Hallcrest, INC.

Product Information
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Applications

DATA SHEET LISTING

Sheet No.	Title
DS-001	Product Summary
DS-002	Technology Background: The use of TLC Products as Research Tools
DS-003	Color Change Properties
DS-004	TLC Coated Polyester Sheets
DS-005	Introductory TLC Kit (KT-500)
DS-006	Shear-Sensitive Cholesteric LC Mixtures
DS-007	Microencapsulated TLC Slurries
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PRODUCT OVERVIEW

A wide range of products are available in a variety of physical forms. The are listed by color-change properties.

TEMPERATURE –SENSITIVE COLOR-CHANGE PRODUCTS

Microencapsulated TLC slurries for use as tracer particles in flow studies in aqueous liquids and in coating manufacture (data sheet DS-007).
Sprayable microencapsulated TLC coatings for heat transfer, thermal mapping and NDT.
(data sheet DS-008).
Polyester sheets coated with microencapsulated TLC mixtures for general thermal mapping and NDT
(data sheet DS-004).

SHEAR –SENSITIVE COLOR CHANGE PRODUCTS

Unsealed cholesteric liquid crystal mixtures for flow visualisation studies on solid surfaces
(data sheet DS-006).

ANCILLARY PRODUCTS

Black backing paints and binder systems compatible with liquid crystals (data sheet DS-009)

INTRODUCTORY KIT

Contains small quantities of representative samples of all products to allow potential users to familiarise themselves as quickly as possible (data sheet DS-005).

STANDARD AND CUSTOM PRODUCTS

Across the range, standard products are available for each major application area. In addition, products can be custom-made to meet precise performance requirements. See the relevant data sheets for further details. Color change properties are discussed in data sheet DS-003.

The sale of our products is supported by extensive reviews of the open and patent literature. Detailed data sheets include guidelines as to how to best use the products. A full listing is given in data sheet DS-000, and general application notes are given in data sheet DS-010.

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TECHNOLOGY BACKGROUND:
THE USE OF TLC PRODUCTS AS RESEARCH TOOLS

INTRODUCTION

The use of thermochromic liquid crystal (TLC) products in research and testing continues to grow. The main application areas are in flow visualization and heat transfer studies, although the materials can be used in virtually any work involving indication of temperature fields and thermal mapping. The chemistry, physics and temperature indicating applications of TLCs are well documented in the open and patent literature.

THERMOCHROMIC LIQUID CRYSTALS

TLCs react to changes in temperature by changing color. They have chiral (twisted) molecular structures and are optically active mixtures of organic chemicals. The proper name for the materials is CHOLESTERIC or CHIRAL NEMATIC liquid crystals. The term cholesteric is an historical one, and derives from the fact that the first materials to show the characteristic properties and structure of this particular type of liquid crystal were esters of cholesterol. This can be misleading, as many non-sterol derived optically active chemicals (and mixtures containing them) also show the cholesteric liquid crystal structure. It is important to differentiate these sterol and non-sterol derived materials because, although they change color in the same way, they have different properties and can be used in different ways to achieve different effects.

TLC mixtures can therefore be divided into 3 types based on their compositions:
(a) **CHOLESTERIC** - comprised entirely of sterol-derived chemicals;
(b) **CHIRAL NEMATIC** - comprised entirely of non-sterol based chemicals.
(c) **COMBINATION** - containing both cholesteric and chiral nematic components. Combination mixtures extend the application possibilities and working ranges of TLC formulations by combining the respective advantages of both groups of component chemicals.

Strictly speaking, all TLCs are CHOLESTERIC LIQUID CRYSTALS, whether sterol-derived, non-sterol-derived or a mixture of the two. Cholesterics are one of the three major classes of THERMOTROPIC liquid crystals (produced by the action of heat). The two others are called smectics and nematics. LYTROPIC liquid crystals result from the action of a solvent.

TEMPERATURE-SENSITIVE AND SHEAR-SENSITIVE FORMULATIONS

TLCs show colors by selectively reflecting incident white light. They should be viewed against non-reflecting backgrounds (ideally black which is totally absorbing) for best visualisation of the colors. The nomenclature used to describe and define the color change properties of TLC mixtures is discussed in detail in data sheet DS-003.

Temperature-sensitive mixtures turn from colorless (black against a black background) to red at a given temperature and, as the temperature is increased, pass through the other colors of the visible spectrum in sequence (orange, yellow, green, blue, violet) before turning colorless (black) again at a higher temperature still. The color changes are reversible and on cooling the color change sequence is reversed.

Temperature-insensitive (**shear-sensitive**) formulations can also be made. These mixtures show just a single color below a given transition temperature (called the clearing point) and change to colorless (black) above it. Both reversible and hysteretic (memory) formulations can be made.

USE OF THE MATERIALS

The unique properties of TLCs can only be used to advantage if they can be controlled, and the materials made to behave predictably for a given period of time (in research applications, the duration of the experiment or study). TLCs can be used in a number of different forms:

(a) As the unsealed liquids or in solution
(b) In the microencapsulated form as aqueous slurries or coatings
(c) Coated (printed) sheets.

UNSEALED LIQUIDS

TLC materials are essentially oils and the consistency of most TLC mixtures at their working temperatures varies between that of a thin oil and a viscous paste (lanolin). They are difficult to use and are commonly applied as the isotropic melts, or as solutions by air brush or spray. Unsealed TLC mixtures need to be applied in thin, uniform films with thicknesses varying from 5-10 microns for chiral nematics up to as much as 50 microns or more for cholesterics. The resulting large surface area to volume ratio gives rise to a high susceptibility to degradation, particularly from ultra-violet light and oxygen, which can diffuse into the shallow film easily. The color play response can be changed by the presence of even small amounts (ppm levels) of certain chemicals (e.g. fats, greases and common organic solvents) Dust and fibre particles can easily become trapped by viscous TLC films causing additional problems.

