The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

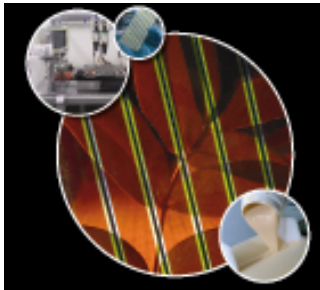
1938-14

Workshop on Nanoscience for Solar Energy Conversion

27 - 29 October 2008

Long Term Stability of Dye Solar Cells - Influence of Dye Chemistry

Keith BROOKS
Chalet Dulex
Route des Ormonts 1854
Leysin
Switzerland



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Long Term Stability of Dye Solar Cells – Influence of Dye Chemistry

Dr. Keith Brooks – General Manager, Greatcell Solar

Joint ICTP-KFAS

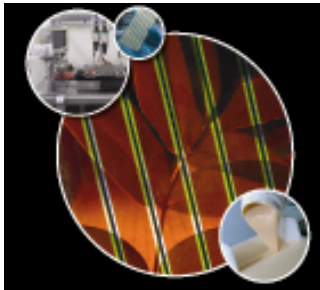
Workshop on Nanoscience for Solar Energy Conversion

October 28th, 2008

DYESOL LIMITED

International CleanTech Company

ASX: DYE



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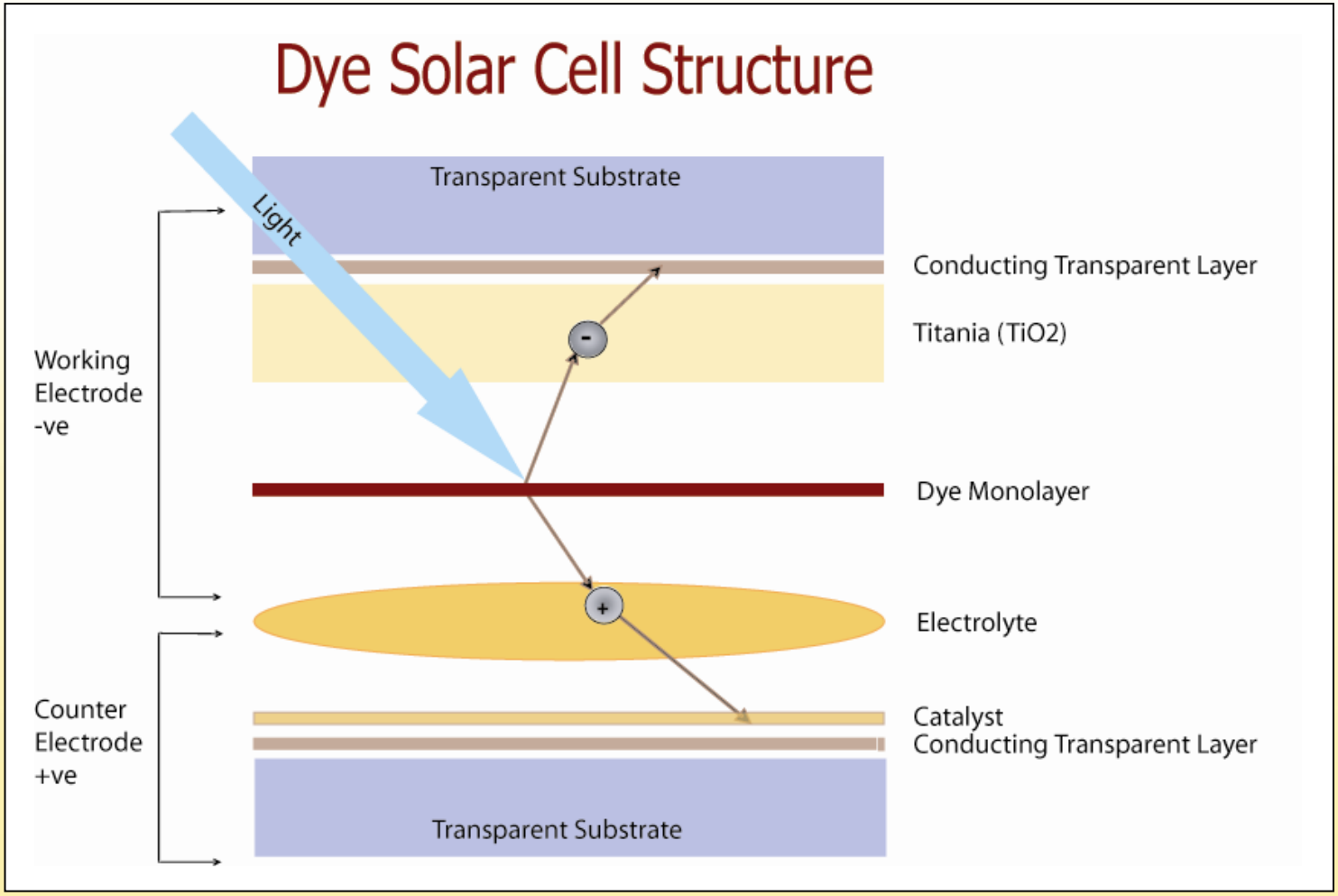
Outline

- **Overview of Dye Solar Cells from a Commercial Viewpoint**
- **Long Term Stability Studies of Dye Solar Cells and Modules**
- **Dyesol Group: Overview of Activities**

Global Leaders in Dye Solar Cell Technology

DSC Structure



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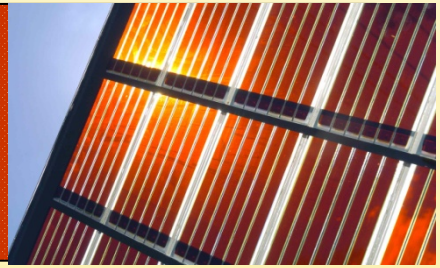
Three Generations of PV

First Generation
Crystalline Silicon

Second Generation
Thin film Semiconductor

Third Generation
Artificial Photosynthesis
Nanotechnology



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Dye Solar Cells

- Artificial photosynthesis (biomimetic) – mimics the energy capture of a leaf
- Two stage process, compared to first and second generation PV
- Dyes derived from archival photography act in the same way as chlorophyll
- Titania (the white pigment in toothpaste & white paint) used as semi-conductor

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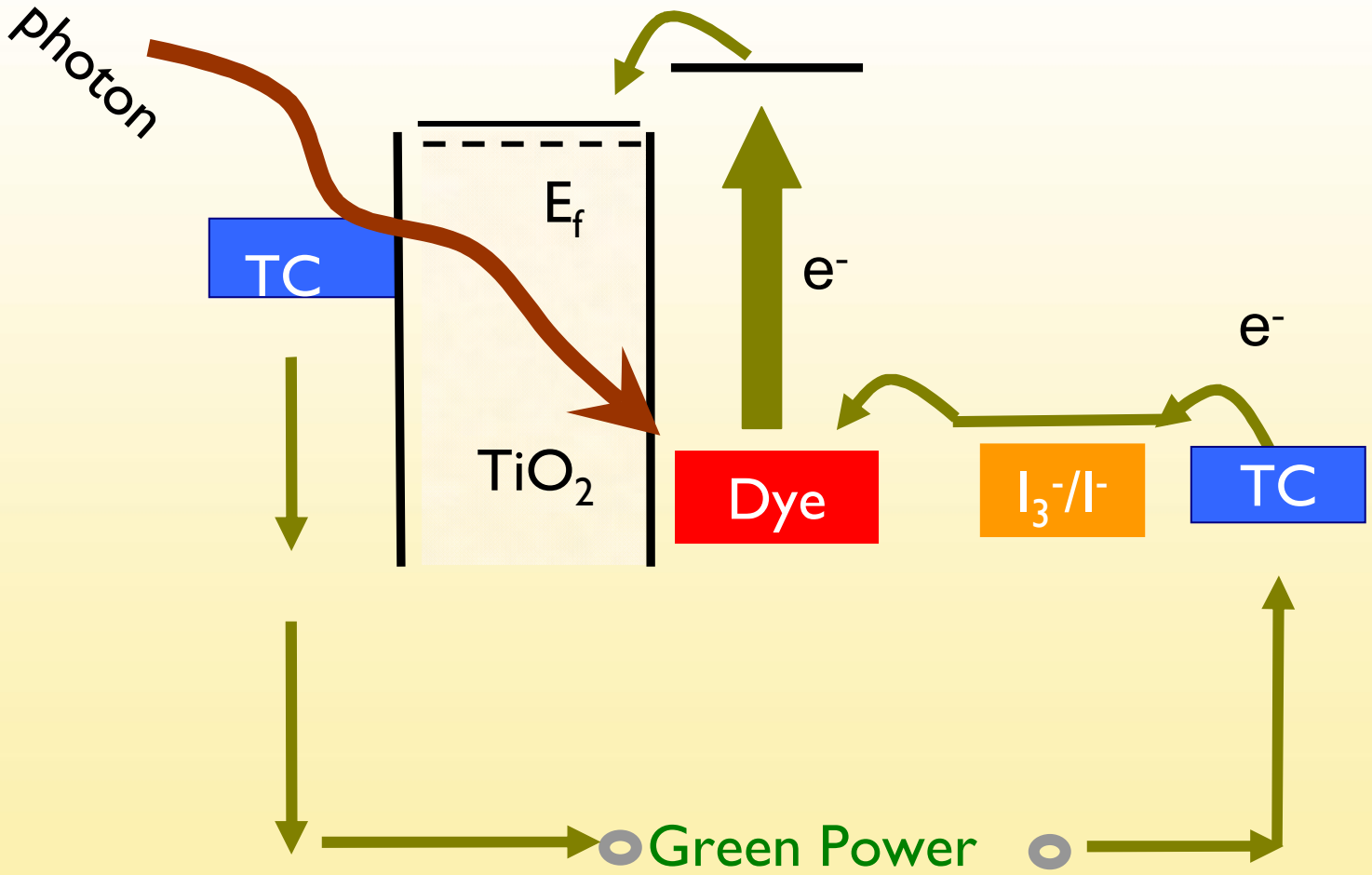
How it Works



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Why DSC as PV ?

- Lowest embodied energy
- Environmentally benign manufacturing and materials
- Can be engineered to the environment and application
- Energy security
  - DSC can be manufactured in any country using simple processes
  - ideally suited to distributed generation
  - BIPV provides security of supply for essential services

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Why DSC as PV ?

