflect light, like crystals, giving rise, in certain circumstances, to brilliant colours (Makow, 1991, p.126) and (Collings, 1990, p.8).

Christie et al (2007) highlight that liquid crystal thermochromic dye systems work differently to the leuco dye systems as they can provide a continuously changing spectrum of colours with temperature change. The colour changes result from the way in which light interacts with the liquid crystals to produce coloured reflection by interference, and from the way the liquid crystalline structure varies with temperature (Christie and Bryant, 2005). There are two types of liquid crystal thermochromic dyes that are presently on the market, which can be used for application to textiles. Depending on how the molecules are oriented within the particular liquid crystal, they can be classified as either cholesteric or chiral nematic (Makow, 1991). The latter have been less commonly used for the application to textiles, maybe due to the fact they are more expensive, although they are reported to provide superior stability and produce a stronger ‘colour-play’ (Personal communication, Booth, 2006). According to (Hallcrest, 1991) the liquid crystals that are commercially available can be classified and understood by their temperature threshold, which refers to the initial temperature at which the liquid crystal is activated. The dyes also have a characteristic red start and mid-green temperatures and colour play bandwidths. The bandwidth is defined as the blue start temperature minus the red start temperature. The ‘colour play’ of a thermochromic liquid crystal is defined by specifying either the red start or the mid-green temperature and the bandwidth. For example R35C1W describes a thermochromic liquid crystal mixture with a red start at 35°C and a bandwidth of 1°C, i.e., a blue start 1°C higher, at 36°C (p. 7). In more general terms, the bandwidth relates to the rate at which the liquid crystals change through their spectrum of colours. For example, R35C20W has a red start of 35°C and a blue start 20°C higher, meaning
that it would exhibit its full colour play over a broader temperature range than R35C1W. Makow (1991) explains that ‘thermochromic liquid crystal microcapsules are commonly supplied dispersed in a polyvinyl alcohol binder and diluted with water, and they form slurry that resembles buttermilk’ (p.129). Through observation of the mixtures currently available this situation does not appear to have changed. Makow (1991) also highlights the use of free cholesteric liquid crystals (non-microencapsulated) that can be used to provide a thermochromic affect. He describes their appearance as a thick viscous liquid that never dries. They are not microencapsulated so they have to be protected by a transparent layer of thin film, such as Mylar, or suitable plastic or glass, that is sealed at the edges to prevent the impurities and oxygen from destroying the thermochromic effect (pp.127-128). This would appear to serve a similar function to microencapsulation. Observing the phenomena given by free liquid crystal behaviour through his creative exploration Makow (1982) reported that to achieve a desirable temperature range of colour play at the required temperature range, two or three liquid crystals could be mixed together. The result produced by this mixing is that original reflectance peaks of individual liquid crystals disappear and this results in a new single peak characteristic of a new colour (p.259). Makow (1991) further explains that the result is different when the liquid crystals are applied in layers, one over the other, with a thin transparent film between each layer. In this case, the two or three peaks are retained and they appear to the human eye as a single colour, as if they had been mixed additively (p.137). Interestingly, Makow (1991) observed similar characteristics of mixing colour when two or three different microencapsulated liquid crystals were applied to a substrate, one over another. He described the visual effect as producing colours by addition, similar to those produced by mixing coloured lights (p.137).

Previous research undertaken at Heriot-Watt University has led to an understanding of the fundamental principles of liquid crystal dye systems and presents the designer with informative technical data that has the potential to be exploited and expanded from a design perspective. Bryant’s (1997) research highlighted that cholesteric and chiral nematic liquid crystals can exhibit bright iridescent colours. However, for the reflected colours to be visible, it is necessary for the transmitted incident light to be absorbed. In practice, placing a thin film of the liquid crystalline material over a dark, ideally black background carries this out to best effect. For the full range of colours to be observed, as many of the transmitted wavelengths as possible must be absorbed, which is most effective using a black background (p.47). Christie and Bryant (2005) have reported the
effect of different coloured backgrounds on the optical and colouristic properties of liquid crystal dye systems known by the Licritherm brand name. Different coloured backgrounds were tested to show how the observed colour-change was affected. Using the instrumental colour measurement system, the results for each coloured background were plotted in an a*, b* diagram to illustrate the observed colours through a temperature range from 23-47°C. A brown background, for instance, shows that slightly richer colours were observed than the black control sample in the red, orange and yellow regions and also at the higher end of the temperature range reddish blues were also richer in chroma (Bryant, 1997). In design terms, these results offer scope to experiment with liquid crystals on different coloured backgrounds; the potential to produce subtle colour change effects through the use of different colour backgrounds has the potential to enhance the design aesthetics in the use of liquid crystals on textiles (Christie et al, 2007).

LCR Hallcrest is presently developing single colour activation (SCA) liquid crystal mixtures, which they currently do not market directly. They are, however, in the process of developing and beginning to offer new ranges of temperature indicating products containing these mixtures. In communication with Mike Parsley (December 2009) he highlighted the basic principles of these new mixtures. They are designed to show a single colour change over their working temperature range. The single colour is presented over the temperature range that is in the cholesteric liquid crystal phase. Usually, in normal (red/green/blue) cholesteric liquid crystal mixtures, the pitch length (of the helical arrangement of molecular layers) changes as the temperature changes. This is the effect that causes the wavelength of the reflected light to change. For the single colour mixtures, the pitch length is effectively held constant over the entire cholesteric range by reducing its sensitivity to temperature changes, i.e., reducing the optical activity. The advantage of the single colour cholesteric liquid crystal mixtures from a commercial perspective, is that they remove the need for subjective interpretation of subtle changes in colour, in working temperature indicating devices.

2.3 Thermochromics in Art and Design

Thermochromics are often used alongside other technologies creating opportunity for multidisciplinary practice. Drawing references from art, design and science gives a depth of understanding to the current trends for the use of smart materials in textile design in which thermochromic textiles fit. Parallels are demonstrated throughout art and design of the influence of science and technology on creative practice. The concept
of ‘smart textiles’ is currently having a significant impact on the design world, through the convergence of the disciplines of science, engineering and design. Berglin et al (2005) highlight that ‘progress in the area of smart textiles will to some extent depend on how successful we are in combining theoretical and experimental work in several different disciplines; from materials science, electronics and computer science to textile technology and textile design’ (p.47).

Projects such as ‘Nobel Textiles’ demonstrate that, through clever mediation of science and design, it is possible to create a unique dialogue between the two disciplines. Carole Collet (Course director MA Textile Futures, Central Saint Martins) curated and participated in the ‘Nobel Textiles’ project that brought together five Nobel Laureates with four leading designers, who were involved in research at Central Saint Martins. The designers responded to the dialogue with their Nobel laureate to produce innovative collections of work based on their translation of scientific discovery (Nobel Textiles, 2008). Geesin (2006) says ‘It is my hope that in the future art and design universities will form partnerships with science departments or have ‘in house’ disciplines which have overlapping interests. The combining of designers’ ideas and aesthetic awareness teamed with lateral thinking from chemistry, micro electronics, engineering and a healthy respect for complementary expertise is, in my view, the way forward’ (p.8).

There is currently a growing specialism at Heriot-Watt University, within design-led research, into the use of chromic materials and related technologies. This is complemented by expertise in colour chemistry that allows designers access to the latest technical knowledge of the application of these dyes on textiles and other related materials. The unique multi-disciplinary environment fosters cutting edge innovation with chromic materials through collaboration, knowledge transfer, in addition to links with industry.

2.3.1 Historical context

Forward-looking art movements have perennially been inspired by the cross-fertilization of science and art. As early as the 1920s, the Hungarian artist Laszlo Moholy-Nagy was profoundly influenced by the new technologies of his time. He had a particular fascination with light, colour and rapid developments in technologies such as photography and advertising displays, which informed his conceptualization and creative activity in a form of art, which he termed ‘kinetic optical composition’ (Moholy-Nagy, 1967). A fascination of this new form of art to create a third dimension,
a non-static picture plane, resulted in new kinetic experiments with light play. Creation of an experience that would force the observer to immerse him or herself, simultaneously comprehending and participating in the optical events was a new direction for art (p.20). Ludwig Hirschfeld-Mack contributed to the new artistic genre in his reflected colour displays, which employed the projection of coloured lights from freely-movable sources through opening and shutting apertures of a variety of shapes, his dynamic multicoloured creations being set to rhythmic musical accompaniment (Moholy-Nagy, 1967, p.81).

New ways for expression were presenting themselves in the 1960s to artists through technology and science. Rein Lemberg published the first literature on the aesthetic use of liquid crystals in 1968. Lemberg (1968) describes liquid crystals as responding with chameleon-like colour change. The literature describes processes for the application of liquid crystals to substrates (pp.45-50).

David Makow (1991) an artist and physicist began to use liquid crystals as a medium for art in 1972, after reading reports in scientific literature on their brilliant colours (p.123). Makow’s abstract paintings from 1972 onwards appear to demonstrate an in depth understanding of the materials. Figure 2.1 shows a painting by Makow (1991, p.403) in which he uses polymers with liquid crystalline properties (PLCs). Different colours can be seen in the liquid crystals from different viewing angles as shown in Figure 2.1. Makow’s (1991) work starts to develop methods of how to use liquid crystals creatively through his paintings, as shown in Figure 2.2. He has used encapsulated liquid crystals on a black substrate and a colour change is apparent at different temperatures (p.405).

In 1974, Yves Charnay started to explore the colour, temperature and the iridescent properties of liquid crystals. According to literature reports in the early 1980s, small pockets of artists started to work with these materials as a result of the appearance of publications on the subject (Makow, 1991, p.122).

Gustav Metzger, an artist and political activist, developed the concept of auto-destructive and auto-creative art. This concept proposed works that could self-destruct, to reflect political and social systems spiralling towards annihilation. The concept also concerned itself with the passing of time, for example the slow disintegration of a sculpture. Works included his pioneering use of liquid crystal projections created in the 1960s and reproduced for the ‘Gustav Metzger’ 2009 exhibition at the Serpentine Gallery, London. These light projections also convey his deep interest in science. The
liquid crystal environment consisted of a five-screen projection of light that shot through liquid crystals compressed between slides whose colours and viscous forms slowly mutate with the temperature fluctuation caused by a fan on the top of the projector (The Tate Britain, accessed 2010), as shown in Figure 2.3.

Figure 2.1: Semi abstract painting using polysiloxane liquid crystals partly covering an orange coloured substrate, David Makow (1991, p.403). The colour change of the image when viewed from the left (a) and from the right (b) is illustrated.

Figure 2.2 Abstract painting, David Makow (1991, p.405). (a) the painting at 19°C and (b) illustration of the colour-change at 22°C
Attempts have also been made to launch liquid crystal fabrics into the fashion arena dating back to the early 1990s. In 1991 a fashion show that celebrated the 150th anniversary of the Royal Society of Chemistry and demonstrated chemistry’s
contribution to fashion over the centuries, showcased the first garments printed with liquid crystal dye systems shown in Figure 2.4 (Coghlan, 1991).

2.3.2 Current practice
Today, smart materials continue to make available a range of new media for creative exploitation. The use of thermochromics to express colour change on a surface fits comfortably into the area of smart design.

Thermochromism has been exploited by a few designers who have been stimulated by recognition of the potential for novel design directions. An overview of some recent relevant design research is presented in this section. The overview deals with design where thermochromism has been directly utilised, and how thermochromism and related technologies have impacted on other dynamic patterning processes. Through the review of design in this niche area, over the period of the research described in this thesis it has become apparent that the use of thermochromics by designers has had an impact on design in more subtle ways. This section also presents work that demonstrates how the use of thermochromics has impacted on innovative practice in this area. A thermochromic design requires a means of application of the thermochromic dyes or pigments to a substrate, in conjunction with a heat generating system, which may, for example, involve simple sources such as human skin contact through to electronic circuitry of varying degrees of complexity. The latter approach combines the creative design process with the technologies of coloration and electronic engineering. Linda Worbin, a lecturer and researcher at the Swedish School of Textiles, has been involved in practice-based discourse through the development of experimental prototypes she describes as dynamically changing textile patterns to extend understanding of the usage and aesthetics of textile patterns in the area of smart textiles. Worbin (2006) has successfully employed thermochromic and other colour-change technology in her practice-based research, using traditional fabrics and printing processes, to develop responsive textile patterns in the area of smart and interactive textiles. In an interesting demonstration, she illustrates how a thermochromic fabric reacts to the warmth of a cup of hot water. The colour disappears in the regions in contact with the hot water as shown in Figure 2.5.
Worbin has worked in an experimental way with a variety of materials; through collaborative research she has used some highly innovative textile patterning techniques/processes, and advanced materials and technologies to create new “smart
materials’. Thermochromic, photochromic, conductive and electroluminescent materials have been used to create the changing or responsive part of the designs, used in combination with more traditional yarns and printing processes (Worbin, 2005).

Following the development of Worbin’s work over five years and from firsthand experience of her presenting her research, it is apparent that thermochromics have opened the door to experimental practice centred around generating innovative responsive materials, that have the ability to self pattern, reversibly or non reversibly. Through this research, Worbin highlights that compared to a traditional textile design process, where the textile pattern is translated from one medium to another, smart textile materials need to be handled in another way, treating the whole design process differently (Worbin, 2005). An example combines the expertise of Worbin and Anna Persson, also a researcher at The Swedish School of Textiles, is an inventive project that uses resistant yarn technology usually used in combination with thermochromic dyes in a textile structure to activate the thermochromic dyes. The project was inspired by earlier work, for example ‘Striped and Checked’, a weave that consisted of both traditional and conductive yarns and screen printed with thermochromic colours. Due to the construction of the electronic textile, when the power was switched on sparks were generated and the textile started to glow or burn, leaving permanent burn marks (Persson, 2009). The underlying technology normally used to activate thermochromic dyes and create a reversible pattern, i.e., resistant yarns, had thus been used to create irreversible patterns (Persson, Worbin, & Landin, 2008).

Zane Berzina explored the use of thermochromics as a metaphoric material that would act as living surface, mimicking human skin and its biology within her practice-led multi-disciplinary research entitled Skin Stories: Charting and Mapping the Skin (Berzina, 2005/6). An interesting outcome of her work is Touch-Me Wallpaper, a prototype multisensory interactive wall covering triggered by contact with the human hand as seen in Figure 2.7. A temporary handprint appears on a thermochromic surface, aroma-therapeutic fragrances are released, and the incorporation of phase change material allows storage and controlled release of heat, prolonging the thermochromic effect and allowing control of room temperature. Berzina has also experimented with what she describes as 'drawing' with electricity. In Sensory Screen, semi-conducting threads are incorporated between layers of thermochromic non-woven fabric. As a circuit connection is switched on and off intermittently, the thermochromic effect produces a line that appears and disappears. (Berzina, 2005, p.18) (Seymour, 2008).
Maggie Orth was the founder of International Fashion Machines (IFM), a company with a focus to produce flexible electronic art, which incorporates new technological concepts into consumer products. IFM have produced an electronically-activated colour change textile, *Electric Plaid*, which combines thermochromic printed textiles with
electronic circuitry, as shown in Figure 2.8. The circuits are woven into the surface of the fabric and activate the thermochromic effect when connected to a power supply. IFM's current direction appears to be leading towards products integrating electronics with textiles that can be used in the home, for example, in interior applications where the products function within the context of the home environment (McQuaid, 2005, pp.186-191).

Berzowska, a co-founder of IFM, has developed *Shimmering Flower*, which deploys thermochromic technology, conductive yarns and custom-designed computer-controlled electronic circuitry to create a non-emissive colour-change textile display as shown in Figure 2.9. The thermochromic effect is activated in areas of the design with individually addressable pixels, the colour change being programmed or controlled in real time. *Shimmering Flower*, woven on a Jacquard loom, allowed the creation of soft woven circuitry through complex weave structures.

*Krakow* is a further piece produced by Berzowska combining thermochromic and Jacquard weave technologies. In this case, human figures in the woven image change from black to transparent when the temperature rises, as can be seen in Figure 2.10. The connection to the power source is visible and adds to the aesthetic value of the design and understanding of the integration of technology in the piece. (Xslabs, accessed 2010)
Figure 2.9: Shimmering Flower, 2004, Joanna Berzowska, xslabs

Figure 2.10: Krakow weaving, Joanna Berzowska, xslabs
Architecture is an arena in which thermochromics are being employed in products for more energy efficient buildings. For instance, the creation of responsive buildings that exhibit the ability to self regulate temperature use smart materials to bring these ideas to reality. Emerging technologies such as thermochromic glazing are being developed to alter the colour of a building during the day. The use of these materials in this capacity could in principle help regulate the solar gain, and thus have an inbuilt ‘self-thermostatting’ capability. Thermochromics are able to adapt to their environment by altering properties, for example, thermochromic glazing changes transparency in response to changing temperatures. A product on the market, Cloud Gel Glazing, is a switchable thermochromic glazing. It automatically changes from clear to white in response to temperature. The product, Cloud Gel, is suspended between two sheets of glass (consumer energy center, accessed 2010). This new generation of windows is being referred to as “smart windows” because they adapt to changing conditions, offering a functional use for the properties of thermochromism. Analysis of the advantages and disadvantages of thermochromic glazing reveals that there is scope for further development in this very specialised and growing area (Addington & Schodek, 2005). Insight into the future use of thermochromics, not only for their aesthetic appeal, but also their environmental impact suggests that our houses could incorporate changes in colour. The materials library at, King’s College London has produced a thermochromic brick that changes colour as shown in Figure 2.11. These types of materials have the potential to impact on reducing consumption. For example, a house that changes from coloured to white when hot, will reflect more sunlight and, in principle, require less air conditioning. It is such considerations that may provide impetus for thermochromic research in these areas. (Miodownik, 2008)

Innovative use of thermochromic materials in architecture is an ongoing area of research. A number of projects demonstrate inventive and unconventional material combinations. Chris Glaister, Afshin Mehin, and Tomas Rosen used thermochromic ink mixed with concrete and a system of nickel chromium wires, linked to a power source which causes the wire to rise in temperature and thus provides the energy stimulus to the thermochromic concrete. Depending on the arrangement of wires, the surface has the potential to display graphics and information. (Interactive Architecture, accessed 2006)
The conceptual climate control tile developed in research, reported by Juliet Johnson, combines phase change material and thermochromic ink on the outer surface of the tile. The concept for its function is enabled through the ability of phase change materials to store heat and release excess when not needed; the combination with thermochromic ink makes it possible to produce a visual thermograph or heat map of the building. (Infotile, accessed 2006) Products such as these tiles could potentially be used to alter colour throughout the day with integrated control technology, giving a building skin the ability to regulate the degree of solar energy gain. With individual tile cells, it is conceivable that calibration of optimum colour-change temperatures would allow each cell to function at its maximum capability. The use of thermochromic materials on the exterior of a building offers immense design challenges. Bamfield and Hutchings (2010) highlight that currently, it is the case that thermochromic materials are susceptible to degradation by ultraviolet wavelengths and, therefore, long term exposure to sunlight would destroy the thermochromic effect. (p. 57)

2.4 Chromic Materials as used in Art and Design
There are few examples of the range of chromic materials in art and design; concentrating on the use of thermochromic and photochromic materials. Ritter (2007) highlights the work of the German Artist Sigmar Polke, who experimented, in the 1970s, in painting with materials that were capable of changing colour. In 1986, for the XLII biennale in Venice, Italy, Polke covered part of the inside of the Federal Republic building of Germany with a hydrochromic paint consisting of a water-bound cobalt chloride solution, as illustrated in Figure 2.12. The paint functioned by changing from
lavender blue through purple to rose red depending on the humidity (moisture in the air).

Figure 2.12: Sigmar Polke, Hygrowall, 1986.

Figure 2.13: Axel Ritter, ‘Hydrophil-hydrophob’, 1995.

Axel Ritter (2007), the author of the recent publication on smart materials in architecture, interior and design, has produced some interesting work, which appears to imitate a hydrochromic effect, without using a hydrochromic material. The work ‘hydrophil-hydrophob’ started in 1995 and is an ongoing project. This work is based on a liquid, silicone-based, transparent damp proofing agent applied in a pattern on cast-stone panels. The result is a semi-invisible pattern on the stone surface and through contact with water a contrasting light-dark effect, similar to the hydrochromic effect is produced as shown in Figure 2.13.
An example of recent research with a combination of chromic materials is due to Marie Ledendal who completed her MA in textiles at the Swedish School of Textiles in 2009, making use of both thermochromic and photochromic materials in her design based research. The research focused on how the materials may be used as an information bridge for isolated patients in healthcare environments. As a visiting scholar for a period of her MA at Heriot-Watt University, Ledendal extruded her own photochromic yarns for use as embroidery threads. The yarns are transparent and when they are exposed to UV light they become coloured. She used photochromic yarns for embroidery, photochromic dispersions for printing onto textiles; these were used in combination with thermochromic leuco dyes. This combination of chromic materials gave the textile designs a multi-responsive nature (Ledendal, 2009).

2.5 Related Colour/Lighting Technologies

There are examples of other technologies that can produce colour change and lighting effects. They are not chromic, as strictly defined, but are relevant to the area of research in this thesis, and offer alternative ways to explore colour-change. Colour-change/adaptive colour research often looks to nature for inspiration. A common term referring to mimicking nature or natural processes is ‘biomimetics’. Morphotex fibre inspired by nature is based on the principle of the iridescent wing scales of morpho butterflies. Figure 2.14 shows the intricate micro structure of the butterflies wings that creates colour. These micro structures have been embraced in an engineered fibre (Morphotex, accessed 2008).

![Figure 2.14: Micro structure of the morpho butterfly](image)

An advantage of this biomimetic principle is that it does not require the use of a dye or pigment so that the energy that would be required for the dyeing process is conserved.
The design of the wings’ surface enables light to be refracted and reflected, filtering out all other colours from the spectrum except blue (Lee, 2005). Nature offers diversity and amazing examples of the intricacies of colour change at a fundamental level. Inspiration for research is often provided by these real natural examples. Japanese researchers at the Fuji Xerox Company in Kanagawa have developed a polymer that switches between coloured and transparent when its environment changes, thus mimicking the way in which animals, such as squid and octopi, control their skin pigmentation patterns. The researchers have created a switchable window by sandwiching the polymer between two glass plates. Heat controls this window, just as electricity switches a liquid crystal display. Other volume-changing gels can be switched by different stimuli, such as light, chemicals, or electric fields. The report suggests that it will be possible to make smart windows that respond to many different triggers. These type of polymers offer other advantages compared with other heat-sensitive or light-sensitive inks, in that any colour can be selected simply by varying the pigment that is loaded into the gel. (Nature News, accessed 2011)

Loop.pH is a London based design and research studio that aims to bridge the gap between design and natural sciences. They specialise in the conception, construction and fabrication of environmentally responsive textiles for the built environment, directed by Rachel Wingfield and Mathias Gmachi. Wingfield’s design work brings technology and science together with traditional textile/craft techniques that emulate natural phenomena. Wingfield is also known for her work with electroluminescent technology (Loop.pH, accessed 2007). Digital Dawn is a reactive blind produced by Wingfield, which is printed with an electroluminescent system that glows brighter and grows when the space around it becomes darker as shown in Figure 2.15. Printed with climbing leaf like patterns, it gives technology a decorative familiarity. Wingfield’s ‘Digital Dawn’ was part of the V&A’s ‘Brilliant’ exhibition in 2004 that showcased innovative lighting. The exhibition engaged designers and the public with the lyrical potential of light. Ranges of dazzling installations showed designers work evolving an aesthetic vocabulary from new technologies such as fiber optics and LEDs. Using shadow play and projection, and by exploiting the possibilities of materials, technologies and visual effects, leading designers revealed through the exhibition how light may be a powerful shaper of space (Pavitt, 2004). Technologies such as electroluminescence are particularly interesting as they are printable, giving the designer, effectively, the means to print light. The process involves screen-printing
several layers of materials on to a conductive polymer fabric/substrate. This ultimately results in a conductive decorative light emitting surface pattern. Wingfield worked in collaboration with Elumin8, who specialised in printed electroluminescent technology.

Figure 2.15: Digital Dawn, light reactive window blind, 2000 (Left) and Blumen Wallpaper, electronic wallpaper display, 2004 (Right), by Rachel Wingfield

2.6 Conductive Materials

Rapid advances in the area of flexible electronics and the emergence of various new conductive materials offer the textile designer enhanced means to integrate electronic technology. Technology is constantly pervading our lives and these technological artefacts commonly combine conductive materials to some degree. Research applied to creating technological artefacts that could make the space we inhabit more meaningful and, more interactive, is ongoing. This research appears to be mainly centred on wearable electronics, an area of research that has been growing due to the technical advancements in fields ranging from conductive fabrics to improved miniaturisation of components. Projects focused on wearable technologies have made some progress in exploring seamless integration of electronics and conductive materials. “The emphasis of technology should be on its uses, it should surprise and add magic” (Papadopoulos, 2005). Companies are forming based on new integral technology and logistical construction techniques. The manufacture of garments with added electronic functionality requires incorporation of viable joining methods for both the textiles and any wire interconnections (Jones & Wise, 2005). Highlighted in this section are materials and processes that are of particular interest and relevance to the development of adaptable electronic systems.

Electric conductivity is apparent in many materials. It is possible to create a conductive surface through coating or adaptation of the surface. A conductive material requires
current to flow. The function of current may be summarised as follows. When a voltage, U is applied between two points on a material an electric field, E, is set up. Electrically charged particles in the material experience an electrostatic force in the direction of the electric field equal to the product of their charge and the electric field. If the charges are free to move, the force causes them to drift through the material. The rate at which the charge is transported is known as electric current, I. Of particular interest for application to the research described in this thesis are conductors that have high resistance, for instance ferric metals such as steel. Steel is used in resistor applications, for example in heated blankets and heated elements in electrical products. The resistance of an electrical conductor depends on four factors: the length of the conductor, the cross-sectional area of the conductor, the type of material and the temperature of the material. The electrical resistance of a material is a measure of its opposition to the passage of electric current. This opposition causes energy loss as heat to a greater or lesser extent in different materials (Bird, 2003). This heating function can be predicted, and may be exploited in combination with thermochromic inks on a surface.

Conductive materials vary in resistivity; the unit of electric resistance is the ohm (Ω), where one ohm is one volt per ampere of current. It is defined as the resistance between two points in a conductor when a constant electric potential of one volt applied at the two points produces a current flow of one ampere in the conductor. (Bird, 2003)

An important impact that resistance has is on the current and voltage required to produce the heating effect. Any conductive yarn or other material has the potential to heat up. For example if a yarn has a lower resistance per cm, it will require a lower voltage (but higher current) compared to a yarn/material with a higher resistance per cm. Experimentation with voltages and currents is required for particular yarns/materials to generate the desired temperature rise. It is possible to estimate the required current and predict temperature rise for particular yarns with the gauge (diameter) of the yarn and also the length of yarn that might be used in a particular structure (Fletcher, 2009).