The lifetimes of unsealed TLC films can vary from a matter of hours to days, depending on how the materials are used. In studies involving shear-induced color changes, the materials must be used as the unsealed liquids. It is possible to design experiments to take the limited lifetimes of the materials into account. However, the degree of stability offered by the materials as the unsealed liquids falls far short of that required for commercial temperature indicating applications.

IN THE MICROENCAPSULATED FORM (SLURRIES AND COATINGS)

To date, the microencapsulation process has been the most versatile, and successful way of packaging and protecting TLC mixtures. The LC is isolated from the atmosphere by a protective barrier and, at the same time, converted into a comparatively easy-to-use form. In simple terms, a microcapsule is a small sphere with a uniform wall around it, and in the microencapsulation process tiny droplets of liquid crystal are surrounded with a continuous polymer coating to give discrete microcapsules. Microcapsule diameters are generally between a few microns and a few millimeters.

The product of the microencapsulation process is an AQUEOUS SLURRY. This can be used directly (e.g. in hydrophilic liquids as tracer particles in flow field studies) or can be incorporated as a pigment, into a COATING FORMULATION optimised for a particular method of application (e.g. spraying, etc.). The dry coating should ideally support the liquid crystal in a uniform film with the minimum degradative effect on the intensity and purity of the reflected light. Microencapsulated TLC mixtures offer improved stability and versatility of use over their unsealed precursors. Further protection can be achieved by the use of materials with UV absorbing properties whenever possible. Water resistant coatings can also be made.

COATED (PRINTED) SHEETS

Most TLC temperature indicating devices are comprised of a thin film of liquid crystal sandwiched between a transparent substrate (sheet), and a black background. They are usually made by printing an ink containing microencapsulated TLC onto the reverse side of the substrate. A black ink is then applied on top of the dry TLC coating and color change effects are viewed from the uncoated side.

The different forms of the materials each have relative advantages and disadvantages and are suited to different applications. Details are given in the relevant data sheets. General Application notes are given in data sheet DS-010.

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COLOR CHANGE PROPERTIES

COLOR PLAYS

The color change properties of TLC mixtures and products made from them are identified by a code called the COLOR PLAY. This specifies the temperatures at which the colors shown by the TLC change.

TEMPERATURE-SENSITIVE MIXTURES

The color play gives EITHER the red start temperature (R) OR mid-green temperature (MG), the temperature scale (C or F) and the bandwidth (W). All definitions are given on Page 2 of DS-002. For example, R35C1W describes a TLC 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; MG60C5W describes a mixture with a mid green at 60°C and a bandwidth (red start to blue start) of 5°C. Red start temperatures can vary from -30°C to +120°C and bandwidths from 0.5°C to 40°C. Green starts, blue starts, mid greens and clearing points vary accordingly. Bandwidths depend on red start temperatures and tolerances depend on the color play. Details are given in the tables below:

TRANSITION	TOLERANCE
Red Start Temperature (R) Green Start Temperature (G)	±0.5°C OR ± 10% of the bandwidth, whichever is greater
Bandwidth (W) Mid Green Temperature (MG) Blue Start Temperature (B) Clearing Point (CP)	± 1.0°C OR ± 20% of the bandwidth, whichever is greater

RED START TEMPERATURE	MIN BANDWIDTH	MAX BANDWIDTH
-30°C	2°C	30°C
0°C	1°C	25°C
30°C	0.5°C	25°C
60°C	1°C	20°C
90°C	1°C	20°C
120°C	1°C	20°C

SHEAR-SENSITIVE (TEMPERATURE-INSENSITIVE) MIXTURES

The color play gives only the color and clearing point. For example R50C describes a LC mixture showing red below its clearing point of 50°C and G81C describes a LC mixture showing green below its clearing point of 81°C. Red, green and blue mixtures are available with clearing points (Ch-I transitions) between -20°C and 100°C.

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TLC COATED POLYESTER SHEETS

STANDARD PRODUCTS

Standard sheets use a substrate of 125 micron clear polyester (Mylar). The sheets are printed on one side, first with the microencapsulated TLC coating, then with a black backing ink. The color change properties of the TLC coating are viewed through the clear, uncoated side of the sheet. Standard sheets are available with, or without, adhesive-backing (pressure-sensitive adhesive); the protective release-liner can be removed for easy adhesion to a variety of flat surfaces. Standard size is 30cm x 30cm, the color plays currently held as standard stock items are set out in the table below.

SPECIFICATIONS

Substrate: Polyester sheet, 125 microns thick
Size: 30cm x 30cm
Total thickness: Without adhesive: 150-175 microns; with adhesive: 175-225 microns
Color Change: Black to red, through the other colors of the visible spectrum to blue, with increasing temperature, and finally to black again.

Color Plays	Red Start (RS) (Black to red)	Green Start (GS)	Blue Start (BS)	Clearing Point (CP) (Blue to Black)	Bandwidth (Blue start minus red start)
	°C	°C	°C	°C	°C
R20C5W	20.0	21.0	25.0	41.0	5.0
R25C5W	25.0	26.0	30.0	44.0	5.0
R30C5W	30.0	31.0	35.0	46.0	5.0
R35C1W	35.0	35.2	36.0	49.0	1.0
R35C5W	35.0	36.0	40.0	49.0	5.0
R40C5W	40.0	41.0	45.0	52.0	5.0

TOLERANCES

Red start and green start temperatures quoted are ±0.5°C
Blue start, blue to black and bandwidth temperatures are ±1°C

CUSTOM MANUFACTURE

In addition to the standard range of sheets, HALLCREST offers a custom-manufacturing service, tailor-making products to customer requirements. A wide range of substrates can be used, both rigid and flexible, with different thicknesses, and it is also possible to cast elastomeric films. Specific problems, like UV stability and water-resistance, for example, can also be addressed.