- Better than alternatives in haze, overcast conditions, shading and indirect light situations
- Modest capital required to establish manufacturing
- Only transparent PV + possibility for various colours = aesthetic appeal
- Flexibility suits new product development
- Bifacial feature of transparent DSC

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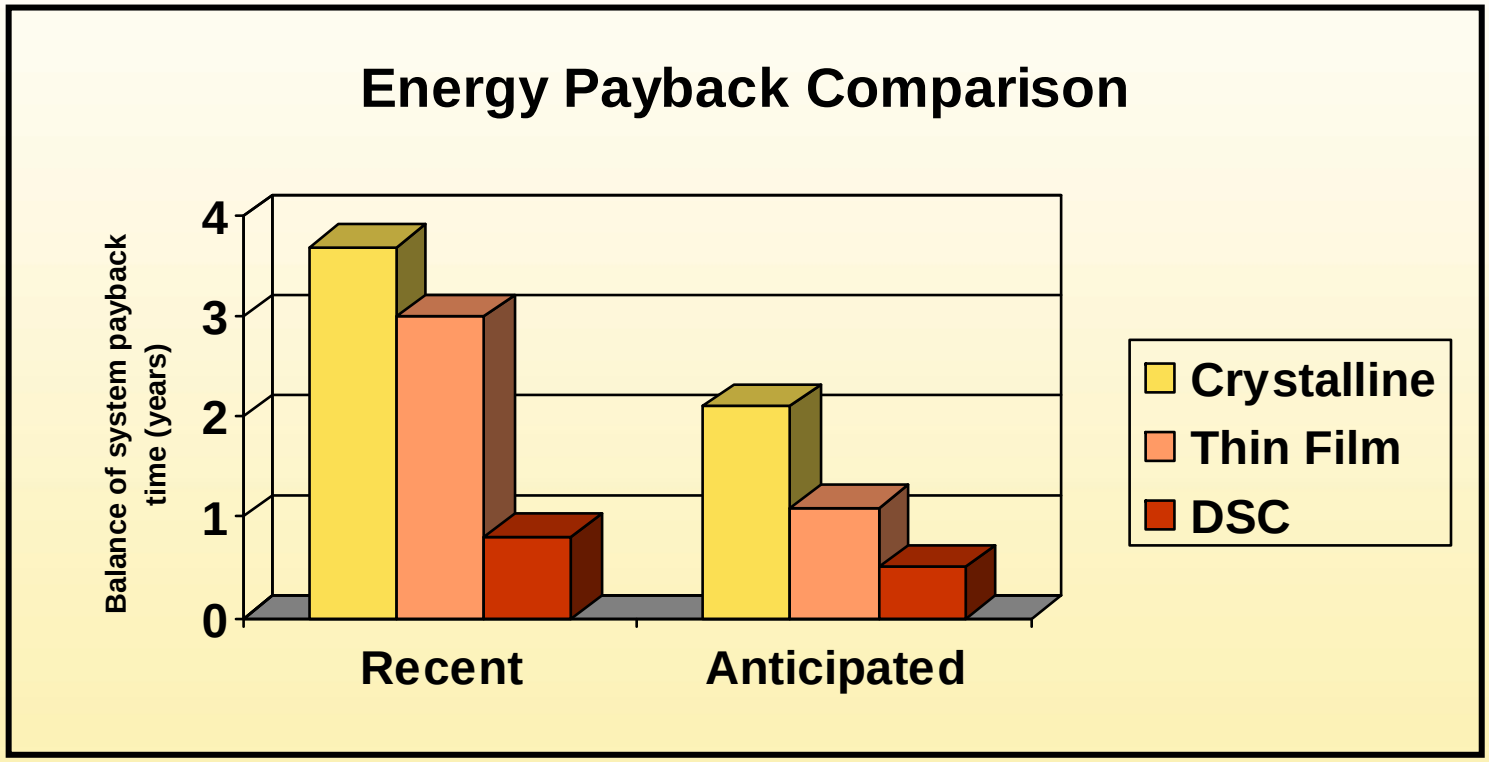
Energy Payback Comparison



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Current Misconceptions

- A long way from commercialisation
- Will it really be cost competitive?
- Efficiency is low and likely to remain so
- Stability and operation at high temperature a major concern
- Patent protection expiring
- Limited market & applications

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Commercialisation

- Dyesol's new manufacturing facilities
- G24i – consumer products and technology
- Corus – researching DSC technology in sheet metal production
- Permasteelisa/ERG Renew – researching building integrated DSC
- Dyesol-Timo – JV commercialising DSC technology in Korea

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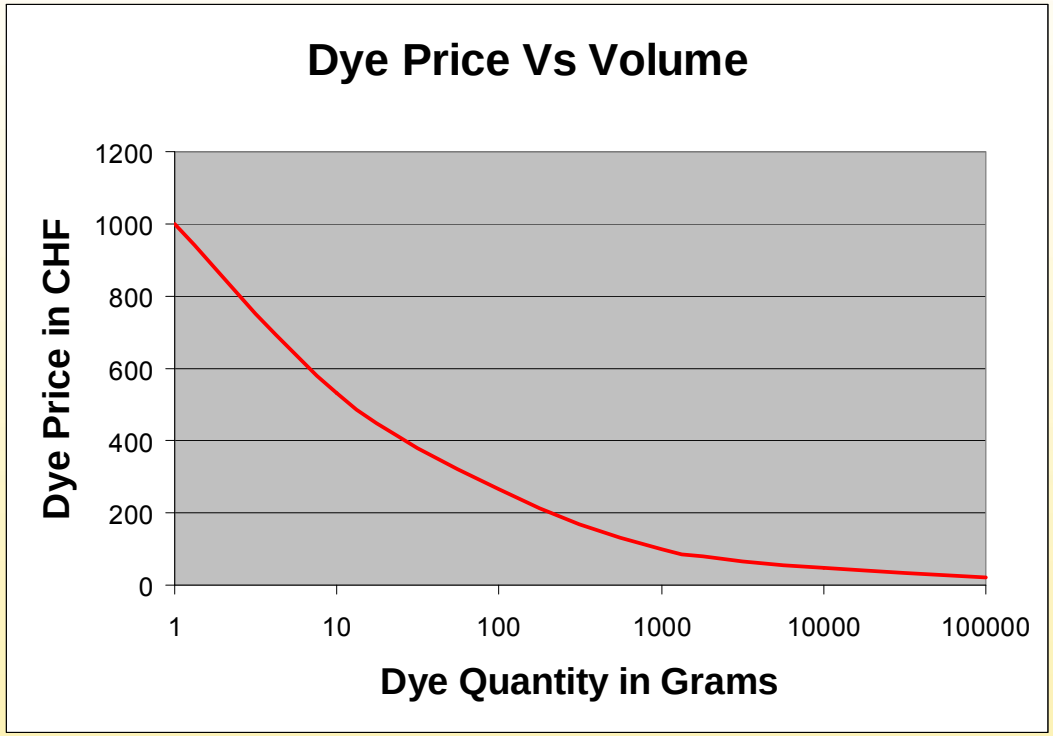
Cost Effective at Volume Production



Usage 1 to 1.4 grams per sqm

- Yield of the dye isomer
- Reactors of appropriate size and construction
- Ru weight is ~1/10 of dye weight
- Stable Ru price

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Efficiency – the Real Story

- DSC efficiency lower but improving
- DSC is still young in development cycle
- Efficiency & Peak Watt are measured under ideal conditions rarely achieved in practice
- DSC produces energy when light exists
- The fairer metric is kwh/m^2/annum in real operating conditions

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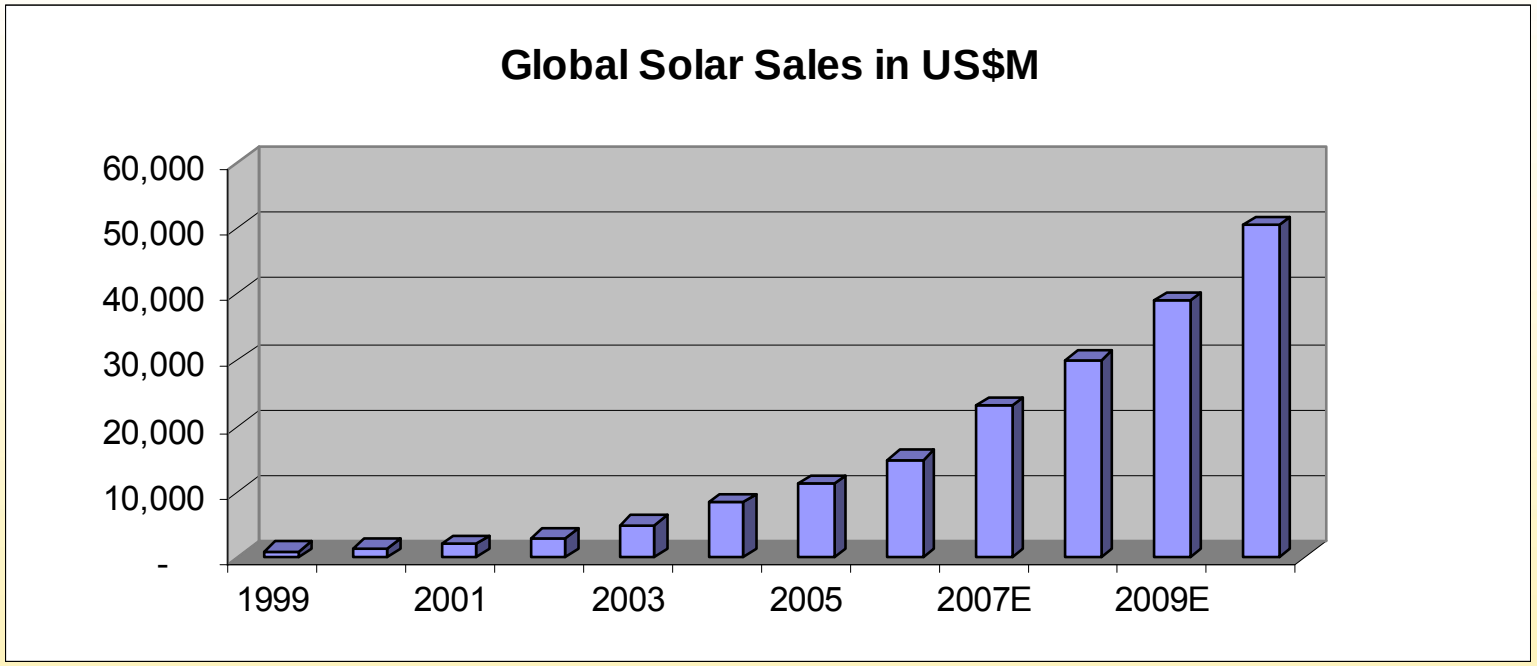
Solar Cells – Market Place



Solar PV industry with >40% average growth rate ($23B in 2007)

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Market Places for PV

- Building integrated
- Consumer products
- Grid connected solar farms
- Remote industrial
- Remote communities

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DSC - Addressable Market

- Portable
  - Cheap consumer electronics power
- BIPV
  - Façade power
  - Metal roofing
- Dyesol supplies the feedstock / input materials and technology for the manufacture of DSC products

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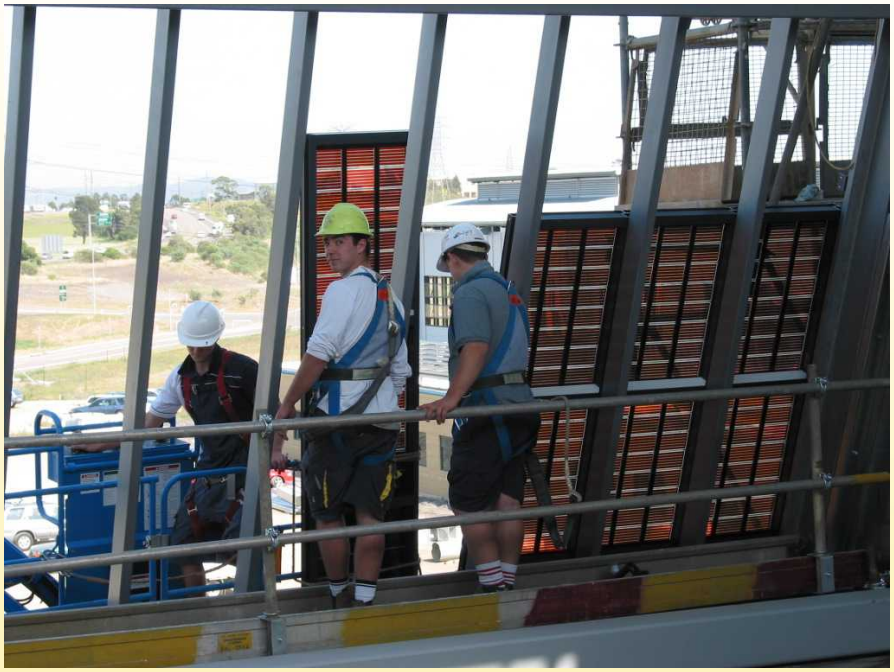
Building Integrated PV



