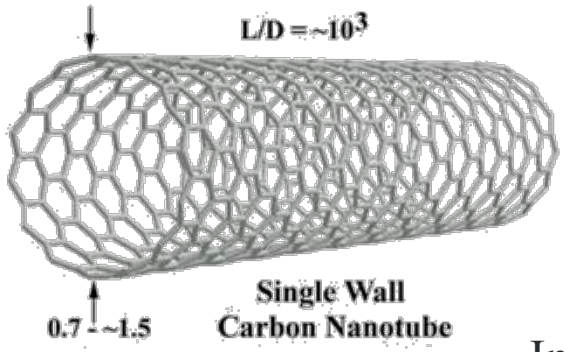
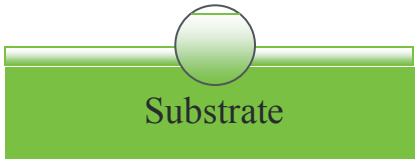


Integrated Invisicon®
Transparent Conductor



Transparent Coatings for Solar Cell Research

Eikos/NREL- PV

Presenter: Paul Glatkowski

Organization: Eikos Inc.

Contact Info: pglatkowski@eikos.com

Date: 5-25-2010

Timeline

Start Date: 6/1/2008
End date: 5/31/2010
(no cost extension pending)
Percent complete: 80%

Barriers

Barriers addressed

- Supply
- Material utilization
- Manufacturing processes
- Efficiency

Budget

Total project funding : $2,460,000

DOE share: $1,818,000(74%)

FFRDC: $150,000(6%-NREL)

Contractor share: $492,000(20%)

Partners

Eikos Inc. is partnered with NREL

- Subcontractor for 6% of funding
- NREL TPOC is Teresa Barnes, PhD

Indium Tin Oxide (ITO) is the dominant TCO for PV applications

Advantages of ITO

- Optoelectronic performance
- Etching
- Chemical inertness
- Heat & humidity stability
- No dangerous/toxic chemicals used in manufacture

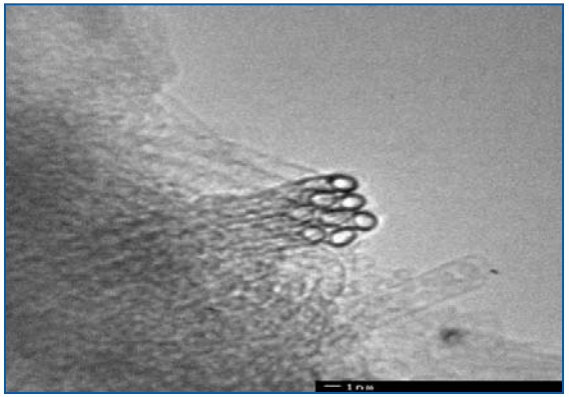
Reasons for Alternative Technologies

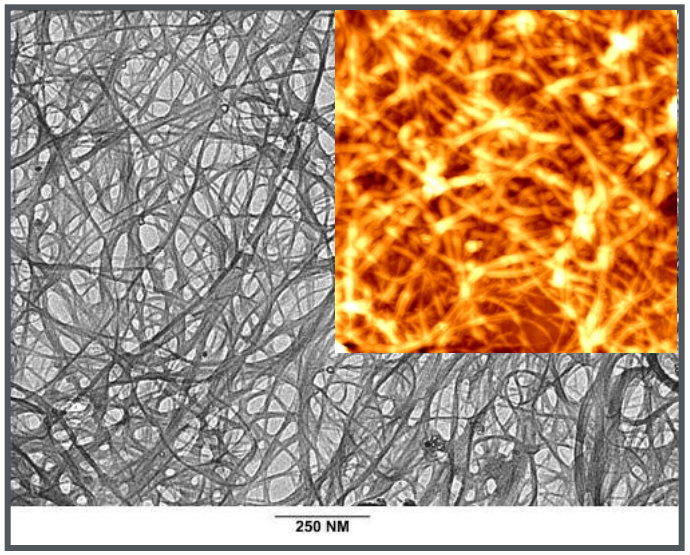
- Cost and availability of Indium
- Expensive vacuum processing
- Batch oriented, subtractive patterning only
- Concerns about future supply constraints, cartels, etc.
- Poor mechanical integrity and CTE mismatch with plastics
- Not the “perfect” TC
- Environmental impact reduction: renewable resource and no mining