USAGE INSTRUCTIONS

1. Clean surface thoroughly to remove all dirt, grease, etc. Acetone, petroleum ether and similar organic solvents may be used. Ensure that the surface is *completely* dry before proceeding.
2. Remove protective backing from adhesive and place sheet lightly in position on surface. Press down firmly with fingers in center of sheet and smooth outward, in each direction in turn, to ensure that no air bubbles are trapped between the sheet and the surface.
3. The sheet is now ready for use as a temperature indicating film.

REMOVAL

After use, the sheet can be removed from the surface by pulling it off, although the sheet will be probably destroyed in the process. Residual adhesive can be removed by washing with a suitable solvent. The choice of solvent will depend on the nature of the surface to which the sheet was attached.

STORAGE

Unused sheets should be stored out of direct sunlight at room temperature (20-25°C), in a solvent-free environment. Sheets in position on test surfaces should be protected from UV light and organic solvents wherever possible. The color play properties of the sheets should be checked at regular intervals. If stored correctly, the sheets should have shelf lives of up to a year or more.

LIFETIMES

TLC coated sheets should retain their color play characteristics for many months under normal handling conditions. Continued submersion and temperature cycling in hot (40°C+) water baths will accelerate degradation, as will continued temperature cycling at elevated temperatures in general, and exposure to UV light.

SIMPLE EXPERIMENTS FOR STANDARD PRODUCTS

1. Dampen the tip of a small cloth or sponge with water and "write" with it on the surface of the R20C5W sheet. The evaporative cooling that takes place will cause color changes.
2. Place the R20C5W film in a refrigerator and observe the change in colors (from blue to red to black). Remove it from the refrigerator and observe the reverse order of color as the temperature rises (black to red to blue). In the wintertime, a windowpane may also be used to cool the film.
3. Using the R25C5W, R30C5W sheets, you can determine the relative hand temperatures of a group of people. Due to variations in blood circulation, and depending on whether a person had been holding a cold glass or had been smoking a cigarette, a wide range of temperature results may be obtained in the group. Even though normal body temperature is 37°C, you will note immediately that skin temperatures fluctuate considerably from this value. Should a person not be able to cause a color reaction on even the R25C5W, move the sheet away from the fingertips to the wrist area. You will eventually find a warmer temperature.
4. You can test an object having a simple flat surface but with a complicated internal structure, which is invisible to the eye; e.g., a honeycomb structure, a flat surface made up of different types of metal or plastic, or a flat surface having a varying thickness. Place the black side of a TLC sheet in direct contact with the surface of the object. Slowly apply heat to the other side of the object. Use a floodlight, heat gun, light bulb, heating pad, or some other suitable heat source. Heat will "flow" through the object to the surface in contact with the TLC sheet causing it to change color. However, it will flow at different rates depending upon the different thermal conductivities of different areas. The sheet will therefore give a thermal map of the structure beneath the surface. These simple experiments are designed as an introduction to the usefulness of TLC products. The materials have many applications, not only in testing, bust also in industry, medicine and the home.

Note: As with all TLC applications, the better the incident lighting, the brighter the colors reflected by the TLC. However, the use of incandescent lamps too close to the TLC sheet should be avoided, as the materials are sensitive to UV light and the color play properties will change on prolonged exposure.

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INTRODUCTORY LIQUID CRYSTAL KIT
KT500

Thermochromic liquid crystals (TLCs) allow the rapid accumulation of experimental data and other information that would otherwise be either unobtainable or only able to be compiled over long periods of time. The materials are inexpensive and easy to use. However, some experience and practice in their use is necessary to develop and optimize application techniques and learn how to control the variables that affect performance. This kit allows such experience to be gained comparatively easily and quickly.

The KT-500 kit contains a selection of products for use in different research areas. A comprehensive literature review is included, together with detailed instructions on how to use the various components.

The kit has been designed so that users may familiarize themselves with TLC products, and the technology of their use in research applications, as quickly as possible. It is hoped that users will be able to optimize the application techniques specific to their needs comparatively rapidly and, in the process, identify which products they will need, and how best to use them.

Contents:

- sprayable TLC coating (R35C1W)	25g
- sprayable black backing paint (BB-G1)	25g
- microencapsulated TLC slurry (R29C4W); (50 – 100 micron capsule diameters)	25g
- unsealed red shear sensitive cholesteric LC mixture CN/R3	25g
- 2 adhesive backed, TLC coated polyester sheets (R29C4W and R35C1W), 15cm x 15cm	

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SHEAR-SENSITIVE CHOLESTERIC LC MIXTURES

- For flow visualization studies on solid surfaces

The use of shear-sensitive cholesteric liquid crystal mixtures has now become established as a useful method for diagnostic flow visualisation. Experimental techniques have been used to illustrate laminar boundary layer transitions, laminar bubbles, shocks and separation in both flight and wind tunnel environments.

STANDARD MIXTURES

Three standard mixtures are available, details of which are given in the table below. All reflect red light under no shear conditions and should not crystallise above 0°C.

	CLEARING POINT (Ch-I Transition Temperature)	RELATIVE VISCOSITY AT 30°C	FLOW SPEED WORKING RANGE (m/sec)
BN/R50C	50°C ± 1°C	1	<30
BCN/192	49°C ± 1°C	4	30 – 75
CN/R3	53°C ± 1°C	15	75 - 200

CUSTOM-FORMULATED MIXTURES

Mixtures with a variety of physical properties can be made. From the performance viewpoint, the physical properties of importance are:

1) the colour of reflected light
2) the viscosity
3) the clearing point

These three variables can all be controlled with good accuracy within predetermined limits, and we will be happy to work with the customer to optimise and custom-formulate mixtures to meet precise application and performance requirements

USAGE INSTRUCTIONS

1. Clean surface thoroughly to remove all dirt, grease, fingerprints, etc.. Acetone, petroleum ether, and other common organic solvents may be used. Ensure that the surface is completely dry before proceeding.