Easy installation

Aesthetics

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Building Integrated PV

Price target	Competitive with building product replaced	✓DSC
Optimum performance	At variable light conditions	✓DSC
Physical form	Aesthetics Conformance	✓DSC
Elements of balance of system	Framing, installation, inverters High light utilisation	✓ DSC

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Steel Roofing Market

- World coated steel market
  - 2008: over 1 billion sqm
  - growing at 7-8% pa
- Potential for solar coated steel cladding 20% i.e. over 200 million sqm/annum
- $75 per sqm added value for Dyesol
- Addressable market $15billion/annum

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Façade Market

- World flat glass market
  - 2007: 5.2 billion sqm
  - 2010: 5.2% growth/year = 6.1 billion sqm
  - 60/40 view and non-view
- DSC technology - addressing non-view market
- Dyesol materials - $75/sqm added value

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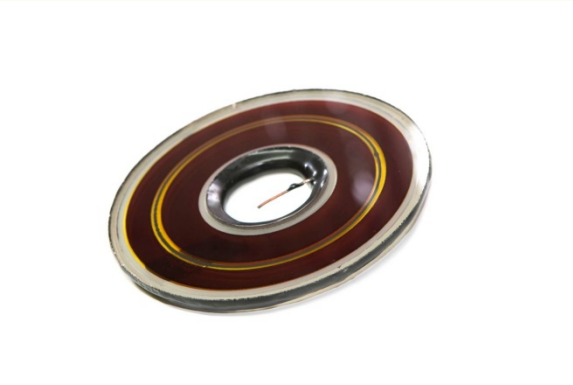
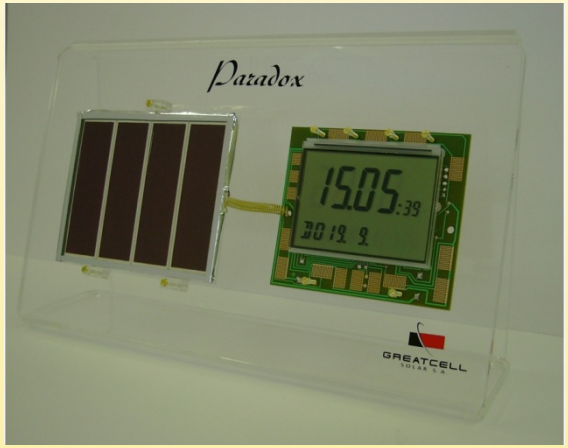
Consumer Products



Shapes

Flexible



Indoor

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Consumer Products

Price target	Electronic component pricing	✓ DSC
Optimum performance	Indoors (low or artificial light)	✓ DSC
Physical form	Not heavy, not fragile	DSC products engineered- DSC flexibles an option
Elements of balance of system	Integration into packaging	DSC engineering underway

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Future Market Segments

DSC promising:

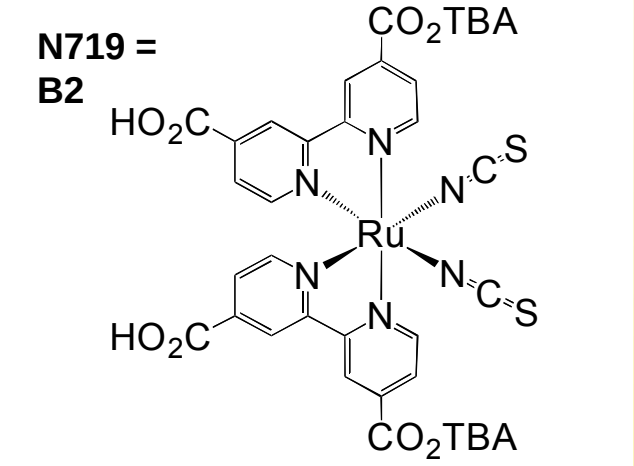
- Hydrogen/chemical production directly from PV
- Tandem storage products – e.g. CEGS
- Tandem functional products – e.g. displays
- Tandem building products – e .g. PVT
- Building energy efficiency – e.g. photoelectrochromics

Experimental

2006 Dyesol DSCs:

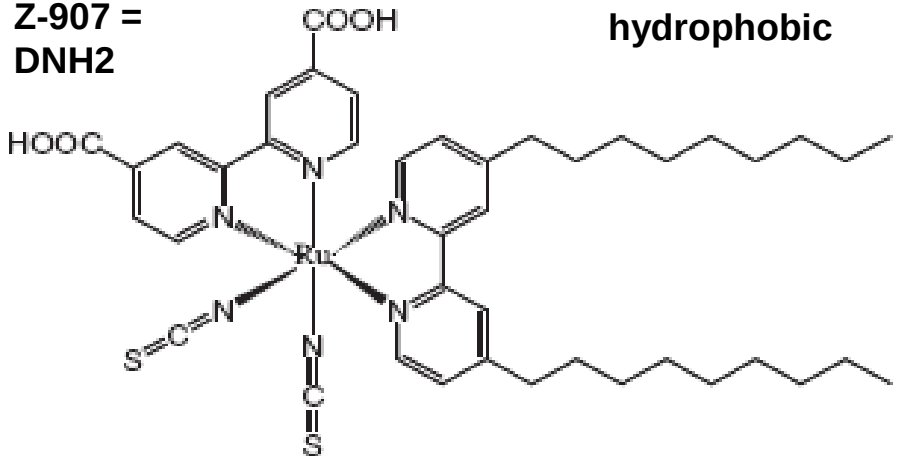
- 0.88 cm^2 active area sealed cells
- MPN-based electrolyte + GuSCN
- N-719 vs Z-907 dyes

N719 = B2



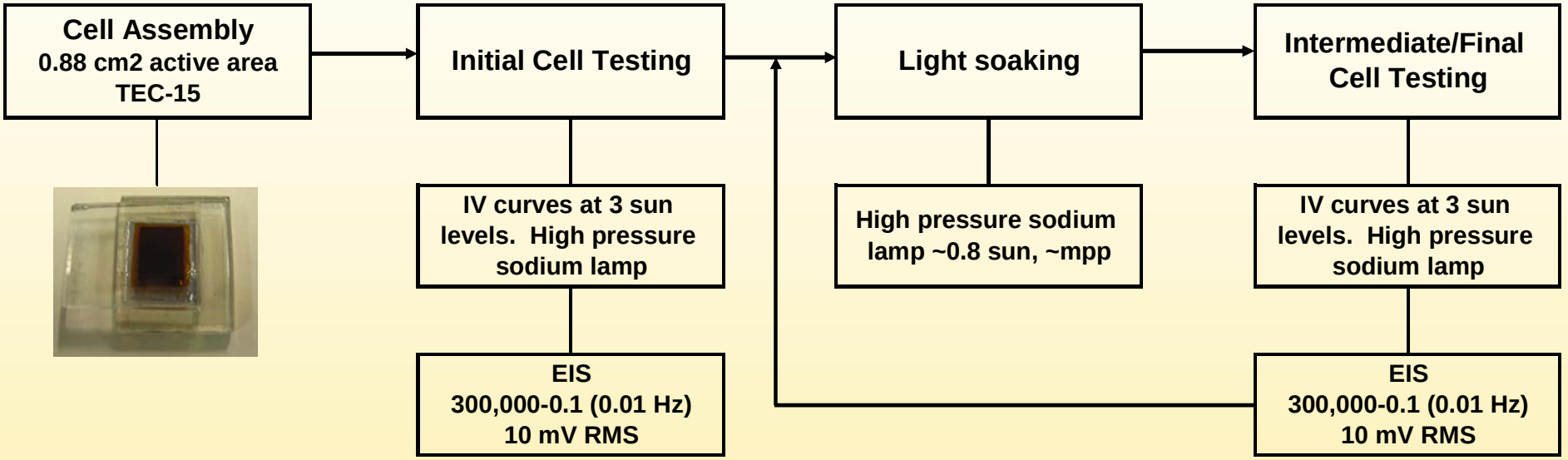
Z-907 = DNH2

hydrophobic

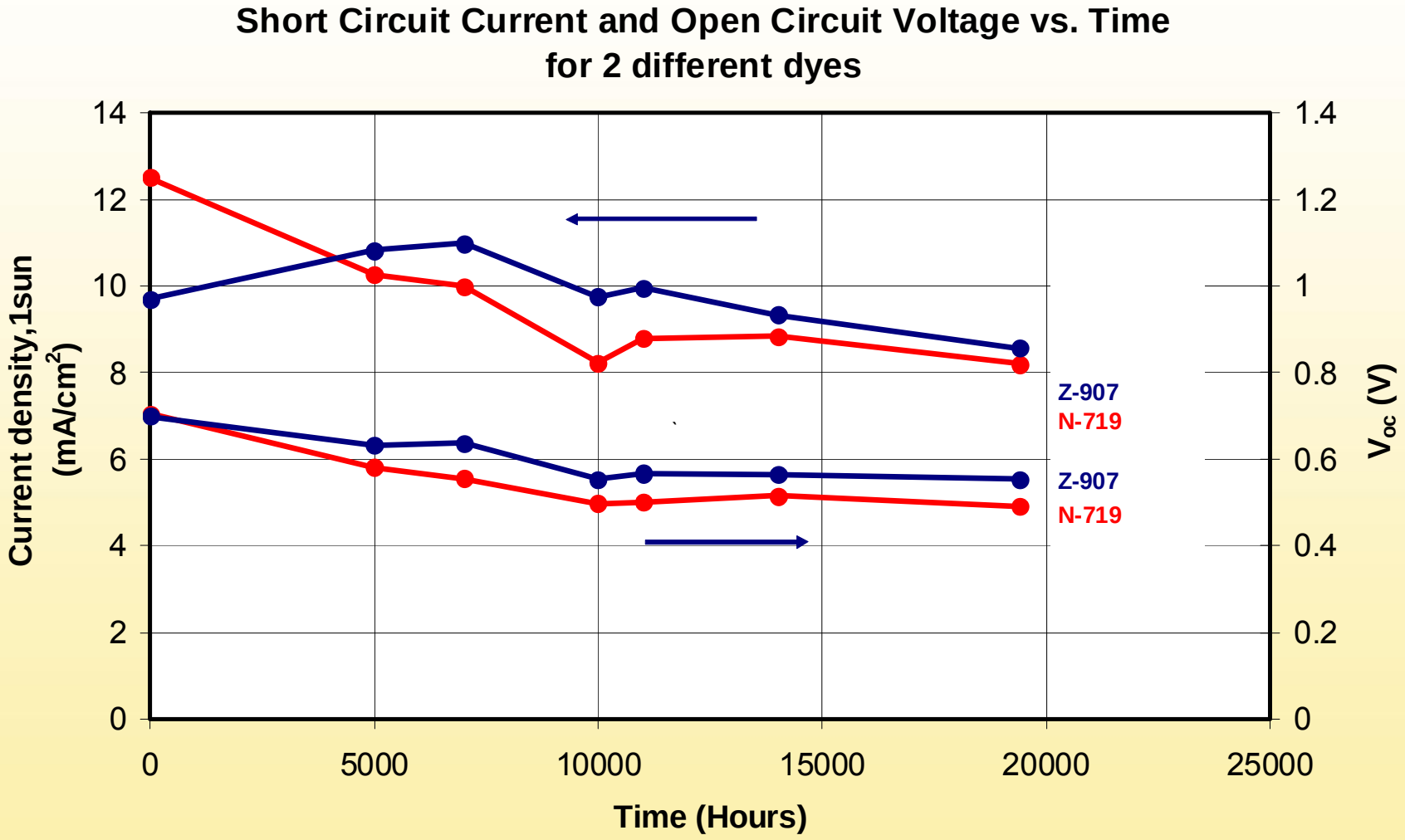


- Light soaking under load (close to mpp) at ~0.8 sun, 55-60°C with periodic assessment through IV characteristics and EIS