2.6.1 Metals

Noble and coloured metals are attractive. They have an association with warmth and luxury so using them as a design medium is common. Attracted by gold’s powerful aesthetic properties, artists Joan Morris and Michele Ratte invented a method for
adhering metals that include gold, silver, platinum, copper and aluminium to substrates such as textiles (Hubbell, 2005). The invention was granted a US patent in 2006, which describes various processes that involve a light-sensitive (or photo-sensitive) bonding material, such as an emulsion or a photopolymer film, that is used to cause a metal to directly adhere to a substrate to provide various forms of metal coatings (Morris & Ratte, 2006). Morris and Ratte (2006) developed a screen-printing method for applying metals to a textile substrate, which is described in the patent; the process involves initially screen-printing a pattern onto the textile with a photo emulsion. While the emulsion is wet, a layer of gold leaf is applied to the surface of the fabric to cover the whole printed area. The printed, gold-covered surface is then covered with a wax paper and an even pressure is applied to the entire area, facilitating the bond between the metal and the emulsion. The wax paper is removed and the printed fabric is dried in the dark. The fabric is then exposed to UV light to harden the emulsion and form the bond between the metal and textile. The excess metal leaf is removed with a soft bristle brush to reveal the pattern. The result of this process is shown in Figure 2.16.

Figure 2.16: Green and gold textile, Joan Morris/Michele Ratte, 2002, 23 karat gold, mono print on dyed silk.
As discussed in the previous section, stainless steel exhibits high resistance and may be used in the creation of conductive fabric surfaces with inbuilt heating potential. Alloys such as nickel-chrome are of high resistance and can be incorporated into a textile surface. Nickel chrome is available in the form of fine wires or foils and can be applied through thin film technology. Copper, silver and gold are more conductive than steel and so have a lower resistance. This does not rule out their use in the design of heating circuit patterns, as they can be used in combination with resistors. Also it is possible to create resistance within a circuit by its design. Copper is commonly used in the manufacture of circuit boards and has beautiful design qualities. It is possible to design circuits produced using copper that produce enough resistance to cause a temperature rise. These circuits can be produced on a flexible substrate via the same method as printed circuit boards (PCBs) (McCulloch, 2006).

2.6.2 Conductive technologies

Engineered fabrics may become the answer to new flexible, soft electronics if used in innovative ways. Sauquoit Industries have developed a fabric, ‘Circuitex’, a finely etched detailed metalized circuit applied to fabric. The process is similar to the production of PCBs (printed circuit boards) (Noble biomaterials, accessed 2010). Silver coated nylon, also produced by Sauquoit, is used in the development of woven sensors and switches. These sensors and switches have uses in different applications from medical devices to control interfaces for wearable electronics.

Convergence of tradition and technology is beautifully demonstrated in the textile surfaces produced by the Nuno Corporation, led by Reiko Sudo. Sudo describes a process in which Nuno adopt ‘inappropriate technologies’ from outside the textile industry to create unprecedented new fabrics. Nuno’s stainless steel series uses a plating technique employed in the car industry. Polyester fabric is spattered with tiny particles of nickel, iron and chrome which fuse into an alloy on surface contact, as illustrated in Figure 2.17 (Millar, 2005). The surface of the fabric resembles liquid steel, giving the cloth a luster of a type only associated with metal.

There are several companies working in the area of soft circuitry. Eleksen, recently acquired by Peratech Ltd, appears to be at the forefront of commercial success with its ‘ElekTex’ electro textile. The touch sensitive interactive textile can be integrated into products to create a soft control panel, a soft interface device. This product is 100%
fabric and has no wires within the layered conductive construction. (Eleksen, accessed 2009).

Figure 2.17: Stainless steel series, 100% polyester and metal plating, Nuno
Electroplating is another method of creating a conductive surface. An example of electroplating used in design is demonstrated in Frances Geesin’s pioneering work. Inspired by text and images of hollow nano capsules designed for drug release, Geesin has created work that emulates these structures and patterns revealed only with an electron microscope. An example of this work is shown in Figure 2.18. Geesin explains that exposure to nanoscience has enabled the development of new work and thinking, a complex layered world of mystery identified by scientists, which can make visible through art works (NanoArt 21, accessed 2010). Other works by Geesin are represented at the Science Museum London, for example Electroplated mug (2002), which is made of knitted polypropylene and electroplated with copper.

Anna Persson of the Swedish School of Textiles is involved in research focused on knitted circuits for visual and tactile interactive expressions. A feature of Persson’s experimental practice-based research is a collaborative project in which she creates electrical burn-out patterns in a knitted textile. The aim of Persson’s research is to explore techniques for the development of textile circuits and design of dynamic textile patterns, bringing together conductive technologies and heating wires that can be knitted with different traditional textile materials (Persson, 2009).

Printed circuit boards (PCBs) and printable conductive inks are particularly interesting in the context of the research described in this thesis, taking into account the researchers background in printed textiles. Leah Buechley has developed a method for creating cloth printed circuit boards (fabric PCBs) and designed the commercially available LilyPad Arduino toolkit (MIT Media Lab, accessed 2010). The LilyPad Arduino is a microcontroller board designed for wearables and e-textiles as shown in Figure 2.19. It can be sewn to fabric and incorporates mounted power supplies, sensors and actuators with conductive thread (Arduino, accessed 2010).

Matthew Fallas work with printed conductive inks brings together technologies in an interactive product. Connect...draw...remix uses conductive ink to enable the control of music using a simple pencil as shown in Figure 2.20. (Matthew Falla, accessed 2010).
Conductive inks (also referred to as polymer thick films) using DuPont microcircuit technology can consist of silver flakes or spheres, a blend of carbon/graphite particles or a blend of silver flakes/carbon particles. When these flakes or particles are suspended in
the polymer binder formulation, they are randomly spaced through the liquid. Once the solvent is evaporated, the particles condense or coalesce, forming a conductive path or circuit. Of the available conductive materials, silver is the least resistive and the most expensive, while carbon/graphite offers the best combination of low resistance and low price. Carbon resistor ink, which can be screen-printed, is available in this range, and it may be possible to apply this ink to a textile surface to create a patterned circuit. Carbon as a conductor is also available in other forms such as fibre, but an issue is that inclusion of carbon in fibre or polymer inevitably imparts a black colour to the end product (DuPont Microcircuit Materials, accessed 2010).

2.7 Discussion
Collaborative research that brings together design, science and technology is a feature that recurs throughout the literature review contained in this chapter. Science offers new ways of thinking about how we design, and uncovers the underlying principles of materials. The variety of examples that have been reviewed all offer insight and a depth of understanding that is essential in the use of new technologies and materials that have played a vital part in the context of the research described in this thesis and affirmation of the successful results that have emerged from multi-disciplinary work. Designers and artists bring new form and aesthetic beauty to materials that are derived from advances in science and technology; they are able to show them in a new light through creative intervention. The techniques used to apply materials emerging from different disciplines offer new ways to create a surface/structure. The designer/artist translates the approach of the application techniques to satisfy their specific needs. The unique approaches that are developed from these multi-disciplinary projects appear to lead inevitably to innovative and forward thinking work. These collaborations between artists/designers and scientists have been essential in developing contemporary thinking around the future direction of textiles, and potential relationships with other disciplines within science and technology opens up even more new possibilities for design. Through the study and analysis of the literature described in this chapter, a deeper understanding of the relevant science and technology has inspired the design direction of the research carried out and described in this thesis. The design research process has been directed through the understanding of the function of thermochromic materials from a technical perspective. Specific technical literature and access to expertise has highlighted possibilities that may have otherwise been overlooked from a design perspective.
Thermochromics and photochromics are highlighted in section 2.1 as being the most commonly documented of the range of chromic materials. The use of chromic materials in design remains limited by availability of the materials and technical information. It is difficult in the absence of collaboration with technical experts to find significant information on the range of chromic materials, and there are limited examples of their use within a design context. Chromic materials can be categorised as ‘smart materials’. However, many ‘smart materials’, either themselves or as part of a design system, have been defined in relation to wearable electronics. These categories include functions that describe sensors, actuators and controlling units. The current defined parameters suggest that smart materials can be classified into three categories that include passive smart, active smart and very smart materials. Based on these definitions, it is possible to start to categorize designs that may include chromic materials as smart materials. Passive smart materials encompass chromic materials, as the inherent function of the material is a sensor of external stimuli. They are also ‘active smart’ as they both sense and act on external stimuli through the function of colour-change, which is the optical signal. Chromic materials, combined with electronic systems that can control the integral functions of the materials through digital means, allowing them to adapt and be adapted means that they have the potential to be categorized as very smart materials. In summary, chromic materials may be categorized as both passive smart and active smart, and with appropriate integrated technology, have the potential to be very smart.

The knowledge obtained from the literature review on thermochromic dye systems given in section 2.2 has highlighted that exploitation of these specialist dyes in textile design is limited by several key factors. These include the stability of the thermochromic dye systems that have a limited lifespan compared to traditional dyes. They are degraded by environmental stimuli such as exposure UV light at a faster rate than other dyestuffs. The limited lifespan may also have encouraged their use in novelty products, creating a short-term gimmick to keep consumers amused, but this, in turn, may have created barriers for more intelligent and creative design with thermochromics. A poignant article ‘The time for thermochromics’ states that “thermochromics are superstar materials often reduced to slumming it as a hot beverage sideshow” (Miodownik, 2008). There is generally a lack of technical information directed at designers for the use and potential of thermochromic materials. This means that designers often have to take a trial and error approach when using thermochromic
dye systems, and it could be said that this inhibits a more rigorous enquiry into the capability of the materials. A question that arises from this discussion is: how can the design profile of thermochromic materials be elevated to establish a more widespread and intelligent use of this ‘superstar material’ from collaboration with academic and industrial technical experts?

Both types of thermochromic dye systems, the leuco dye type, that change from coloured to colourless with temperature change, and the liquid crystal type that changes through a spectrum of colours with temperature change, offer immense design potential through their specific function as highlighted in section 2.2. Established experience with leuco thermochromic dyes, and discussion with collaborators at LCR Hallcrest provided key information and direction on their use for textile application. Through the review of literature, it became clear that there was less documentation on the use of the liquid crystal dye types in design, and this offered a challenge for uncovering their potential. A significant avenue for the design exploration of thermochromics, highlighted in section 2.2 points towards the potential for the utilisation of the range of activation temperatures. The literature highlights the different colour-change properties of both types of thermochromic dye systems, which in turn point towards the potential to create more complex layers of change on a surface through judicious selection of dye combinations. With reference to section 2.2 (b) the layering of different temperature threshold liquid crystal dye systems has interesting and unexploited design potential. The potential to achieve an additive colour gamut when layers of liquid crystals, with different activation temperature thresholds are superimposed, but separated from each other, is suggested by David Makow from the 1970s onwards. As the liquid crystal thermochromic dye systems are produced in microencapsulated slurry, they can be applied in separated layers exploiting these possibilities. An observation of the research reported by Lemberg and Makow that dates from the late 1960s, suggests this to be the basis of the commercial exploitation of liquid crystal dye systems. The fundamental research reported by Lemberg and Makow does not appear to have progressed significantly through further intervention, meaning the approach to the treatment and application of liquid crystals is the same 42 years on.

From the examples identified in this review, that combine electronics and thermochromics, it is apparent that there is a heavier weighting of research focused on
the conductive yarns and an electronic textile structure, than on the thermochromic materials/surface they were intended to activate. The conductive textile control mechanisms have been developed as a means in particular projects to activate a dynamic pattern. The thermochromic dyes systems are applied to the conductive surfaces via screen-printing or a similar process, a process which is additive to a highly developed textile. These technology combinations build surfaces that have not been fully explored for the aesthetic potential, taking account of the complexity of the available thermochromic dye systems. Previous research has created responsive patterns that can be activated and controlled, but fail to fully exploit the complete range of possibilities available through thermochromism. Thermochromic fabrics that in their own right, have an intelligent complexity, in terms of their combination and colour change abilities, appear not to be represented fully within design.

Another focus of current research within the field appears to be on technological function rather than optimising the aesthetic qualities. For example, there has been an emphasis on creating surfaces that mimic pixel displays rather than conceptualisation on more abstract qualities. The aesthetics have almost been dictated by technology and a quest to create an artefact approaching an LCD screen (liquid crystal device) on a textile surface. These ideas are all valid but, when knowledge of such advanced technology exists, surely it is vital to focus research on aesthetic qualities and design that suggests new communicative and functional qualities. Thermochromism undoubtedly offers new ways to design technologically smart surfaces that can change, adapt and are original.

Related technologies offer other ways to explore colour-change and lighting effects. Some of these are based on biomimetic research, for example the Morphotex fibre designed to mimic the morpho butterflies iridescent wing scales, highlights technology that creates colour without the need for dye. The use of structure to create colour has relevance within the research as the molecular structure and the way light interacts with that structure within the liquid crystal thermochromic dye systems creates the observed colour and, therefore, has significance in designing with the materials. The leuco thermochromic dyes have a designed molecular function that, on heating, causes a chemical conversion to change the observed colour. These structural changes have influenced the design thinking on how these materials have been used and the design concepts. Materials that are capable of emitting light can inform ways to integrate
technologies; printable electroluminescent light, for example, is a screen printed circuit and light source that can be applied to a flexible substrate.

The literature reviewed on thermochromics in art and design and conductive technologies provides a breadth of understanding of the techniques and methods required for integrating electronic technologies alongside thermochromic materials. The review reveals that significant work has emerged on the integration of conductive and resistant yarns through woven or knitted textile structures. These methods offer a fully flexible textile with an integral conductive system. The review of previously-reported and ongoing research has provided an essential base for the new research which is described in this thesis. It is important, however, that within practice-based research, creative exploration must point to the future, ask new questions, and exploit potential new directions for research, with thermochromics in this case exploiting access to expertise such as colour and electronic technology.
Chapter 3 Application and Finishing Methods

3.1 Introduction and Objectives

This chapter presents the application methods for preparing thermochromic fabric samples and related materials to be used in conjunction with heat-profiling circuits. The research benefitted from technical know-how, access to specialist materials and facilities including printing formulations and methods of application from thermochromic dye manufacturers, LCR Hallcrest. Collaboration, over the three-year period, provided a unique opportunity to gain knowledge of both liquid crystals and leuco dye systems. The main objectives were:

- to prepare a selection of sourced fabrics and related materials through screen-printing and coating, with the leuco and liquid crystal thermochromic dye systems, potentially applicable to interior environments;
- to explore the methods of formulation and application of liquid crystal thermochromic dye systems to fabric and related materials;

3.1.1 Design decisions

To explore design potential with thermochromic dye systems, methods for applying them to fabrics were needed in order to establish knowledge and understanding of how they could be used on textiles. Existing research did not provide technical information on how to approach print paste formulation or application methods. At this stage of the research a technical approach was adopted in order to produce a range of thermochromic fabrics. LCR Hallcrest provided a wide range of different temperature threshold dyes that were activated between 15 and 60°C. The higher temperature thresholds needed mechanisms with which to activate them, and thus a series of PCBs were produced in order to explore the visual qualities achievable with the thermochromic fabrics. Chapter four describes the development of the circuitry for activating the thermochromic fabrics. The design decisions at this stage were mainly focused on fabric selection, for example, fabrics were selected for a number of reasons:

- for an interior context due to high temperature thresholds of some of the thermochromic dyes;
- underlying circuitry would not be integrated and therefore fabrics needed to be opaque to obscure the underlying electronic system;
- thermochromic fabrics offer interest for interior applications in terms of their response to temperature change;
3.2 Fabric Selection

The selection of fabrics and related materials was determined to a significant extent by the inherent differences in function of each of the thermochromic dye systems. Technical information as described by Bryant (1997) and Makow (1991) in the literature review suggested choices of black or dark coloured backgrounds for the application of liquid crystals. Similar weight and textured fabrics appropriate for interior applications were selected. The design direction was based on the author’s previous experience using thermochromics and findings from the review of literature that highlights the development of design work and products for interior environments. Plastic materials were also selected that could potentially be used in product development. Plastics were selected from those already used in commercial thermochromic product applications with both types of thermochromic systems. It was therefore possible to access key technical information on the application of both thermochromic systems and adapt this information and expertise for a design-led approach.

3.2.1 Fabrics and related materials for leuco dye application

A range of five materials was selected for the application of leuco thermochromic systems, three fabrics: (1) and two plastics: (2):

1: Furnishing weight white cotton, medium weight merino wool, and a non-woven phase change material (PCM).
2: A transparent and semi-transparent 100µm polyester film.

The phase change materials inherent function to store and release heat was of particular interest, in particular to establish how this function might be used to prolong colour-change.

3.2.2 Fabrics and related materials for liquid crystal dye application

A range of five materials were selected for the application of the liquid crystal thermochromic systems that would potentially provide interesting surface qualities when combined with various finishing methods. Good quality black fabrics were chosen to achieve the strongest ‘colour-play’ as required by the function of the liquid crystals: black brushed cotton (medium weight), black wool felt (medium weight), and
black waxed cotton, a thin transparent polyester film currently used for commercial liquid crystal products; and black leather effect paper (100gsm).

3.3 Application of Leuco Dye Systems

Leuco thermochromic dye systems are comparable in some ways to traditional pigments. For example, they can be handled in similar way, and can be combined with the traditional binder systems used for pigments. The thermostar binder is recommended for use with the commercially available Chromazone leuco thermochromic dye systems. It is similar to a transparent standard binder (Bricoprint SF20) a polyacrylate, aqueous binder for use in pigment printing, which may also be used with the leuco dyes. Similar to traditional pigments, the leuco thermochromic dyes are commonly supplied in a concentrated slurry form, which has a thick, viscous consistency. The colour slurry is added drop-wise to a ready-mixed binder to achieve the required colour strength and mixed thoroughly with a spatula. Leuco thermochromic slurries can be mixed together with traditional pigment slurries to achieve a colour change from one colour to another depending on the nature and proportion of colours used. Opaque binders, that are commercially available for use in a pigment printing system, can also be used with leuco dyes. It is recommended to follow the formulation guidelines for use with traditional pigments, incorporating the thermochromics according to the desired effect. For example, if a pastel shade, opaque colour is required; opaque white binder can be added to the standard binder. Incorporation of 50% opaque white binder into the formulation can be adequate but sampling is always necessary. With some colours, up to 70% opaque white is necessary to achieve fully opaque coverage. This can result in a stiff handle to the final fabric. When using opaque white binder combined with the leuco thermochromic dyes, the colour-change proceeds from its designated colour to white as the temperature is raised.

The leuco dye systems that were used in this research were supplied by LCR Hallcrest in standard colours: blue, black, red, magenta, green, orange, and non-standard colours: turquoise, brown, purple and yellow. These colours are available in the following standard response temperatures: 15°C, 29°C, 31°C, and 47°C. The colours that were available for use in this research were mixed in several batches due to their availability and to benefit from the findings from each batch. The batches were mixed with different colour to binder ratios and different temperature threshold thermochromics to create different temperature responses (colour-change) when combined with electronic heat-
profiling circuitry as described in chapter 4. LCR Hallcrest recommended the ‘Thermostar’ binder for use with their leuco thermochromic dye systems for textile application.

Batch 1 samples of the leuco thermochromic dye systems were mixed using a 1:5 ratio of colour to binder and consisted of the standard seven colours: blue at three temperature responses 15°C, 31°C and 47°C, red at three temperature responses 15°C, 31°C and 47°C; black at two temperature responses 31°C and 47°C; green at 31°C; magenta at 31°C; and orange at 31°C as shown in Table 3.1

Table 3.1 Batch 1: Leuco thermochromic dye colour mixtures prepared for testing.

<table>
<thead>
<tr>
<th>Thermochromic colour and temperature response</th>
<th>Amount of colour (Chromazone)</th>
<th>Amount of Binder (Thermostar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 Blue 15°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.2 Yellow 15°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.3 Black 47°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.4 Red 15°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.5 Red 47°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.6 Red 31°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.7 Magenta 31°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.8 Black 31°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.9 Blue 47°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.10 Blue 31°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.11 Orange 31°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
<tr>
<td>1.12 Green 31°C</td>
<td>6 g</td>
<td>30 g</td>
</tr>
</tbody>
</table>

Batch 2 samples combined two colours of leuco thermochromic dye systems with different temperature thresholds to explore multi-colour change effects, as shown in Table 3.2.

Table 3.2 Batch 2: Leuco thermochromic colour mixtures prepared for testing.

<table>
<thead>
<tr>
<th>Thermochromic colour and temperature response</th>
<th>Amount of colour (Chromazone)</th>
<th>Amount of binder (Thermostar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermochromic colour and temperature response</td>
<td>Pigment base and amount</td>
<td>Amount of colour (Chromazone)</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>-------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>3.1. Red 47°C and Blue 31°C</td>
<td>Light blue (8g)</td>
<td>Red (3g)/ Blue (4g)</td>
</tr>
<tr>
<td>3.2. Black 47°C and Green 31°C</td>
<td>Yellow (15g)</td>
<td>Black (4g)/ Green (8g)</td>
</tr>
<tr>
<td>3.3. Blue 47°C and Orange 31°C</td>
<td>Orange (8g)</td>
<td>Blue (6g)/Orange (5g)</td>
</tr>
</tbody>
</table>

Batch 3 samples combined two leuco thermochromic dye systems using different temperature thresholds and a base pigment colour as shown in Table 3.3. The bricoprint (SF20) standard transparent pigment binder was used in conjunction with a base pigment colour. These samples were prepared to further explore multi colour-change effects.

Table 3.3 Batch 3: Leuco thermochromic colour mixtures.

Batch 4 samples were prepared on site at LCR Hallcrest in a 3:5 ratio of colour to binder. This batch contained binders that were suitable for printing plastics in combination with the thermochromic leuco dye systems of non-standard colours with high temperature thresholds of 47°C. The thermochromic leuco dyes were mixed with a recommended polyvinyl alcohol based binder to allow adhesion to the plastics. This particular batch is not detailed here because of the numbers involved and their
experimental nature, although several were useful in the evaluation of the electronic circuitry described in Chapter 4.

Batch 5 samples were prepared to illustrate the range of full strength colours, at 1:1 ratio colour to binder, 3:5 ratio colour to binder and 1:5 ratio colour to binder as shown in Table 3.4. The addition of opaque white binder as shown in Table 3.5 and Table 3.6 to the full strength range of colours created a selection of pastel shades.

Table 3.4 Batch 5a: Leuco thermochromic colour mixtures.

<table>
<thead>
<tr>
<th>Thermochromic colour and temperature</th>
<th>Amount of colour (Chromazone)</th>
<th>Amount of binder (Thermostar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1. Magenta 31°C</td>
<td>10g</td>
<td>10g</td>
</tr>
<tr>
<td>5.2. Magenta 31°C</td>
<td>6g</td>
<td>10g</td>
</tr>
<tr>
<td>5.3. Magenta 31°C</td>
<td>2g</td>
<td>10g</td>
</tr>
<tr>
<td>5.4. Red 31°C</td>
<td>10g</td>
<td>10g</td>
</tr>
<tr>
<td>5.5. Red 31°C</td>
<td>6g</td>
<td>10g</td>
</tr>
<tr>
<td>5.6. Red 31°C</td>
<td>2g</td>
<td>10g</td>
</tr>
<tr>
<td>5.8. Orange 31°C</td>
<td>10g</td>
<td>10g</td>
</tr>
<tr>
<td>5.9. Orange 31°C</td>
<td>6g</td>
<td>10g</td>
</tr>
<tr>
<td>5.10. Orange 31°C</td>
<td>2g</td>
<td>10g</td>
</tr>
<tr>
<td>5.11. Blue 31°C</td>
<td>10g</td>
<td>10g</td>
</tr>
<tr>
<td>5.12. Blue 31°C</td>
<td>6g</td>
<td>10g</td>
</tr>
<tr>
<td>5.13. Blue 31°C</td>
<td>2g</td>
<td>10g</td>
</tr>
<tr>
<td>5.14. Green 31°C</td>
<td>10g</td>
<td>10g</td>
</tr>
<tr>
<td>5.15. Green 31°C</td>
<td>6g</td>
<td>10g</td>
</tr>
<tr>
<td>5.16. Green 31°C</td>
<td>2g</td>
<td>10g</td>
</tr>
<tr>
<td>5.17. Black 31°C</td>
<td>10g</td>
<td>10g</td>
</tr>
<tr>
<td>5.18. Black 31°C</td>
<td>6g</td>
<td>10g</td>
</tr>
<tr>
<td>5.19. Black 31°C</td>
<td>2g</td>
<td>10g</td>
</tr>
<tr>
<td>5.20. Purple 31°C</td>
<td>10g</td>
<td>10g</td>
</tr>
<tr>
<td>5.21. Purple 31°C</td>
<td>6g</td>
<td>10g</td>
</tr>
<tr>
<td>5.22. Purple 31°C</td>
<td>2g</td>
<td>10g</td>
</tr>
<tr>
<td>5.23. Turquoise 29°C</td>
<td>10g</td>
<td>10g</td>
</tr>
<tr>
<td>5.24. Turquoise 29°C</td>
<td>6g</td>
<td>10g</td>
</tr>
<tr>
<td>5.25. Turquoise 29°C</td>
<td>2g</td>
<td>10g</td>
</tr>
</tbody>
</table>
Table 3.5 Batch 5b: Leuco thermochromic colour mixtures with the addition of opaque white.

<table>
<thead>
<tr>
<th>Thermochromic colour and temperature</th>
<th>Amount of colour (Chromazone)</th>
<th>Amount of binder (Thermostat)</th>
<th>Amount of binder (Opaque white)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.29. Magenta 31°C</td>
<td>10g</td>
<td>10g</td>
<td>5g</td>
</tr>
<tr>
<td>5.30. Red 31°C</td>
<td>10g</td>
<td>10g</td>
<td>5g</td>
</tr>
<tr>
<td>5.31. Orange 31°C</td>
<td>10g</td>
<td>10g</td>
<td>5g</td>
</tr>
<tr>
<td>5.32. Blue 31°C</td>
<td>10g</td>
<td>10g</td>
<td>5g</td>
</tr>
<tr>
<td>5.33. Green 31°C</td>
<td>10g</td>
<td>10g</td>
<td>5g</td>
</tr>
<tr>
<td>5.34. Black 31°C</td>
<td>10g</td>
<td>10g</td>
<td>5g</td>
</tr>
<tr>
<td>5.35. Purple 31°C</td>
<td>10g</td>
<td>10g</td>
<td>5g</td>
</tr>
<tr>
<td>5.36. Turquoise 29°C</td>
<td>10g</td>
<td>10g</td>
<td>5g</td>
</tr>
<tr>
<td>5.37. Yellow 31°C</td>
<td>10g</td>
<td>10g</td>
<td>5g</td>
</tr>
</tbody>
</table>

Table 3.6 Batch 5c: Leuco thermochromic colour mixtures with the addition of opaque white.

