WHITEPAPER 11

Preventing Mura, Light Leakage and Colour Shift

Understanding Industrial Display Uniformity

Root causes, measurement and design controls for stable industrial image quality

An engineering guide to luminance and chromaticity variation, pressure mura, edge leakage, backlight non-uniformity, viewing-angle effects and production acceptance.

Created by Crystal Display Systems Limited

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Executive summary

Mura, light leakage and colour shift are not one defect and cannot be controlled by a single centre/corner ratio. Their visibility depends on pattern, brightness, angle, temperature, mechanics and the operator task.

A robust industrial approach separates panel variation from integration stress, combines visual and instrumented inspection, and uses controlled golden units and process data to maintain the qualified result.

> **Core recommendation**
> Define defect types and task-relevant viewing conditions before setting limits. Use progressive assembly maps to find where mura or leakage is introduced rather than rejecting finished units without root-cause evidence.

How to use this whitepaper

- Use the requirement table to convert display uniformity expectations into measurable pass/fail criteria.
- Use the comparison matrix to shortlist architectures without allowing one headline specification to dominate.
- Apply the weighted scorecard using the actual operating environment, duty cycle and commercial lifecycle.
- Validate the preferred approach in the final mechanical, optical, electrical and software implementation.

Contents

Key decision principles

- Define which uniformity defects affect the user task before setting a generic cosmetic limit.
- Separate panel-native variation from stress introduced by bonding, mounting, heat and enclosure mechanics.
- Measure at controlled warm-up, grey level, angle and luminance because many defects are condition dependent.
- Use both instrumented maps and controlled visual inspection; neither method alone captures every relevant defect.
- Control mechanical preload and optical materials as tightly as the panel acceptance class.

1. Define the visual task and defect taxonomy before selecting acceptance limits

A useful uniformity specification states content, grey levels, luminance, viewing distance/angle, warm-up, environmental conditions and defect size/location. It should distinguish luminance, chromaticity, leakage, pressure and temporal artefacts.

Requirement domain	Questions to resolve
Visual task	Backgrounds, grey levels, colour-critical images, dark-room use, viewing distance, operator movement and acceptable detection threshold.
Panel behaviour	LCD mode, backlight architecture, cell gap, polariser, optical films, viewing angle, temperature and drive/inversion pattern.
Mechanical stack	Bezel pressure, mounting points, foam/gasket compression, bonding, cover-glass flatness, enclosure twist and thermal expansion.
Optical measurement	Luminance/chromaticity grid, camera uniformity correction, dark-field method, warm-up, test pattern, angle and ambient conditions.
Cosmetic taxonomy	Clouding, spot mura, line mura, light leakage, colour shift, dead/stuck pixels, scratches, particles and bond defects.
Production control	Golden units, supplier class, sampling, process capability, visual inspectors, automated inspection and change notification.

A practical weighting model

Assign each criterion a weight from 1 (low importance) to 5 (critical). Score each candidate from 1 (poor fit) to 5 (strong fit), then multiply score by weight. The arithmetic does not replace engineering judgement, but it exposes where the uniformity-control and inspection approach depends on assumptions, incomplete test evidence or optimistic supplier data.

Do not average away a fatal constraint
A candidate that fails a non-negotiable requirement for display uniformity should be removed before weighted scoring. Typical fatal constraints include unsafe operation, an unachievable environmental limit, incompatible interfaces, unacceptable field reliability or no credible supply route.

Recommended process

- Set pass/fail gates for the mandatory display uniformity requirements before comparing desirable features.
- Agree criterion weights with electronics, mechanical, software, product, service and procurement stakeholders.
- Score only from controlled data, supplier evidence or representative testing; mark unknowns explicitly.
- Run sensitivity checks by changing the highest weights and identifying whether the preferred architecture changes.
- Document assumptions, test conditions and revision status so the decision can be revisited after a component or firmware change.

2. Uniformity mechanisms and inspection architectures

2.1 Backlight luminance non-uniformity

LED pitch, light-guide extraction, diffuser films, reflector fit and edge coupling determine backlight uniformity. Edge-lit systems can show bright edges or corners; direct-lit systems can show LED patterning. Temperature and LED bin variation change the pattern over time.

- Strengths: often measurable and correctable through optical-stack, LED-current or mechanical improvements.
- Limitations: may vary with brightness, temperature and panel lot; local correction can create new colour or lifetime differences.
- Best fit: all LED-backlit LCD systems, especially large, high-brightness and local-dimming designs.

2.2 Cell and pressure mura

Mura describes low-spatial-frequency brightness or colour variation caused by cell-gap non-uniformity, polariser stress, mechanical pressure, bonding strain or material variation. It is often most visible on mid-grey fields and can change with temperature or enclosure torque.