Experimental



20,000 hours test – 2006 Dyesol DSCs
Light soaking at ~0.8 sun, 55-60°C



20,000 hours test – 2006 Dyesol DSCs

Light soaking at ~0.8 sun, 55-60°C

- **20,000 hours = 27.4 months of continuous illumination**
- **Corresponding to 16,000 kWh/m²**
  - **Middle Europe: ~1,000 kWh/m² solar irradiation (London: 970 kWh/m²)**
  - **Southern Europe or Sydney: ~1,700 kWh/m²**
- **Average temperature during solar irradiation: ~45°C**
- **Acceleration factor of 2-3 per 10°C**
- **Assuming a factor of 2:**
  - **Middle Europe: 32 years**
  - **Southern Europe or Sydney 18 years**

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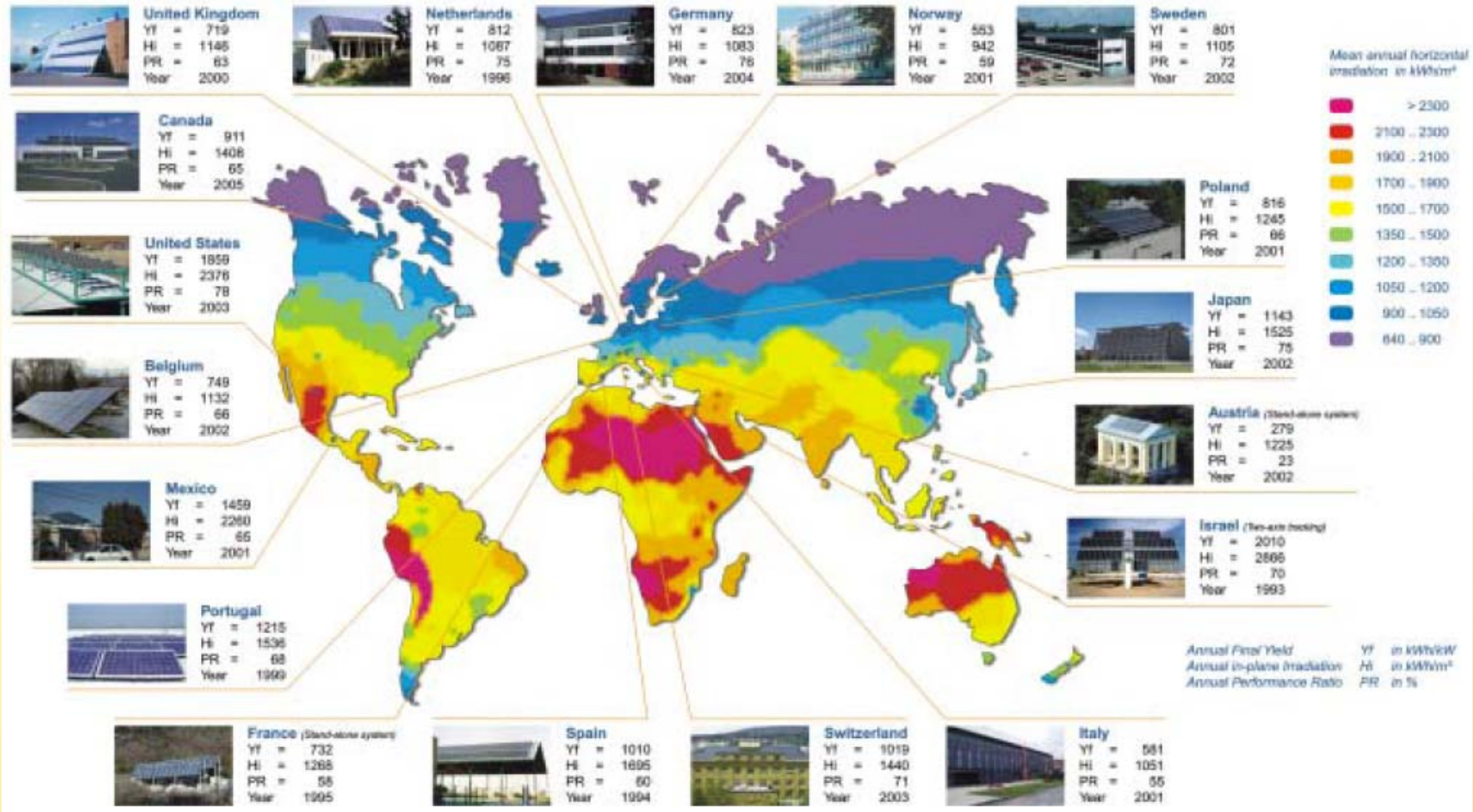
Global Solar Radiation



Source: http://www.iea-pvps.org/products/download/pap0_061_slides.pdf

20,000 hours test – 2006 Dyesol DSCs

Light soaking at ~0.8 sun, 55-60°C

But

- **These cells are getting "tired"**
- **Decrease of open circuit voltages, due to increased electron back transfer with aging**
- **Decreased photocurrents, particularly for N-719, due to dye desorption or decomposition?**

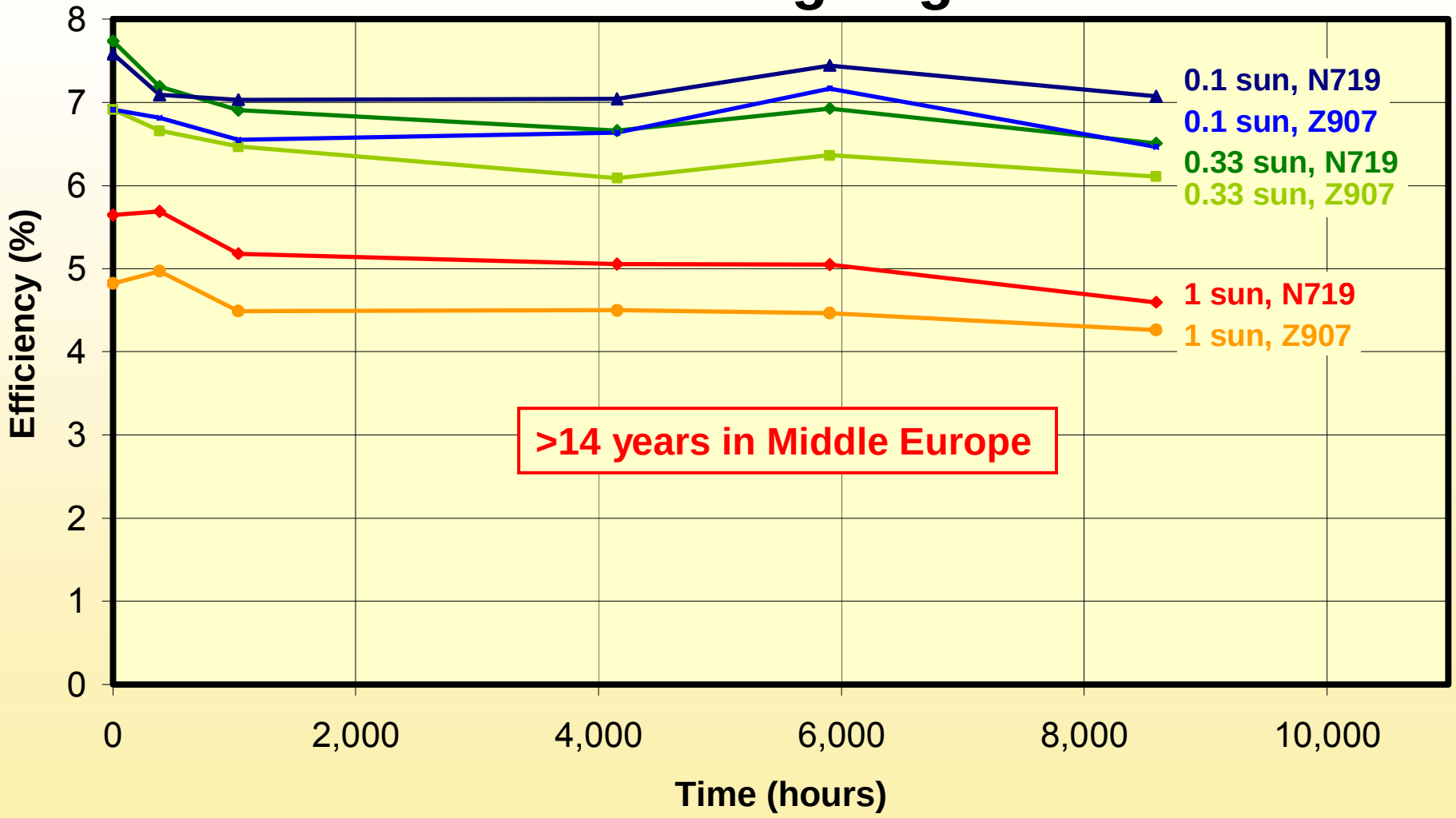
2008 Dyesol DSCs

- **with higher efficiencies (electrolyte formulation, TiO_2)**
- **EIS measurements: constant TiO_2 potential, i.e. -0.65V vs I_3^-/I^-), rather than constant cell voltage (prior -0.68V)**