<table>
<thead>
<tr>
<th>Thermochromic colour and temperature response</th>
<th>Amount of colour (Chromazone)</th>
<th>Amount of binder (Thermostat)</th>
<th>Amount of binder (Opaque white)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.38. Magenta 31°C</td>
<td>10g</td>
<td>10g</td>
<td>8g</td>
</tr>
<tr>
<td>5.39. Orange 31°C</td>
<td>10g</td>
<td>10g</td>
<td>8g</td>
</tr>
<tr>
<td>5.40. Blue 31°C</td>
<td>10g</td>
<td>10g</td>
<td>8g</td>
</tr>
<tr>
<td>5.41. Green 31°C</td>
<td>10g</td>
<td>10g</td>
<td>8g</td>
</tr>
<tr>
<td>5.42. Black 31°C</td>
<td>10g</td>
<td>10g</td>
<td>8g</td>
</tr>
<tr>
<td>5.43. Purple 31°C</td>
<td>10g</td>
<td>10g</td>
<td>8g</td>
</tr>
<tr>
<td>5.44. Turquoise 29°C</td>
<td>10g</td>
<td>10g</td>
<td>8g</td>
</tr>
<tr>
<td>5.45. Yellow 31°C</td>
<td>10g</td>
<td>10g</td>
<td>8g</td>
</tr>
</tbody>
</table>
Batch 6 samples as shown in Table 3.7, combined different proportions of temperature threshold leuco thermochromic systems in red, yellow and blue. This enabled traditional colour mixing to achieve a range of secondary colours and a range of different temperature response colours within one sample.

Table 3.7 Batch 6: Different temperature threshold leuco thermochromic mixtures

<table>
<thead>
<tr>
<th>Thermochromic colour and temperature</th>
<th>Amount of colour (Chromazone)</th>
<th>Amount of binder (Thermostar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1. Yellow 47°C and Red 37°C</td>
<td>Yellow (2g)/ Red (8g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.2. Yellow 47°C, Blue 40°C and Red 37°C</td>
<td>Yellow (2g)/ Red (6g)/ Blue (2g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.3. Yellow 47°C, Blue 40°C and Red 37°C</td>
<td>Yellow (2g)/ Red (4g)/ Blue (4g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.4. Yellow 47°C, Blue 40°C and Red 37°C</td>
<td>Yellow (2g)/ Red (2g)/ Blue (6g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.5. Yellow 47°C and Blue 40°C</td>
<td>Yellow (2g)/ Blue (8g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.6. Yellow 47°C and Blue 40°C</td>
<td>Yellow (4g)/ Blue (6g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.7. Yellow 47°C, Blue 40°C and Red 37°C</td>
<td>Yellow (4g)/ Red (2g)/ Blue (4g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.8. Yellow 47°C and Blue 40°C</td>
<td>Yellow (6g)/ Blue (4g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.9. Yellow 47°C and Blue 40°C</td>
<td>Yellow (8g)/ blue (2g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.10. Red 37°C and Blue 47°C</td>
<td>Red (8g)/ blue (2g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.11. Red 37°C and Blue 47°C</td>
<td>Red (6g)/ blue (4g)</td>
<td>10g</td>
</tr>
<tr>
<td>6.12. Red 37°C and Blue 47°C</td>
<td>Red (4g)/ blue (6g)</td>
<td>10g</td>
</tr>
</tbody>
</table>
### 3.3.1 Screen-printing

The leuco thermochromic dye systems were applied to each material by hand using a traditional screen-printing method, which was deemed most suitable for the application of both dye systems, and is a widely used method for colouration of almost any substrate. Print designs of 10cm x 10cm were prepared using traditional photochemical exposure on aluminium frame screens containing a stretched polyester monofilament mesh (100 T). The print table was prepared with a backing cloth and selected fabrics were pinned directly on to this. The dyes were fixed at slightly lower temperatures than those used with traditional pigments based on recommendations by LCR Hallcrest. According to literature and expert advice, the thermochromic function can deteriorate during the fixing process (baking) if the temperature exceeds certain thresholds. The dyes were therefore fixed at 130°C for 5 minutes. These printed fabric samples provided an extensive range for testing, the results of which are discussed in chapter 4.

### 3.4 Application of Liquid Crystal Dye Systems

The liquid crystals were supplied in a microencapsulated form as slurry that could be incorporated in an appropriate binder and ready mixed liquid crystals slurries that could be applied directly to a surface. Currently, there is no recommended binder for use with liquid crystals on textiles. Russell Booth, managing director of LCR Hallcrest, recommended testing the ‘thermostar’ pigment binder as used with the leuco thermochromic dyes. To establish if this or other binders would be suitable, a series of initial tests were carried out. The aim was to achieve as close a match to the colour strength as possible to the dramatic ‘colour-play’ produced by the commercially available liquid crystal films, (which are a sandwich of polyester film, liquid crystal and black backing), as shown in Figure 3.1, on textiles.
It was judged to be important at this stage of the research to attempt to recreate as strong a colour play as possible on a textile surface, as more subtle effects could then be produced. The following tests were carried out using a hand screen-printing method as before. The results are shown in Table 3.8.

- **Test 1:** The first test was carried out to establish if the ‘thermostar’ binder could be used and provide strong ‘colour play’. A 1:1 ratio of binder and cholesteric liquid crystal slurry was applied to black cotton and fixed at 130°C for 5 mins. The results were unsatisfactory, producing weak ‘colour play’ with a dull appearance.

- **Test 2:** Latex and PVA (polyvinyl alcohol) were recommended for testing at this stage. A 1:1 ratio of binder and cholesteric liquid crystal slurry was used. Both these binders dried at room temperature, therefore avoiding the possibility of any degradation to the thermochromic effect through fixing with heat. The results were not satisfactory in the strength of ‘colour play’; again, a dull colour–change was visible and not comparable to the strength provided by the commercially available liquid crystal films.

Both tests demonstrated that the binders used gave a matt finish, which affected the ‘colour play’, creating a subdued colour transition. Taking these preliminary results into account, it was decided to find a binder that would provide a shine/gloss to the finish and that preferably dried at ambient temperature reducing the risk of degradation.
through the fixing process. Synthomer supplied a binder Revacryl 275–for textiles, a fine particle size, surfactant stabilised, self-cross linking acrylic copolymer dispersion. Revacryl dries with a slight sheen to the surface and can be cured at low temperatures over a short period of time. Revacryl can also be blended with other Revacryl 27 series dispersions, to modify the film properties.

- Test 3: Revacryl 275 was tested as a binder with the cholesteric liquid crystal slurry as a 1:1 ratio of binder to liquid crystal slurry. This was applied through a screen to black cotton and the fabric samples were allowed to dry at an ambient temperature. It was immediately apparent that Revacryl 275 provided a means to a much stronger ‘colour play’, interesting surface quality and fabric handle. This binder provided the closest comparable ‘colour-play’ to that of the liquid crystal films on textiles. Revacryl 275 was also reported to provide good wash and solvent resistance properties; these performance properties would potentially be beneficial for the application of liquid crystals on fabrics that might be used in an interior environment to protect the function of colour change against possible degradation.

Table 3.8: The results of binder tests with cholesteric liquid crystal thermochromic dye systems.

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Visual and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1: Black cotton ‘thermostar’ binder</td>
<td>Very weakly visible colour-change</td>
</tr>
<tr>
<td>Test 2: Black cotton PVA binder</td>
<td>Uneven surface and slightly milky appearance obscuring colour-change</td>
</tr>
</tbody>
</table>
Test 2:
Black cotton
Latex binder

Milky appearance and subdued colour-change

Test 3:
Black cotton
Revacryl

Improved visibility of colour-change and quality of surface coating

Figure 3.2: Black wool felt sample (10cm x10cm) coated with a cholesteric liquid crystal and Revacryl mix.
Revacryl provided reasonable ‘colour play’ but due to its thin viscosity it did not produce a quality printed surface. Application by alternative hand methods such as brush, roller or drawdown bar\textsuperscript{1} provided a superior finish, but this in turn limited the range of finishing effects. It was concluded that Revacryl 275 is the most appropriate binder for use with liquid crystals on textiles, giving strong ‘colour-play’ and protective properties. Several successful samples were produced with this binder and slurry mix as shown in Figures 3.2 and 3.3.

3.4.1 Multiple colour change liquid crystal samples

As the research progressed it became apparent that it was possible to create more complex, multiple colour change effects with liquid crystals, which consequently became the focus of the research. There was also much less evidence of their previous

\textsuperscript{1} The drawdown bar method allows a material (fabric) to be coated when it is secured on a firm horizontal surface. An appropriate amount of liquid crystal slurry is poured at one end of the fabric and the drawdown bar placed behind the liquid crystal slurry. The drawdown bar is then drawn uniformly along the length of the fabric toward the operator to apply a uniform coating (no pressure is needed). The dry coating thickness obtained is dependent on the combination of the bar used, the volume solids of the coating, and the speed of the drawdown motion.
use in textile design experimentation. The quality of colour achievable with these materials was of immense interest from a design perspective, compared with traditional colours on textiles. A chance discovery in the initial testing of liquid crystals resulted in an unusual ‘colour play’ effect when two liquid crystals with two different temperature thresholds were layered through printing. Traditional liquid crystals are usually restricted, to red, green and blue. Layering produced turquoise, lilac and purple in addition as shown in Figure 3.4.

![Figure 3.4](image)

Figure 3.4: Unusual liquid crystal ‘colour play’ on a wool felt sample showing more colours in the spectrum.

This result prompted the potential of layering the liquid crystals in order to create a new spectrum of colours on textiles. In order to explore this effect further a wide range of chiral nematic liquid crystal slurries with different temperature thresholds and bandwidths that were held in stock by LCR Hallcrest were made available. A range of chiral nematic liquid crystals with temperature thresholds from 60-25°C and bandwidths from 1–20°C as shown in Table 3.9 were applied using the 25µm drawdown bar method on the selected fabrics: black brushed cotton; black wool felt; black waxed cotton; and, thin polyester film.

<table>
<thead>
<tr>
<th>Liquid crystal slurry code</th>
<th>Activation temperature</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 R60 C1W C17-10</td>
<td>60°C</td>
<td>1°C</td>
</tr>
<tr>
<td>2 R60 C10W C17-10</td>
<td>60°C</td>
<td>10°C</td>
</tr>
<tr>
<td>3 R55 C5W C17-10</td>
<td>55°C</td>
<td>5°C</td>
</tr>
<tr>
<td>4 R42 C1W C17-10</td>
<td>42°C</td>
<td>1°C</td>
</tr>
<tr>
<td>5 R40 C5W C17-10</td>
<td>40°C</td>
<td>5°C</td>
</tr>
<tr>
<td>6 R40 C15W C17-10</td>
<td>40°C</td>
<td>15°C</td>
</tr>
<tr>
<td>7 R40 C20W C17-10</td>
<td>40°C</td>
<td>20°C</td>
</tr>
</tbody>
</table>
3.4.2 Liquid crystal films

A series of liquid crystal films were produced at the research and development site of LCR Hallcrest, Poole, Dorset. The films were produced by drawdown bar method as described on a 100µm transparent polyester film with the range of chiral nematic liquid crystal slurries as indicated in Table 3.9. Different combinations of the liquid crystal slurries were used to produce 10cm x 10cm film samples. Each layer was given time to dry before applying the next. The films were then left to dry over night and were finished with a black backing (an oil based black paint applied with a drawdown bar), which required a minimum of 24 hours to dry. The range of temperature response liquid crystal films produced is shown in Table 3.10.

Table 3.10: Liquid crystal films

<table>
<thead>
<tr>
<th>Liquid crystal film sample slurry codes:</th>
<th>Activation temperature</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. R31/C1W/C17-10</td>
<td>31°C</td>
<td>1°C</td>
</tr>
<tr>
<td>2. R35/C5W/C17-10</td>
<td>35°C</td>
<td>5°C</td>
</tr>
<tr>
<td>3. R38/C1W/C17-10</td>
<td>38°C</td>
<td>1°C</td>
</tr>
<tr>
<td>4. R40/C1W/C17-10</td>
<td>40°C</td>
<td>1°C</td>
</tr>
<tr>
<td>5. R42/C1W/C17-10</td>
<td>42°C</td>
<td>1°C</td>
</tr>
<tr>
<td>6. R55/C5W/C17-10</td>
<td>55°C</td>
<td>5°C</td>
</tr>
<tr>
<td>7. R60/C10W/C17-10</td>
<td>60°C</td>
<td>10°C</td>
</tr>
<tr>
<td>8. R40/C15W/C17-10, R55/C5W/C17-10</td>
<td>40°C, 55°C</td>
<td>15°C, 5°C</td>
</tr>
<tr>
<td>9. R60/C10W/C17-10, R55/C5W/C17-10</td>
<td>60°C, 55°C</td>
<td>10°C, 5°C</td>
</tr>
<tr>
<td>10. R38/C1W/C17-10, R40/C5W/C17-10</td>
<td>38°C, 40°C</td>
<td>1°C, 5°C</td>
</tr>
<tr>
<td>11. R35/C5W/C17-10, R38/C1W/C17-10</td>
<td>35°C, 38°C</td>
<td>5°C, 1°C</td>
</tr>
</tbody>
</table>
3.4.3 Single colour change liquid crystal films

Several single colour liquid crystal mixtures, orange, red, violet and magenta active at 25°C were made available for application at the research and development site in Poole. Single colour liquid crystal films were prepared using the same method as described in section 3.4.2.

3.5 Summary

The main observations at this stage were as follows:

In terms of the fabric selection:

- there was no significant difference in the colour-change properties of both types of thermochromic dye systems in terms of function when combined with the heating mechanism;

In terms of the leuco dye systems:

- ‘Thermostar’ was recommended by LCR Hallcrest as the optimum binder for leuco dyes. This provided better colour strength with more of a sheen to the finished fabric sample than the SF20 binder traditionally used with pigments;
- a 3:5 ratio of colour to binder provided good colour strength, better than that of a 1:1 ratio of colour to binder, in spite of the fact that it used less dye.

In terms of the liquid crystal dye systems:

- established that Revacryl 275 provided the most intense colour strength and best quality of finish to the fabric.
- The draw down bar method of application provided a simple and effective mechanism that produced good results.

In terms of the single colour liquid crystals:

- produced rich colours at ambient temperature (25°C) and then revert to black.
Chapter 4 Development of Heat-Profiling Electronic Systems

4.1 Introduction and Objectives

The aim of the research discussed in this chapter was to design, produce and optimise heating mechanisms to activate thermochromic colour-change. The development of three controllable electronic systems included: a heat-sink system, a track resistor system and an ‘off the shelf’ heat pad system. Each system was tested with thermochromic fabric samples to activate temperature change and allow observation of the colour-change response. Research was carried out with technical support from Dr John Fletcher from the University of Strathclyde from an electronic engineering perspective.

The key objectives were:

- To devise and develop electronic heating mechanisms to exploit the conduction properties of copper;
- To develop flexible track-based resistant circuits to compare heating effects;
- To incorporate digital mix (DMX) technology and temperature sensing to exploit the design potential of multicolour effects using controllable electronic heating circuitry with thermochromic substrates.
- To demonstrate the aesthetic potential of thermochromic dyes with varying temperature-induced colour change thresholds;

4.1.1 Design decisions

The research described in this chapter has a technical and design approach intertwined. The development of the heat-profiling circuits that activate the thermochromic fabrics were optimised based on both technical and aesthetic decisions. The design decisions taken are influenced by the technical development and vice versa. The main design decisions were:

In terms of the circuit development:

- copper shapes were chosen for the heat-sinks to establish different motifs on the thermochromic fabric surface;
- the star shape heat-sink circuit was chosen to explore in more depth as it was the most complex shape achievable with the simple rectangular components of the heat-sink construction; it also produced an interesting organic motif;
- the star shape was used throughout the circuit development to give continuity to the visual results and to compare different circuit mechanisms;
• sketches were used to communicate circuit designs and these were developed and optimised in terms of the motif produced;
• the interaction between the circuit (heat-profile) and the thermochromic fabrics led further development of surface design described in Chapter 5.

4.2 Heat-Sink Technology

4.2.1 Heat-sink concept development

In consultation with power electronics expert Dr John Fletcher, a circuit was produced that took advantage of traditional printed circuit board (PCB) technology and the conduction properties of copper. The circuit was composed of several different sized copper shapes (four squares and three circles). When electronic current was applied, the copper shapes increased in temperature. Each shape was connected to small resistors that were applied by hand soldering to the circuit board, as shown in Figure 4.1. The resistors allowed heat flow into each shape in effect creating a heat-sink effect. A previously prepared thermochromic fabric was tested in conjunction with the circuit in order to observe the effective transfer of heat across the copper shapes. The results proved that this mechanism had the potential to be developed further to create the heating effects needed to activate thermochromic fabrics. Several observations were made at this stage; the resistors used within the circuit were raised which prevented the fabric from laying flat against the circuit. Close contact with the heating element was necessary for effective activation of the thermochromic fabric. It was therefore concluded that a more discreet incorporation of the resistor technology was needed to
ensure that the combination of technologies was as unobtrusive as possible.

Figure 4.1: Concept copper heat-sink circuit design

4.3 Circuit Optimisation and Testing

4.3.1 Test 1: star shaped heat-sink and grid circuit

The follow-up circuit development was designed to test two principal ideas. Designs were based on an understanding of the heat-sink and resistor concepts for circuits and translations of sketches of potential circuit designs shown in Figure 4.2. The first idea was based on the heat-sink concept in a complex shape that could be used to establish the parameters necessary for surface mount device (SMD) resistor technology. It was envisaged that this process would allow further optimisation of the resistance and heat-sink size needed to generate sufficient heat flow in silhouette heat-profile shapes. A star shape heat-sink design was chosen that was built up of smaller rectangular shapes. Small resistors with an external depth of 0.65mm and an external width of 1.65mm with a resistance value of 150ohms were soldered by hand between the copper shapes as shown in Figure 4.3. The heat-sink was divided into eight arms measuring 4.4 cm x 1cm with a 0.1cm gap for the resistors to be soldered. There was also provision for switch control on the individual arms. The second idea was used to test the practicality and heating performance of a matrix/grid style circuit on which a pixel type arrangement of resistors could be soldered to any simple predetermined pattern. It became quickly apparent that this technique was not practical due to the need for soldering and de-
soldering of resistors and it also proved very difficult to control the heating effect. It was decided to focus primarily on the optimisation of the heat-sink circuit as this provided a much better degree of control of the parameters for creating heat-profiles.

Figure 4.2: Circuit design sketches, showing the grid design concept (left) and a star shaped heat-sink design (right).

The heat profile results obtained from combining batch 1, leuco thermochromic fabric samples (as listed in Table 1.1, Chapter 3) with the initial star shape heat-sink circuit provided useful information for ongoing development. The heat-sink produced a simple stylised flower-like shape as shown in Figure 4.4. Although an interesting silhouette was achieved the heat-profile appearing was not as close as was desired to the underlying circuit design. The aim was to establish the parameters required for a high level of control of the silhouette. These parameters, once established could then be used to work creatively within. Further optimisation of the heat-sink was required at this stage to provide working parameters for further testing.
4.3.2: Test 2: optimisation of heat-sink size and spacing

The follow-up circuit was designed to test more effective heat flow across a variety of copper shapes to establish parameters for the optimum heat-sink size and spacing between heat-sinks and therefore generate a more accurate and efficient heat-profile.
This circuit was used to establish working voltages for various heat-sink shapes. The design consisted of a variety of shapes that had potential to be repeated as more complex designs. The shapes that provided the most interesting and adaptable results are included in Tables 4.1, 4.2, and 4.3.

- Oval heat-sink

The oval shape as shown in Figure 4.5 provided a range of working voltages over which 31°C and 47°C temperature threshold leuco thermochromic fabric samples were observed to change colour.

![Oval heat-sink](image)

Figure 4.5: Oval heat-sink

An electronic thermometer was used to measure the temperature of the thermochromic fabric over a range of voltages. The ambient temperature was recorded at the beginning of the test and any shift in ambient temperature during testing was also recorded. The temperature was generally taken after 5 minutes, a time, which had been established as generally that required for the temperature to stabilise and form the heat profile. The thermometer was placed directly onto the fabric where the heat-profile was appearing on the surface. This method was used throughout the following circuit tests.
Table 4.1: Blue leuco thermochromic cotton fabric 31°C combined with heat-sink oval-ambient temperature ranged from 23°C - 25°C

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.00</td>
<td>24°C</td>
<td>5</td>
<td>N/A</td>
<td></td>
<td></td>
<td>4.00 50°C</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Blue leuco thermochromic cotton fabric 47°C combined with heat-sink oval-ambient temperature ranged from 23°C - 25°C.

<table>
<thead>
<tr>
<th>Fabric: Cotton</th>
<th>Voltage</th>
<th>Working temp</th>
<th>Time to warm up (minutes)</th>
<th>Time to cool down (minutes)</th>
<th>1. Small dot apparent on the fabric surface</th>
<th>2. Oval appearing with faint edges</th>
<th>3. Almost full oval, still faint edges</th>
<th>4. Still slightly faint edges of oval shape</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.00</td>
<td>36°C</td>
<td>5</td>
<td>0.5</td>
<td></td>
<td></td>
<td>7.50 50°C</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fabric: Cotton</th>
<th>Voltage</th>
<th>Working temp</th>
<th>Time to warm up (minutes)</th>
<th>Time to cool down (minutes)</th>
<th>1. 3 minutes to nearly full and 5 minutes shows full shape</th>
<th>2. Full oval after 3 minutes, full clear shape at 6 minutes</th>
<th>3. Full oval – no heat-spread</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.50</td>
<td>56°C</td>
<td>5</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Referring to the results for fabric test 3 in Table 4.2, the oval heat-sink takes 5 minutes at 7.5 volts to reach 50°C, just above the activation temperature of the thermochromic fabric. It was expected that this would provide a clear heat-profile on the thermochromic fabric in the shape of the underlying heat-sink. However it appears that
due to the shape (in relation to the distance of furthest part of shape from the resistor) and the surface area of copper, (in relation to the heating capacity supplied by the resistors) the heat-profile does not fully appear on the surface of fabric although the circuit is above the activation temperature. The result provided was thus not optimal in terms of efficient heat transfer from the copper heat-sink. It was possible through raising the voltage further to achieve the desired heat-profile. However, in order to achieve the full shape, the temperature of the heat-sink needed to be raised 10°C higher than the activation temperature of the thermochromic fabric.

This pattern is also apparent in results given in Table 4.1 for the lower activation temperature thermochromic fabric 31°C. Referring to the results of fabric test 4, the oval heat-sink takes 5 minutes at 5 volts to reach 31°C, which is the activation temperature, but this does not provide the full heat-profile on the fabric. The temperature required is closer to 36°C before the full shape is achieved, 5°C above the activation temperature. The temperature difference needed to achieve the full shape is not as high as with the higher activation temperature threshold fabric as the ambient temperature is closer to the working temperature. With the higher temperature threshold thermochromic dyes, the difference from ambient temperature is acting as a significant cooling force.

The general observations of the oval heat-sink established that the voltage for the lower temperature threshold fabric 31°C was most effective at 5.5 volts. That achieved a working temperature of 34°C and this did not change between the range of fabrics tested. The control of the image forming on the lower temperature threshold thermochromic fabrics was affected due to being close to the ambient temperature. The heat generated by the heat-sink warming the surrounding air meant that the clarity and control of the heat-profile appearing was affected. In general terms, it was observed that the lower temperature threshold dyes change quicker, tend not give a sharp shape, and take much longer to return to their original colour. An unexpected result, that could potentially be used in a design context, was achieved through repeatedly heating the lower temperature threshold thermochromic fabrics. An observation was made that heat-shadows were being left on the surface of the fabric, a memory or imprint of the past heating as shown in Figure 4.6. These heat-shadows were sometimes permanent, and in some cases, would gradually disappear over time, or if placed in the fridge for a couple of seconds would disappear. The heat-shadows changed in reaction, to rising
temperature, at a slightly lower temperature than the rest of the fabric, resulting in those shapes appearing first on the fabric surface. In discussion with Russell Booth, Managing Director of LCR Hallcrest, he suggested that this was most likely caused by the constitution of the microencapsulated particle. The low melting solvent within the particle that is activated at 31°C, through repeated heating, appeared to change in melting temperature. Effectively repeated localised heating was, in some cases, destroying the function of the thermochromic fabric. This degradation could potentially be developed as a design mechanism to explore colour-change effects.

Figure 4.6: Heat-shadows apparent on the surface of the fabric.

The results, at this stage of the research, determined that working with the higher temperature threshold thermochromic fabrics would allow more control relative to ambient temperature when combined with electronic systems. They were not as sensitive to the effect of ambient temperature and needed a controlled external heating mechanism of some sort to bring about a colour-change. The activation temperature was roughly 20°C above ambient temperature and this worked as a cooling/switching effect in relation to the higher temperature thresholds. It was possible to achieve more control over the higher temperature threshold thermochromic fabrics.

- Staggered line heat-sink

To develop the heat-sink technology further it was important to establish the optimum size of the heat-sink for the resistor to enable the most efficient heating capability in relation to activation temperature. The test circuit was constructed of 14 heat sinks (1cm x 1cm), with each heat-sink spaced approximately 1mm further apart from the last as shown in Figure 4.7. The staggered line circuit also allowed the observation of heat spread between the heat-sinks to find the right spacing between heat-sinks.
It was envisaged that this test would in principle give a set of parameters for the development of more complex shapes and designs. These parameters are recorded in a series of tests. (Table 4.3 shows the most significant information.)

Table 4.3: Staggered line with 14 heat-sink sections circuit test with blue leuco 47°C thermochromic cotton fabric.