INVISICON® Invisible Conductors

Carbon Nanotubes

- 1-2 nm diameter
- >1 μm long (>1000:1 L:D)
- Self assembling networks
- P-type conductivity
- Chemical & heat stability
- Renewable material



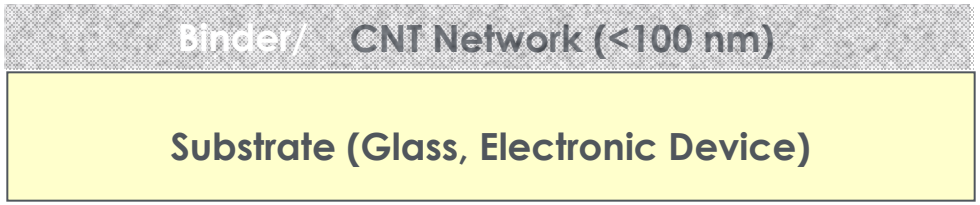


Transparent Carbon Nanotube Films

- Broad Sheet Resistance (Rs) Range
  $0.1 - 10^7\ \Omega/\square$
- Optical transmittance (%T) >90%
- 10 - 100 nm thickness
- Wet processing
- Flexible structure
- Porous network

Two Steps to CNT Composites

Step 2: Infiltrate with Binder



Solution Processed CNT:

MWCNT, DWCNT, SWCNT, SWCNT2…

Application specific selection for:

- Conductivity
- Process conditions
- Smoothness
- Stability
- Cost

Solution Processed Binders:

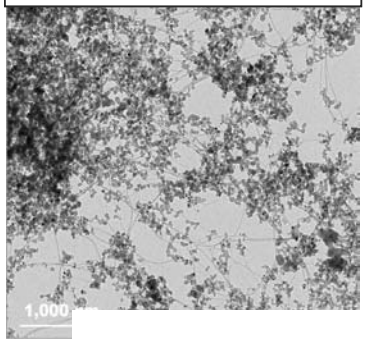
- Organic –Polymers
- Inorganic –Metal Oxides
- Hybrid –Ceramers
- Air –Composite

Multifunctional Performance:

- Electronic tunability
- Optical (i.e. ARC, UV)
- Durability/stability
  - Mechanical
  - Heat & Humidity
  - UV
  - Abrasion
  - Adhesion
  - Bonding

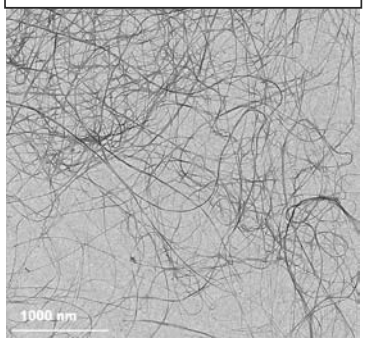
CNT Ink Production Process

CNT (As Produced)



Purification

CNT (Purified)



Dispersion & Formulation

Invisicon™ CNT Ink

Ink formulations customized for specific coating or printing methods.

Coating & Printing

Binder Deposition

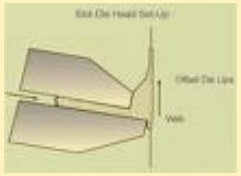
Transparent Electrode

Simple coating with spray, dip, flow, slot die, gravure, ink jet, etc.