2. Coat surface black. If the surface is already black, or sufficiently dark, the TLC may be applied directly. A black water-based paint (BB-G1) is available and will dry in 30-45 minutes when sprayed through a good quality compressed gas sprayer like an artist's airbrush. Applying the black paint by brush is not recommended, as uneven coatings affect the thermal response properties of the TLC. The black paint supplied will isolate the TLC from traces of grease which may be left on the surface after cleaning. The black backing paint must be dry before applying the TLC. Drying times may vary with ambient temperature and humidity, and can be accelerated by gentle blowing with hot air.

3. Apply the TLC.

a) Neat Mixtures: Heat the TLC mixture gently on a hot place until it clears (turns (melts) to an isotropic liquid). TLC mixtures are comparatively insensitive to short periods of heating as isotropic liquids; however, care should be taken to avoid excessive heating for prolonged periods of time. The clear liquid can be brushed onto the dry black surface. Gentle warming with a heat gun as the liquid is applied may be necessary to achieve a uniform thin coating.

b) Solutions: Apply the TLC solutions through a good quality compressed gas sprayer, such as an artist's airbrush. The colors will not appear until all the solvent has evaporated. Gentle blowing with a fan, hair dryer, or heat gun may speed up the evaporation, but care must be taken not to disturb the TLC film. The TLC coating is now ready for use.

Cleaning Up: The TLC coating can be removed with acetone, petroleum ether and other common solvents. The BB-G1 can be washed off with water. A hot, soapy wash will normally remove both the TLC and the black paint.

Storage: Unsealed TLC mixtures should be stored out of direct sunlight. Surfaces coated with unsealed TLC should ideally be cleaned (the TLC removed) each day. If coated surfaces are stored overnight, they should be kept out of UV light, and in a solvent and dust-free environment. The colour-temperature response of all coated surfaces should be checked at regular intervals to ensure that no loss of calibration has occurred during use, or between experiments, etc..

NOTES ON THE USE OF TLC SOLUTIONS

The preferred solvent for use with TLC mixtures is acetone (CAS Registry No. 67 - 64 - 1). An alternative is petroleum ether, boiling range 40 - 60^{o}C (CAS Registry No. 8032 - 32 - 4). Both solvents are flammable and readily available through laboratory chemical suppliers.

The use of 15% (weight) TLC solutions is recommended, however, it should be possible to increase the liquid crystal concentration to 20% in most cases with no problems.

Because of the nature of the preferred solvents for TLCs and the care that needs to be exercised in their use, it is recommended that the materials are applied as the isotropic melts.

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MICROENCAPSULATED TLC SLURRIES

-Pigments for use in the manufacture of temperature-sensitive color change coatings

-Temperature-sensitive color change tracer particles for use in fluid flow field studies

SLURRIES FOR COATING MANUFACTURE

TLC mixtures are offered for use as color change pigments in the form of microencapsulated slurries in water, 40% (weight) solids content with microcapsule diameters centered in the range 10-15 microns. They are custom formulated to the required color change properties. These slurries can be used to make sprayable TLC coatings by addition to aqueous binders. See data sheet DS-008.

TRACER PARTICLES FOR FLUID FLOW STUDIES

Custom-formulated TLC mixtures are also offered for use as tracer particles in fluid flow studies. An optimized microcapsule diameter range for such products has been determined to be 50-100 microns, and products with microcapsule diameter distributions in this range are recommended for this type of application. Other microcapsule diameter distributions can be made to order. It is also possible to control the buoyancy (apparent specific gravity) characteristics of the microcapsules within limits by varying the composition of the TLC mixture and the microcapsule diameter and wall properties. Further details are available on request.

CUSTOM MANUFACTURE

All microencapsulated slurries are manufactured to order. They can be tailor-made to customer requirements of, for example, color change properties, microcapsule diameter distribution and solids content. For most common applications where average capsule diameters are less than 100 microns, the preferred solids content is 40%

USING TLC SLURRIES AS TRACER PARTICLES

1. Some simple tests need to be carried out before proceeding.

   i) **The compatibility of the carrier fluid must be determined**. This can be done by adding some TLC slurry to a small sample of the carrier fluid and checking the stability of the colour play response with time. The colour-temperature response should be stable for the duration of the study.

   ii) **The optimum doping level should be evaluated**. This will depend on the nature of the study. As a starting guide, a doping level between 0.01 and 0.1% is recommended, however, it may be that the optimised level falls outside this range.

2. The TLC slurry can be added directly to the carrier fluid. The composition of the slurry provided (40% capsule solids) should be borne in mind throughout to keep check on the doping levels. Alternatively, the slurry can be filtered before use if the carrier is not 100% water, and the excess water in the slurry is not required. A note of the amount of water removed should always be kept for doping level calculations to be made accurately. Because the doping levels are relatively low (a 50 litre tank will only require approximately 65ml slurry (40% capsule solids) to dope to a level of 0.05% capsules), it may be easier to add the slurry/microcapsules to a small sample of the carrier fluid 1:1 and then add this to the remainder of the carrier.

3. For optimum performance, reference to the general notes below should be made, particularly to (a),(d) and (e).

4. **Storage.** Microencapsulated slurries should be stored in a refrigerator (5 -10°C) when not in use - DO NOT FREEZE. If stored correctly, the materials should have shelf lives of at least 6 months.