<table>
<thead>
<tr>
<th>Fabric: Cotton</th>
<th>Voltage</th>
<th>Working temp</th>
<th>Time to warm up (minutes)</th>
<th>Time to cool down (minutes)</th>
<th>Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>6.00</td>
<td>48°C</td>
<td>5</td>
<td>2</td>
<td>Sections, 1,2,3 &amp; 4 joined with faint edges at 3 minutes</td>
</tr>
<tr>
<td>Working temp</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.50</td>
</tr>
<tr>
<td>Time to warm up (minutes)</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>8.00</td>
</tr>
<tr>
<td>Time to cool down (minutes)</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>8.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fabric: Cotton</th>
<th>Voltage</th>
<th>Working temp</th>
<th>Time to warm up (minutes)</th>
<th>Time to cool down (minutes)</th>
<th>Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>9.00</td>
<td>60°C</td>
<td>5</td>
<td>3</td>
<td>Section 9 &amp; 10 joined but still slight separation between other sections at 3 minutes</td>
</tr>
<tr>
<td>Working temp</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.50</td>
</tr>
<tr>
<td>Time to warm up (minutes)</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>9.00</td>
</tr>
<tr>
<td>Time to cool down (minutes)</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>8.50</td>
</tr>
</tbody>
</table>

All sections joined from 9-11 at 5 minutes
The observed results for the staggered line heat-sink gave a range of working voltages that could be related to temperature and spread of heat. The results revealed that the optimum size of heat-sink (1cm x 1cm) worked efficiently in relation to the resistor. The range between 6 and 7.5 volts brought about a temperature rise above the activation temperature of 47°C. The most efficient gap between heat-sinks, in relation to heat-profile and activation temperature, was 1mm, 1.5mm and 2mm. These results provided the optimum size of heat-sink in relation to the resistor used, 1mm as the spacing between heat-sinks, and a voltage of 6-7 with a heating time of 5 minutes to reach a temperature at or just above 47°C to provide a stable heat-profile on the surface on the fabric. One noticeable, unexpected feature revealed that the solder heated faster than the copper and created small dots of colour-change on the fabric surface. This was not a desired effect. The small dots distracted from the clarity of the motif appearing on the fabric surface. This problem could be solved through a method in PCB design referred to as ‘through plating’ which would allow the soldering to be applied on the other side of the board.

4.3.3 Test 3: Optimised star shaped circuit

The next stages of the development took forward the optimum results from the staggered line heat-sink design and were used to optimise the star shaped heat-sink design. The arms of the star were divided into three smaller heat-sinks (1cm x 1cm) to allow more efficient heat spread and the same resistors were used. By optimising the size of the heat-sink it was anticipated that this would allow more control of the heat-profile. The optimised design is shown in Figure 4.8. This circuit design also allowed for the addition of switches to control on-off power to each arm of the star, for a staggered heating effect.

The circuit was initially combined with a range of leuco thermochromic samples to provide optimum voltages (through a variable power supply) that could create stable heat-profiles on the surface of the textiles. It was anticipated that these voltages would be used as a guide for further testing and design development. From the results provided from the tests given in Table 4.3, the staggered line heat-sink gave a range of useful working voltages and it was therefore anticipated that 6-7 volts would be optimum voltages for the star shaped heat-sink combined with a 47°C thermochromic
fabric. Table 4.4 shows visual results of the optimised heat-sink circuit combined with a leuco thermochromic sample (47°C).

![Optimised star heat-sink circuit design](image)

Figure 4.8: Optimised star heat-sink circuit design.

The optimised star heat-sink provided a more efficient heating effect and a heat-profile that more accurately resembled the underlying circuit. The testing at this stage of the research was beginning to provide an overview of the voltages required in relation to the temperatures developed. The voltages that would generate certain temperatures on the optimised star heat-sink were now more easy to predict. One observation was that sometimes the measured temperatures over several tests at set voltages were different and in such cases re-testing was carried out to ensure accuracy.
Table 4.4: Blue leuco thermochromic cotton fabric 47°C tested in combination with the optimised star heat-sink circuit.

<table>
<thead>
<tr>
<th>Fabric: Cotton</th>
<th>Voltage</th>
<th>Working temp</th>
<th>Time to warm up (minutes)</th>
<th>Time to cool down (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>7.00</td>
<td>50°C</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dots appear quickly after 1 min, creating an interesting aesthetic</td>
<td>The dots join creating softer shading between copper shapes after 3 minutes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fully formed star shape.</td>
</tr>
<tr>
<td>2.</td>
<td>6.50</td>
<td>48°C</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Full star shape after 5 minutes</td>
<td>Visually the cool down is interesting creating abstract effects.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cool down creating an interesting aesthetic.</td>
</tr>
<tr>
<td>3.</td>
<td>6.00</td>
<td>47°C/48°C</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nearly formed star shape but still faint shading at edges</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dots and shading making up faint star shape - this provided an interesting aesthetic quality</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fabric: Cotton</th>
<th>Voltage</th>
<th>Working temp</th>
<th>Time to warm up (minutes)</th>
<th>Time to cool down (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>5.50</td>
<td>47°C</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Almost formed star shape at 5 minutes</td>
<td>Interesting aesthetic after 5 minutes</td>
</tr>
<tr>
<td>6.</td>
<td>5.25</td>
<td>45/46°C</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Interesting aesthetic</td>
</tr>
</tbody>
</table>

4.3.4 Test 4: Optimised star shaped circuit combined with liquid crystal films.

Further testing of the star shape heat-sink circuit was conducted with the liquid crystal films to further establish the relationship between voltage and temperature and to make initial observations on aesthetic qualities. The test results, shown in Table 4.5, 4.6 and 4.7, demonstrate the working voltages for a polyester film liquid crystal sample (8, 9 and 10) with two activation temperature thresholds (38°C/40°C, 40°C/55°C, and 55°C/60°C), as previously described in Table 3.10, section 3.4.2, chapter 3.
Table 4.5: Liquid crystal polyester film with red start temperatures of 38°C and 40°C used in combination with the star heat-sink circuit.

<table>
<thead>
<tr>
<th>Polyester film (Liquid crystal) R38C1W R40C5W</th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>4.00</td>
<td>4.50</td>
<td>5.00</td>
<td>5.50</td>
</tr>
<tr>
<td>Working temp</td>
<td>35°C</td>
<td>38°C</td>
<td>40°C</td>
<td>42°C</td>
</tr>
<tr>
<td>Time to warm up (minutes)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Polyester film (Liquid crystal) R38C1W R40C5W</td>
<td>5.</td>
<td>6.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage</td>
<td>6.00</td>
<td>7.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working temp</td>
<td>43°C</td>
<td>45°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to warm up (minutes)</td>
<td>5</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6: Liquid crystal polyester film with red start temperatures of 40°C and 55°C used in combination with the star heat-sink circuit.

<table>
<thead>
<tr>
<th>Polyester film (Liquid crystal) R40C1W R55C5W</th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>5.00</td>
<td>6.00</td>
<td>7.00</td>
<td>8.00</td>
</tr>
<tr>
<td>Working temp</td>
<td>40°C</td>
<td>46°C</td>
<td>54°C</td>
<td>60°C</td>
</tr>
<tr>
<td>Time to warm up (minutes)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Polyester film (Liquid crystal) R40C1W R55C5W</td>
<td>5.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage</td>
<td>9.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working temp</td>
<td>69°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to warm up (minutes)</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.7: Liquid crystal polyester film with red start temperatures of 60°C and 55°C used in combination with star heat-sink circuit.

<table>
<thead>
<tr>
<th>Polyester film (Liquid crystal) R60C10W R55C5W</th>
<th>1.</th>
<th>2.</th>
<th>3.</th>
<th>4.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>7.00</td>
<td>8.00</td>
<td>9.00</td>
<td>9.20</td>
</tr>
<tr>
<td>Working temp</td>
<td>N/A</td>
<td>60°C</td>
<td>62°C</td>
<td>65°C</td>
</tr>
<tr>
<td>Time to warm up (minutes)</td>
<td>N/A</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

The results provided by the tests recorded in Tables 4.5, 4.6 and 4.7 also showed differences in the voltage to temperature relationship. This difference in results may have been caused by a variation in the ambient temperature or from a heat loss between the back and face of the thermochromic substrate to which the thermochromics were applied. This suggestion seems reasonable as ambient temperature can shift and incremental heating can change the ambient temperature in close proximity with the test samples. In order to validate these results and further clarify the correct voltage with respective temperature thresholds, a further test was carried out. The same method of testing as described earlier in this chapter, section 4.2, was conducted. The results are recorded in Table 4.8 and they have been related to the range of liquid crystals used throughout the research. The Table shows the voltage needed to generate the activation temperature which gives rise to the full colour spectrum.

Table 4.8: The voltage and time to reach specific activation temperatures of the liquid crystal thermochromic dye systems. These measurements are relevant at an ambient temperature of 23-24°C.

<table>
<thead>
<tr>
<th>Liquid Crystal Slurry code</th>
<th>Activation temperature (red start)</th>
<th>Voltage needed to reach activation temperature</th>
<th>Activation temperature plus the bandwidth (for full spectrum to be viewed)</th>
<th>Voltage needed to reach final full spectrum temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>R60 C1W C17-10</td>
<td>60°C</td>
<td>8 volts over 5 minutes reaches 60°C</td>
<td>61°C</td>
<td>8.5 volts over 5 minutes reaches 62°C</td>
</tr>
<tr>
<td>R60 C10W C17-10</td>
<td>60°C</td>
<td>8 volts over 5 minutes reaches 60°C</td>
<td>70°C</td>
<td>9 volts over 5 minutes reaches 70°C</td>
</tr>
<tr>
<td>R55 C5W C17-10</td>
<td>55°C</td>
<td>7.5 volts over 5 minutes reaches 55°C</td>
<td>60°C</td>
<td>8 volts over 5 minutes reaches 60°C</td>
</tr>
<tr>
<td>----------------</td>
<td>------</td>
<td>-------------------------------------</td>
<td>------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>R42 C1W C17-10</td>
<td>42°C</td>
<td>6.00 volts over 5 minutes reaches 43°C</td>
<td>43°C</td>
<td>6.00 volts over 5 minutes reaches 43°C</td>
</tr>
<tr>
<td>R40 C5W C17-10</td>
<td>40°C</td>
<td>5.5 volts over 5 minutes reaches 41°C</td>
<td>45°C</td>
<td>6.5 volts over 5 minutes reaches 45°C</td>
</tr>
<tr>
<td>R40 C15W C17-10</td>
<td>40°C</td>
<td>5.5 volts over 5 minutes reaches 41°C</td>
<td>55°C</td>
<td>7.5 volts over 5 minutes reaches 55°C</td>
</tr>
<tr>
<td>R40 C20W C17-10</td>
<td>40°C</td>
<td>5.5 volts over 5 minutes reaches 41°C</td>
<td>60°C</td>
<td>8.00 volts over 5 minutes reaches 60°C</td>
</tr>
<tr>
<td>R38 C1W C17-10</td>
<td>38°C</td>
<td>5.5 volts over 5 minutes reaches 40°C</td>
<td>39°C</td>
<td>5.5 volts over 5 minutes reaches 40°C</td>
</tr>
<tr>
<td>R35 C1W C17-10</td>
<td>35°C</td>
<td>5.0 volts over 5 minutes reaches 37°C</td>
<td>36°C</td>
<td>5.0 volts over 5 minutes reaches 37°C</td>
</tr>
<tr>
<td>R35 C5W C17-10</td>
<td>35°C</td>
<td>5.0 volts over 5 minutes reaches 37°C</td>
<td>40°C</td>
<td>5.5 volts over 5 minutes reaches 40°C</td>
</tr>
<tr>
<td>R31 C1W C17-10</td>
<td>31°C</td>
<td>4.00 volts over 5 minutes reaches 32-34°C</td>
<td>32°C</td>
<td>4.00 volts over 5 minutes reaches 32-34°C</td>
</tr>
<tr>
<td>R32 C20W C17-10</td>
<td>32°C</td>
<td>4.00 volts over 5 minutes reaches 32°C</td>
<td>52°C</td>
<td>7.5 volts over 5 minutes reaches 55°C</td>
</tr>
<tr>
<td>R30 C20W C17-10</td>
<td>30°C</td>
<td>4.00 volts over 5 minutes reaches 32°C</td>
<td>50°C</td>
<td>7.00 volts over 5 minutes reaches 50°C</td>
</tr>
<tr>
<td>R25 C20W C17-10</td>
<td>25°C</td>
<td>Activated at ambient temperature</td>
<td>45°C</td>
<td>6.5 volts over 5 minutes reaches 45°C</td>
</tr>
</tbody>
</table>

The results of this series of tests confirmed that the initial tests were valid. There were slight variations in the temperature of up to 3°C. This reflects the shifts in ambient temperature which can vary by 2-3°C in any given series of tests.

In summary, the results of the testing at this stage of the research provided an optimum heat-sink design that could be easily re-produced and re-configured in different design arrangements if desired. The optimisation process enabled a wide range of leuco and liquid crystal thermochromic fabric samples to be tested providing a range of voltages (4–10 V) that related to thermochromic activation temperature thresholds. The results, at this stage, informed further research and formed a useful basis in continuing testing enabling controlled colour change on thermochromic textiles and related materials. The aesthetic qualities generated informed the circuit development and vice versa.
4.4 Prototype Development using the Heat-Sink Concept

The initial circuit development provided an optimised PCB based on the heat-sink concept and a range of voltages that provided activation in relation to the thermochromic fabrics. However, these results related to a rigid PCB and, although the boards could be relatively easily produced, the heat-sinks would always be configured in the set arrangement on the rigid PCB. A system that was more flexible (creative) in which the heat-sinks could be freely arranged was developed. This more flexible method also provided an opportunity to produce a prototype with which to test a programmable digital mix system in combination with the heat-sink system. It was anticipated that this would establish the parameters for creating colour-change sequenced patterns.

4.4.1 Test 1: Hand-made heat-sink design

The results, from the PCB heat-sink development, established an optimum size of heat-sink and resistor. However, due to the considerable time needed to design and manufacture each circuit, it was decided that this would hinder the creative intervention and possibilities. There was, therefore, a need for a more flexible approach to creating the heat-sink that could be produced in-house by hand, to provide a more appropriate means to further explore pattern and shape. Throughout the research, ongoing additional experiments with conductive materials and development of other methods of applying circuits directly to fabric were explored. The discovery of self-adhesive copper sheet (commonly used in electronics and for educational purposes in circuit design), was key to developing a more flexible approach to the production of the heat-sink. The copper was supplied by Technology Supplies Ltd, and is referred to as ‘cutronic foil’. Its normal use is for laser cutting simple circuits. The copper was cut into shapes and applied directly to the reverse of the thermochromic fabric. A similar method to create the heat-sink as with the PCB design was chosen. The copper shape was cut in half with a small gap left for a resistor to be soldered between the copper halves. A circular shape was chosen to try in various sizes, based to an extent on previous results but also taking into consideration that the heat-sink was in this case applied directly to the fabric. The approach was aimed less at creating optimum parameters but rather a method that offered a more flexible approach to explore. Figure 4.9 demonstrates that, in practice, the method of applying the copper directly to the fabric surface and soldering a resistor between the copper shapes, worked to generate a successful heat profile on the
thermochromic fabric. It was necessary to solder a wire to each side of the shape to create a circuit linked to a variable power supply.

Figure 4.9: (Left) Self-adhesive copper applied directly to thermochromic fabric; (Right) resulting heat-profile when current was applied.

4.4.2 Test 2: Handmade heat-sink star
Further experiments with the self-adhesive copper were completed. Figure 4.10 shows a self-adhesive copper circuit that was cut by hand from the copper and fine insulated wires were used to join the heat-sinks. Laser technology was also used, in this case, to create a hollow in the industrial black felt surface in which the circuit could sit. The star shape was etched in the felt surface and the copper was cut to fit that size. A cholesteric liquid crystal active at 25°C was applied to the other side of the felt. The heat-profile appearing is shown in Figure 4.11. The nature of the surface and thickness of the felt meant that the result lacked aesthetic qualities. However the result proved that this method could be used to produce more complex circuit shapes.
Figure 4.10: Circuit created with adhesive copper in the style of the star shaped heat-sink. The circuit is embedded into a felt fabric.

The visual result shown in Figure 4.11 showed a soft hazy quality in the heat-profile appearing. Informed by previous results, this appeared to be due to the low temperature threshold liquid crystal and the thickness of fabric between the heating circuit and the liquid crystal layer. A good clear image was unlikely with these two variables.

Figure 4.11: (Left) star shape heat-profile on the surface of the felt in its green phase; (right) heat-profile further advanced in to the blue phase of the colour spectrum.

4.4.3 Prototype design

Building on the flexible approach to the hand applied heat-sink circuit, it was decided, at this stage of the research, to create a prototype that would combine heat-sinks in a larger scale pattern. The concept was that each heat-sink would to be linked to a DMX (digital mix system) enabling the control of power into each heat-sink and a system that could be programmed to travel through a colour and pattern changing sequence. Several other experiments were conducted that tested different sizes of circular heat-sinks as shown in Figure 4.12.
The prototype was made up of 102 circular heat-sinks. Black medium-weight felted wool was used as the fabric to which the heat-sinks were applied. The wool was coated with a cholesteric liquid crystal dye system active at 27°C before being stretched over a wooden frame approximately 1m x 40cm. The design for the arrangement of the heat-sinks is shown in Figure 4.13.

Each heat-sink needed wiring, one wire connected to the positive track of the circuit eventually linking to the positive terminal of the power source and one wire that was eventually linked to a channel on the DMX system. The process is shown in a series of Figures 4.14 to 4.16 that demonstrate the wiring process. The heat-sinks were cut from
the self-adhesive copper and applied to the reverse of the fabric. Copper was also applied to the inside of the frame of the prototype in order to link all the heat-sinks in parallel as shown in Figure 4.14. A close up of the wiring is shown in Figure 4.15. The wiring from each heat-sink was colour coded for reference. Figure 4.16 shows the finished prototype wired and ready to link to the DMX system and power supply.

Figure 4.14: Heat-sinks shown in the process of wiring soldered to the copper frame to link them to the positive terminal of the power source.

Figure 4.15: Example of colour coded wiring.
Figure 4.16: The finished construction and wiring for the first liquid crystal prototype.

4.4.4 DMX digital mix system

The digital mix system allowed digital control of individual heat-sinks through power input. This control mechanism provided a means to relate the voltage to activation temperature and therefore use this to explore colour change sequence that would create a developing pattern. With advice from Dr John Fletcher, a product called ‘SpriteDrive™’ was purchased. This was chosen for its competitive price, and for its relative simplicity in use. The 12 volt version of SpriteDrive™ offered a DMX system with 32 output channels capable of delivering up to 1.25A per channel, with each channel individually programmable. The system was programmed with simple software supplied with the drive. The input sequence was required to be created as a comma-separated file in a spreadsheet and saved as a .CSV file extension (also known as “Comma Delimited”, “Comma Separated Variables” or “Text CSV”).

The SpriteDrive™ required to be powered by a supply (in this case, a variable power supply). Selections of sequences were tested with the prototype. The aim was to achieve a colour-changing pattern that developed over time. The programming was important in terms of the way the pattern would change and the timing of those changes. The sequences were roughly planned before-hand through storyboard style sketches as shown in Figure 4.18. The colours correspond to colour coded groups of wired heat-sinks on the prototype that would be connected to a channel on the SpriteDrive™.
Figure 4.17: Planning sketches for the sequence of colour-change.

4.4.5 Prototype testing and results

The prototype was linked to the SpriteDrive and the power supply for the purpose of testing various sequences and to observe the visual results. Previous to this, testing of the circuits in combination with the thermochromic fabrics had been performed with the piece lying horizontal. This piece had been designed to stand vertically meaning the heat-sinks were in a vertical as opposed to horizontal position. The first obvious effect as soon as power was applied to the prototype, was that heat profiles that had remained circular when horizontal slowly turned into the teardrop shapes (as hot air rises) shown in Figure 4.19. This effect had not been anticipated and was only observed at this point in the research. It appeared obvious, with hindsight, but it had been overlooked throughout early testing.
Figure 4.19: Tear-drop shape heat-profile. As hot air rises, the circle becomes distorted.

Figure 4.20: The prototype proceeding through its programmed sequence.

The collective effect of heating 102 heat-sinks significantly affected the surrounding ambient temperature and the low activation threshold of the liquid crystal used in the prototype meant that the whole surface eventually started to change colour. From a
positive perspective, the ability to combine the DMX system with heat-profiling circuitry had proved successful in allowing programmable colour changes and thus different sequences were able to be tested. The focus on the underlying circuitry was necessary at this stage of the research. However, visual colour change results and surface quality were ultimately envisaged as central to the future research direction. The electronics of this prototype were more interesting, visually, than the colour-change results.

4.5 Exploring the Creative Flexibility of the Hand-applied Heat-sink

The development of the self-adhesive heat-sink provided a mechanism that could be tested by designers to explore colour-change more flexibly. Using a workshop scenario, conducted with designers at the Swedish School of Textiles, Boras, it was possible for them to exploit the creative potential of the heat-sinks alongside thermochromic fabrics. The aim was to observe their design outcomes to enhance understanding of the potential of the heat-sinks as part of a design system.

4.5.1 Results of designers’ heat-sink exploration

Designers, who were involved in the workshop, were able to produce their own heating circuit with the heat-sink mechanism. The process for applying and soldering a heat-sink was demonstrated, with suggestions that they use simple shapes and certain rules according to results informed by previous testing. It was interesting to observe that this advice was quickly overlooked and heat-sinks of varying complexity started to appear. This process resulted in surprising results demonstrating that, in the hands of designers, this system is easily adaptable and can produce a diverse range of visual effects. The fact that the designers involved did not apply the fundamental rules that had been previously tested, led to visual results that were abstract and designs of the heat-sinks themselves were very interesting. A simple star shape created by one of the participants provided a surprisingly clear and detailed heat-profile as shown in Figure 4.21. The designers were extremely creative with the low-tech technology. The results obtained and observations made during this workshop informed future design decisions to some extent in terms of colour-change effects achievable and a more creative approach to the underlying circuitry.
Figure 4.21: The creative shapes produced by participants at the workshop.
4.6 Track Resistors

To investigate further heat profile formation, another mechanism for creating localised heating was tested. The resistance properties of stainless steel were exploited to provide tracks in flexible circuit designs that were produced on a thin Mylar film. This technique allowed the development of linear circuit designs as well as block shapes, in contrast with the heat-sink technology, which only gave block shapes. The resistance of the tracks was predetermined to address the optimum size and length of tracks in the circuit design. The circuit construction was outsourced to a specialist in flexible circuit technology.

Although the circuit designs were made up of linear tracks it was anticipated that a silhouette shape would be achieved in the heat-profile. The flexible board was designed with several test shapes including a star shape, for continuity, as shown in Figure 4.22. The design of the flexible circuit had not been considered in sufficient detail to allow it to be tested properly. In designing the circuit, the connection points were not fully considered and this made the wiring of the flexible circuit very difficult and ineffective. The stainless steel pads from which to solder the wires were fragile and easily breakable and the wiring had to pass right under the flexible circuit resulting in reduced flexibility. The expense and time required to create a new design was prohibitive at this stage of the research, so that it was decided to make the most of and gain as much information as possible from this circuit design.

Figure 4.22: Flexible stainless steel circuit design.
4.6.1 Results of flexible circuit testing

The circuit was tested to compare the visual results with those given by the heat-sink technology, but was not tested as extensively as the heat-sink technology as it became clear that using this expensive circuit technology was not practical for further development. The ranges of working voltages obtained from testing the heat-sink technology were used as a basis to begin testing the flexible track resistor technology. The range from 4 – 7 volts worked effectively (as was observed in the heat-sink technology) at the thermochromic activation temperatures. The observed results were as anticipated. The appearance of the heat profile was smoother, the transition was quicker and the heat-profile more accurately resembled the underlying circuit design. The flexible film appeared to dissipate heat more effectively than the thicker plastic substrate on which the heat-sink circuit designs were produced. This in effect meant that the heat-profile kept clarity with very little heat spread into the surrounding substrate.

The difference in heating effects was very apparent in the colour-change results. The heat-sink technology initially produced a spot of colour created by the resistor; the gradual spread of heat into the copper produced the full appearance of the heat-profile. In contrast the track resistor heating effect was more uniform and fluid throughout. As power is applied and current travels through the track, heat is generated uniformly throughout the whole length and therefore the resulting visual effect is smoother and has more clarity. Aesthetically, there were, therefore, positive benefits in the colour-change effects provided by the track resistors.

4.6.2 Minco heat pads (track resistors)

Further exploration of track based resistor technology utilised a commercially available Minco Polyimide/ULA heat pad (HK5950P) with a resistance of 61Ω. The heat pad dimensions are shown in Figure 4.23.

![Figure 4.23: Minco HK5950P heat pad.](image)
The heat-pads were chosen as a low cost option to establish another method of control of the thermochromic fabrics. The combination of the heat-pad with a commercially available temperature sensing system was set up to control the activation temperature of the thermochromic fabric samples more accurately in relation to ambient temperature.

4.6.2 Testing a temperature controlled system

The heat pad was fixed to the back of a sample of brushed cotton, which had been laser etched to give a patterned surface. The cotton sample had 3 layers of liquid crystal dye with each layer having a different thermochromic threshold: 35°C, 38°C and 40°C (as described in Chapter 3, section 3.5.2). Figure 4.24 shows the heat pad mounted on the back of the dye-coated sample.

![Figure 4.24: Rear of dye-coated cotton sample showing the heat pad and thermistor mounted on the fabric sample in a photo frame. The two pairs of wires provide the heat pad connections and the thermistor feedback to the temperature controller.](image)

The heat pad could be energised by a DC source. The voltage applied was used to control the heat generated of the heat pad and the temperature of the fabric sample. A 50kΩ thermistor was mounted on the back of the heat pad. The thermistor fed back temperature information to an ‘off-the-shelf’ Minco temperature controller (CT325TF2A1). Figure 4.27 shows the DC source supplying the temperature controller.
The temperature controller fed the heat pad and sensed the temperature using the thermistor. The temperature controller is an On-Off controller that energises the heat pad when the temperature is below the set point value. As the temperature rises and exceeds the set point, the controller turns off the power supply to the heat pad. The temperature controller is fed from a 10VDC source with a 250mA maximum current capability. The temperature set-point of the controller is controlled via a multi-turn potentiometer on the controller. This is not an ideal mechanism to adapt for digital control but served the purpose of evaluating the capability of an off-the-shelf On-Off temperature controller to regulate the temperature of the fabric sample over a well-defined region set by the heat pad geometry.

![Temperature controller](image)

*Figure 4.27: Temperature controller coupled to the heat pad and thermistor on dye-coated cotton sample. Temperature controller is supplied from a 10V DC source*

In the first set of tests the heat pad was directly energised from the DC source (rather than using the temperature controller). These tests were performed in order to assess the power dissipation required in the heat pad to raise the temperature of the fabric and cause the thermochromic changes to occur. The heat pad was energized with a voltage that raised the temperature at the centre of the heat pad region to a known value (corresponding with temperatures measured later with the temperature controller at set points of 35°C, 40°C, 45°C, 50°C, 55°C).