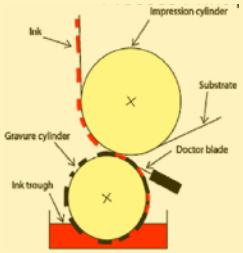
Low Cost Manufacturing

Spray

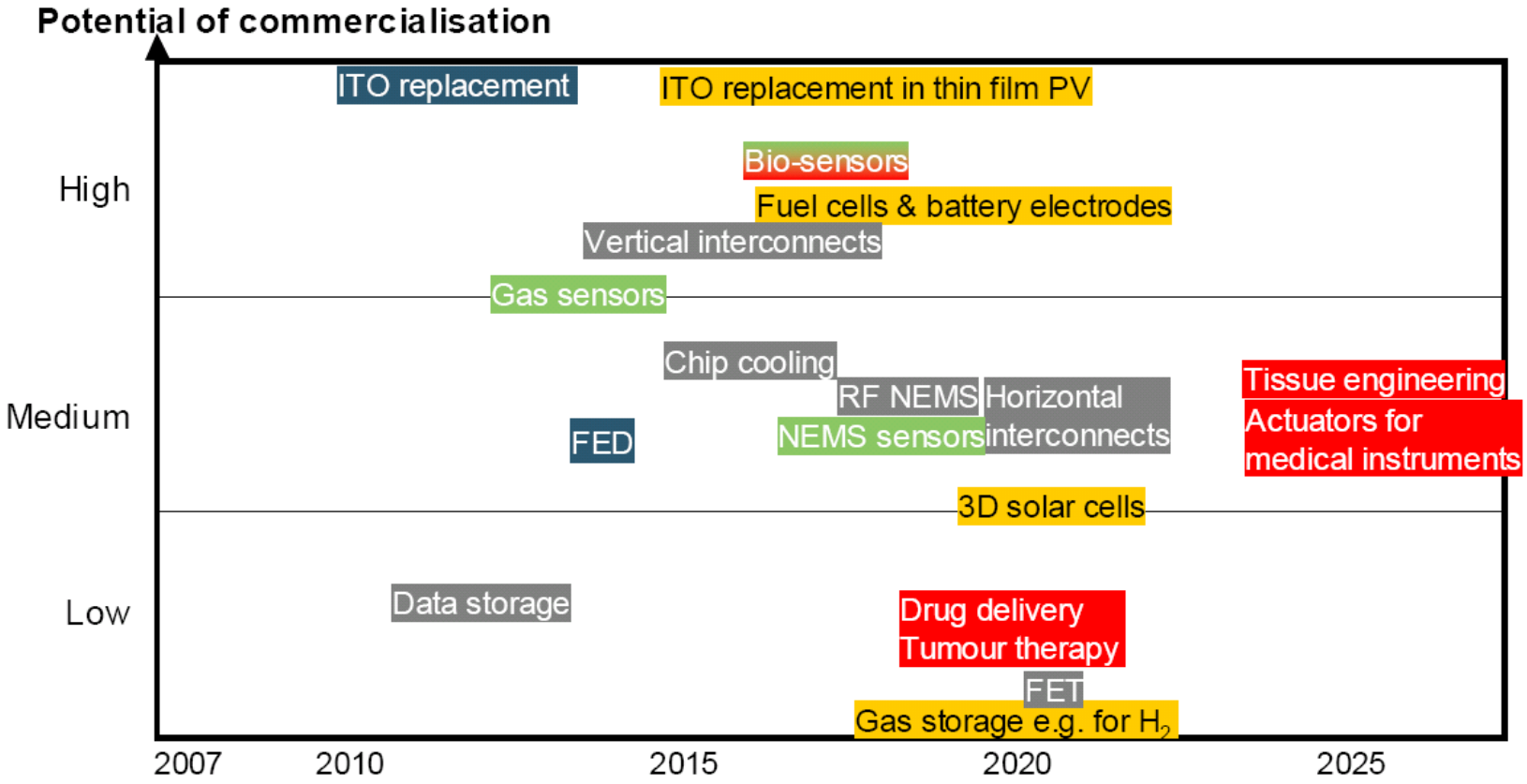
Slot Die



Gravure



Avenue for Material Replacement



Nanotubes's best opportunity for commercialization is to replace ITO

Source: Applied Research Roadmaps for Carbon Nanotubes Opportunities, Requirements, Challenges, EU Public Report, 4/3/08