- Strengths: root causes can be isolated with progressive assembly and pressure/temperature mapping.
- Limitations: subjective visibility, complex interactions and the possibility that a compliant bare panel becomes unacceptable after integration.
- Best fit: bonded, bezel-constrained and colour-critical HMIs.

> **Progressive assembly test**
> Inspect the bare panel, bonded module, mounted assembly and final enclosure using the same grey patterns. The first stage at which the defect appears usually identifies the stress source.

2.3 Edge and corner light leakage

Backlight leakage appears where bezel pressure, cell sealing, black matrix, tape, frame gaps or enclosure flex allow excess light near the perimeter. Dark-room operation and black content make it more visible than bright industrial screens.

- Strengths: often improved by frame support, opaque masking and controlled gasket load.
- Limitations: masking can hide symptoms while increasing heat or pressure; leakage may grow after vibration or thermal cycling.
- Best fit: night HMIs, diagnostic screens and premium products with dark UI themes.

2.4 Colour and viewing-angle non-uniformity

LCD retardation and colour filters produce angle-dependent gamma and colour. IPS, VA and TN modes behave differently, and a large display viewed from close range presents different angles across the screen. Cover and polariser films can add colour shift.

2.5 Temporal and pattern-dependent artefacts

Inversion patterns, frame-rate interactions, PWM, local dimming and image processing can create flicker, checkerboard, line or transient non-uniformity. Static uniformity measurements should therefore be complemented by motion and grey-ramp tests.

3. Comparative decision matrix

Criterion	Visual-only inspection	Spot meter grid	Imaging photometer	Automated line inspection
Low-frequency mura detection	Moderate	Strong	Excellent	Excellent
Colour-map capability	Limited	Strong	Excellent	Excellent
Human relevance	Excellent	Moderate	Strong	Moderate
Repeatability	Limited	Strong	Excellent	Excellent
Spatial resolution	Moderate	Limited	Excellent	Excellent
Throughput	Moderate	Poor	Moderate	Excellent
Capital cost	Excellent	Strong	Limited	Poor
Inspector dependence	Poor	Excellent	Excellent	Excellent
Traceable data	Poor	Strong	Excellent	Excellent
Production scalability	Moderate	Poor	Moderate	Excellent

Indicative only. Actual performance depends on the complete system architecture, supplier implementation, environmental conditions and validation method.

Example weighted scorecard

Criterion	Weight	Visual + grid meter	Imaging photometer	Automated imaging
Detect subtle grey-field mura	5	3	5	5
Correlate with operator perception	4	5	4	3
Production throughput	4	2	3	5
Repeatable supplier acceptance	5	3	5	5
Colour uniformity mapping	4	3	5	5
Capital / engineering burden	3	5	2	1
Stored traceability	4	2	5	5
Weighted total		**93**	**124**	**125**

For this premium industrial monitor, an imaging photometer gives the best balance between human correlation, spatial data and manageable throughput. Automated imaging becomes preferable at higher volume; visual plus grid measurement remains useful for development and dispute resolution.

Reading the result

- Visual inspection should be retained because some pattern-dependent artefacts are more obvious to a moving observer than to a fixed metric.
- Imaging systems require flat-field correction, controlled geometry and correlation thresholds rather than default software limits.
- Automated line inspection is justified when process feedback and traceability recover its capital and programming cost.

4. Engineering trade-offs that change the answer

4.1 Uniformity is grey-level dependent

A display can pass at full white and fail badly at 20-50% grey. Use black, multiple greys, white, primary colours and gradients that reflect the actual UI.

4.2 Warm-up and temperature change the result

LED output, LCD retardation and mechanical stress stabilise at different rates. Define warm-up, ambient and operating brightness for every acceptance measurement.

4.3 Mechanical torque can create or remove mura

Mounting screws, gasket compression and chassis flatness load the LCD. Establish torque sequence and allowable flatness, then inspect under worst tolerance.

4.4 Optical bonding can reveal panel variation

Removing the air gap increases contrast and can make existing panel non-uniformity more visible while also adding bond stress. Qualify panel class and bonding process together.

4.5 A ratio can hide local defects

Minimum/maximum or corner-centre ratios may pass while a local spot remains objectionable. Include spatial size, contrast and location limits.

4.6 Viewing-angle colour shift is a system geometry issue

Large screens at close range and side-view operators see different effective angles. Measure colour and luminance at task-relevant positions, not only normal incidence.

5. Application-led recommendations

Factory machine HMI

Moderate uniformity variation is often acceptable if alarms and text remain clear. Control pressure mura and glare more strongly than studio-grade colour.

Medical imaging or diagnostic aid

Use calibrated luminance/chromaticity mapping, stable warm-up and strict low-frequency mura limits. Verify ageing and viewing-angle behaviour.

Night-time transport display

Control edge leakage, black-level clouding, PWM and dimming uniformity at the lowest operating luminance.

Large control-room monitor

Assess close-view angle variation, thermal gradients and local-dimming artefacts across the full field.