Table 4.9 details the absolute temperature, the ΔT (temperature rise above ambient 25°C), the required voltage and power dissipation. Also included in Table 4.9 is an indication of the power required to raise a square centimetre of fabric by 1°C. This is estimated at around 2.7 mW/cm²/°C. The estimate of power required appears relatively independent of the final temperature of the fabric.
Table 4.9: Absolute temperature, the temperature rise above ambient (25°C), the required voltage and power dissipation.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>ΔT (°C)</th>
<th>Voltage (V)</th>
<th>Power (mW)</th>
<th>Power/area (mW/cm²)</th>
<th>Power/area/°C (mW/cm²/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>14</td>
<td>3.82</td>
<td>240</td>
<td>36</td>
<td>2.6</td>
</tr>
<tr>
<td>43.3</td>
<td>18.3</td>
<td>4.47</td>
<td>328</td>
<td>49</td>
<td>2.7</td>
</tr>
<tr>
<td>49.7</td>
<td>24.7</td>
<td>5.18</td>
<td>440</td>
<td>66</td>
<td>2.7</td>
</tr>
<tr>
<td>54.4</td>
<td>29.4</td>
<td>5.72</td>
<td>535</td>
<td>81</td>
<td>2.8</td>
</tr>
<tr>
<td>58.0</td>
<td>33.0</td>
<td>6.22</td>
<td>634</td>
<td>96</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Figure 4.28 shows thermal images of the heat pad, taken with a Fluke Ti25 (thermal imaging system), when the heat pad is energised with the voltages detailed in Table 4.9. The heat pad generates a well-defined heated region on the fabric demonstrating the capability of the heat pad to form well-defined regions of colour change on the fabric. In this section, the heat pad temperature is controlled using the CT325 On-Off temperature controller energised from a 10V supply with feedback from the 50kΩ thermistor mounted on the heat pad. The set-point was set at values of 35°C, 40°C, 45°C, 50°C, 55°C. Table 4.10 summarises the temperature measured at the centre of the heat pad at each of the set points.
Figure 4.29: Thermal images of heat pad operating with voltages shown in Table 4.9
Table 4.10: Set-point and resulting fabric temperate measured at the centre of the heat pad.

<table>
<thead>
<tr>
<th>Set-point Temperature (°C)</th>
<th>Fabric Temperature (°C)</th>
<th>Error (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>38.4</td>
<td>3.4</td>
</tr>
<tr>
<td>40</td>
<td>43.8</td>
<td>3.8</td>
</tr>
<tr>
<td>45</td>
<td>49.4</td>
<td>4.4</td>
</tr>
<tr>
<td>50</td>
<td>54.9</td>
<td>4.9</td>
</tr>
<tr>
<td>55</td>
<td>58.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

From Table 4.10, it is evident that the absolute temperature of the fabric is greater than that expected given the set-point on the temperature controller. Figure 4.30 shows thermal images of the fabric at each of the set-points as shown in Table 4.10.

Figure 4.30: Thermal images of heat pad temperature with temperature set-points shown in Table 4.10.
A series of photographs of the heat-profile induced by the heat pad underneath the thermochromic fabric are shown in Figure 4.31.

![Figure 4.30: Photographs of liquid crystal fabric with temperature set-points shown in Table 4.10.](image)

There were three possible factors contributing to these results. The first was that the temperature controller set point was dependent on the accuracy of the thermistor resistance and its variation with temperature. The accuracy of the thermistor was quoted as 1% of full-range (75°C) giving an accuracy of 0.75°C for the thermistor. The temperature controller also has an accuracy of around 1% of full-range contributing an additional 0.75°C of error.
The second contribution was associated with the unequal thermal resistances between the heat pad and the fabric, and the heat pad and the thermistor. The thermal resistance between the heat pad and the fabric was lower than the thermal resistance between the heat pad and the thermistor. The temperature drop between the heat pad and the fabric was less than the temperature drop between the heat pad and the thermistor. Therefore, the fabric was at a higher temperature than the thermistor, and as the temperature of the thermistor determined the instant that the controller senses the set-point has been reached, the fabric always attained a temperature higher than the thermistor. This difference in the future could, relatively easily, be compensated for in a digital system by adding an offset to the set-point, in essence, calibrating the system to control the fabric temperature by offsetting the set point.

The third contribution was from error in the thermal imaging system. The Fluke Ti25 has an accuracy of ±2°C before errors in emissivity are taken into account. Therefore, the imaging system adds a considerable error in the measurement of absolute temperature. The cycle time of the heat pad was an important property of the system. If the cycle time was too long then the heated region grows and shrinks as the temperature of the region first increases towards the set-point. Then, when the threshold is reached and the temperature controller cycles off, the region’s temperature decays and the region shrinks. With the controller voltage used (10V), the only set-point where such cycling was evident was at the 35°C set point. The cycling effect could be eliminated by providing a superior thermal connection between heat pad and thermistor, or by adopting a proportional-integral controller rather than an (on-off) type controller used in the experiments. The proportional-integral controller would output a constant but controllable voltage using, for example, pulse-width modulation and therefore would provide a near-constant heat input, rather than a pulsed input of heat as is provided by an on-off type controller.

4.6.3 Results of the temperature controlled system

The temperature-controlled system gave a provision for setting the activation temperature for each liquid crystal layer using the temperature controller. This provided a means to activate the thermochromic effect in a controlled way. This stage of the research has evaluated the use of on-off temperature controllers for regulating the temperature of the thermochromic fabrics using commercially available heat pads and controllers. The results are encouraging and, with modification, would be suitable for
digital adaptation thereby providing a mechanism for novel, creative, dynamically changing displays.

The combination of commercially available track resistors has illustrated that an off-the-shelf, on-off type temperature controller was capable of regulating the temperature of the heat pad and hence the thermochromic fabric. Some important and valuable modifications could be made to the temperature controller.

The first of these would be to adapt the temperature controller electronics from an on-off type to a proportional-integral, pulse-width modulated controller. Such a controller would provide a more measured and continuous heat input to the pad, thereby avoiding the pulsed nature of the colour-change region observed at low temperature set-points.

The second would be to design a temperature controller that can be easily interfaced to a digital control system, for example, a DMX controller. From a design perspective the use of a more compact temperature controller to interface with a DMX system would allow the demonstration of the full potential of the combination of technologies as a design system. It would allow precise temperature activation of the textile surface and add a programmable interface.

A third stream of work would attempt to estimate better the thermal dynamics of the system, particularly the time response of the temperature control system and the fabric. Time and the expense of materials did not allow for this type of exploration within the research, but the highlighted points will be recommended as future research directions.

4.7 Other Circuit Experiments

Throughout the research, other investigations to create a conductive heating circuit design were explored. This was not part of the main focus of the research but occurred as a result of the design process. At an early stage of the research, the use of inkjet printing of conductive inks was considered as an option for producing the circuit designs. Xennia, an inkjet manufacturer, (as result of a meeting at a conference) offered to test inkjet printing of a copper conductive ink on fabric using one of their commercially available inkjet rigs. Xennia test printed copper onto cotton as shown in Figure 4.31. The results were beautiful but did not create a conductive track. The fragility of the track, the texture and the multi-directional flexibility of the fabric meant that the conductive ink tended to break. The results have an aesthetic beauty that is unique to printing metal on textiles. This technique has immense potential for further exploration from a functional point of view and taking into account aesthetic
considerations. The potential offered from printing conductive inks via inkjet and screen-printing directly onto textiles would be highly beneficial to the diversity of research in the area of smart textiles and wearable technologies.

Other experiments were inspired by this result from the inkjet printing of conductive inks onto fabric. The application of conductive ink directly to fabric and other related materials was thus further explored. In a similar vein to the hand-applied copper heatsinks, a product was found that enabled the application of hand-drawn conductive tracks. A ‘circuitworks’ silver conductive pen available from ‘Maplin Electronics’ was used to draw silver tracks directly onto the reverse side of several liquid crystal thermochromic fabric samples and plastic leuco thermochromic samples. The concept of being able to draw a circuit was very attractive. However, in reality this particular pen is not designed for drawing, but rather to repair broken tracks on circuit boards. This made it difficult to achieve a good quality of mark. However it did offer a silver conductive ink that could be applied by hand to most surfaces. It dried at room temperature in minutes and could be soldered at low temperatures. The series of photographs shown in Figure 4.32 shows a plastic blue thermochromic 31°C sample with a silver conductive track drawn on the back of the sample. When the sample is
connected to a variable power supply a colour-change occurs. Firstly the track heats creating a line, and then as heat spreads a silhouette shape appears.

Figure 4.32: Silver conductive ink hand drawn onto a thermochromic sample, (left) before colour-change, (middle) connected to power and starting to change colour, (right) full colour-change.

Figure 4.33 shows a liquid crystal printed fabric sample with silver conductive ink applied to back of the fabric. When connected to a power supply the colour-change becomes visible. The sample is presented for the photograph as a convex curve, and shows the potential flexibility of this method of applying conductive inks directly to fabric.

Figure 4.33: Liquid crystal sample presented in a convex curve combining silver conductive ink.

The silver tracks were resistant and warmed when connected to a power source thus activating the thermochromic surface. The resistance of the track along its length varied as it was difficult to achieve an even thickness of silver ink. Although showing interesting results, the experiments were not continued due to the fact that a large amount of further technical development was needed. The silver ink was fragile, the multi-directional structure of fabric meant that the ink cracked very easily when flexed.
It was, however, important to demonstrate that this type of application was technically possible and created interesting aesthetic effects in terms of a linear colour-change that eventually created a silhouette shape. The linear colour-change achievable with this technology could be further explored to complement the silhouette shapes achievable with the heat-sink technology.

4.7 Summary
The observations at this stage were based on both technical and design findings as follows:

In terms of technical findings:

- the surface mounted resistors and copper heat-sinks worked effectively to create heat-profiles on the thermochromic fabric;
- the star shaped heat-sink design created a relatively complex silhouette shape on the thermochromic fabrics;
- the self adhesive copper heat sinks provided more flexibility and freedom when designing patterns that would heat the surface of thermochromic fabrics;
- the DMX system enabled more control over heating capacity and control of colour-changing sequences;
- the track resistors and the minco heat pads offer further research opportunity.

Particular design considerations:

- the liquid crystal thermochromic fabrics combined with the circuits provided visually interesting results: the spectrum of colour change provided a gradient heat profile;
- higher temperature threshold leuco dyes provided aesthetic interest as they were cooled by the ambient temperature providing a switching effect.

The visual colour-change qualities recorded and discussed in this chapter are explored further in textile designs discussed in Chapter 5. The research in Chapter 3 and 4 provided knowledge and understanding to work with the dye systems and heating mechanisms to explore design on a textile surface.
Chapter 5 Design Informed by Colour and Light

This chapter discusses the aesthetic qualities achievable through design with thermochromic dye systems drawing on the results of electronics testing (chapter 4) and application testing (chapter 3) which have culminated in three final prototype pieces.

5.1 Introduction and Objectives

The focus of the research was to explore the potential of thermochromic dyes for textile design. It was therefore important to present the results in a design context in order to highlight the aesthetic qualities which could be achieved. The main objective of the research described in this section was

- to exploit the aesthetic qualities achieved with colour-change in a design context and present the research evidence in prototype form.

5.1.1 Design decisions

Design was approached through having a greater understanding of the thermochromic dye systems in combination with heat-profiling mechanisms. The design process is described throughout the chapter. The main considerations when designing with the thermochromics dye systems were:

In terms of inspiration:

- use Eddie Squires work to inform textile design that combines the influence of new technologies in pattern design;
- to take inspiration from James Turrell’s work with light which had similarities with the colours viewed in the liquid crystal spectrum;
- to explore the pattern development based on crystal structures taking inspiration from the mechanisms of structural colour change;

In terms of thermochromic colour:

- combine both leuco and liquid crystal dye types to exploit more complex colour change
- exploit colour change through pattern design
- explore combinations of dye systems and temperature thresholds in order to promote diverse colour-change effects.

5.2 General Colour Observations and Inspiration

Colour is at the core of the research. However, the function of colour-change has meant that colour selection has not always been by design but often by serendipity. The
research has allowed the exploration of colour on textiles as a transitional medium. Thermochromics provided an opportunity to explore colour in a new way within textile design. Colours result from light waves, a particular form of electromagnetic energy. The human eye can only perceive light as wavelengths between 400 and 700 nanometres. The light waves are not in themselves coloured. The sensation of colour arises as a response in the human eye interpreted by the brain (Itten, 2003). The interrelationship of light and colour has been heightened to a more significant level by working with liquid crystal dye systems through the mechanics of structural colour change (which are inherent in thermochromic dye systems). The potential to form and alter colour through changes in the molecular structure is fascinating from a design perspective. Makow (1991) describes ‘Colours produced by constructive ... interference owe their appearance to the internal structure of the materials ...These colours are usually produced when the material in question is layered and light that penetrates the material is partially reflected from each layer’ (pp.124).

The colour effects achieved that have been particularly interesting have an ethereal quality as shown in Figure 5.1. The adjective ethereal can be described as delicate, refined and tenuous, and in this sense it pertains to colour that appears as a delicate entity, only becoming visible through light and structure. The delicate overlay of colour on the surface has a refined beauty; the colour seems to transcend the material.

Figure 5.1: Liquid crystal sample with ethereal like qualities of colour on the fabric surface.
Colour in the context of this research is created through combining thermochromic fabrics with electronic control systems. This method of controlling colour digitally on a textile surface suggests the idea of ‘virtual’ colour. Trimming (2007) describes a fundamental concept of ‘virtual’ from the philosopher Gilles Deleuze, ‘that everything in a fixed or permanent state be superseded in favour of a constant state of becoming, where things are in a constantly changing developing state’. ‘Virtual colour’ in this sense is not simply a case of computer input but implies that the virtual nature of the colour is dependent more on the material function, the reality of which is that it is never permanent.

5.2.1 Coloured light

Artists working with light, particularly the work of James Turrell, inspired the final design development and in many ways links to the colour observations of liquid crystals on textiles. Turrell’s work with light has influenced the design development directly in the use of colour and indirectly from a conceptual sense. His works present the viewer with new ways to see light ‘Turrells work reminds us that we are surrounded by unseen realities all the time – time, light…’ (Lienhard, p.29). Turrell’s light sculpture, Afrum-Proto (1966) consists essentially of beams of light projected from one corner of a room to the other and when they strike the opposite wall they meet at right angles. The pool of light becomes a 3D cube standing out from the wall as shown in Figure 5.2.
Figure 5.2: Afrum Proto (1966), James Turrell,

A visit by the author to Houston, in 2008, enabled first hand experience of Turrell’s work, ‘The Light Inside’ (1999) commissioned by the Museum of Fine Arts, Houston, which is a light-filled tunnel that joins two buildings. The light that surrounds the observer in Turrell’s work seems to have no beginning and no end. It is somehow undescrivable and unquantifiable. The work ‘Milk Run’ as shown in Figure 5.3 seems to have a similar quality of light to the ‘Light Inside’ (1999) and also has a sense of perspective and space created by the coloured light.
The effects that these optical planes of colour have on perception are reminiscent of the works of the op art movement in the mid 1960s, which are often perceived as having movement within the picture plane and outwards into physical space. These optical works that play with one’s perception can transform colour and light from different viewing angles affecting the space in which the viewer is situated; the planar is transformed to three-dimensions and the viewer has a new experience of seeing colour and light. The viewer is subjected to an experience that alters the perception of the physicality of colour and light and also presents a virtual nature to the work that could be seen to be in constant flux. These works with light/colour have inspired the approach to create new ways of seeing colour on textiles.

5.3 Design Exploration Through Pattern
Pattern provided a means to create additional visual and surface interest on thermochromic fabric samples. Using a combination of screen-printing and laser technology it was possible to exploit the active and non-active surface of a colour
changing fabric. Pattern was also used to enhance the black non-active surface of specific thermochromic fabric samples. The design exploration at this stage of the research provided, through pattern design a way to combine both leuco and liquid crystal thermochromic systems. It was anticipated that bringing both thermochromic systems together through pattern would allow the potential of more complex colour change effects. At this stage the fabric samples produced were intended not only to represent development towards the final design ideas but also to point towards the additional diversity of effects that thermochromics could offer in design development.

Patterns were designed inspired by a visit to the Whitworth Art Gallery, the University of Manchester, to view the Eddie Squires archive. This allowed reference to textile designs such as Intermezzo, Conics, and Microchip first hand. The late 1960s saw creative work inspired by the computer, in which artists and designers alike took onboard the possibilities of new technology associated with the computer as visual inspiration to inform composition, colours and aesthetics. The collection of printed textiles by Eddie Squires dates from the mid-1960s and was inspired by this new technological phenomenon. Squires moved away from the traditional convention of textile patterning with a collection entitled ‘programmed patterns’, featuring designs inspired by computers and electrical circuitry. (Millar)

Inspiration derived from these sources resulted in a decision to use two types of design, linear patterns (based on electronics) and organic motifs (with a graphic quality). The linear and organic patterns were designed to work with the function of the different temperature threshold thermochromics. The patterns were scaled to approximately 10x10cm in size to correspond to the printed fabric sample and the heating mechanism. The full range of patterned samples produced is shown in Table 5.1, given in Appendix A.

5.3.1 Results of screen-printed pattern

The results from using pattern to observe whether combining the leuco and liquid crystal dyes, would create more colour change options are demonstrated in Figure 5.4. The screen-printed pattern is produced initially with a permanent black pigment and an additional layer of a black leuco dye activated at 40°C; this is then overprinted a with liquid crystal dye that is activated at around 32°C. As the temperature is raised progressively the liquid crystal is activated first and starts to travel through its ‘colour
play’. As this is happening the black leuco dye starts to change from black to colourless and as a result the underlying pattern is revealed. The liquid crystal overlaying the permanent black pattern develops its blue colour phase. Essentially the design transforms from a black and white pattern to a blue and white pattern through a series of colour-changes.

These transformative visual qualities were some of the most interesting results and provided another mechanism to create change of pattern through colour. The benefits of using both thermochromic systems were enhanced by the pattern design and exploited the diversity of colour changes when using colour-colourless change and a spectrum of colour change. The organic patterns had similar visual qualities. However, the transformation of the pattern was more subtle due to the design, as shown in Figure 5.5.

Figure 5.4: Cotton sample; (left) before heating, (middle) liquid crystal ‘colour play’ visible and the black changing; (right) final stage of colour change black now colourless and liquid crystal in its blue phase.

Figure 5.5: Organic pattern with a combination of thermochromic dye systems proceeding through a series of colour changes.
5.3.2 Laser etched patterns

A second collection of samples employed an FB Series carbon dioxide (CO2) laser cutter\(^2\). The technology can be used to cut through or etch the surface of textiles. In this research it was used to pattern the surface both before and after the application of the liquid crystals. On the basis of a discussion with Mike Parsley (LCR Hallcrest), it was decided to explore the potential for laser etching to see if this would enhance the colour change properties. Potentially, laser engraving could affect the surface structure of the fabric. Tests would determine whether a change in surface structure could cause different interference effects within the molecular structure of the liquid crystals and cause different colour effects. Parsley presented examples of spray-coated textiles, produced by Merck from the 1990s as shown in Figure 5.6. These were early examples produced when Merck were attempting to launch these types of fabrics into the fashion market. The sample was not laser etched but had a similar surface texture. It demonstrated that this kind of surface when combined with liquid crystals could affect the thermal dynamics of the system and thus cause the light to behave differently across the surface, therefore affecting ‘colour play’.

The design process was aimed at re-creating the delicate quality of pattern inspired by the symmetrical nature of the crystal structures and led to a range of linear patterns one of which is shown in Figure 5.8. An image was discovered at the Natural History Museum, London, produced by the German scientist Max von Laue (1879-1960) who first used x-ray to investigate the arrangement of atoms within a crystal. The pattern is produced when the x-rays hit the layers of atoms and the diffracted beams are recorded on a photographic plate. This image is shown in Figure 5.7 and demonstrates the hidden symmetrical beauty within nano structures.

The nature of laser etching allowed the creation of a delicate change in the surface structure of the fabric. Optimisation of the laser etching settings for each surface was carried out as required to achieve an appropriate visibility of design, and to create the texture desired. Through experimentation, the optimised settings for engraving the

\(^2\) A laser device produces an intense, coherent beam of electromagnetic radiation of a specific wavelength. The FB Series laser cutters use low power sealed carbon dioxide lasers. The principle of the CO2 laser is that the gas inside the laser is energized using electricity. When the gas reaches a critical energy level it emits infrared (invisible) radiation, i.e. the laser beam.
cotton and wool fabrics were derived. Particular materials such as black wool felt needed several passes with the laser to create an (embossed like) surface texture. The optimised settings for the laser cutter and the range of samples etched are shown in Table 5.2 (Appendix A).

Figure 5.6: Spray coated liquid crystal on an embossed textile sample produced by Merck in the 1990s before (left) and after (right) heating.
Figure 5.7: X-ray of an atomic crystal structure, by Max von Laue (1879-1960), held at The Natural History Museum, London.

Figure 5.8: Design for laser engraving based on crystal structures.

5.2.1 Results of laser etched patterns: Additive colour mixing

The results observed from the coated liquid crystal and laser engraved samples used in combination with heating using the optimised star-shape heat-sink circuit design (see chapter 4, section 4.2) demonstrated that it was possible to create a wider range of colours in the spectrum through layering different temperature threshold liquid crystals than by using a single layer of liquid crystal. The samples produced show that a wide range of different colours is possible as illustrated in Figures 5.10-5.12. The colours produced when liquid crystals are applied in layers are additive. This is due to the microstructure of the materials, which reflect the incident light as colours, and these mix as if they were coloured lights. This process creates a different range of colours compared with traditional subtractive colour mixing. For example, if red and green paints are mixed brown is achieved (subtractive colour mixing), but if red and green lights are mixed yellow is obtained (additive colour mixing). A diagram of the additive colour principle is shown in Figure 5.9. Three beams of red, green and blue light are projected onto a white surface; where the red and green light overlaps yellow is created; where the green and blue overlap cyan is created and where the blue and red overlap
magenta is created. The three additive primary colours of red, green and blue light are the commonly observed colours within liquid crystal ‘colour play’.

Figure 5.9: The diagram shows three coloured beams of light projected onto a wall and as they overlap the colours mix showing a range of additive colours.

The ability to mix colour additively on a fabric surface makes liquid crystal colours particularly unique in terms of textile design. They provide a means of generating a new type of colour palette. In terms of design the use of the underlying circuit to provide a motif is also interesting, in principle allowing a mechanism for colour mixing and pattern generation on the fabric surface.

Figure 5.10 is a photograph of a particular sample proceeding through its ‘colour play’. This sample has a 35°C and a 40°C (red start) liquid crystal fabric surface (as described in chapter 3, section 3.4.1). It is possible to observe at least 3 unique colours arising from the additive colour mixing in this sample. The blue phase of the lower temperature threshold mixing with the red phase of the higher temperature threshold liquid crystal may be creating the strong purple. The pink may be created by the red phase of higher temperature threshold mixing with the blue phase of the lower temperature threshold liquid crystal. The thin band of yellow, a colour that is usually barely visible with a single layer of liquid crystal thermochromic, is probably a result of the red and green phases mixing. Potentially, with the appropriate combination of liquid crystals it might be possible to create a wider band of yellow.
Figure 5.11 shows a sample that also has two liquid crystals layers 32°C and 40°C (red start). The more subtle colours are associated with the wider bandwidths at 20°C of the two liquid crystals. The cyan is likely to be due to the green and blue phases mixing.

Figure 5.10: Sample showing, pink, purple and yellow and an emerald green in the spectrum.

Figure 5.11: Sample showing, a pale pink, cyan, purple, green and orange.
Figure 5.12 has two liquid crystal layers 38°C and 60°C. It is difficult to interpret the purple colour in this case without further scientific investigation. The colour effects are interesting as the temperature thresholds of the two liquid crystals are further apart; there is 22°C between them. This means one heat-profile (motif) forms and travels through its full ‘colour play, and then after a further temperature rise of 22°C the next heat-profile forms creating a staggered colour-change response. In this case, the 38°C liquid crystal had proceeded through its full spectrum at 39°C. Hence, the second star shape (60°C) appears inside the outline of the heat-profile of the lower temperature threshold liquid crystal. This constant movement of pattern and colour creates an unusual sense of life on the fabric surface.

The use of laser engraving as described was observed to further affect the liquid crystal colour change as shown by example in Figure 5.13. The fine engraved areas create another dimension to the surface interest as the liquid crystals pass through their spectrum. The laser-engraved areas create a lighter colour of the same hue. For example in the purple phase the laser etched line creates a lilac.
Figure 5.13: A close up view of the surface of the sample shown in Figure 5.12 shows the darker purple of the liquid crystal phase overlaying the black fabric and the lighter lilac hue of that purple phase overlaying the laser engraved areas.

A possible explanation for these different hues is that due to the laser engraving removing the surface colour of the black fabric essentially leaving a scorched pattern or line, which is brown in colour. The brown background colour at the higher end of the temperature range of the liquid crystal is creating reddish blues (lilac), which are also richer in chroma than on the black background. This effect has been proposed from a technical investigation reported in the literature review section 2.2.1.

5.2.3 Colour comparison of the liquid crystal films

Another observation is that the liquid crystal films produced, as described in section 3, show a more vivid ‘colour play’ than the liquid crystal fabrics. This was an expected result from a visual comparison of the liquid crystal coated fabrics with commercially available liquid crystal films. The fabrics do produce a reasonably vivid ‘colour play’ but it does appear that the more reflective the surface coating or binder that encapsulates the liquid crystals the more dramatic and vivid the colours observed. However, the more shiny or glossy the surface of the sample, the more reflection interferes with the colour-change. The fabrics thus have a more matt finish (with a slight sheen) and the colours are more subtle. Figure 5.14 shows the vivid colours achievable with the liquid crystal films. The colours observed here are similar to the colours observed in Figure 5.10 in section 5.2.2. A strong magenta is observed, the emerald green appears more yellow and all the colours appear more vivid. This sample also has a more visible band of yellow, shown in Figure 5.15 that is more vivid in the liquid crystal film.
The original intention of the research was to work on fabric primarily, but it emerged that the liquid crystal films offered such beautiful vivid colours and sometimes it was easier to see the colours with more clarity than on the fabric samples offering a tool to better understand the ‘colour play’. Other films (the single colour liquid crystal type) produced were difficult to capture in their transition due to the reflections on the surface of the film. The single colour liquid crystals described in section 3.4.3 were designed to display development of a single colour through the full spectrum threshold (25-35°C). It was possible when applying the colours to film to have a single colour layer with a
normal liquid crystal hidden behind that would be revealed when the single colour had proceeded into the isotropic phase as shown in Figure 5.16. The combination of single coloured thermochromic liquid crystals and traditional chiral nematic liquid crystals has implications for even more complex colour-change effects. Due to the limited amount of material (single colours and liquid crystals) it was not possible to fully explore the potential, but the colours offered are warm and have an unusual depth of colour.