9,000 hours test – 2008 Dyesol DSCs

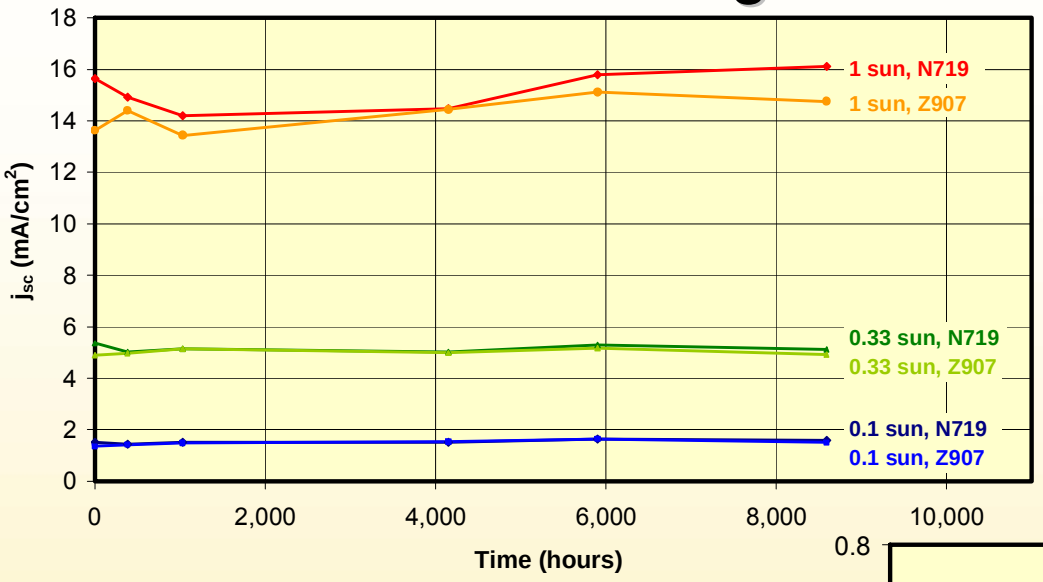
Light soaking at ~0.8 sun, 55-60°C

Ongoing Tests

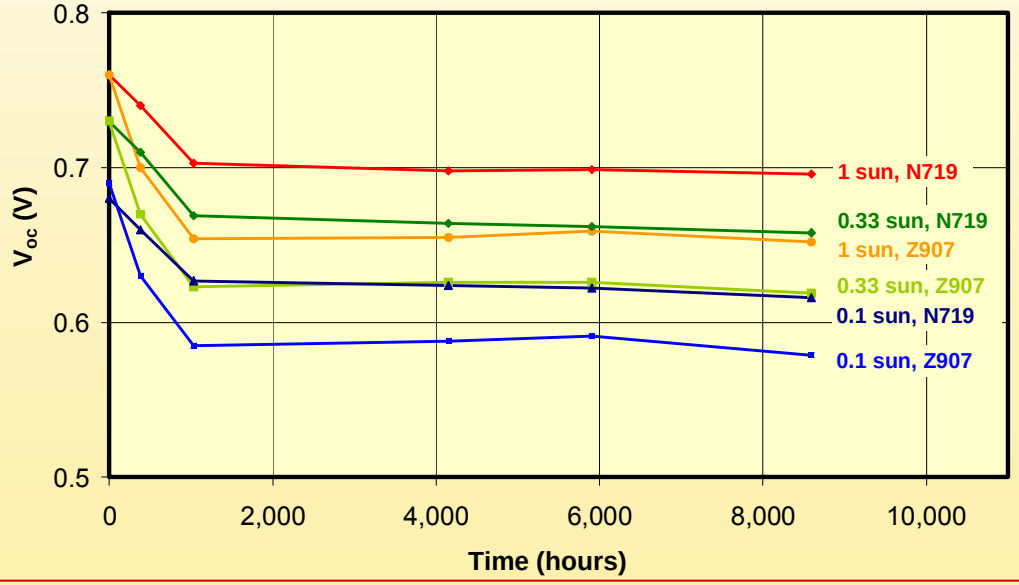


9,000 hours test – 2008 Dyesol DSCs

Light soaking at ~0.8 sun, 55-60°C



Current

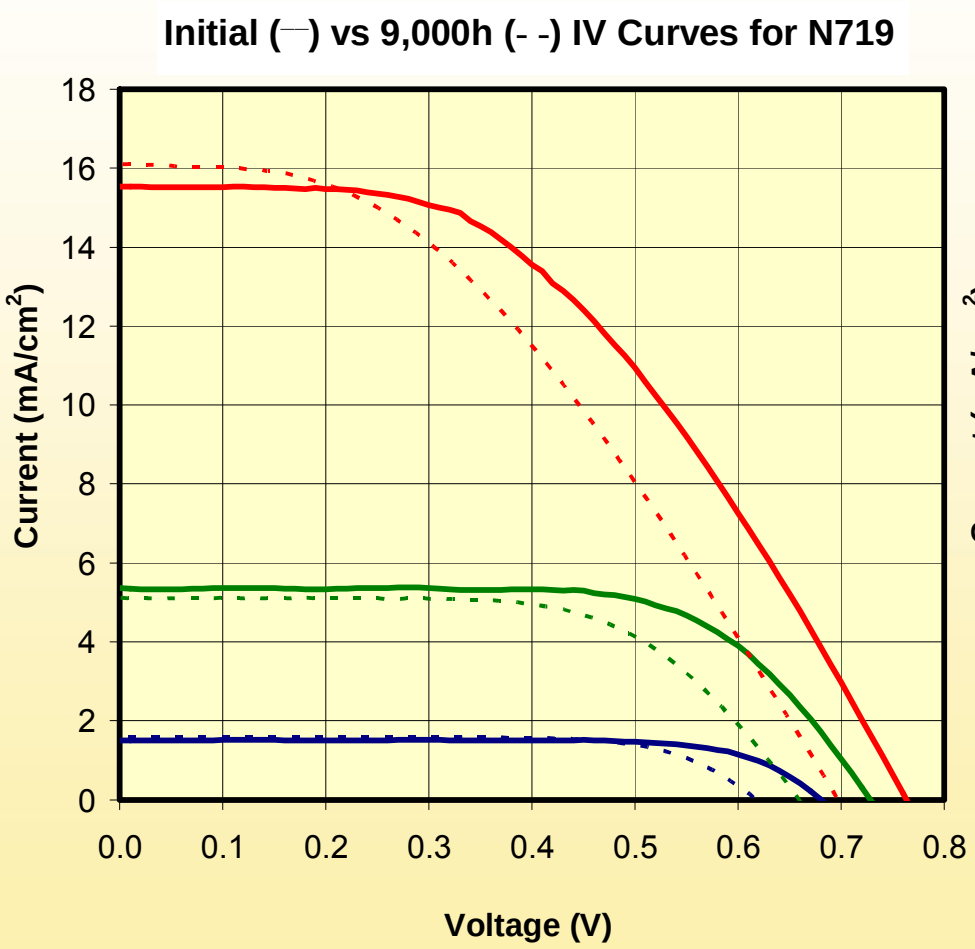


Voltage

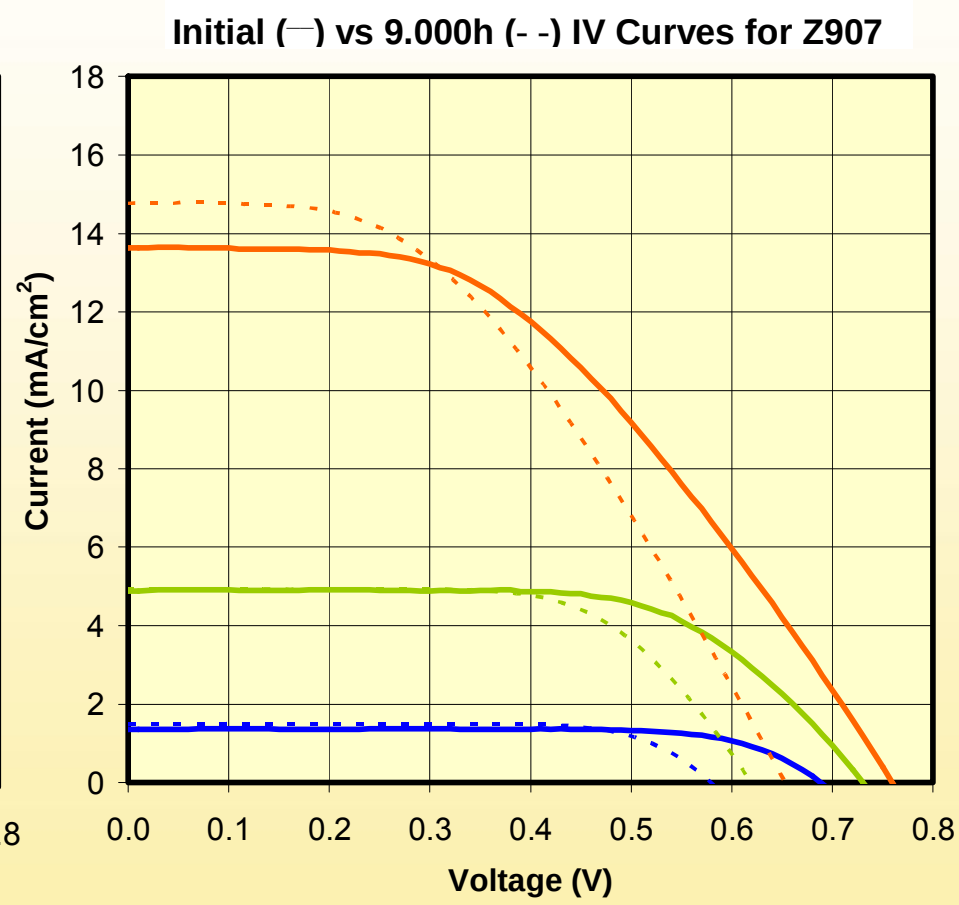
9,000 hours test – 2008 Dyesol DSCs

Light soaking at ~0.8 sun, 55-60°C

N-719



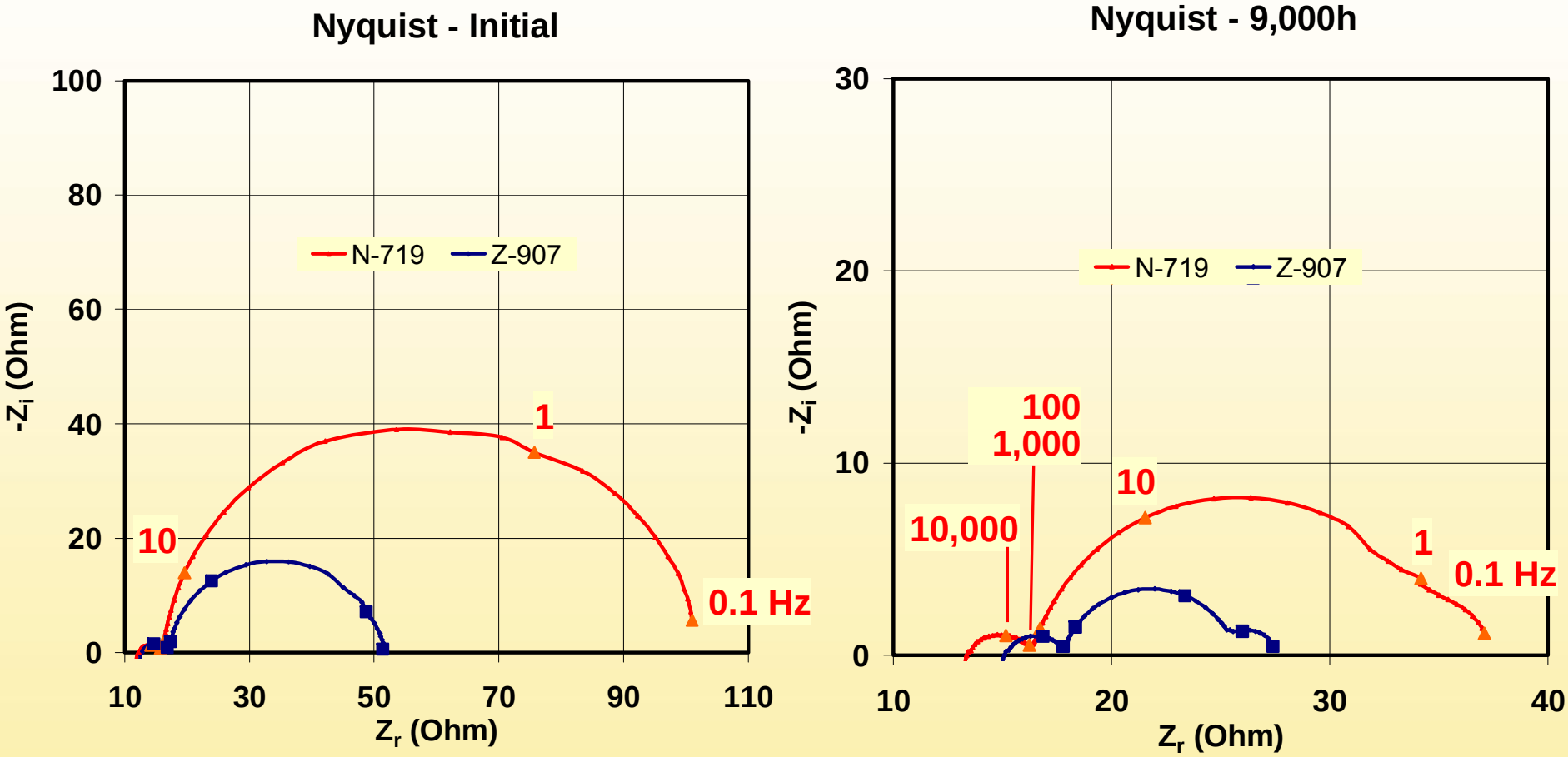
Z-907



9,000 hours test – 2008 Dyesol DSCs

Light soaking at ~0.8 sun, 55-60°C

EIS measured in the dark at constant TiO_2 potential, i.e. -0.65V vs I_3^-/I^-



Significant decrease in electron back transfer resistance R_{br} ⇨ R_{diff} becomes apparent