Program Overview

The objective of this project is to research and develop transparent conductive coatings (TCC's) based on novel nanomaterials, which comprise nanotubes, nanofibers (NF), and other nanostructured materials along with supporting binder materials.

- Generate new structures and chemistries with improved Resistivity and Transparency (RT) performance.
- Show these materials are capable of being deposited using low energy, low temperature processes under atmospheric conditions and at a cost that is competitive with the current state of the art in transparent conductors.
- Pursue basic studies on the coating deposition techniques and the coatings durability to assess these novel nanomaterial TCC's for use in various solar PV applications

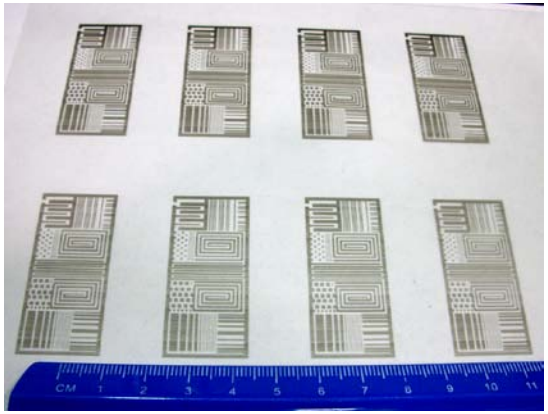
Technical Objectives

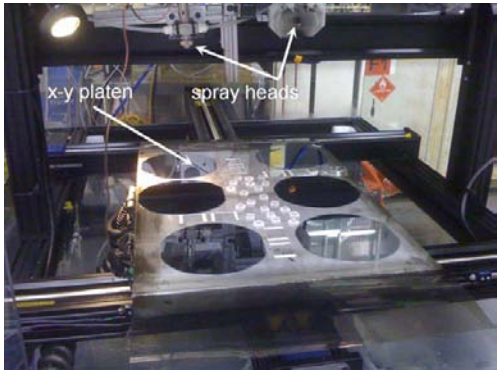
1. Survey of TCCs for Energy Applications
2. Development of Novel Nanomaterials
3. Formulation of Inks and Dispersions from Novel Nanomaterials
4. Coating/Deposition Development
    a. Ink-Substrate Interactions
    b. Development of coating methods, including inkjet, gravure, spray
    c. Coating Characterization;
    d. Post-Processing Treatment
5. Binder Process Development, Formulation, and Characterization
6. Durability Testing
    a. Define Pertinent Techniques and Standards
    b. Durability Testing using Standard Methods

Ink Formulation and Deposition

Eikos is able to formulate stable CNT inks for a variety of deposition techniques.

- Spray Coating
- Dip Coating
- Flow Coating
- Draw Down Casting
- Ink-Jet Printing
- Roll-Roll