Notes:

a) Studies should always be carried out against a dark, preferably black background.

b) The interactions likely to occur between the TLC and any materials used with it to produce colour change effects must always be considered. The colour change properties of TLCs are produced by a very delicate and sensitive arrangement of molecules, and it is very easy to change and even destroy the colour play properties.

c) The carrier fluids must be aqueous. Recommended fluids include water, glycerol, ethylene glycol, and other similar low molecular weight polyhydric alcohols. Using mixtures of such highly hydroxylated materials with water, it is possible to produce a range of carrier fluids with a variety of viscosities to suit most applications.

d) The colours observed depend not only on temperature, but also on the angles of illumination and observation. Colour play specifications supplied with materials have been calibrated using a technique with both incident and reflected light normal to the surface of a thin film of TLC. In the use of the materials as tracer particles in fluids, illumination and viewing are generally not carried out from the same direction, and the observed colour change properties will probably be different to those supplied in the materials specification. In addition, TLCs have different properties when used in bulk fluids as opposed to their use as thin films. It will thus be necessary for the user to recalibrate the colour play properties of the materials to suit the particular method of use.

e) As with all TLC applications, the better the illumination, the brighter the colours reflected by the TLC. However, the use of incandescent lamps close to the materials should be avoided if possible, as the materials are sensitive to UV light, and the colour play properties will change on prolonged exposure. Colour temperature profiles should be checked at regular intervals to ensure that no shift has occurred.

SPRAYABLE TLC COATINGS

Two series of TLC coatings are available both aqueous acrylic based and designed for application by spraying through an airbrush or similar compressed gas sprayer. They have good adhesion to most surfaces and matt and gloss finishes are achievable by varying the coating thickness.

C17-10 Coatings - For optimum color brightness.
They can be removed by washing with water.

C20-10 Coatings - For some degree of water resistance.
They can be used underwater for limited periods.

Note: Once formulated, C20-10 coatings have limited lifetimes.
It is recommended that the coatings are made up immediately prior to use. See over.

COLOR CHANGE PROPERTIES

Temperature sensitive coatings can be made using microencapsulated TLC mixtures with red start temperatures from -30°C to 120°C and bandwidths from 0.5°C to 30°C. Bandwidths depend on red start temperatures and tolerances depend on the color change profile (color play). See data sheet DS-003 for further details.

PACK SIZES:

250g and 500g

USAGE INSTRUCTIONS

1. **Clean surface thoroughly** to remove all dirt, grease, fingerprints, etc. Acetone, petroleum ether, and other common organic solvents may be used. Ensure that the surface is completely dry before proceeding.

2. **Coat surface black**. If the surface is already black or sufficiently dark, the TLC coating may be applied directly. Black water-based paints BB-G1 and BB-M1 are available which will air dry in 20-45 minutes when sprayed through a good quality compressed gas sprayer like an artist's airbrush. Applying the black paint by brush is not recommended, as uneven coatings affect the thermal response properties of the TLC. The black coating must be dry before the TLC coating is applied. See data sheet DS-009 for details.

3. **Apply the Microencapsulated TLC coating**. The TLC coating will separate to some extent on storage, and should be mixed thoroughly before use. The following instructions are a guide to provide the user with a starting point from which to optimize the application techniques (coating thickness, etc.) specific to their needs. Minimum application, surface and drying temperatures of 20°C are required for best results.

   i. Spray through airbrush (15-20cm) above substrate surface.
   ii. Air brush pressure = 20 psi/1.41kgcm-²/1.3 bar (approx)
   iii. Drying times at 20-25°C are 30-45 minutes for C17-10 and 20-30 minutes for C20-10 depending on coating thickness. This can be accelerated by gently blowing warm air onto the coating.
   iv. The coating thickness alters the surface texture. Thin coats are matt and slightly rough. Thicker coats flow together more, giving smoother gloss finishes. Coating thickness and surface texture will affect the brightness and shade of the Color produced, and may also affect the temperatures at which each color appears.
   v. Optimum dry film thicknesses are around 10 microns. To achieve this, a total wet film thickness of around 100 microns will need to be applied. Best results are likely to be achieved by building up the coating gradually, drying between applications.
   vi. 250 grams should be adequate to cover 2.5m² .

4. The microencapsulated TLC coating is now ready for use. The Color play should be checked and calibrated if necessary. Prolonged exposure to temperatures in excess of 70°C should be avoided if possible.

5. **Cleaning up**: Dry C20-10 coatings have a good degree of water resistance. They can be removed by vigorous scrubbing with hot, soapy water or, alternatively, acetone. C17-10 coatings can be easily removed by washing with water.

6. **Storage**: Ideally, all TLC coatings should be stored in a refrigerator at 5-10°C but MUST NOT BE FROZEN. They should be allowed to warm up to room temperature (20-30°C) before use. Binders should be stored at room temperature. Surfaces coated with microencapsulated TLC coatings should be stored out of UV light, and in a solvent free environment. Ideally, no stress should be applied to the coated surface. The Color play response should be checked at regular intervals to ensure that no loss of calibration has occurred. If stored correctly, microencapsulated TLC coatings have a useful shelf life of at least 6 months.

TO MAKE TLC COATINGS YOURSELF:

Use the appropriate S40 TLC slurry and binder AQB-2 for C17-10 and AQB-3 for C20-10.
Add the binder to the slurry, 3 parts binder to 1 part slurry, with thorough mixing. Both the binder and slurry should be mixed well before use. Ideally the finished coating should also be filtered before use.

Note: Once formulated, C20-10 coatings have limited lifetimes before the Color play profile changes, and the Color brightness diminishes. The coatings should be made up from the binder and slurry immediately prior to use. Useful lifetimes are not more than four (4) weeks from the date of mixing.