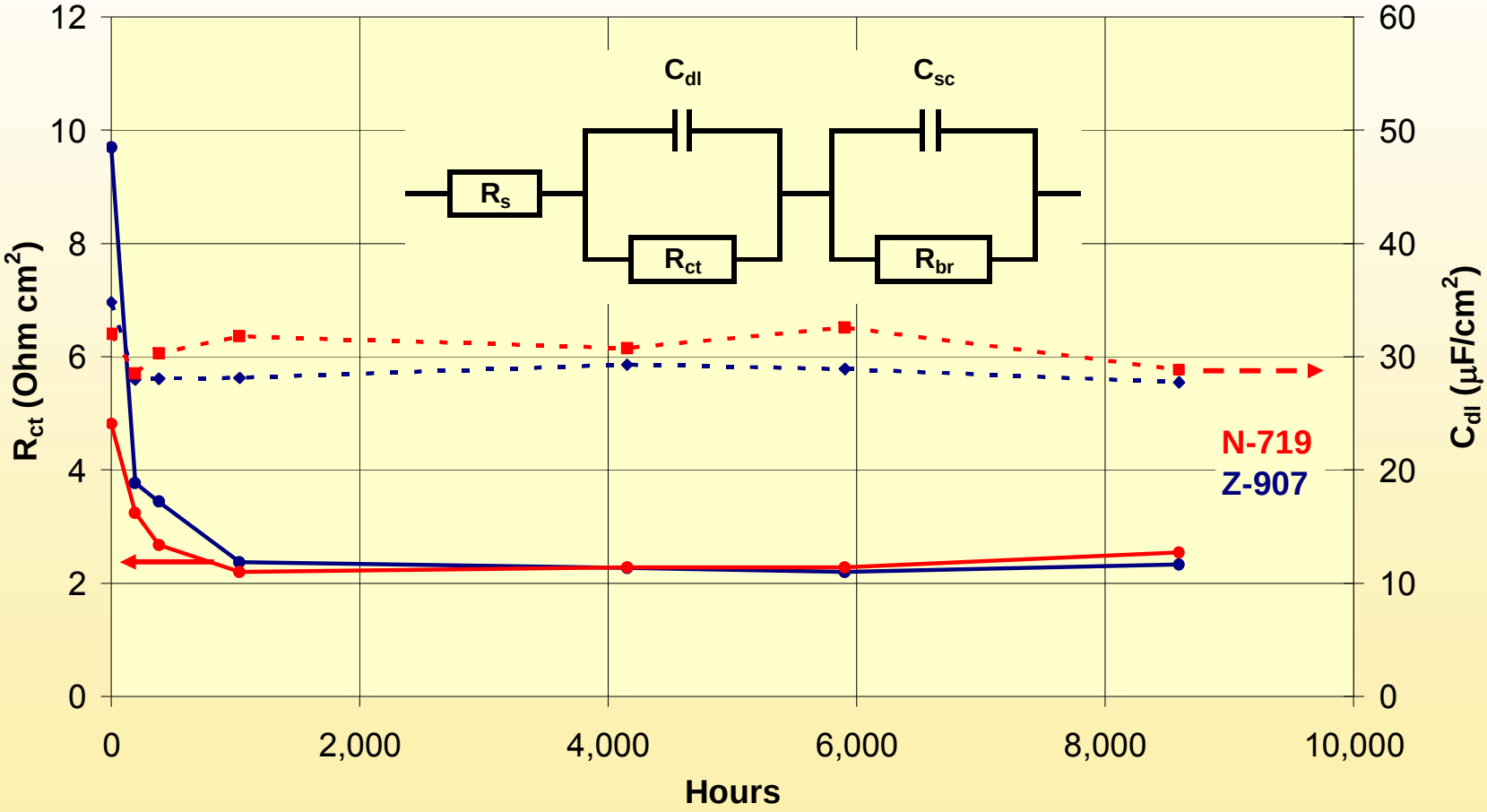
Due to Dye Desorption or Decomposition?

9,000 hours test – 2008 Dyesol DSCs

Light soaking at ~0.8 sun, 55-60°C

EIS measured in the dark at constant TiO_2 potential, i.e. -0.65V vs I_3^-/I^-

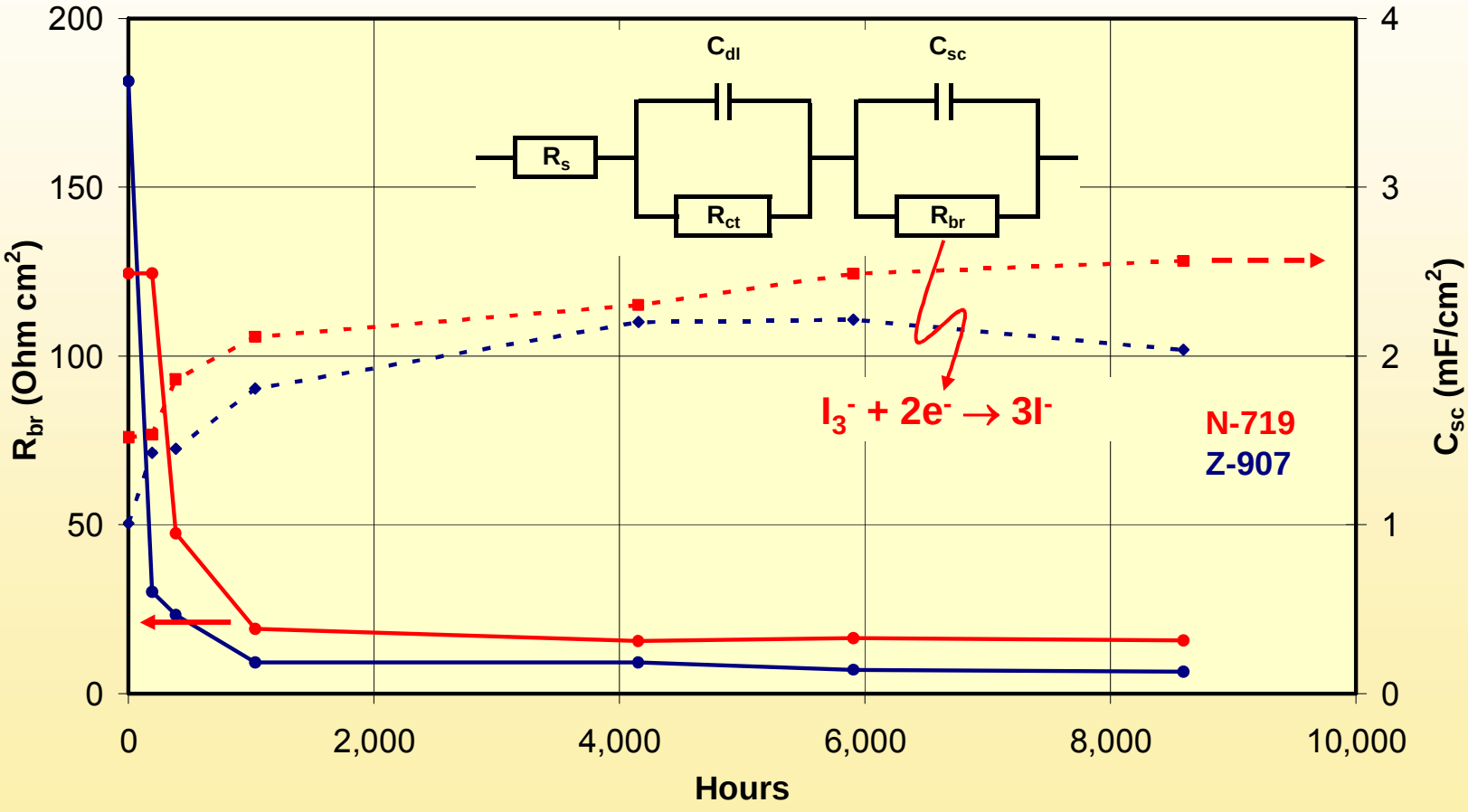
Charge Transfer Resistance and Double Layer Capacitance



9,000 hours test – 2008 Dyesol DSCs
Light soaking at ~0.8 sun, 55-60°C

EIS measured in the dark at constant TiO_2 potential, i.e. -0.65 V vs I_3^-/I^-

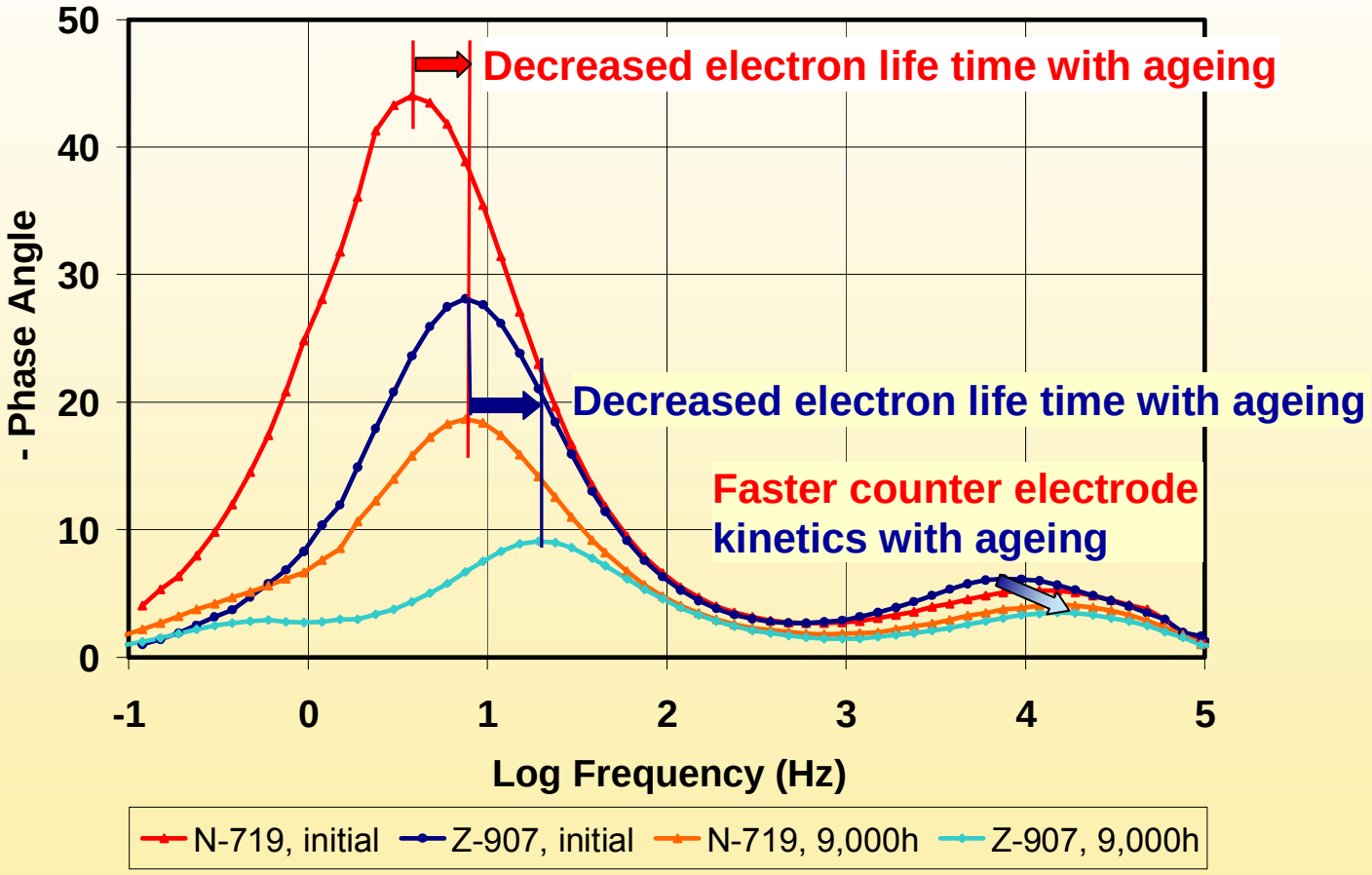
Electron Back Transfer Resistance and Chemical Capacitance