Some of the single colour change liquid crystal polyester films were also laser engraved. This produced some unusual colour effects. The laser engraved pattern on the surface of film appeared to change colour from different angles, giving a subtle ‘holographic’ effect. Also, on transition from coloured to isotropic (black) the pattern became more visible as shown in Figure 5.17

The observations of the colours achieved with the films were very similar to light (emissive colour) and not to those one would associate with non-emissive (flat printed colour). The qualities observed with the vivid colours and reflective colours from the films were very interesting in that they seemed to have a physical presence on colour change. This physicality appears from the combination of the movement of colour with colour resembling light, in a sense. Colour on a surface that resembles light is not a feature that a textile designer would normally have in his/her palette choice.

Figure 5:16: Orange single colour liquid crystal film with a 30°C red start liquid crystal layer behind.
Figure 5.17: Orange single colour change film with laser engraved pattern showing difference in visibility from orange to black colour-change.

5.4 Final Design Prototypes ‘Transitional Stripes’

‘Transitional Stripes’ refer to the final design prototypes which demonstrate the potential of the electronic activation of thermochromic dye systems and bring together key colour change results. The digital control of the qualities of colour was approached through an integrated DMX system. The key design features that were important to highlight within the prototypes were the additive colour mixing and the combination of both types of thermochromic dye systems. The observations of the colour aesthetics confirmed a decision to highlight movement of colour-change rather than a motif (such as the star) appearing on the surface of the fabric.

5.4.1 Prototype development

The concept for the prototypes was to create artefacts that would demonstrate the key results and show the potential of additive colour mixing and combinations of the dye systems working together. Adobe Photoshop was used to bring together sketches of the ideas for the prototypes and to simulate liquid crystal colour change. The simulations were useful in providing an overall look of the prototypes as a series of colour changes. Figure 5.18 shows five steps of colour-change and demonstrates the desired movement of colour across the surface of the fabric. It was proposed that a similar ombre or graduated movement of colour could be achieved by using the circuitry that had been developed in the early stages of the research, as described in chapter 4, section 4.2. The heat-profiling circuitry was used to create stripes of heat, although this would create bands of colour change and not the intended movement of colour across the whole surface. It was envisaged that is would create a gradient effect similar to Figure 5.18.
Turrell’s work with coloured light (shown in Figure 5.3) provided inspiration for the prototype. The vivid colour mixing had a similar feel to the colour mixing seen in the liquid crystal fabric samples. The linear patterns were developed further from the crystal structures and were applied to the fabric surface through laser technology and screen-printing. The intention at this stage was to develop the underlying circuitry based on previous testing that would be compatible with all the prototypes. The fabric that would overlay the circuitry would be treated differently to achieve different colour change effects – highlighting key results.

Several tests were conducted to create the banded (striped) effect. The results of early circuit experiments as described in chapter 4, section 4.2 were consulted to provide the optimum design and voltages. Figure 5.19 shows oblong copper heat-sinks that are 1.5cm x 1.1cm in size. The gaps between them were of particular interest, to create a clear stripe effect. The spacing between the heat-sinks was required to be 8mm or 7mm. Based on previous testing, (see section 4.2), it was anticipated that this design would provide the optimum colour-transition effect. To test that the circuit provided the desired effect, a small test PCB was produced, with the guidance and cooperation of Dr John Fletcher, of Strathclyde University, Glasgow, as shown in Figure 5.20. The PCB was produced ‘in house’ at Strathclyde University.

A liquid crystal sample with a series of temperature thresholds (R30C20W/C17-10, R40C5W/C17-10, and R25C20W/C17-10) was tested in combination with the prototype PCB. The combination of 25°C, 30°C and 40°C temperature threshold liquid crystals produced an interesting colour range when heated. It was hoped to reproduce similar colour changes in a larger scale prototype piece. The selection of optimum voltages of 5, 6, and 6.4 to create colour-change at the specified temperature thresholds was informed by the testing described in chapter 4 and provided the starting point for the prototype test. The prototype PCB was used to establish the working voltages in combination with the selected liquid crystal fabric sample to optimise the final circuit design. The sample was placed over the circuit linked to a variable power supply. The colours were recorded at a series of voltages 5, 6, 7, 8 and 9 volts as seen in Figures 5.21 to 5.25.
Figure 5.18: Initial design concept sketch, five stages show gradual temperature change and the liquid crystal colour change from black through to a fully coloured fabric surface.
Figure 5.19: PCB showing heat-sink circuit on which the final circuit design was based.

Figure 5.20: Prototype PCB to allow testing of striped colour-change effects.

Figure 5.21: Liquid crystal sample in combination with prototype circuit at 5 volts
Figure 5.22: Liquid crystal sample in combination with prototype circuit at 6 volts

Figure 5.23: Liquid crystal sample in combination with prototype circuit at 7 volts

Figure 5.24: Liquid crystal sample in combination with prototype circuit at 8 volts
This series of tests provided the desired graded transition of colour-change at the specific voltages. The PCB could be scaled up and could be outsourced for manufacture when necessary. Due to constraints in the availability of technical equipment for the application process and in materials (liquid crystal dyes), it was not possible at this stage to produce a larger scale piece based on the sample shown in Figures 5.21 to 5.25. Therefore, a compromise was made to design a thermochromic fabric that would still show the additive colour mixing effect achievable by combining leuco and liquid crystal thermochromic dye systems that were available.

5.4.2 Prototype one

Figure 5.26 shows a Photoshop simulation of the colour change effect that could potentially be achieved with the striped circuit and thermochromics. The visualisations were used to help communicate ideas and to provide a basis for the look of the prototype. Planning how the prototype would look prior to production was an important part of the design process and also demonstrated the knowledge of the materials and technology coming together. The final circuit design was guided by the maximum size that a PCB could be manufactured (21cm x40cm); the design of the prototype was based on the size (21 cm x 80cm) and constructed from two PCBs. In consultation with John Fletcher the final design for the specifications was produced and the manufacture outsourced. The fabric design was based on the underlying circuit dimensions. A design was produced on black cotton, laser engraved, screen printed with a red leuco dye 47°C, coated with two liquid crystal layers 27°C and 31°C and finished with a layer of
Revacryl 275 to protect the fabric surface. This piece was placed in combination with the heat-profiling circuitry and linked to the DMX (digital mix system). Several sequences were programmed and tested with this piece as shown in Figure 5.27.

Figure 5.26: Top image, visualisation showing striped colour-change created by underlying circuit design – Bottom image, visualisation showing colour-change over time as heat spreads.

Figure 5.27: Prototype one, thermochromic fabric overlying heat-profiling circuitry displaying a programmed sequence via a DMX system.
The prototype worked well and demonstrated most of the desired colour change results, but the un-activated surface on a larger scale was not satisfactory in terms of aesthetic quality and finish. This was attributed to scaling up and the coating technique. To achieve an even coat of liquid crystal over a larger area was difficult and led to slight flaws in the surface quality. The flaws were more visible in the surface over a larger area. Additionally, the rates of the colour changes due to the nature of the programmed sequence were slow. The intention of the piece was directed towards subtle aesthetic qualities of colour mixing. However, the colour changes were problematic due to the scale and quality of the surface finish. Therefore, it did not clearly present the potential of the material combinations.

5.4.3 Prototype two

The second prototype was directed towards improving the overall surface quality and creating a more vivid colour change effect. To achieve this a sample was produced with a red leuco dye screen-printed on black cotton, coated with two liquid crystals 27°C and 31°C. It was anticipated that the predominant red screen-printed surface would potentially provide a better quality surface finish and clearer additive colour mixing than the previous prototype. The final design was based on this sample as shown in Figures 5.28 and 5.29.

Figure 5.28: Red thermochromic fabric sample overlying prototype circuit, linked to DMX system.
The colour mixing in the sample demonstrated the potential to show three secondary colours, magenta, yellow, and cyan with the three primary colours red, blue and green together with black and white. A range of eight colours was demonstrated on temperature change, which essentially covers the full colour gamut. The same linear design was prepared for screen-printing. White textured cotton was selected as the base fabric to provide another dimension to the finished surface. As before, the design was produced to the size of the underlying circuitry 21x80cm. Constructing this design gave no room for error, as the materials required to produce it were very limited in availability, custom made and expensive at this stage. The production of the piece involved several stages: two screen-prints to apply the base colour (permanent black and red leuco dye 47°C) and pattern. The fine linear patterns had to be registered accurately to achieve a quality finish. Finally, two layers of liquid crystals 31°C and 35°C were applied and a finishing coat of Revacryl 275 to protect the surface.

Figure 5.29: Red thermochromic sample and additive colour mixing diagram, showing the blue phase of liquid crystal mixing with the base red to create magenta, and the green phase of the green phase of liquid crystal mixing with the base red to create yellow and more subtly the blue and green phase of the liquid crystal layers creating a turquoise.

The finished result shown in Figures 5.30 and 5.31 had a better aesthetic quality than the previous prototype due to the texture of the fabric and screen-printed surface. The colour and the sheen (from the Revacryl finish) added to the overall quality of the finished surface. The prototype was accepted for exhibition at the ‘Smart Textiles Salon’ Gent, Belgium, September 2009. To finish the prototype to a high standard,
black Perspex was cut to frame the piece. This also served to hide the wires from the underlying circuitry. Several sequences were programmed for the DMX system to power the piece. These were tested until satisfactory colour-change results were achieved. The success of the sequences were judged based on several factors, including the capabilities of powering the colour-change, the dynamism of the changes, and the ability to take the prototype through its full range of colour changes. The sequence is based on the voltages required to reach each temperature threshold. Each channel on the DMX system was programmed in relation to these voltages and therefore activated the different temperature thresholds as discussed in chapter 4, section 4.2.1.

![Figure 5.30: Prototype two before heating](image)

![Figure 5.31: Prototype two after heating](image)

Overall this prototype was highly successful, with the colour change demonstrating additive colour mixing. The close up of the surface shown in Figure 5.32 highlights the surface interest. The prototype presented a series of colour changes on textiles which were quite unique.
5.4.4 Prototype three

The third prototype was designed to work alongside and complement the second prototype. The same circuit design was used but the thermochromic fabric surface was designed to proceed through different colour changes. The prototype was designed to be more subtle in its colour transition and to highlight the more traditional colour change of liquid crystal dye systems. White cotton (duck) was chosen to give the piece good weight and surface quality. A permanent black pigment was screen-printed and a black leuco thermochromic dye system 40°C to create the base black colour. A liquid crystal with a 25°C red start was screen printed over the permanent black pigment. A further coat of liquid crystal 31°C was applied over the whole piece followed by a final coat of Revacryl to protect and seal the surface. The lower temperature threshold liquid crystal (25°C) had a 20°C bandwidth. This resulted in the green phase of liquid crystal being the predominant colour in the transition, as shown in Figure 5.33.

The linear pattern of permanent black pigment with the liquid crystal overprinted firstly gave the effect of the lines changing colour to a rusty red and then green stripes started to appear and spread. Eventually the black leuco dye changed at 40°C and revealed the white base fabric and blue linear pattern (here the blue phase of the liquid crystal at

Figure 5.32: Close up of prototype surface
around 45°C is observed). The prototype framed with Perspex and linked to the DMX system is shown in Figure 5.34 starting to proceed through its programmed sequence of colour-change.

Figure 5.33: Prototype three, close up of surface showing green phase of liquid crystal within the stripe.
5.5 Summary

The main observations from the research described in this chapter which are discussed further in Chapter 6 were:

• the combination of both types of thermochromic dye systems, leuco and liquid crystals through pattern provided more options for colour-change:
• a combination of pigments, leuco thermochromic and liquid crystal dye systems were used to create designs that transformed in colour and pattern.
- Laser engraving provided another mechanism to apply pattern in a controlled way.
- The combination of the liquid crystal laser engraved fabrics used with the heat-sink circuits provided strong aesthetic results.
- Transitional colour changes involving the principles of additive colour mixing were discovered and created a range of highly unusual colours in the liquid crystal spectrum.
Chapter 6 Conclusions and Suggestions for Future Work

6.1 Overview

Thermochromic dye systems are those that change colour in reaction to temperature change. The research described in this thesis dealt with the application of these dye systems to textiles and the creation of controllable heating systems that are able to activate colour change.

The microencapsulation of the components making up the dye systems, giving the thermochromic effect, has provided a means to apply colour change to a wide variety of substrates. The dye systems used in this research provided a novel and functional colour phenomenon, which had not been fully exploited in a design context previously. In terms of the aesthetic qualities achievable there was an obvious gap in previous design investigations of these dye systems, especially those of the liquid crystal types. The research problems encountered highlighted that while the thermochromic dye systems were not specifically developed for use on textiles, they offered enormous potential as a dye system for use on textiles. However, this potential appears to have been overshadowed, to an extent, by a negative association especially linked with the leuco thermochromic dye systems that have been used in novelty products. This stigma has been perpetuated through the common exploitation in simple products that play on gimmick as a feature using colour change in a one-dimensional way (usually colour to colourless).

This research presents a body of work supported by actual thermochromic fabric samples and prototypes incorporating electronic technology that are aimed at shedding some of these past preconceptions and promoting the potential of the dyes in an intelligent, creative and novel way. This research has significantly enhanced the understanding of the aesthetic qualities achievable with thermochromic dye systems used in combination with heat profiling circuitry and their application to textiles.

The aims of the research included:

- to explore the design potential of thermochromic dye systems on textiles and related materials;
• to establish design systems, which demonstrate the capabilities of multi-colour change on textiles;
• to investigate electronic devices to activate colour-change on textiles.

To achieve these aims it was necessary to explore application methods including screen-printing, and coating of thermochromic dye systems onto textiles and related materials. It was important to explore transitional colour-change and pattern effects to address these aims. In order to view the possibilities of colour and pattern change it was necessary to design and develop a series of heat-profiling circuits to be used as a methodological tool. This research strategy in turn allowed exploitation and promotion of an understanding of the aesthetic qualities achievable with the use of thermochromic dye systems on textiles.

Initially the research concept was directed toward producing textile-based products or artefacts for an interior environment. As a result of the enhanced of understanding of the systems as the research developed, it emerged that using thermochromics within an interior context had application potential. However, it was decided as the research progressed that the focus on producing such a prototype product or artefact was less important than developing an understanding of the function of the dye systems and also the technology with which to activate them. Developing a strong understanding of the dye systems offered insight into the scope of potential applications within interior contexts and within product design. Thermochromics offer possibilities for responsive materials for buildings and products that are part of the infrastructure of a building. Although specific scenarios for these potential uses have not ultimately been explored within this research, opinions on the reasons why they might be particularly suited for use within an interior context have formed throughout the research. The need for heat as an activation mechanism may detract from their use within fashion. However, in an interior context, the ability to make heat visible might be used as a mechanism for signalling energy usage and loss. Combined with electronic heating mechanisms, thermochromics have the potential to provide programmable products that might be integrated into the structure of a building offering both aesthetic and functional qualities and at the same time serving as low energy heating mechanisms. It has been clearly demonstrated that more complex colour changes are possible when thermochromics are combined together with several different temperature thresholds and provide higher aesthetic appeal. The electronic systems developed within this research and the nature
of the application and fabrics used points towards more intelligent and complex applications achievable for interiors.

Leuco and liquid crystal dye systems operate by different mechanisms of colour change. Leuco dyes are coloured and are known to change from coloured to colourless when activated by heat. They can be printed on and provide a colour change effect on any colour background. Liquid crystal dyes are colourless; colour is activated by temperature change. Ideally they should be printed on a dark coloured background to give maximum colour strength. However more subtle colours can be achieved when printed on other lighter backgrounds. It is possible to work creatively within the parameters of the dye system mechanisms in addition to other variables such as, individual dye temperature thresholds, ambient room temperature and heat activation. These variables can be adapted to suit different design applications.

6.2 Summary of The Main Research Conclusions
A key aim was to explore the design potential of thermochromic dye systems on textiles and related materials. A series of tests were devised to explore the two dye systems, application techniques and the heating systems used to activate colour-change. Screen-printing was used to apply the dye systems to the fabrics. This offered a very well tried and tested method and provided good adhesion to the fabric. The fabrics and related materials that were selected to print the thermochromic dye systems were applicable for an interior context and the fabrics were all of a similar weight. They provided a variety of surfaces on which to test the application of thermochromic dye systems. In terms of the range of fabrics and related materials, there was no significant difference in the colour-change properties of both types of thermochromic dye systems in terms of function when combined with the heating mechanism. The thermochromic leuco dye systems behaved and were handled in a very similar way to the traditional pigments used in textile printing. This feature, together with their lower cost and better availability appears to make them the more common type of thermochromic dye used on textiles and more readily understood by designers. The binder ‘Thermostar’ was recommended by LCR Hallcrest for leuco dyes. This provided better colour strength with more of a sheen to the finished fabric sample than the SF20 binder traditionally used with pigments. It was also observed that a 3:5 ratio of colour to binder provided good colour strength, better than that of a 1:1 ratio of colour to binder, in spite of the
fact that it used less dye. This was an unusual finding but it has clear benefits in terms of material conservation. The variety of leuco thermochromic dyes provided by LCR Hallcrest allowed the exploration of thermochromics with different temperature thresholds not readily available for general use, some of which were custom made. The costs associated with custom-made dye systems would be expensive. If there was future demand for the custom-made dye systems in smaller quantities it might offer the designer an opportunity to experiment with these dyes. Leuco thermochromic dye systems offer alternative design potential and are easily applied to textiles.

There was limited available literature on liquid crystal application to textiles. The main literature that guided the development of application methods was obtained from previous research undertaken at Heriot-Watt University (Bryant, 1997). In discussion with experts, application methods were tested to apply the liquid crystal dye systems to textiles successfully. There was no recommended binder to use with the liquid crystals for textiles, which proved a significant challenge for the research. Several tests were carried out initially to combine different binders with cholesteric liquid crystal slurry, which established that Revacryl 275 provided the most intense colour strength and best quality of finish to the fabric. Screen-printing was used at an early stage of the research to apply the liquid crystal and Revacryl mixtures to the fabric. The low viscosity of the formulation meant that it was difficult to achieve an appropriate quality of print. Other methods for application were explored; a draw down bar method was used with more success and worked well on different substrates. The chiral nematic liquid crystals, that were used at later stages of the research, were ready dispersed in polyvinyl alcohol slurry and were applied in this form to the fabric via the draw down bar method. Revacryl was used as a final coat to seal and protect the liquid crystal coating. The draw down bar method of application provided a simple and effective mechanism that produced good results. The opportunity arose to produce a range of liquid crystal films within the company; these were also produced with the draw down bar method. This allowed observation of the different colour intensities between the liquid crystal films and coated fabrics. The results provided an understanding of the method used for producing the commercial films and products that use liquid crystals.

Single colour liquid crystals were made available for testing by LCR Hallcrest. These are not commercially available in dye form. They have application in commercial temperature indication devices. They are designed to display a single colour change.
These dyes offer another range of unusual colours in addition to the liquid crystal and leuco dye systems. They were supplied already dispersed in poly-vinyl alcohol binder and were applied directly to films and other substrates using the draw down bar method. The samples produced rich colours at ambient temperature (25°C) and then revert to black.

To fully explore the colour changes of the different thermochromic samples, it was necessary to design and construct heating mechanisms that would demonstrate the capabilities of multicolour change on textiles. Copper was exploited for its particular conductive qualities and its traditional use in circuit boards. Traditional PCBs are constructed with copper and this offered a relatively low cost and in house mechanism to explore simple circuit design with inbuilt heating capability. A variety of circuits were designed and produced in the early stages of the research. These circuits were used to optimise heating capability and to gain an insight into the visual possibilities. Initially the focus was to achieve as much control as possible over the effects through combining the circuit and the thermochromic substrates. The surface mounted resistor technology and the copper heat sinks worked effectively and led to the conclusion that they could be potentially adapted to suit different design configurations offering a flexible and effective system. The optimised circuit that was configured in a star shape provided a means to create a relatively complex silhouette on the thermochromic substrates. As the colour changed, a motif appeared so that both colour and pattern were dynamic.

The method of using copper heat sinks were applied directly onto fabric. A self-adhesive copper sheet was discovered that could be cut by hand and applied to the surface of the fabric and it was found through experimentation that a resistor could be soldered between shapes effectively. This process provided the possibility of a hands on approach to circuit construction. It also added a higher degree of freedom and control over design layouts. It was found that the adhesive copper was flexible and the design could be changed relatively quickly. The advantages of this approach included the possibility to produce a variety of designs in house and to allow quick activation of a thermochromic fabric. The heat-sink circuit designs of both the PCB type and hand-made copper heat sinks were combined with a DMX system in order to test the effect of digital control of colour change sequences. The results provided verification that it was possible to programme a colour and pattern change sequence on textiles. The three-way
combination of heat-sink circuitry, DMX control and liquid crystal fabrics provided a unique means to mix colour on a textile surface.

To compare the effectiveness of different heating mechanisms, a track resistor circuit was designed with stainless steel tracks on a flexible film. The design took advantage of inherent resistant qualities of the stainless steel. It was linear in contrast to the block shapes of the heat-sink design. The track resistor circuit provided a continuous heating effect throughout the tracks thereby providing a more instantaneous flow of heat to the fabric and a smoother transition of colour change. However it was not possible to fully exploit this method due to design flaws and expense. This result subsequently prompted an investigation into off-the-shelf track resistor circuits, ‘minco heat-pads’. These were used in conjunction with a temperature-sensing device to establish the parameters required for generating the required temperature control. This system provided the capacity to adjust the power in relation to ambient temperature. The off-the-shelf minco heat-pads were limited in size and shape and this limited creative design options. It was recognised that the temperature sensing system worked well however it was considered too complex and costly to pursue. Other circuit experimentation used a silver conductive pen to hand draw circuits directly onto substrates. These trials were successful, although the fragility of the tracks meant that they had a limited lifespan. It is possible that soft electronics integrated within knitted and woven fabrics might well prove useful in future research on thermochromic textiles.

The screen-printed designs were produced to explore the change of pattern and colour facilitating the combination of both types of thermochromic dye systems, leuco and liquid crystals. Designs were developed which exploited a combination of pigments, leuco thermochromic and liquid crystal dye systems. Patterns were developed for screen-printing and laser etching. Laser engraving provided another mechanism to apply pattern in a controlled way. It was a particular focus of the research to develop more aesthetically interesting fabrics that worked well with the static heat-sink circuit mechanisms. This was addressed by further exploiting laser engraving with liquid crystals. The circuits worked extremely well as a means of providing visual colour-change and created beautiful effects on the textiles. The most interesting combination of technology and design were the liquid crystal laser engraved fabrics used with the heat-sink circuits. This line of enquiry brought about transitional colour changes involving
the principles of additive colour mixing and created a range of highly unusual colours in the liquid crystal spectrum.

In order to demonstrate the key findings of the research, final prototypes were developed which showed the capabilities of multi-colour change on textiles within effective design systems. The effects of pattern and colour-change were felt important to develop further. Three prototypes were developed that would present and demonstrate different colour change effects through the use of a variety of thermochromic dye combinations. The heat-sink circuitry was based on the earlier conclusions from the preliminary testing for the staggered heat-sink line. Inspiration from the molecular structure of liquid crystals and solid crystal structures was used to further develop design ideas.

6.3 General Conclusions and Possibilities for Future Work

In order to test the creative potential of the key results, it was decided to observe how other designers would use thermochromic dyes in combination with copper heat-sinks in a workshop environment. The participants were able to creatively use a new knowledge base working with the thermochromic dye systems and electronic materials. This provided an opportunity to disseminate research knowledge and confirm the creative possibilities of the research findings. This platform was beneficial in terms of the effective practical communication of the application of liquid crystals and the diversity of results produced by the participants. The ideal anticipated outcome was to enable the participants to gain understanding of the potential of liquid crystal thermochromic dye systems, how to apply them to textiles and to enable them to be able to take this information forward creatively within their own research context. One of the participants used the knowledge from this research to inform part of her MA in the area of smart textiles. The workshop provided an insight into how other designers might use liquid crystals in future design.

In terms of colour, the liquid crystals offered the most exciting possibilities. More importantly they had not been explored previously to a significant extent on textiles. The result of the effects using multiple layers of additive colour mixing essentially provided a new colour palette for textile design. Using heat-profiling circuitry and a DMX system, the potential to mix colour and create pattern on the textile surface became possible. The colour effects produced were unique.
The exploitation of additive colour mixing on textiles is highly original. The unique colours obtained through layering liquid crystals on textiles has prompted a technical research investigation within the University aimed at quantifying the temperature and colour correlation and understanding the scientific principles. This has the potential to lead to a colour predicting system for designers. The research in question complements this design-led investigation from a scientific perspective which adds an analytical approach. The use of laser engraving combined with the liquid crystal fabric samples was interesting in terms of surface interest on the fabric. It also added more subtle hues within the colour spectrum. It also offers the potential for further exploration and would benefit from collaboration with an electro optics expert to explore the potential of other aspects of laser technology.

Further investigation of binder systems to work with the liquid crystals would support their use in design. The use of viscosity modifying agents in the formulation might well achieve the desired effect. The leuco thermochromic dyes systems offer a similar colour palette to that of traditional pigments. They are mixed before being applied to the fabric, and traditional subtractive colour mixing principles apply in this case. Although the colours are not available in as wide a variety as traditional pigments, the colour gamut is still reasonable and are available in blue, red and yellow. In principle they can be mixed in any combination. Leuco dye systems used in combination with liquid crystal thermochromic dyes offer an immense range of options for dynamic colour-change. The intrinsic function of colour to colourless can be used in combination with screen-printing and coated liquid crystals to achieve transformative effects. Both thermochromic dye systems thus offer exciting colour dynamics for application to textiles; however, the research concentrated largely on the less well-known colour potential of liquid crystals. The liquid crystals indeed provided the most significant results.

The most successful electronic heating system that was developed, was the copper heat-sink combined with the DMX system. The copper heat-sinks were easily adaptable; PCBs were capable of being produced within the University or could be outsourced at relatively low cost. The hand-applied heat-sink developed with the self-adhesive copper provided a flexible process. The advantage of the hand-applied heat-sink was that it could easily be cut to different shapes and sizes to facilitate creative exploration. These
designs showed potential to be adapted to suit a rigid PCB design to produce a more permanent and reliable form. The self-adhesive copper heat-sink was therefore a good tool for facilitating quick trials to visualise colour change effects, and also provided a means to create more complex arrangements of heat-sinks with the DMX system. The successful combination of the heat-sinks and DMX system informed the development of the final prototype pieces.