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ANCILLARY PRODUCTS

- **Sprayable black backing paints**
- **Binder systems (and overcoats)**

BLACK BACKING PAINTS

Two water-based, TLC-compatible, sprayable black-backing paints are available. Both adhere well to most surfaces and can be modified to give matt or gloss finishes by varying the coating thickness.

BB-G1	-	For use in air (not under water)
BB-M1	-	Dries to give a good degree of water-resistance. Can be used in underwater studies for limited periods

BINDER SYSTEMS

Two aqueous binder systems are available for addition to S40 TLC slurries to enable the customer to make finished coatings. The products can also be used as clear protective over-varnishes.

AQB-2	-	Acrylic system for manufacture of C17-10 coatings.
AQB-3	-	Acrylic system for manufacture of C20-10 coatings

PACK SIZES

250g and 500g

USAGE INSTRUCTIONS

The following instructions are a guide to provide the user with a starting point from which to optimize the application techniques (coating thickness, etc.) specific to their needs. Minimum surface application and drying temperatures of 20°C are required for best results throughout.

BB-G1 and AQB-2 (as an over-varnish)

1. Spray through air-brush/spray gun 15-20cm above the surface. Pressure approximately 20psi/1.41kgcm^{-2}/1.3bar.

2. Drying times at 25-30°C are 30-40 min. These can be shortened by gently blowing warm air.

3. Surface texture depends on coating thickness. Thin coats are matt and slightly rough. Thicker coats flow together more and give smoother, gloss finishes.

4. The dry coating can be removed by washing with hot, soapy water.

BB-M1 and AQB-3 (as an over-varnish)

1. Spray through air-brush/spray gun 20-25cm above the surface for a gloss finish, and 35-30cm for a matt finish. One heavy coat gives the best gloss finish and several light coats give the best matt finish. Pressure approximately 30psi/2.11kgcm^{-2}/2.0bar.

2. Drying times at 25-25°C are 20-30 min. A minimum drying temperature of 20°C is required.

3. A continuous unbroken coating is necessary for best water resistance. The coating must be completely dry before immersion. Pin holes in the dried coating surface allow water to get beneath the coating and cause it to lift.

4. Removal: either a) Scrub vigorously with hot, soapy water or b) Wash with acetone.

Notes:

a) All equipment used during application (e.g. spray gun, containers, etc.) should be washed with hot, soapy water immediately after use.
b) The coatings will separate to some extent on standing, and should be mixed thoroughly before use.
c) Store at 20-30°C. DO NOT FREEZE.
d) All coatings can be diluted with water.

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GENERAL APPLICATION NOTES

a) Applied as thin films, unsealed TLC mixtures have limited lifetimes before their colour play properties begin to change. Generally speaking, temperature-insensitive mixtures are more stable than temperature-sensitive mixtures. Films of unsealed TLC will not dry. They will always be wet and oily to the touch. Microencapsulated TLC coatings should be used if dry films are required.

b) Unsealed TLC mixtures are usually applied as the isotropic melts, obtained by heating the LC mixture until it turns transparent. The materials have better flow properties as the isotropic liquids. However, application of the materials as solutions can sometimes give better results. The solvent evaporates to leave a uniform thin film of TLC on the surface. Colour plays of TLC formulations are very sensitive to the presence of solvents, even in minute amounts, and it might be necessary to warm gently with a heat gun to remove the last traces of solvent.

c) In some cases, particularly after being subjected to a number of temperature cycles, the colours shown by the unsealed TLC film can be improved by gentle brushing *in one direction only* with a soft brush. This helps orientate the TLC into its maximally reflecting texture.

d) The use of microencapsulated TLC coatings overcomes many of the problems associated with using unsealed TLC mixtures, although the reflected colours are slightly less bright. Applied as a thin film, the coatings will dry to give a finish which will resist light abrasion. They can be sprayed onto the surface under study and are of particular use when the surface is not flat.

e) Surfaces must be black, or painted black, before the TLC coating is applied. Any black coating should be completely dry before the TLC coating is applied.

f) Coated sheets are the most stable form in which TLCs are readily available.

f) The brightness of the colours reflected by the TLC depends on the intensity of the incident illumination. However, the use of incandescent lamps too close to TLC coated surfaces and sheets should be avoided. The materials are sensitive to UV light and the colour play properties will change on prolonged exposure.

h) Colours reflected by the TLC depend not only on temperature, but also on the angles of illumination and observation relative to the coated surface. Ideally, a TLC coated surface should be viewed and illuminated in a direction normal to it. The colors shown by microencapsulated TLC coatings have less angular dependence than unsealed TLC mixtures, although the effect can still be noticeable.

i) The surface finish of the TLC coating is very important to the quality of color images obtained. Coating thickness is an important variable as color plays of microencapsulated TLC coatings are dependent on thickness of lay-down. Generally, the thicker the coat, the lower the onset of color. Too thick a coating often results in the normally bright colors appearing milky, more noticeably at the red end of the spectrum.

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LITERATURE REVIEW: TLC APPLICATIONS (1)
ENGINEERING AND AERODYNAMIC RESEARCH; HEAT TRANSFER AND FLOW VISUALIZATION STUDIES

This review was compiled during August and September 1987 and revised in October 1990. It is intended to be both an introduction and a guide. It is not claimed to be an exhaustive study, and apologies are offered to workers whose publications have not been included.

EARLY WORK

TLCs were first used in wind tunnel experiments by Klein (1,2) in 1968, primarily to evaluate the feasibility of their use in determining the location of laminar and turbulent boundary layer transitions on aircraft models. Non-microencapsulated cholesteric LC mixtures were applied directly to the surface under study. At the appropriate conditions of free stream air temperature and velocity, the area of the model surface wetted with a turbulent boundary layer exhibited a different color to its laminar counterpart. The color difference resulted from the slightly higher adiabatic wall temperature associated with the turbulent flow. Although such qualitative information was readily available, attempts to obtain accurate quantitative data were unsuccessful due to the adverse effects that surface contamination, UV light and flow-induced shear stress produced on the unsealed liquid crystal mixtures.