9,000 hours test – 2008 Dyesol DSCs
Light soaking at ~0.8 sun, 55-60°C

EIS measured in the dark at constant TiO_2 potential, i.e. -0.65 V vs I_3^-/I^-

Bode plots - initial vs after 9,000 h



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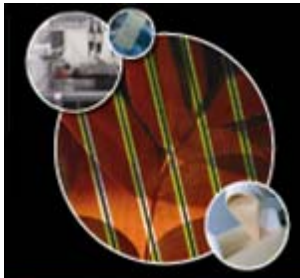
At the cell level:

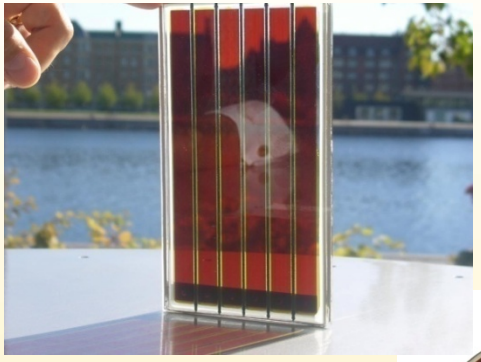
≥ 20 years stability feasible based on Dyesol DSC technology

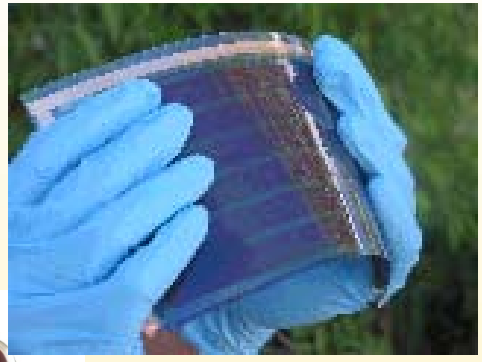


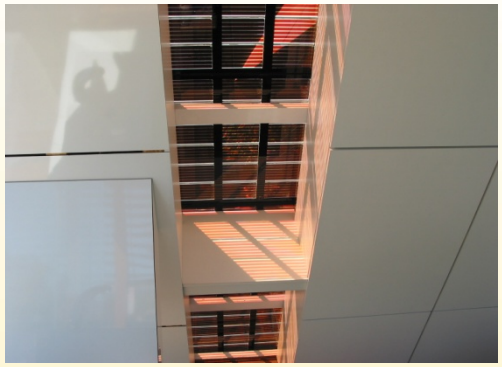
Dyesol Overview

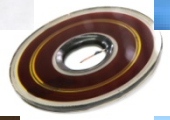
- Public Listed Company Based in Australia
- 15 Years DSC Experience
- 70+ Employees
- Cover All Aspects of DSC Research and Development
- Manufacture Materials for Laboratory and Production
- DSC Manufacturing and Testing Processes / Standards
- Develop New DSC Applications/Devices

Dyesol Patented Products



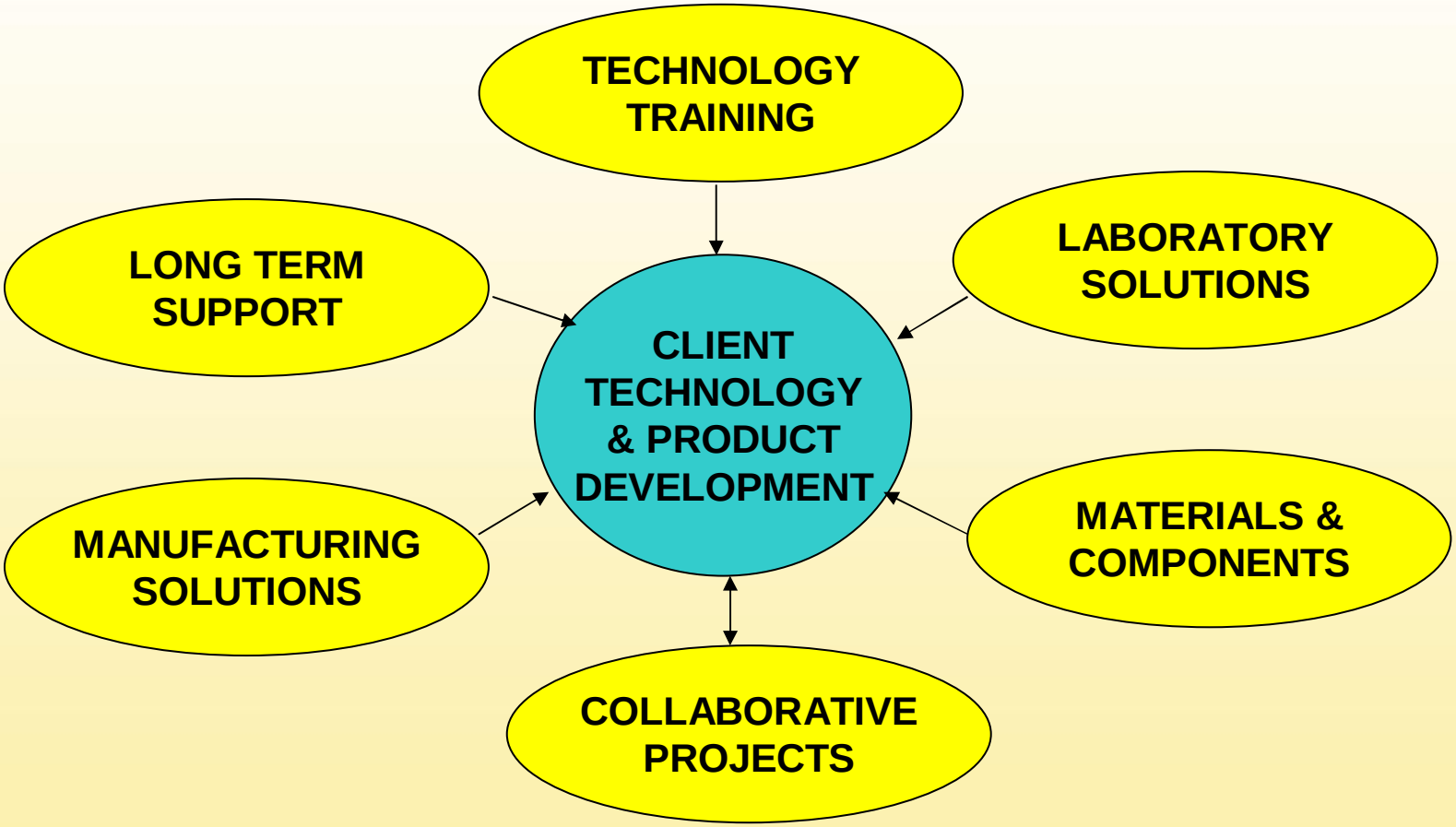


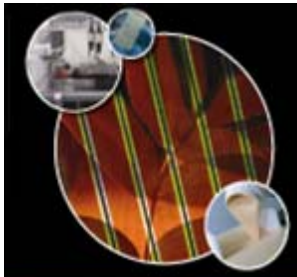




Dyesol Processes and Know How = $50 Million Investment 14 Years

Dyesol a Technology Platform Co.





Dyesol Lab/R&D Solutions

1. DSC Open Cell Production for materials evaluation

- Equipment – laboratory furnace, dryer, dye applicator, electrolyte applicator. UPTS
- Materials – Electrodes, dyes, electrolytes, conductor paste

2. DSC Sealed Cells for Long Term Testing

- Equipment – Level 1 plus printer, TCAM, EFM. LTTS
- Materials – Substrates, printing pastes, dyes, electrolytes, sealants, conductor pastes

3. DSC Laboratory scale Modules

- Equipment – Level 2 plus laser, hole driller, interconnect applicator,
- Materials – Level 2 plus interconnect

4. DSC Prototyping Facility – Rigid substrate

- Equipment – Level 3 plus module assembly equipment, encapsulator
- Materials – Level 3 plus continuous furnace, encapsulant, product sealants

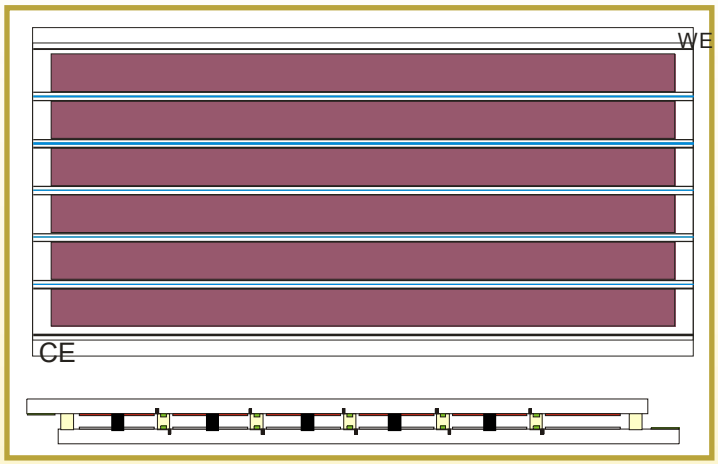
5. DSC Prototyping Facility – Flexible substrates

- Equipment - Roll to roll prototyping facility
- Materials – Level 3 materials plus laminating plastics,

6. DSC Test & Evaluation Facilities

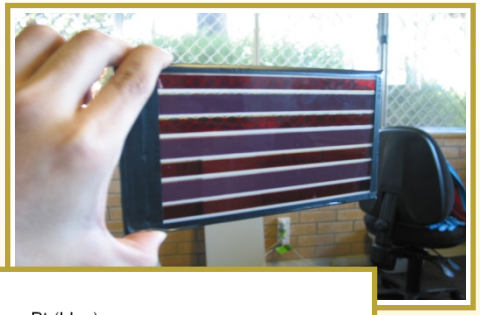
- Equipment – EIS, Vis Spec, MUPTS, HPLC, IPCE, Calibration Sources