The electronic systems became a means to activate, control and produce colour changes and inspired the design development. The range of electronic developments fulfilled the objectives of the research in terms of systems that could be used in combination with thermochromic fabrics. The design development of the thermochromic fabrics and conceptual thinking were enhanced by the development of optimised electronic systems which allowed controlled colour change and pattern. Further development of the electronic systems for products would require research focused on bespoke electronic systems, components and power devices specifically aligned to activate colour-change on a range of substrates. A bespoke mixing device would allow designers to be able to understand and exploit colour change. The research specific to developing bespoke electronic systems that can activate thermochromic colour-change has already inspired other research approaches and is resulting in interesting output. A research team at Ecole Polytechnique Federale de Lausanne, Switzerland, are currently exploring thermochromic information surfaces for interactive architectural environments. They have commented on the useful information that they have derived through publication based on the research contained within this thesis as given in Appendix B.

The potential to print/coat/etch circuits directly onto fabric would bring the technology closer together in an integrated thermochromic fabric system. Future research in this direction would be advantageous to further develop systems capable of colour and pattern change. This would seem to present a natural progression of this research. The results of this research have generated a record of the unique colour-change effects of thermochromic dye systems. The combination of technology via electronic systems has provided a means to view colour change. To develop further the potential of thermochromics in design, creative approaches to activating the dyes systems should be developed. Creative intervention with thermochromics should present them as part of a design process or system the challenges the materials and highlights new ways of design thinking. Thermochromics offer a material that can give insight into new ways
to think about the way we design and how a material can function within a product. Thermochromics not only offer aesthetic and functional application opportunities but can expose inventive processes that have wider ramifications within design.
Appendix A

Table 5.1: A collection of thermochromic samples exploring the potential combinations of materials and techniques.

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>Finished Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton Satin</td>
<td></td>
</tr>
<tr>
<td>3 layer screen-print</td>
<td></td>
</tr>
<tr>
<td>Layer 1: Permanent black pigment</td>
<td></td>
</tr>
<tr>
<td>Layer 2: Black Leuco thermochromic dye system 40 °C</td>
<td></td>
</tr>
<tr>
<td>Layer 3: Liquid crystal: 35 °C</td>
<td></td>
</tr>
<tr>
<td>Laser engraved</td>
<td><img src="image1.png" alt="Sample Image" /></td>
</tr>
</tbody>
</table>

| Cotton Satin       |                |
| 2 layer screen-print. |
| Layer 1: Leuco thermochromic dye: Purple 37°C, magenta 31°C |
| Layer 2: Liquid crystal: 30°C | ![Sample Image](image2.png) |
Merino wool
2 layer screen-print.
Layer 1: Leuco thermochromatic dyes: Blue 31°C, Turquoise 29 °C, Yellow 31°C
Layer 2: Turquoise 29 °C

Merino wool
3 layer screen print.
Layer 1: Leuco thermochromic dyes: Blue 31°C
Layer 2: Leuco thermochromic dyes: Black 40°C
Layer 3: Liquid crystal 35°C
| Textured white cotton 3 layer screen print.  
| Layer 1: Permanent black pigment.  
| Layer 2: Leuco thermochromic dyes: Black 40°C  
| Layer 3: Liquid crystal: 35°C |

| Textured white cotton 3 layer screen print.  
| Layer 1: Permanent black pigment.  
| Layer 2: Leuco thermochromic dye: Purple 37°C  
| Layer 3: Liquid crystal: 30°C |
Black brushed cotton
2 layer screen print
Layer 1: Leuco
Thermochromic dyes: Blue
31°C
Layer 2: Liquid crystal: 35°C
Laser engraved pattern

Polyester Film
Drawdown bar application.
Layer 1: Single colour liquid crystal: Magenta 25°C
Layer 2: Liquid crystal: 35°C
bandwidth 5°C *

* Note: These samples are shown after heating to show the differences between samples, as before heating, they simply appear black.
| Layer 1: Single colour liquid crystal: Violet 25°C |
| Layer 2: Liquid crystal 40°C |
| bandwidth 15°C |

<p>| Layer 1: Single colour liquid crystal: Red 25°C |
| Layer 2: Liquid crystal: 31°C |
| bandwidth 1°C |</p>
<table>
<thead>
<tr>
<th>Material</th>
<th>Application Method</th>
<th>Layer 1: Liquid Crystal</th>
<th>Temperature °C</th>
<th>Bandwidth °C</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester Film</td>
<td>Drawdown bar application</td>
<td>Liquid crystal</td>
<td>31</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Paper</td>
<td>Drawdown bar application</td>
<td>Single colour liquid</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>crystal: Orange</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Black Paper
Drawdown bar application
Layer 1: Single colour liquid crystal: Magenta 25°C

Black Paper
Drawdown bar application
Layer 1: Single colour liquid crystal: Violet 25°C
Black Paper
Drawdown bar application
Layer 1: Liquid crystal: 31°C
bandwidth 1°C*

Black Paper
Drawdown bar application.
Layer 1: Liquid crystal: 30°C
bandwidth 1°C, 30°C
bandwidth 20°C*
| 143 | Black card  
|     | Drawdown bar application.  
|     | Layer 1: Liquid crystal: 40°C  
|     | bandwidth 15°C*  
| ![Image](262x275) |  
| 124 | Black wool felt  
|     | 1 layer screen-print  
|     | Layer 1: Liquid crystal: 31°C  
|     | Laser engraved *  
| ![Image](262x534) |
Merino Wool
1 layer screen print
Layer 1: Leuco thermochromic dyes: Blue 31°C
Laser engraved pattern

Polyester film
Drawdown bar application.
Layer 1: Single colour liquid crystal: Magenta 25°C
Laser engraved pattern *
| Layer 1: Single colour liquid crystal: Violet 25°C Laser engraved pattern *
| Layer 1: Single colour liquid crystal: Orange 25°C Laser engraved pattern * |
Table 5.2: The series of laser engraved samples after coating with the liquid crystals before heating and technical details.

<table>
<thead>
<tr>
<th>Sample description</th>
<th>Close up of finished sample before heating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brushed black cotton</td>
<td></td>
</tr>
<tr>
<td>Liquid crystal: R25/C10W/C17-10, R40C5W/C17-10</td>
<td></td>
</tr>
<tr>
<td>Laser setting: cotton</td>
<td></td>
</tr>
<tr>
<td>Scan lines: 0.2</td>
<td></td>
</tr>
<tr>
<td>Power: 25%</td>
<td></td>
</tr>
<tr>
<td>Speed: 100%</td>
<td></td>
</tr>
<tr>
<td>1 pass</td>
<td></td>
</tr>
<tr>
<td>Brushed black cotton</td>
<td></td>
</tr>
<tr>
<td>Liquid crystal: R30/C1W/C17-10, R35/C1W/C17-10, R38/C1W/C17-10</td>
<td></td>
</tr>
<tr>
<td>Laser setting: cotton</td>
<td></td>
</tr>
<tr>
<td>Scan lines: 0.2</td>
<td></td>
</tr>
<tr>
<td>Power: 25%</td>
<td></td>
</tr>
<tr>
<td>Speed: 100%</td>
<td></td>
</tr>
<tr>
<td>1 pass</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Liquid Crystal</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Brushed black cotton</td>
<td>R40/C5W/C17-10, R60/C1W/C17-10</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Waxed black cotton</td>
<td>R40/C5W/C17-10, R60/C1W/C17-10</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Waxed black cotton
Liquid crystal:
R30C20WC17-10
Laser setting: cotton
Scan lines: 0.2
Power: 25%
Speed: 100%
1 pass

Brushed black cotton
Liquid crystal:
R30/C10W/C17-10
R35/C1W/C17-10
R40C5W/C17-10
Laser setting: cotton
Scan lines: 0.2
Power: 25%
Speed: 100%
1 pass
Waxed black cotton
Liquid crystal:
R40/C5W/C17-10
R60/C1W/C17-10
Laser setting: cotton
Scan lines: 0.2
Power: 25%
Speed: 100%
1 pass

Brushed black cotton
Liquid crystal:
R32/C20W/C17-10
Laser setting: cotton
Scan lines: 0.2
Power: 25%
Speed: 100%
1 pass
Waxed black cotton
Liquid crystal:
R38/C1W/C17-10
R35C1W/C17-10
Laser setting: cotton
Scan lines: 0.2
Power: 25%
Speed: 100%
1 pass

Black wool felt
Liquid crystal:
R30/C20W/C17-10
R30C10W/C17-10
Laser setting: wool
Scan lines: 0.2
Power: 50%
Speed: 70%
3 passes
Black brushed cotton
Liquid crystal:
R40/C20W/C17-10, R60C1W, R30C10W/C17-10
Laser setting: cotton
Scan lines: 0.2
Power: 25%
Speed: 100%
1 pass

Waxed black cotton
Liquid crystal:
R25/C5W/C17-10, R27/C6W/C17-10, R30/C20/C17-10
Laser setting: cotton
Scan lines: 0.2
Power: 25%
Speed: 100%
1 pass
<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Liquid Crystal Details</th>
<th>Laser Settings</th>
<th>Scan Lines</th>
<th>Power</th>
<th>Speed</th>
<th>Passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waxed black cotton</td>
<td>R60/C1W/C17-10</td>
<td>cotton</td>
<td>0.2</td>
<td>25%</td>
<td>100%</td>
<td>1 pass</td>
</tr>
<tr>
<td></td>
<td>R30/C20W/C17-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R35/C1W/C17-10</td>
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<td></td>
</tr>
<tr>
<td>Brushed black</td>
<td>R40/C5W/C17-10</td>
<td>cotton</td>
<td>0.2</td>
<td>25%</td>
<td>100%</td>
<td>1 pass</td>
</tr>
<tr>
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<td>Laser setting: cotton</td>
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<td>Speed: 100%</td>
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**Black wool felt**
- Liquid crystal: R35/C1W/C17-10
- R40/C5W/C17-10
- Laser setting: wool
- Scan lines: 0.2
- Power: 70%
- Speed: 50%
- 3 passes

**Black brushed cotton**
- Liquid crystal: R30/C20W/C17-10
- R40/C5W/C17-10
- R25/C20W/C17-10
- Laser setting: cotton
- Scan lines: 0.2
- Power: 25%
- Speed: 100%
- 1 pass
<table>
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<th>Liquid crystal</th>
<th>R38/C1W/C17-10</th>
<th>R60/C1W/C17-10</th>
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<th>Scan lines: 0.2</th>
<th>Power: 25%</th>
<th>Speed: 100%</th>
<th>1 pass</th>
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| Black waxed cotton | Liquid crystal | R40/C5W/C17-10 | Laser setting: cotton | Scan lines: 0.2 | Power: 25% | Speed: 100% | 1 pass |
Appendix B

Thermochromic Information Surfaces

Interactive Visualization for Architectural Environments

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Abstract: In this paper we describe a series of nine prototypes that were constructed to explore the benefits and limitations of thermochromic ink as a material for the design of architectural information surfaces. Among the goals of the project were the identification of inexpensive fabrication methods that could be used to build thermochromic surfaces at the scale of a room. Our primary design concerns were the ability to communicate information about indoor climate, and the integration of the information surfaces in an architectural environment. We propose a method for building thermochromic surfaces based on printed circuit boards (PCB) that is cost-effective, highly precise, and allows the fabrication of large surfaces through tiling.

Keywords: Thermochromic display; interactive architecture; information visualization; fabrication process; communication.

Introduction

Thermochromism is the ability of a substance to change color due to a change in temperature. Thermochromic pigments have a large range of possible colors, and sensitively register changes in temperature by changing color or becoming transparent at a precisely-determined threshold temperature. The change is reversible, and can be repeated over long periods of time without substantial degradation in the pigment’s thermochromic properties (Christie et al, 2007).

We first became interested in architectural applications of thermochromic pigments while searching for options to display information about indoor air quality (luminosity, humidity, temperature, CO\textsubscript{2}, dust, ...) in a workplace environment. Our goal was to build a panel with graphic elements that could be selectively turned on and off to communicate indoor climate parameters (Meagher et al, 2009). For a number of reasons, thermochromic ink was chosen for this application. First, it is non-emissive and thus less distracting than LED or other emissive displays in an architectural environment: the contrast increases with the environmental light level (natural or artificial light), unlike light-emitting displays that have to compete with daylight. The graphic element can be made visible from both sides of the display, and can also be molded in various shapes. The relatively low refresh rate (the surface needs several seconds to cool down) is well-adapted to the representation of data that do not change quickly, like air quality parameters.

There are only few research papers describing
architectural applications of thermochromic pigments. Some attention has been given to the development of architectural glazing incorporating thermochromic pigments that rejects unwanted solar heat gain while maximizing daylighting (Seebold et al, 2000; Fernandez, 2007). Thermochromic pigments have been used in many product design applications including fabrics capable of dynamic color change (Berzowska, 2004) and as a means of designing ‘smart textiles’ that respond to changes in their environment (Christie et al, 2007).

The use of thermochromic pigments for information display has been reported for very small displays (Liu et al, 2007) or low resolution outputs (http://www.we-make-money-not-art.com/archives/2004/07/notsowhite-walls-interactive-w.php: Jul 2004).

Various fabrication technologies have already been explored for selective heating of the thermochromic surface:
- Conductive particles mixed with other materials (Liu et al. 2007),
- Conductive yarns (Shibutani & Wakita, 2006),

We decided to explore the use of printed circuits boards (PCB) to fulfill this task. PCB is commonly used for electrical circuits and allows patterns to be etched in the copper layer covering an epoxy plate. This technology which is used worldwide makes it possible to realize detailed etching patterns with an almost complete freedom in design.

The fabrication of a thermochromic panel prototype

For this study we built a set of nine prototype panels: seven were the size of an A4 paper sheet and two panels had a display surface area of 0.48m² (0.74 by 0.64 m).

We used a thermochromic reversible leucodye micro-capsules based ink which is blue below 40°C and transparent above this temperature. The temperature threshold of the thermochromic pigments can be freely defined on order, between -15°C and 80°C. Our goal was to use this property to display information by selectively heating an ink covered panel above the threshold temperature.

The PCB fabrication facility of our university allows patterns to be made with a linewidth of about 0.1mm (the order of size of a human hair). The boards used have a copper layer thickness in the range 5 to 18 micrometer. The thickness of the epoxy substrate was chosen depending on the prototype and was in the range of 1.6 to 0.1mm. The 0.1mm substrate board was as flexible as a sheet of paper and could easily be molded to a curved surface such as a structural column (figure 1f).

When we apply an electrical voltage at both ends of a conductive element, it will heat, in turn heating the painting and cause a change in the color of the ink with which it is in contact.

The figure to be displayed could be designed as an outline (figures 1c, 1d, 1e, 1f) or a filled in figure (figures 1g, 1h, 1i, 1j, 1k). In order to display a filled in figure, the pattern on the PC board consisted of a coiled wire filling in precisely the surface area of the figure. The line width and length of the heating elements were adjusted to reach an optimum electrical resistance and be compatible with the requirements of the power supply. Because of the low value of the electrical resistivity of copper, the linewidth was in general chosen as small as possible while still easy to manufacture.

We were able to build boards with a maximum dimension of 23 x 30cm using standard processes;
Figure 1
Thermoelectronic prototypes:

a-b) This design, borrowed from a fabric pattern by Klaus Jahnke, uses density and brightness as variables to communicate information, for example change in indoor climate.

c) One prototype implementing the concept of figure b, fixed on a frame, hanging on the wall (display surface of 6m x 3.6 m)
d-e) Close-up of the pattern displayed on the wall panel. Bird (6m x 3m), ostrich (7m x 4m), elephant (7m x 4m)
f) Same panel as in c, hung wrapped around a column

g-h-k) Filled in figures. ISS logo (4m x 4m), arrow (7m x 0.6m), water bottle (7m x 6m)
i) Overlapping patterns

j) Pixel-based prototype, the PCB before being covered with paint (256 pixels of one square centimeter)
larger panels could be constructed by tiling these boards together, and two of our prototypes were built with four boards each to form an apparently homogeneous surface of almost 0.5m².

Among the advantages of PCBs for our application were the flatness and the smoothness of the surface in contrast with glued conductive materials such as nichrome wire. To assure high contrast, we first applied a layer of white paint on the boards before adding the blue: when the blue thermochromic paint is heated it becomes transparent and the white paint becomes visible.

The idea is to use a convenient voltage, to limit risks of overheating of the circuits and to simplify the power management. So the circuits’ length should be adapted to the available voltage. Tests were made using either DC or PWM (Pulse-width modulation) power supplies. The current depends on the PCB characteristics chosen.

The first prototypes explored the use of conductive pixels (figure 1j) to activate the thermochromic pigment: we realized an array of 16 x 16 pixels (1 x 1cm), each of which contained ~40cm of tightly coiled copper lines in order to reach an optimal resistance for heating. The activated pixels provided a high level of contrast and legibility from a distance, but we were not satisfied with the aesthetic quality of the visualizations obtainable using such a small pixel array.

Following the pixel display, we tried “filled shapes” (figures 1g, 1h, 1i, 1k) with several boards that used commonly recognizable icons to communicate information. We experimented with the spacing of the copper wires used to activate the filled shape, and found that the spacing had a direct effect on the color and brightness of the resulting shape. We explored the design possibilities afforded by overlapping several figures on a board, either by printing circuits on both sides of the PCB or by interleaving one circuit with another on a single-sided board (figure 1i).

Our final set of prototypes explored the use of “outline only shapes” and “patterns” - figures formed by a single copper wire. We found these outline figures particularly appealing in that they compared favorably to an LCD display in terms of resolution, because the unit of display was now a line rather than a pixel.

Discussion

One advantage of thermochromic panels is the fact that the power consumption is not dependent on the total surface area of the display, but rather on the power required to turn on the desired pattern: unlike LCD’s, no power is required when no content is being displayed. And even switched on, the power consumption of our large prototypes is competitive with a LCD display of the same size. A LCD display of a size equivalent to our largest board (~0.5m²) has a typical power consumption of 200W-400W. With all the patterns switched on, our board has a power consumption around 100W.

In terms of design, the possible patterns displayed are fixed for the lifetime of the product. They have to be defined when the board is ordered. This makes them specially adapted to visualization interfaces displaying a fixed kind of information.

Thermochromic surfaces are particularly suited for uses that do not require frequent changes in the displayed content, and can be especially valuable for environments where subtle, non-intrusive information visualization surfaces are required. When parts of the surface are switched off after being activated, the patterns gradually fade away and the color returns to its initial state, a process that requires several seconds, depending on the ambient temperature and the mechanical properties of the board. This gradual rate of change was seen as a benefit in terms of integrating information displays in the built environment without introducing a source of distraction. The non-emissive property of thermochromic surfaces also contributes to the specific quality of thermochromic displays. Thermochromism may be a valuable answer to information visualization challenges, specially in electromagnetically sensitive...
environments like hospital, airplanes, or high-tech labs.

In regard to information visualization, we concluded that pixels are not an ideal method for thermochromic information interfaces, at least as implemented in our prototypes. The use of patterns formed by a single thickness of copper wire is more successful in terms of information display and aesthetic results. The primary benefit of single-wire patterns is the precision of the lines, and the ability to produce a vector figure with the resolution of a printed graphic.

Conclusions

For the design of architectural information surfaces we propose a method using the property of thermochromic ink to change color when heated above a threshold temperature. The ink is applied to a thin wire copper pattern etched on a standard PCB board using standard PCB techniques, and heated by passing an electrical current through the wire pattern.

The feasibility of the technique is demonstrated by the construction of nine prototypes with different technical parameter choices. The design parameters can be optimized to improve the display contrast and lower the power consumption. The manufacturing costs can be reduced by volume production.

In terms of architectural integration, the primary goals of the project were to reduce the cost of fabrication, to maximize the surface area of the display, and to identify techniques for the display of information that would be minimally distracting in a workplace environment. It was shown that the display surface area can be increased by tiling A4 size boards together. The prototype was made up out of four boards with a display area of 0.48m².

Acknowledgements

We are indebted to the many people at EPFL who assisted with the production of the prototypes, including: Antoine Gagliardi, Mitchell Heynick and Laurent Emmenegger of the “Atelier des Maquettes” for their help with the painting; André Badertscher, Pierre-André Joly, Manuel Leitos, Mose Silvestri, Philippe Vosseler, Berthoud Andrie, and José Luis Ganciaco of the “Atelier des Circuits Imprimés” for generous assistance with soldering and the fabrication of the PCB’s; and Joseph Guzzardi for his introduction and continued assistance with Protel.

References


Design concepts for a temperature-sensitive environment, using thermochromic colour change.

Robert M. Christie*, Sara Robertson & Sarah Taylor.

School of Textiles & Design, Heriot Watt University, Scottish Borders Campus, Galashiels TD1 3HF, Scotland, UK

SUMMARY

Thermochromic dyes and pigments, of both leuco dye and liquid crystal types, offer significant potential for aesthetic and functional textile design in the area of smart materials. This paper presents an overview of some of the most important recent design applications of thermochromism, illustrating the potential they offer the designer together with a discussion of the technical features of the materials which have limited their exploitation to date. Our approach to research on thermochromic textiles at the design/technology interface is presented in terms of an illustrated discussion of the application of a specifically-developed variable temperature colour measurement methodology to inform predictively the creative design process, complementing the fundamental skills of the textile design practitioner.

INTRODUCTION

Colour is generally the most immediately visible aspect of textile design and is thus an essential design consideration, for many designers the principal aesthetic concern. The physical properties of fabric which can allow colour to be enhanced through light play, surface and structure effects are also of immense value to designers (reflective qualities of gold yarn, light-absorbing properties of velvet, light diffusion properties of organza). Colour is emotive; it can move us, and inspire us. Each designer has a personal take on colour and a preferred colour palette which contributes to his uniqueness. The current commercial range of dyes provides the textile designer with the ability to introduce a wide gamut of colours into yarn or fabric. These dyes are required to provide a constant, predictable and reproducible colour and, as far is technically feasible, a permanent colour in terms of exposure to external effects such as light and washing. A variation in the colour of a dyed or printed fabric, for example when exposed to temperature change...
or to light, would normally be regarded as highly undesirable - a defect. However, it has been recognised in recent years that there are potential commercial niche applications for dyes which exhibit a distinct colour change when exposed to an external stimulus, especially when that change is controllable and reversible. Such dyes are collectively now commonly referred to as chromic materials, of which there are a variety of types.[1,2] For example, photochromic dyes acquire a colour when exposed to UV radiation and revert to their original colourless state when the light source is removed. Photochromics find their most important commercial applications in sun-screening ophthalmics (sunglasses, ski-goggles), security printing and in 'high-technology' applications, such as optical data storage. The focus of this paper is on thermochromic dyes and pigments which change colour in a controlled way when the temperature is varied.[3,4] The colour change is used to indicate temperature variation, for example in plastic strip thermometers, food packaging, medical thermography, and non-destructive testing of engineered articles and electronic circuitry. There has been commercial exploitation of thermochromic textiles, probably most notably (some would argue notoriously) the T-shirts which changed colour with skin temperature, a transient novelty fashion item of the late1980s. There is, however, considerable potential for functional textile applications of thermochromism associated with so-called smart fabrics and clothing, which are designed to sense and react to environmental conditions and stimuli.[5,6] Smart materials are also of intense interest to artists and designers, inspired by the possibilities for the development of new creative design directions towards interaction, response and ultimate functionality. Colour change technology thus offers the designer unique and challenging design opportunities.

In the School of Textiles & Design of Heriot-Watt University, we have been engaged for a number of years in research aimed at the technical development of photochromic and thermochromic materials specifically for use in textile applications, and of methods for the assessment of their performance on textiles.[7-9] The outcomes of this research have provided textile designers in the School with unique access to optimised materials, technical expertise and predictive tools to complement their unique creative skills in the use these materials. In this paper, we demonstrate how technological understanding and specifically-devised experimental methodology applied to thermochromism is now informing an AHRC-funded programme of research at the design/technology interface.
THERMOCHROMIC DYES AND PI戈MENTS

There are two principal types of thermochromic systems which may be applied to textiles. The term 'system' is used advisedly as these materials are not dyes in the conventional sense. The system which has been most commonly used is referred to as of the leuco dye type. This system relies on colour formation from the interaction of three materials, a colour former (the leuco dye), an acid (or activator) and a low melting solvent. The mode of action involves a series of physical transformations within the composite system, which induces a chemical interconversion between coloured and colourless forms based on the leuco dye chemistry. Scientific details of the mechanism may be found in the literature.[3,4] The observed thermochromic effect is usually a change from coloured to colourless (which is reversible) as the temperature is raised, although by mixing with traditional dyes and pigments an interchange between two single colours may be achieved. The second type of thermochromic system which can be applied to textiles is based on liquid crystals. Liquid crystals, often termed the fourth state of matter, are liquid-like in behaviour but the molecules have a tendency to line-up in an ordered pattern, unlike normal (isotropic) liquids in which there is random orientation. The thermochromic effect provided by certain types of liquid crystals is quite different from the leuco dye types in that they commonly provide a continuously changing spectrum of colours over a range of temperatures (referred to as ‘colour-play’). The colours arise from physical changes in the orientational structure of the liquid crystal rather than from the chemical conversion involved with leuco dye types. The colour changes result from way light interacts with the liquid crystals to produce coloured reflection by interference, and from the variation of the the liquid crystal structure with temperature.[7,8] There are two broad groups of liquid crystal thermochromics, cholesteric (chemically modified natural products) and chiral nematics (purely synthetic products). Of these, the chiral nematics show a more dramatic colour-play, but are more expensive. By careful formulation, each of the thermochromic systems can be fine-tuned to give colour changes in different temperature ranges, although commonly the requirement is for systems which change colour around ambient room temperatures or at human skin temperatures.

A feature of both thermochromic systems applied to textiles is the requirement for microencapsulation, a process which wraps the ingredients in a tiny hard shell. This is necessary to ensure that the materials are contained and provides them with protection.
against their environment to which the materials may be sensitive. Since they are
applied as discrete solid particles, they are often considered as pigments rather than
dyes. There are relatively few manufacturers of thermochromics. Major manufacturers
include TMC (Thermographic Measurements), UK, Color Change Corporation, USA
and Matsui, Japan.

THERMOCHROMICS IN ART & DESIGN

The concept of smart textile materials is currently having a significant impact on the
design world, through the convergence of the disciplines of science, engineering and
design. However, the fascination of artists and designers with the ability to create
tentities capable of transformation, for example by changing appearance in an interactive
environment, is not new. Forward-looking art movements have perennially been
inspired by the cross-fertilization of science and art. As early as the 1920s, the
Hungarian artist Laszlo Moholy–Nagy was profoundly influenced by the new
technologies of his time. He had a particular fascination with light, colour and the
developments in technologies such as photography and advertising displays, which
informed his conceptualization and creative activity in a form of art which he termed
*kinetic optical composition.*[10] One of his contemporary Bauhaus artists, Ludwig
Hirschfeld-Mack contributed to the new artistic genre in his *reflected colour displays,*
which employed the projection of coloured lights from freely-movable sources through
opening and shutting apertures of a variety of shapes, his dynamic multicoloured
creations being set to rhythmic musical accompaniment.[10] Today, the development
of these technologies into the digital era and the introduction of smart materials
continue to make available a range of new media for creative exploitation. The use of
thermochromics to express colour change on a textile surface fits comfortably into the
area of smart design.