In a follow-up study, Klein and Margozzi (3,4) used the shear stress sensitivity of certain non-microencapsulated cholesteric LC mixtures in attempts to develop a technique for visually measuring shear stress. Although they found that it was possible to formulate cholesteric mixtures which were relatively sensitive to shear and insensitive to temperature, they found it difficult to accurately interpret the color signal produced, since the LC coating tended to flow and develop a rough texture in response to the shearing effects of the flow. It was concluded that while it appeared feasible to measure shear stress using non-microencapsulated cholesteric LC mixtures, much additional research would be needed to develop TLC mixtures that would exhibit high shear sensitivity, while at the same time maintaining low temperature, angle and pressure dependence. Since this study, significant advances have been made on the materials side and the availability of chiral nematic and combination TLC mixtures has enabled workers to overcome many of the problems encountered in the original study.

In an investigation similar in principle to that originally conducted by Klein (1,2), McElderry (5) used microencapsulated TLC mixtures to determine boundary layer transitions on a flat plate placed in a supersonic air stream. The color displays produced were relatively independent of viewing angle and were not affected by the adverse sensitivity to shear and contamination experienced by Klein with unsealed TLC mixtures.

Other early studies of heat transfer and temperature field visualization using TLCs yielded only qualitative results, i.e. hot and cold regions were observed without regard to precise temperature levels (6-15). The first quantitative results were published by Cooper et al in 1974/5 (16,17), who observed boundary layer transition and separation on a heated cylinder in cross-flow, and evaluated the variation of Nusselt number around the cylinder. More recently, quantitative as well as qualitative use of TLCs in flow visualization and heat transfer studies has become increasingly widespread (e.g. see refs 18-36, 65-71, 88-91, 97-99).

HEAT TRANSFER STUDIES; NEW TECHNIQUES - STEADY STATE AND TRANSIENT

HEAT TRANSFER STUDIES; QUALITATIVE AND QUANTITATIVE

New steady state techniques for measuring and mapping heat transfer coefficients using integral heater/TLC indicator combinations have recently been described (26, 28, 57). Heater uniformity, and the generation of uniform heat fluxes at the surface of interest were verified. The techniques have been evaluated, extended and improved by other workers (37, 38) where chiral nematic LC mixtures and different packaging arrangements have been used. Although the methods have wide general application in heat transfer studies (29, 39), they are particularly useful in the design and study of thermal performance of gas turbine components (38, 40). New transient techniques using microencapsulated chiral nematic TLC mixtures have been developed by Jones (51, 52) to measure local heat transfer coefficients in gas turbine blade geometries. The methods do, however, have far wider application potential. During the course of the work, the response of a film of microencapsulated chiral nematic to a rapidly increasingly surface temperature was assessed (53). Rates of increase in temperature of greater than 2000°C/sec were employed and experiments showed the delay between the time at which the surface reaches the steady state color display temperature, and the occurrence of the color display in the TLC film to be no more than a few milliseconds. This compares with values for thermal time constants of cholesteric mixtures which are of the order of hundreds of milliseconds (54, 55).

FLOW VISUALIZATION IN FLUIDS

TLCs have been used in fluids as well as air. Temperature distributions have been visualized using the materials in the unsealed (neat) and microencapsulated forms as both tracer particles in flow field studies, and as surface coatings (41-46, 71-74, 92-96). The studies include flow visualization of a recirculating flow using 0.02% doping of water with TLC microcapsules (42) and simultaneous measurement of temperature and velocity field in thermal convective flows with unsealed TLC being dispersed directly into the flow medium (45). The background theory for the measurement of color recorded by cine photography has been reviewed and applied in the color/temperature calibration of temperature-sensitive liquid crystal tracer particles (76). In addition, coatings containing microencapsulated TLC mixtures, and TLC coated polyester sheets, insensitive to the effects of shear stress, have been used to obtain quantitative surface temperature measurements on water tunnel models (43, 75) and shear-sensitive unsealed TLC mixtures have been used successfully in hydrodynamic flow visualization on surfaces producing high resolution observations of both steady and unsteady boundary layer separation and transition characteristics (44).

SURFACE FLOW VISUALIZATION USING SHEAR-SENSITIVE TLC MIXTURES

The visualization of laminar to turbulent boundary layer transitions plays an important role in flight and wind tunnel aerodynamic testing of aircraft wing and body surfaces. Following the early example set by Klein and Margozzi (3,4), Holmes and co-workers at NASA have developed new techniques for visualizing transitions using shear-sensitive TLC mixtures (e.g. 47-50). In these methods, unsealed TLC mixtures were applied to the test surface, and air flow over the surface produced shear stress that induced a color change between high shear turbulent flow and low shear laminar flow regions. Although other earlier studies in which the shear was also applied perpendicular to the helical axis of the unsealed TLC mixture have also been undertaken (81-84), it has been the work of Holmes et al. which has pioneered the use of shear-sensitive TLC mixtures as a qualitative diagnostic tool for flow visualization. The use of TLCs overcomes some of the limitations of sublimating chemicals and oil flow techniques and provides transition visualization capability throughout almost the entire altitude and speed ranges of virtually all subsonic aircraft flight envelopes. The methods are also widely applicable for supersonic transition in flight and for general use in wind tunnel research over wide subsonic and supersonic speed ranges. Reda has demonstrated the dynamic capability of shear-sensitive liquid crystals on an oscillating airfoil (87,100) and found that the TLC response was fast enough to trace 1 Hz oscillations. Reda has also investigated the use of the materials at hypersonic speeds (101). An improved method for visualizing flow has been proposed by Jones, McDonnell and Bonnett (64) which utilizes a shear induced texture change from the uncolored (non-reflecting) focal -conic texture to the colored Planar (Grandjean) texture. This work is also the subject of a UK patent application (80). These novel experimental techniques together with the availability of new and improved TLC formulations have led to much interest in this area of research in particular, and the use of shear-sensitive liquid crystals has now become an established technique for diagnostic flow visualization. The technique has been demonstrated to illustrate laminar boundary layer transitions, laminar bubbles, shocks and separation in flight and wind tunnel environments (102). The validity of the technique has been evaluated by most authors (102) and transition locations indicated by shear-sensitive TLCs have been confirmed using other techniques including sublimation chemicals, hot film transducers and pressure rakes (102, 103). Steps are currently being taken to resolve the few issues that remain from the TLC viewpoint in order that the technique may be developed to its full potential and facilitate its widespread use throughout the aerodynamic testing community.