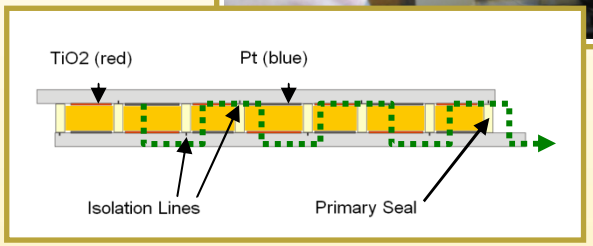
Dyesol Glass Modules

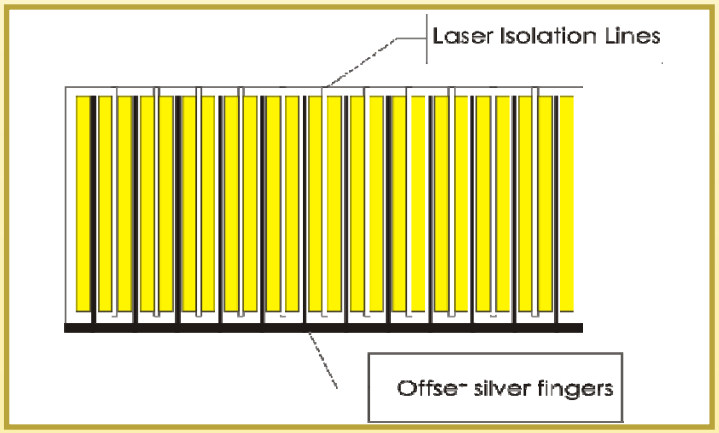


Z Interconnect Design

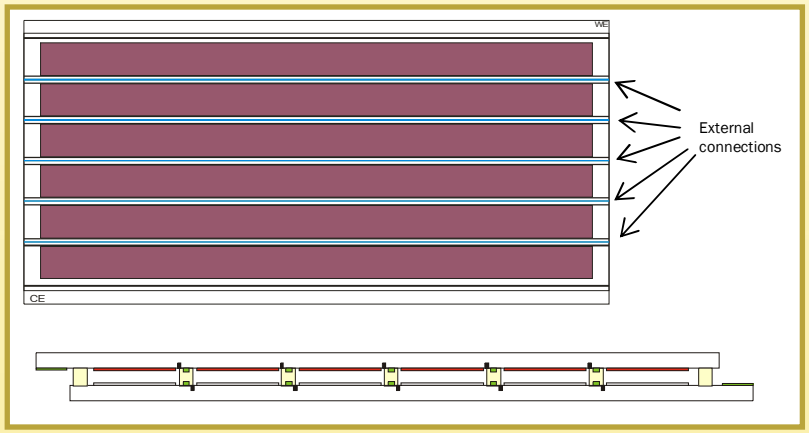
W Design



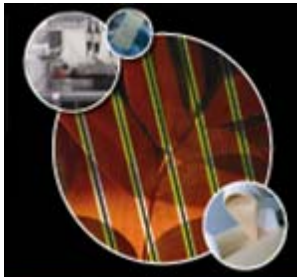




Parallel Design



External Connect Design



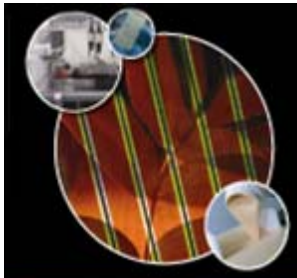
Dyesol Global Position

Dyesol Group of Companies

Australia, Singapore, Switzerland, UK, Italy, Japan, Korea

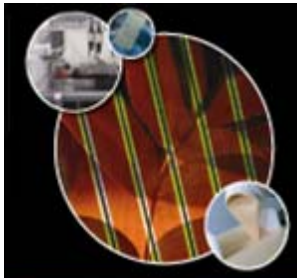
Dyesol Representatives

Thailand, Turkey, Canada, China, Taiwan, Germany



Dyesol's Business

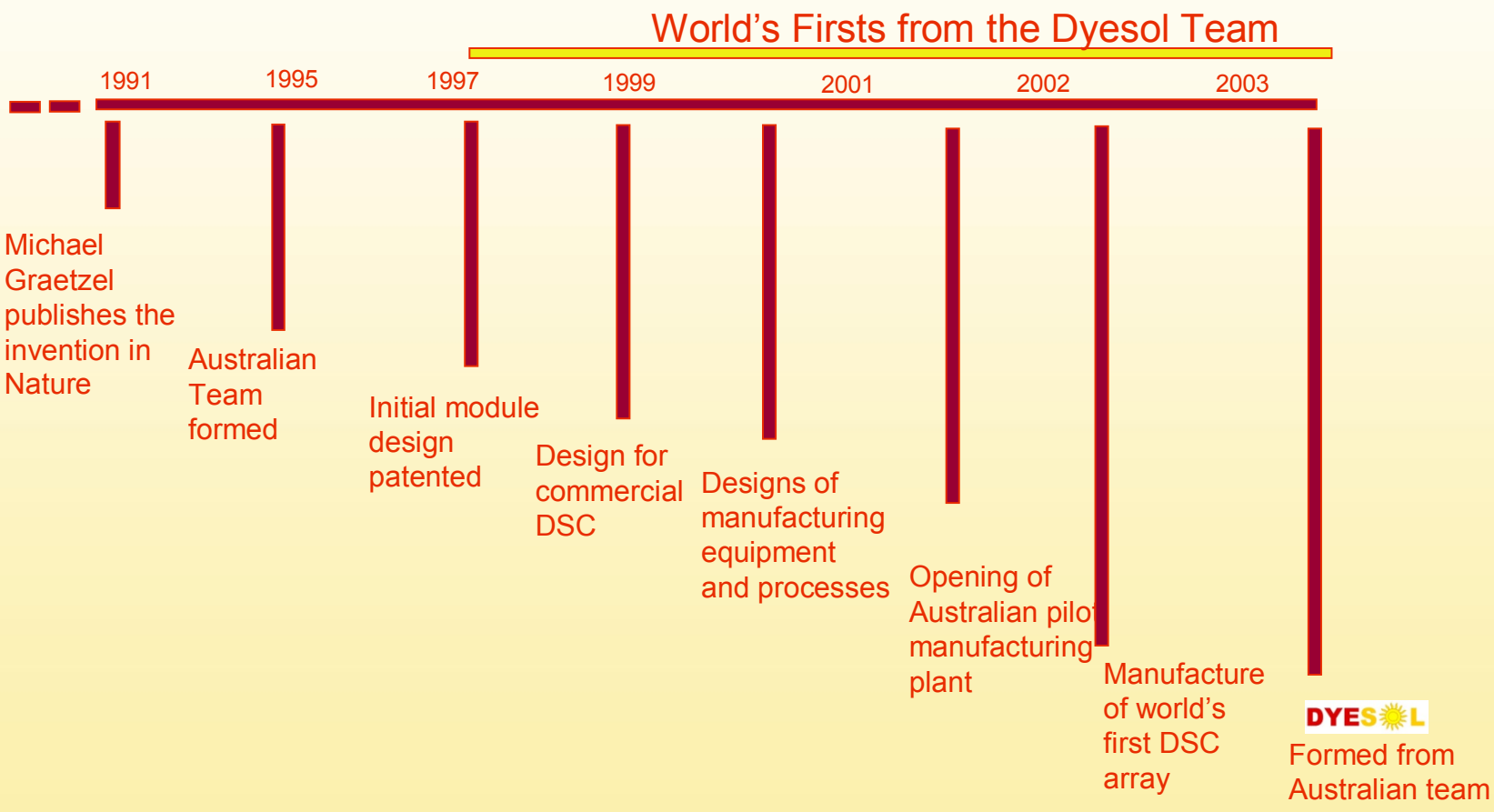
- Focused on the Development of DSC Technology
- Promise Cheaper Power – DSC Materials are Cost Effective
- Proven Technology – Performed at Pilot – Moving to Volume Production
- Control all IP needed to Meet Commercial Goals
- World-Wide Addressable Market of over 100B/annum
- Partners / Customers are International Majors
- Largest Producer of DSC Materials World Wide

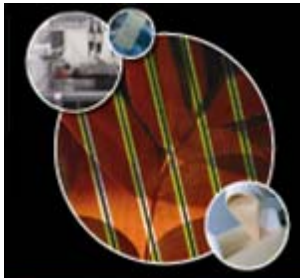


Dyesol Business…

- Focused on the Development of DSC Technology
- Collaborative Programmes in Steel, Glass, Flexibles
- Jointly Develop New Products/Applications/Devices
- Guaranteed Supply Agreements for Key Materials
- Offer Prototype, Laboratory & R&D Capability Solutions
- Provide Technology Support/Solutions to Projects
- Provide IP/Licence Needed to Meet Commercial Goals
- Provide a Rapid Entry to World-Wide Markets

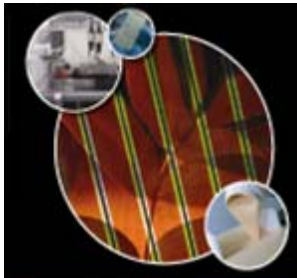
DSC/Dyesol History





DSC Market

- Consumer Electronics – $15B/annum = 10% of Mobile Phones
- BIPV Façade – $40B/annum = 10% of EU Facades
- Steel Roofing – $10B/annum = 15% of EU Roofing
- Rest of the World x 5 = $325B



Dyesol Materials

Dyesol has a suite of materials suitable for R&D and manufacturing DSC

Ruthenium Dyes

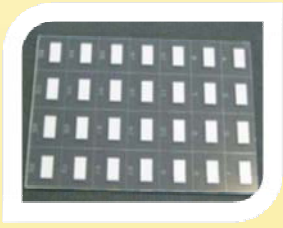
B2 (N719) Dye
B4 (N3)
DNH2 (Z907) Dye
DBL (N749) Black Dye
DBA3 (K77) Dye

TiO2 Paste

DSL 90T
Transparent paste formulated for thin layers (e.g. 3 micron) and Screen printing using a synthetic 90T mesh screen (or similar)

DSL 18NR-T
Transparent paste, formulated for screen printing using a synthetic 43T mesh screen (or similar)

DSL 18NR-AO
Active opaque paste, formulated for screen printing using a Synthetic 43T mesh screen (or similar)



WER2-O
Reflector paste (Opaque) with anatase titanium oxide particles in the range 150nm to 250nm acting as a reflector.

WER4-O
Reflector paste (Opaque) with anatase titanium oxide particles in the range 350nm to 450nm acting as a reflector.

Electrolyte

EL-141 Electrolyte
EL-HPE High Performance Electrolyte
EL-HSE High Stability Electrolyte
EL-HTE High Temperature Electrolyte
EL-ILE Ionic Liquid Electrolyte
MS-PMII Electrolyte Ionic Salt

Platinum Paste

Platinum Paste - PT1
Transparent platinum paste formulated for screen printing using a synthetic 77T mesh screen (or similar).

CELS Counter-Electrode Solution (Low Viscosity)
Transparent platinum paste formulated for application by spin-coating or spraying.

Sealants

Thermoplastic Sealants

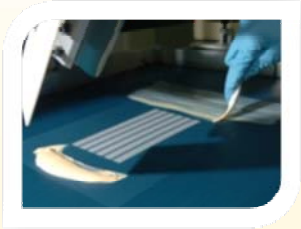
Softening **under** 100ºC	Softening **over** 100ºC
30µm (nominal thickness)	30µm (nominal thickness)
50µm (nominal thickness)	50µm (nominal thickness)

Hermetic Sealing Compound 2 part
Semi-rigid 2 part sealing compound for hermetic sealing of cells. Cure at room temperature to 50ºC

Neutral Assembly Polymer 2 part
Flexible 2 part neutral sealing compound for sealing cells and modules. For short term testing programmes. Curing between 40ºC and 80ºC

Dyesol Equipment

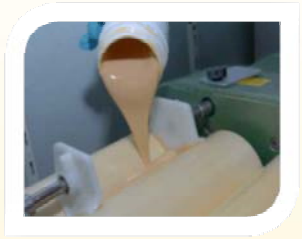
Dyesol has developed a range of equipment suitable for R&D, prototyping and volume manufacturing DSC



- Dye Applicator
- Dye Profiling Machine
- Electrolyte Filling Machine
- Fill Hole Sealer
- Hole Drilling Machine - Automatic
  - Manual
- Interconnect and Seal Applicator
- Laboratory Belt Oven
- Laser Scribing Machine
- Programmable Hotplate
- Screen Printer
- TCAM – Test Cell Assembly Machine
- EIS Instrumentation
- Light Soaking Chamber
- UPTS – Universal Photovoltaic Test System
- UV-VIS-NIR Spectrophotometer

Dyesol Solutions

- Materials Suitable for R&D, Prototyping Manufacture
- Range of Test and Light Soaking Equipment
- Specialist Research Equipment
- Collaborative Development
- Turnkey Laboratories and Prototype Facilities
- Pilot Production and Turnkey Production Solutions
- Training Courses and Consultancy



Thank You

www.dyesol.com