Thermochromism has been exploited by a few designers who have been stimulated by a
recognition of the potential for novel design directions. An overview of some recent
relevant design research is presented in this section. A thermochromic design requires a
means of application of the thermochromic dyes or pigments to a substrate, in
conjunction with a heat generating system which may, for example, involve simple
human skin contact or electronic circuitry. The latter combines the creative design
process with the technologies of coloration and electronic engineering. Linda Worbin has successfully employed thermochromic colour-change technology in her practice-based research, using traditional fabrics and printing processes, to develop dynamically changing and responsive textile patterns in the area of smart and interactive textiles.[11,12] In an interesting demonstration, she illustrates how a thermochromic fabric reacts to spillage of a cup of hot water. The colour disappears in the regions in contact with the hot water. In some prototype designs, she used thermochromic printed fabric with laser-cut heating elements beneath the fabric. When connected to a power source, the heat generated reveals the printed pattern on the fabric surface. She also produced thermochromic designs with carbon fibre woven into the fabric, producing a colour and pattern change on the fabric surface when connected to the power supply.[11,12] Zane Berzina’s paper Skin Stories: Charting and Mapping the Skin collects together the results of her practice-led multidisciplinary research which adopted multiple approaches to design.[13] Her interests in the human skin and its biology from a textile designer’s perspective provided the inspiration to use thermochromic textiles to act as a metaphor for a 'living membrane' capable of sensing environmental change. An interesting feature of her work is Touch-Me Wallpaper, a prototype multisensory interactive wallcovering triggered by contact with the human hand. A temporary handprint appears on a thermochromic surface, aromatherapeutic fragrances are released, and the incorporation of phase change material allows storage and and controlled release of heat, prolonging the thermochromic effect and allowing control of room temperature. Zane Berzina has also experimented with 'drawing' using electricity. In Sensory Screen, semi-conducting threads are incorporated between layers of thermochromic non-woven fabric. As a circuit connection is switched on and off intermittently, the thermochromic effect produces a line that appears and disappears.[13] A further important contributor to designing with thermochromics is Maggie Orth, who was the founder of International Fashion Machines (IFM), a company with a focus to produce flexible electronic art which incorporates new technological concepts into consumer products. IFM have produced an electronically-activated colour change textile, Electric Plaid, which combines thermochromic printed textiles with electronic circuitry. The circuits are woven into the surface of the fabric and activate the thermochromic effect when connected to a power supply. IFM's current direction appears to be leading towards products integrating electronics with textiles that can be used in the home, for example in interior applications where the products function within the context of the home environment.[14] Joanna Berzowska, a co-
founder of IFM, has developed *Shimmering Flower* which deploys thermochromic technology, conductive yarns and computer-controlled electronic circuitry to create a non-emissive colour-change textile display. The thermochromic effect is activated in areas of the design with individually addressable pixels, the colour change being programmed or controlled in real time.[15] *Shimmering Flower*, a highly poetic design piece, was woven on a Jacquard loom, which allowed the creation of soft woven circuitry through complex weave structures. *Krakow* is a further piece produced by Joanna Berzowska combining thermochromic and Jacquard weave technologies. In this case, human figures in the woven image change from black to transparent when the temperature rises. The connection to the power source is visible and adds to the aesthetic value of the design.[16]

Research into the use of thermochromic materials in architecture has demonstrated inventiveness using unconventional material combinations in response to significant technical and design challenges. This has introduced the concept of interactive architecture which allows aspects of a building to sense, respond and adapt. Glaister, Mehin, and Rosen have incorporated thermochromic materials into concrete with a system of nickel-chromium wires linked to a power source. The thermal energy activates the thermochromic effect at the surface of the concrete to allow, in principle, the display of graphics and information.[17] (Interactive Architecture, assessed 2006). A climate control tile has been developed by Johnson. The tile combines phase change material and thermochromic technology on its outer surface. The ability of phase change material to store and control release of heat in combination with the thermochromic technology makes it possible to produce a visual thermograph or heat map.[18] (Infotile, assessed 2006) These tiles might be used, in principle with appropriate integrated control technology, to change colour throughout the course of the day, and to provide temperature regulation.

There are recurring themes in the commentaries from designers who are making use of thermochromics providing some explanations for the relatively limited exploitation of the technology to date. The materials are limited in scope and availability, and they are relatively expensive. The dyes cannot be used in exactly the same way as traditional dyes and pigments and there is generally limited access to technical expertise, information and support for their use in the range of media with which designers would
wish to experiment. As a result, practitioners commonly resort to the inevitable trial and error approach. The dyes may also show limited stability in certain environments, leading to questionable longevity of textile design products. Another factor which may have limited their exploitation in textiles is the ingrained memory of their use in the past for novelty effects, presenting a barrier to more intelligent and creative use in complex design systems. It has been acknowledged that compared with other markets, the textile sector lags behind in the exploitation of thermochromic materials and that continuing research in the chemistry and technology of dyes for textile applications will be important to widen the range of materials and to improve their performance.[19] At the same time, it is important for designers to recognise not only the potential of this colour changing technology but also the technical limitations, and to embrace the challenges within design. The approach to the concept in the School of Textiles & Design of Heriot-Watt University is reflected in our parallel programmes of research on technical aspects of chromic materials and in textile design using the materials, informed by our acquired technological expertise.

**AN INTERDISCIPLINARY APPROACH TO TEXTILE DESIGN USING THERMOCHROMICS**

Thermochromics are most conveniently applied to textiles by screen printing using pigment printing formulations. It cannot be assumed necessarily that the materials will behave as normal pigments because they do not have comparable levels of stability. In the case of leuco dye types, traditional pigment printing binder formulations and curing conditions generally can be made to work reasonably well.[20] Examples of the colour change behaviour of textiles printed with leuco dye thermochromics are shown in Figs 1-3.
Figs. 1 - 3. Thermochromic printed textiles (a) before and (b) after heating.

Fig. 1(a) illustrates samples of textiles screen-printed separately with green, magenta and blue leuco thermochromics in a transparent binder, showing the bright individual colours which can be obtained at ambient temperatures. Fig. 1(b) illustrates the same samples with the temperature raised using a hair dryer, which causes the disappearance of the pattern. The designs re-emerge when the samples cool back to room temperature. Fig. 2 shows a design inspired by electronic circuitry and demonstrates a different colour change function. The background was printed with an open screen using an orange thermochromic together with an opaque white pigment to produce a more subtle, muted colour effect. The permanent design was overlaid using a brown pigment. On heating with the hair dryer, the background disappears leaving the image of the permanent design. Fig. 3 illustrates a textile printed with thermochromics incorporated into a puff binder, using magenta and blue in different regions of the design. The thermochromic effect of three resistant nickel-chromium wires connected to a power source and located under the print is evident as lines in which the colour has disappeared.
We have previously reported our investigations of the colour change properties of thermochromic pigment-printed textiles using a unique system developed in our laboratories to measure colour as a function of temperature. An important feature of these studies was the exploration of the ways in which the data may be presented and interpreted. Since colour is itself a 3-dimensional property, introducing temperature as a further variable adds a fourth dimension to the complexity. The methodology we have established provides a unique tool for designers to establish the exact form of the colour changes and the temperatures at which these changes occur. The technique may be applied usefully to determine the temperature ranges over which leuco dye thermochromics change colour, and the interpretation in such cases is relatively straightforward as it involves simple interchange between two colours.

4(a) 4(b)
Fig. 4 Thermochromatic textiles printed (a) before and (b) after heating.

The design illustrated in Fig. 4(a) was printed with a blue thermochromic as the predominant component, mixed with a magenta thermochromic and with permanent yellow and opaque white pigments in smaller quantities. Fig. 4(b) illustrates the print blown with a hair-dryer in such a way that there is a temperature profile across the print, the top of the print at the lowest temperature and the bottom at the highest. At the top
there has been no colour change, while at the bottom there has been complete loss of thermochromic colour leaving a visual colour effect due only to the yellow and white pigments. In the centre, it is apparent that the blue has decolourised, but the colour of the magenta thermochromic remains (providing a mauve colour when combined with the yellow and white), because its response temperature is evidently higher than that of the blue. The thermochromics were reported by the suppliers as having similar temperature change ranges, but it is clear that there are differences possibly due to the rate of change, or indeed to batch variation in the commercial samples. While in this case the interesting effect was discovered serendipitously, it is of interest that our colour measurement method offers the facility to predict such effects for use as a design tool.

We have applied the methodology more extensively on liquid crystal thermochromics, where the colour change phenomena are more complex and, arguably, create a wider range of exciting possibilities for design applications. Thermochromic liquid crystals are rather sensitive materials, requiring extreme care in formulation and presenting technical limitations in textile applications. These features, together with their relatively high cost, may explain why they have been less extensively exploited by designers. The designer requires to understand and work within these parameters for maximum impact. A particular deficiency, which may limit application for manufactured articles requiring longevity when exposed to a demanding environment, may not so important for a set of exhibition artefacts which can have a reasonable lifetime if stored and used carefully. However, we have demonstrated that thermochromic liquid crystal printed fabrics can show reasonable fastness to washing under mild conditions.[8] It is commonly stated that thermochromics are sensitive to light, especially to the damaging UV radiation in sunlight and we have demonstrated this from our quantitative measurements.[8] Nevertheless, we have examples of these thermochromic prints made up to 15 years ago which have been exhibited and used as conference lecture illustrations on numerous occasions over that period in venues around the world with minimal apparent deterioration in thermochromic performance. The prints thus have reasonable longevity if stored out of light but with no other special precautions.
In our previously published reports of the various ways in which thermochromic colour variation with temperature can be expressed numerically and graphically, we have made use of 3-dimensional CIELAB colour space, an accepted standard method of colour representation, as illustrated in Fig.5. The human eye can distinguish millions of colours and any one of these is represented as a single point in this colour space. The attribute of lightness ($L^*$) is given in the vertical axis. An ideal white would give an $L^*$ value of 100, with $L^* = 0$ for an ideal black. Hue is represented by the parameters $a^*$ (redness / greenness) and $b^*$ (yellowness / blueness) values. Chroma ($C^*$) is the distance from the origin and describes the saturation (or richness) of colour, often described as 'colourfulness'. Thus strong bright colours give high chroma values, while neutral colours (white, grey and black) give chroma values close to zero and hence they are

Fig.5. CIELAB Colour space
commonly termed *achromatic*. Because of the complexity in attempting use 3-dimensional representations, we have found 2-dimensional a*b* diagrams, such as those given in Figs 6 - 8, useful to represent the colour changes. In our previous publications, we have separately illustrated lightness (L*) and chroma (C*) values to provide a complete characterisation of the colour changes.[7,8]

![Fig. 6. a*b* diagram illustrating the colourplay of a thermochromic liquid crystal print over black and grey backgrounds. The colours used to illustrate the curves have been selected to indicate the colour of the background.](image)

It is commonly stated that in order to produce the most striking thermochromic effect from liquid crystals, it is necessary to apply the prints to a black background. This is commonly cited as a factor which restricts the versatility of their application to textiles. The physical reason is that, for optimum visual effect, a black background is required to absorb the transmitted light so that the reflected colours are displayed to their full effect. Fig. 6 shows a*b* diagrams obtained from measurements for a print formulated to show colourplay at temperatures just above room temperatures printed on to substrates with black and grey backgrounds over the temperature range 26 - 47°C. Each of the individual points constitutes a measurement at a particular temperature, a few of which are indicated on the curve for the black print. Initially, the film is essentially colourless and the measured colour is given by a point close to the origin, characteristic of the background. As the temperature is raised, the colours pass rapidly through red and yellow shades and progressively more slowly through green and blue shades. The shape
of the curve demonstrates that the system produces richer (higher chroma) colours in the green and blue regions, than in the red region, in agreement with visual observation. At a sufficiently high temperature the print becomes colourless as the liquid crystal converts to a normal liquid and the curve thus returns essentially to its original point. As shown in Fig. 6, the print on the grey background, because of its lower light absorption properties, provides generally lower richness of reflected colour compared to the print on black.

**Video 1 here**

Video 1. A demonstration of the reversible thermochromic effect obtained from liquid crystal prints on textiles.

Video 1 shows a design derived from a thermochromic ink containing microencapsulated chiral nematic liquid crystal printed on to black nylon-lycra fabric. Initially, at ambient temperatures, the design is essentially colourless, although weakly visible because of the slightly opacity of the print. It is then subjected to blowing with a hair dryer. Because of the rapid heating rate, the reds and yellows are transient and the green rapidly develops, converting to deep blue as the temperature rises. After a heating period of about 1 minute, the hair-dryer is switched off and the colour changes are seen to reverse as the print cools. This time, a colour commonly described as red-tan is more clearly observed due to the slow rate of cooling.
Thermochromic colour change technology offers the designer the ability to create both subtle and dramatic effects. By using different background colours it is possible to explore a range of colourplay effects, offering immense design potential when used in conjunction with the range of fabric types available today. To illustrate the possibilities, measurements were made of the same ink printed on to different coloured backgrounds. The graphical representations of the data are shown in Figs. 7 and 8 and allow an interpretation of the way in which the colours change as the temperature is varied. For clarity, the colour of the background is indicated in the colour of the curve and the individual measurement points are omitted. In each case, similar curve shapes are obtained, offset to a position on the a* b* diagrams defined by the background colour. Fig. 7 shows the curves provided by prints on to relatively dark background colours, namely brown, navy-blue and olive-green, with the curve for the black background include for comparison. The curves show that highly chromatic colours can be achieved on such backgrounds. The reddish-brown background gives marginally stronger yellowish hues, but with reduced chroma greens and blues. The blue and green backgrounds give stronger colours when the light reflected from the liquid crystal is the same as, and thus reinforces, the background colour, but there is reduced intensity in other colour regions.
Fig. 8. a*b* diagram illustrating the colourplay of a thermochromic liquid crystal print over black, burgundy and red backgrounds.

Fig. 8 shows the curves obtained from the thermochromic print on two red backgrounds, a burgundy and a bright yellowish-red, with the black again reproduced for comparison. The burgundy background, as the temperature is raised progressively, provides stronger chromatic reaction than over black in the red and yellow regions, weak greens, but a reasonably chromatic reddish-blue. The thermochromic outcome of the print on the bright red is a subtle change of properties within the red to yellow colour regions. As the temperature is raised, the red hue becomes initially yellower, losing chroma, but later transforms to a bluer shade of red with increasing chroma. It is our opinion that there is significant scope for the designer to make creative use of such subtle colour changes.

CONCLUSIONS

The textile designer has a unique set of fundamental skills which include the ability to select, combine and transform colour. Designers are also continuously influenced by external trends and market demands. Developments in the emerging area of smart materials are providing access to new and innovative fabric and yarn types and coloration systems which offer the designer a set of exciting new opportunities, together with significant creative and technical challenges. The unique features of colour change technology, such as thermochromism, allow design skills to be embedded as a function within textiles. Our approach, exemplified by the results described in this paper, combines research in colour-inspired design, research in colour technology, and research at the design/technology interface. An important aspect of this set of parallel programmes is an AHRC-funded programme of textile design research, based on fundamental design skills, supported by the technical capability to measure and predict colour changes on printed thermochromic textiles, in combination with specifically designed electronic circuitry to provide controlled and regulated temperature profiles, with the aim to produce dynamic and responsive textile designs and artefacts.

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Designing with a responsive colour palette: The development of colour and pattern changing products.

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Thermochromic; electronics; heat-profiling; textiles; smart design.

Abstract
This paper presents an illustrated discussion of the potential for creative design applications of thermochromic textiles brought into contact with specifically designed heat-profiling circuitry. The results are derived from a current research programme at the design/technology interface on the application of colour change technology in interior textile design. Examples are given of textile samples combining printed thermochromics with circuitry to demonstrate the aesthetic qualities that can be achieved from integration of the technologies in a flexible fabric system. Dynamic colour change effects controlled by prototype circuitry and power electronics are demonstrated. The paper concludes with an analysis of the potential for product/artefact development in the area of “smart” design and how, as a consequence, a responsive interior might be envisaged.

Introduction
In recent years the design potential for dyes that exhibit a distinct colour change when exposed to an external stimulus, especially when that change is controllable and reversible have been recognised across design fields. [1] Such dyes are referred to as ‘chromic materials’, of which there are a variety of types. The focus of this paper is on thermochromic dyes and pigments that change colour in a controlled way when the temperature is varied. There is considerable potential for functional textile applications of thermochromism associated with ‘smart’ fabrics and clothing, designed to sense and react to environmental conditions and stimuli. [2] Smart materials are also of intense interest to artists and designers, inspired by the possibilities of the development of new creative design directions towards interaction, response and ultimate functionality. Colour change technology thus offers designers unique and challenging design opportunities. [3]

This paper presents the results of a collaborative research programme to assess the aesthetic qualities and technical performance of thermochromic dyes on textiles used in conjunction with integrated heating mechanisms. The collaborative team, which comprises textile designers working at the technology interface, a colour chemist and electronic engineers, brings together collective expertise to facilitate design applications using two classes of thermochromic dyes - leuco dye and liquid crystal types. The research forms the basis of an AHRC funded practice-led PhD programme in the School of Textiles and Design, Heriot-Watt University supplemented by a Smart.idea award from the DTI,
with the support of LCR Hallcrest, a world-leading company involved in the commercial exploitation of thermochromic materials.[4] The School of Textiles and Design has been engaged for a number of years in research aimed at the technical development of photochromic and thermochromic materials specifically for use in textile applications, and of methods for the assessment of their performance on textiles, with growing emphasis on research at the design/technology interface [3,5,6].

The Design Process

To evaluate the design aesthetics and potential of thermochromic textiles used in combination with heat profiling electronic circuitry, the design of several electronic circuits was undertaken. A collection of thermochromic fabrics and related materials was prepared for assessment in combination with the constructed electronic circuits. Assessment of the colour change properties of the thermochromic fabrics reacting to temperature changes when brought into contact with specially designed heat profiling circuits was a particular of the research. Another focus, determined by observation of the colour-change performance of individual textile samples in contact with the circuitry, was to optimise and control the heat profile generated by the circuitry. Control of temperature within the circuitry was used to achieve dynamic colour change effects with exciting ‘colour play’ aesthetics, taking advantage of the availability of dyes with varying temperature response thresholds.

Two different techniques were used to design and construct a range of heating elements. Copper heat-sinks were used in combination with surface mount devices (SMD technology) which act as resistors enabling heating of the copper. The second technique used Track resistors, consisting of distributed elements, long narrow metal tracks deposited on both rigid and flexible substrates. Using these techniques a series of circuits were designed for optimum heating capability. The circuits were controlled using a variable power supply, providing a mechanism which offered flexibility for monitoring and evaluating the influence of voltage on temperature (both the final temperature and the rate of heating) and the consequent effect on colour change. Simple switch mechanisms were used to control individual heating elements.

Heat-sink technology with surface mount resistors offered flexibility in sizing and, from a design perspective, provided considerable scope for pattern design in the form of block shapes. Copper, with its good thermal conductivity, was exploited using a series of rigid printed circuit board (PCB) designs and in a system that allowed the application of the heat-sink directly on to a thermochromic fabric thus further integrating the two technologies to allow development of controllable colour-change materials. The circuits were constructed by hand allowing easy adjustment and testing of fundamental functionality, refer to: Fig. 1

![Figure 1a heat-sink applied directly to a fabric printed with liquid crystal thermochromics](image1a.png)

![Figure 1b ‘colour-play’ effect when connected to a power supply](image1b.png)
Resistors were soldered on to the copper shapes in order to allow internally generated heat flow into the metal surface, creating the “heat-sink”. The design of the first proto-type circuit was used to establish the boundaries of the technology and to monitor variables associated with the heat profiles across simple block shapes. For continuity in the experimental process, and for recording colour change, a star shaped circuit design, composed of connecting heating elements, was selected to observe the thermal behaviour within a complex shape and to assess optimal design potential. Other shapes, including circles, were also tested in simple repeating patterns.

As a further development, circuitry using track resistors were designed and tested as an alternative mechanism for creating localised heating in contact with thermochromic fabric. The resistance properties of stainless steel were exploited for the track construction in this flexible circuit design produced on a thin film. This technique allowed the development of linear designs as well as block shapes, in contrast to our use of heat-sink technology. The potential to create fine, linear heated patterns provided more versatile design options. The board was designed to include several test shapes, including a star shape for continuity. The resistance of tracks was predetermined to address the optimum size and length of tracks in the circuit design. The circuit construction was outsourced to a company who specialise in flexible circuit technology.

**Thermochromic Textile and Related Material Preparation**

A wide selection of fabrics and other related materials were screen-printed with thermochromic dyes. Microencapsulated leuco dye thermochromic systems with two different temperature-induced single colour change thresholds (31°C and 47°C) and liquid crystal thermochromics, of both cholesteric and chiral nematic type, that exhibit ‘colour-play’ through a spectrum of colours just above ambient temperatures were tested. [3] The thermochromics were printed on to a range of white and black fabrics, plastics and functional materials. The following materials were chosen for their surface qualities and to allow the assessment of behaviour of the thermochromics when printed on different the base material: medium weight furnishing cotton, woven merino wool, Outlast phase change material, black wool felt, wax coated cotton, Fothergill engineered carbon fabric (black), linen black (furnishing weight), viscoe/acetate, textured cotton, vinyl, polyester film and textured polyester film, refer to Fig. 2. Mixtures of microencapsulated leuco dye thermochromic systems with different temperature change thresholds, and in combination with permanent base pigments, were tested. With each circuit design, optimum voltage settings were established to achieve clear developed image resolution as well as image disappearance effects. The effect of ambient temperature on colour change, both in heating and cooling cycles, were observed over temperature / time intervals. Photographs and videos were used to record and analyse the dynamic colour transition effects.

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![Figure 2 a range of sample materials printed with thermochromics in a variety of colours](image)
Research Outcomes

Fig. 3 shows some of the visual qualities obtained. For printing the thermochromic textile samples, various binders were evaluated to establish the most effective formulation. Thermochromic liquid crystals are particularly sensitive to the environment (chemical and physical) in which they are incorporated. Interestingly, the use of a water-based acrylic binder, adapted for suitability for screen printing, cured at ambient temperatures provided strong colour-change effects with the liquid crystal thermochromics on textiles. Interesting ‘colour play’ effects were achieved using the various colour change temperature thresholds within individual samples.

The method of mounting electronic circuitry and heat-sink arrangements on rigid boards proved effective in creating colour-changes on thermochromic textiles and related materials. For this circuitry, a range of voltages (4 – 7 v), generated different colour change qualities from the thermochromic materials due to different temperature responses. It was found that the response of microencapsulated leuco dye thermochromic systems that change at 31°C was affected by variations in ambient temperature, often leading to inadequate shape resolution. Due to slow cooling after the power was switched off from a temperature threshold close to ambient, they remained in their colour-changed state for a prolonged period, making the image visually static and with reduced clarity. Higher temperature change threshold microencapsulated leuco dye thermochromic systems (47°C)
were more effective, as they were less affected by ambient temperature, and cooled at a much faster rate, the fabric quickly reverting to its original colour state.

Further development of the heat-sink system was conducted, combining a digital mix (DMX) system to successfully activate individual heating elements in the circuit design in a controlled way, with the heat-sink directly applied to fabric. This hand-constructed approach offers the designer a very flexible, craft-like approach to integrating technologies providing freedom and creative control.

Track resistors proved visually effective in creating a smoother colour change transition and a higher resolution of the image. Resolution was clearer due to the thermal behaviour of the base film, which made dispersion of heat very effective. When combined with a thermochromic fabric the thermal response of the track design gave a clear, gradual colour change transition, in contrast to the staggered stages of colour change with the heat-sink circuit design. Flexible track technology is more expensive, but provides visually more sophisticated design possibilities and more effective colour change response in terms of smoothness and clarity of image.

Conclusions
The project has developed a knowledge base for predicting heat profiling effects on printed thermochromic textiles and related materials and has enabled us to design a series of controllable electronic circuits that have been optimised for heat transfer. Techniques have been developed which further amalgamate these technologies, creating novel colour change phenomena and demonstrating how design challenges can be met using the synergy between technology and traditional textile design processes. By using a responsive colour palette, control using designed electronic circuitry can lead to the creation of highly unique pattern and colour change effects, refer to: Fig. 4

Advancing colour–change technology for use in design-based applications is at the core of this research. This paper illustrates the immense potential which colour-change technology, specifically thermochromics in this case, offers designers and demonstrates how a multidisciplinary approach to innovation in smart textiles may advance all levels of the creative process by integration of technologies, such as electronics and colour technology, with design through to product development. Colour-change, as a developing pattern on thermochromic textiles, may be achieved through the arrangement of heating elements on the circuit board design. The collaboration with LCR Hallcrest has allowed experimentation with a wide range of both leuco and liquid crystal thermochromic dyes leading to enhanced understanding of thermochromic dyes printed on to textiles and related materials.
to give single as well as multi-colour change thermochromic effects. New formulations for unusual multi-colour change effects through combining different temperature threshold dyes have been realised.

Summary and Future Design Direction

The initial design-led results are informing ongoing research towards more complex electronic circuit construction. Development of thermo-foil type heaters and sensors used in combination with a DMX system will allow concept design-controlled heating mechanisms used with appropriate combinations of printed thermochromics.

The research is aimed ultimately at a collection of design-led pieces for the interior market. It is envisaged that these products will encompass the idea of ‘smart living’ and re-think the way the interior reacts or is reacted to. These controllable colour-changing products allow us to envisage a future interior that may resemble a soft space that adapts, changes, and develops to contain the essence of the individuals who use it and responds to their routines. These imagined spaces will be friendly and tactile - a mix of high tech and low-tech applications creating an interior that metaphorically ‘hugs you’. The challenge is to advance the technologies, crossing disciplines to bring different technologies closer and, as a result, to develop innovative design systems. ‘Smart’ design can be understood on different levels. Commonly, the term refers to design that responds to external stimuli in some way. Equally it may be design that uses technology in an innovative way that is seen as smart or because it uses technology efficiently, providing an ecological edge - ‘smart’ is sustainable. Should a ‘smart’ interior respond without anyone noticing, should it be very efficient, and should it ultimately make life more comfortable within a space? Or should it make a loud statement, change dramatically, unpredictably or quietly like the weather, make people take notice, be intelligent? These questions will be answered through design, designers responding, directing and innovating with new materials. ‘Smart’ design is already diverse and will continue to grow in unpredictable directions as smart materials, structures and systems come to the forefront of knowledge.

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