Custom bonded touch assembly

Inspect before bonding, after bonding, after mounting and after environmental cycling to separate panel, process and mechanical causes.

6. Qualification and sourcing checklist

	Area	Verification action
[ ]	**Test conditions**	Define patterns, grey levels, luminance, warm-up, ambient light, distance, angle and camera/meter settings.
[ ]	**Bare panel**	Map panel-native luminance, colour, leakage and mura before value-added processing.
[ ]	**Bonded stack**	Repeat maps after bonding; inspect bubbles, stress patterns, colour shift and edge effects.
[ ]	**Mechanical**	Vary torque, orientation, gasket compression and enclosure twist; map pressure sensitivity.
[ ]	**Environmental**	Repeat after hot/cold operation, thermal cycling, humidity, vibration and ageing.
[ ]	**Temporal**	Check PWM, inversion, scrolling, grey ramps, local dimming and transient artefacts.
[ ]	**Production**	Correlate visual standards with instrument thresholds, gauge R&R and sampling/capability.
[ ]	**Change control**	Monitor panel, LED, optical film, adhesive, bezel, gasket and firmware changes.

Questions to ask a display partner

- Which patterns, luminance and viewing conditions define the proposed uniformity limits?
- Are supplier figures bare-panel metrics, and how do they change after bonding and mounting?
- How are pressure, torque, flatness and gasket variation represented in qualification?

- What instrument calibration and measurement uncertainty apply to luminance and chromaticity maps?
- How are visual golden units correlated with numerical thresholds and inspector training?
- Which optical, mechanical or firmware changes trigger requalification of uniformity?

Minimum evidence pack for design approval

- Controlled defect taxonomy and visual acceptance standard with example images/golden units.
- Instrumented luminance/chromaticity maps at defined grey levels, angles and temperature.
- Progressive assembly results for bare, bonded, mounted and final enclosure states.
- Mechanical tolerance/torque and environmental-cycle correlation data.
- Measurement-system analysis, calibration and production inspection work instructions.
- Approved panel class, process controls, sampling plan and PCN/requalification rules.

7. Beyond simple centre-and-corner measurements

Uniformity engineering is moving toward full-field, condition-aware measurement and production feedback. The aim is not to create stricter numbers automatically, but to detect defects that matter and identify their process source.

Perceptual uniformity metrics

Spatial filtering can weight defects by size and human visibility. Metrics need validation against actual users and content, not only algorithmic scores.

In-line imaging photometry

Fast cameras can map every unit and feed process trends. Calibration, fixture stability and data storage must be maintained.

Digital mura compensation

Per-pixel or zonal correction can improve luminance/colour but consumes dynamic range, may age unevenly and must remain tied to panel identity.

Thermo-mechanical simulation

FEA can predict pressure and CTE stress before tooling. Models require correlation with measured mura and actual material properties.

Self-monitoring backlights

Integrated current and temperature sensing can identify LED-string drift and local-dimming faults, enabling service diagnostics or adaptive correction.

> **Adoption gate**
> A new uniformity metric or compensation method should enter production only when it correlates with task-relevant visual quality, remains stable across temperature and ageing, and has controlled calibration and panel identity.

8. Working with Crystal Display Systems

Crystal Display Systems Limited supports industrial display integration, optical bonding, custom mechanics and production qualification, including selection and control of panels, backlights, cover stacks and complete monitor assemblies.

Relevant CDS resources

Resource	Purpose
LCD TFT Displays	Industrial panel range, long-life options and value-added integration.
Optical Bonding	Optical bonding options for readability, durability and condensation control.
Sunlight Readable Displays	High-brightness and optically engineered outdoor display solutions.
LCD TFT Display Components	Display components, interface boards, touch sensors and specialist technologies.
CDS Knowledge Centre	Display guides and technical training documents.
Request a Quote	Submit project requirements for technical and commercial review.
Contact CDS	Contact details and enquiry routes.

Contact Crystal Display Systems Limited

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Conclusion

Uniformity defects arise from the panel, backlight, optical process and mechanical enclosure as a coupled system. Effective control combines a clear defect taxonomy, task-relevant visual standards, full-field measurement and progressive assembly testing. The acceptance plan must remain valid after temperature, vibration, ageing and production variation.

Final engineering rules

- Define uniformity using relevant patterns, angles, luminance and viewing distance.
- Inspect progressively to separate panel-native, bonding and mechanical stress sources.
- Use full-field spatial data as well as controlled human visual assessment.
- Qualify torque, flatness, thermal cycling and ageing, not only room-temperature samples.
- Control optical films, LEDs, adhesives, bezels and firmware under change management.

Disclaimer

This whitepaper provides general engineering guidance and does not replace application-specific design review, supplier specifications, regulatory assessment or formal product qualification. Performance depends on the exact components, implementation, environment and usage profile.