MISCELLANEOUS

In another novel study, the analogy between heat transfer and skin friction within the laminar sublayer of a turbulent boundary layer has been used as the basis for the development of a liquid crystal/skin friction measurement device (56). This can also be used to indicate boundary layer transition and separation, and should be applicable to flows with strong pressure gradients.

JAPANESE STUDIES

Following the leads set by workers like Kasagi, Kimura and Akino (e.g. 31, 77, 78, 85, 86) and the general high level of interest in experimental techniques utilizing TLC products, Japanese work in all areas has grown significantly, evidenced by the increasing number of publications (e.g. 68-73, 79, 95-97).

NOTES

Publications covering the use of TLCs in heat transfer, flow visualization and related research continue to appear at an ever increasing rate. Attempts will be made to update and revise this review at regular intervals. It should also be noted that much of the pioneering work that has been undertaken to date in these areas is classified and is unlikely to appear in print, at least for the foreseeable future. While every effort has been made to make reference to all papers published, it is likely that a number of publications may have been overlooked or omitted and apologies are offered accordingly.

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LITERATURE REVIEW: TLC APPLICATIONS (3)
GENERAL THERMAL MAPPING AND NON-DESTRUCTIVE TESTING (NDT)

Thermal mapping can be defined as the measurement of the temperature of a surface at enough points on the surface to build up a picture of temperature differences across it.

Non-destructive testing (NDT) is assumed here to comprise thermal mapping applications outside the medical area of thermographic skin temperature measurements. Medical applications are considered elsewhere.

General information on the use of TLCs in NDT applications is widely available in the literature (e.g. 1-16, 65-68). Special equipment is not usually necessary, although apparatus has been developed for special cases (e.g. 17, 18). Some representative examples of specific applications are reviewed below; the coverage is not exhaustive since most articles describe essentially the same approach applied to a large number of different test items.

Flaws, bonding faults and internal defects have been detected in **composites, laminates and honeycomb structures** (6, 7, 15, 19-38). Surface and sub-surface flaws can be detected in metals e.g. Lueder lines (regions of unstable plastic flow) in aluminum and aluminum alloys (19, 22), welded metals (39-41) e.g. cracks, voids or leaks in **pressure vessels** (8,42) and metal adhesive bonds (19, 30, 43). Laminations in sheet metal caused by hot or cold rolling (5), stress areas and potential **fracture sites in metals** (23) and defects in springs (4, 26) have also been detected. Other studies have addressed the localization of plastic deformations during fatigue tests of metals (44), the detection of shrinkage cavities in **metal castings** (11), the testing of the thermal isolation of aluminum rivets (27) General reference to the use of TLCs as **heat flux sensors** has also been made (70).

The use of the materials in **engineering research** is

and the temperature distribution on the surface of **heating coils** (5).

Thermal mapping with TLCs has been used to test ordinary **printed circuits** (4, 6, 7, 42, 45, 46-48, 69) and multilayer **printed circuit boards** (22, 49) for electrical shorts and to inspect high resistance connections on circuit boards (8, 30). Shorts in field effect **transformers** (49) have been detected and the temperature pattern of **resistors** (8, 45, 51, 27), **transistors** (45, 51) and **transducers** (52) have been visualized. Other applications cover the determination of deposits on thin film resistors (50), the detection of inhomogeneities in sapphire substrates of IR detectors (53), the observations of switching phenomena in Au, B or Si films (54, 55) and Zr-ZrO_2-Au junctions (56) and the effects of annealing and laser irradiation on amorphous films of As, Te and Ge (57). Discontinuities of electrical conductors embedded in **automobile windshields** (58), heat leaks of **refrigerator doors** (59) and heat patterns generated by vibrations of piezoelectric transducers (52, 60) and miniaturized ultra-high frequency devices (61) have also been detected.

Restricted coolant channels of **aerospace components** (19, 22), flaws in coalescers used for the filtration of jet fuel (62-64), non-uniformities of the resistive coatings of aircraft/spacecraft windows (22, 40) and hot spots for miniature heaters for spacecraft (49) have all been visualized.

continuing to grow, based mainly on improvements in performance and other advantages offered by chiral nematic (non-sterol based) and combination mixtures. Areas where TLCs have already made important contributions include **flow visualization** studies, wind tunnel experiments, general **temperature field indication** and **heat transfer** measurements (71-106). The materials can also be used in fluids as well as in air (107-111). The results of such research studies are having an ever increasing commercial impact as information previously unobtainable or only able to be collected over very long periods of time is now able to be acquired comparatively easily and rapidly. TLCs have been used as both the neat liquids and in the microencapsulated form and studies have also used the shift of the color band of unencapsulated mixtures caused by shearing actions of air and water flows (112-114). Cholesterics have also been used in the NASA space program aboard Apollo 14 (115-117) and Apollo 17 (118-120) as temperature indicators in low gravity environments and to estimate heat flow through textiles (121).

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