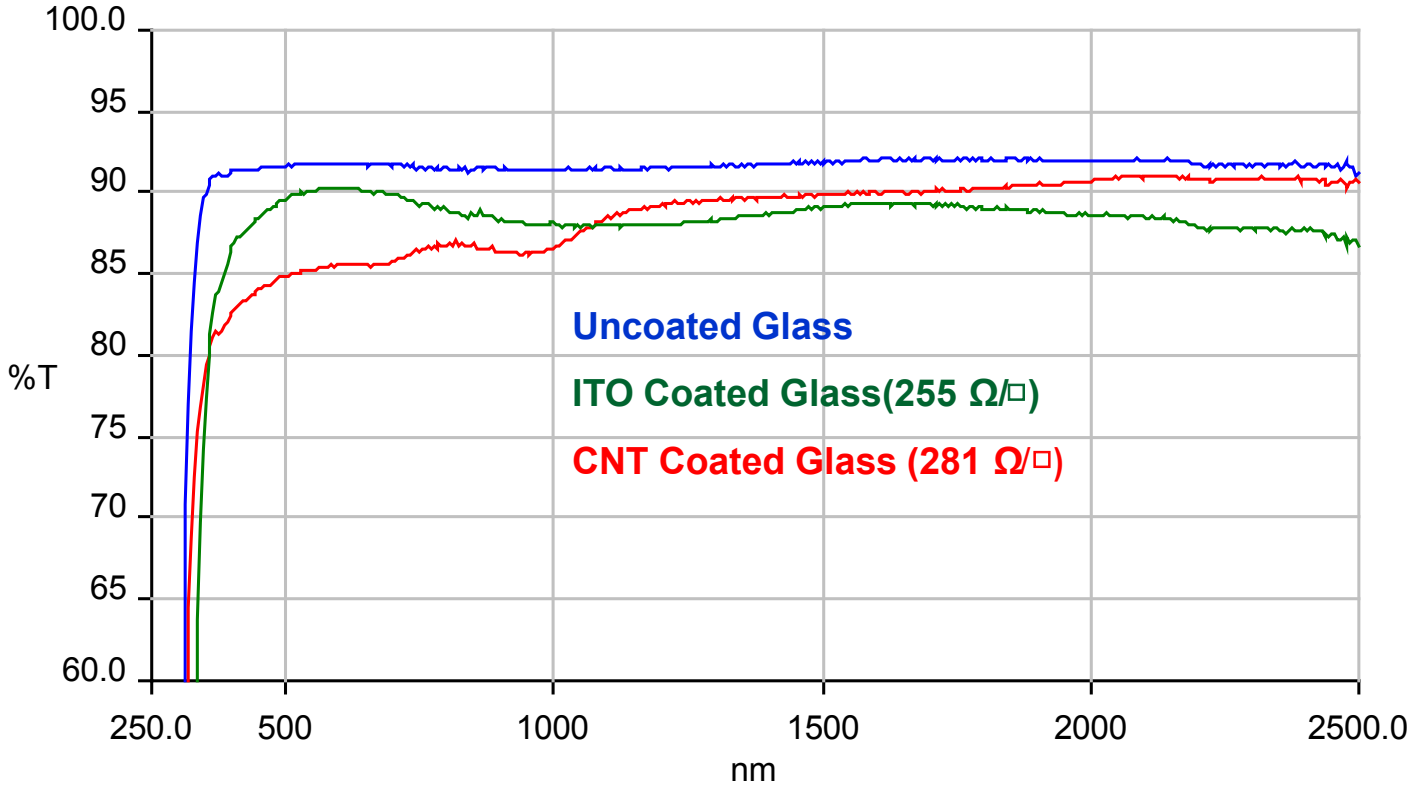


RT Performance

Processing advantages of CNT

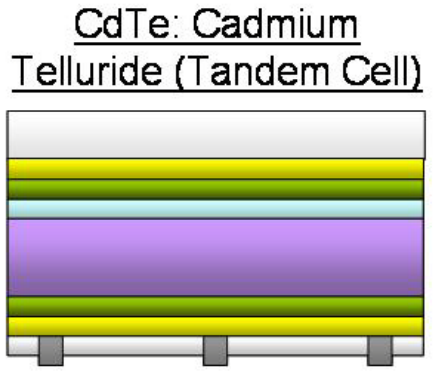
- Low temp deposition
- Transferable and scalable deposition
- Lower equipment costs

CNT have better performance than ITO in UV and RF

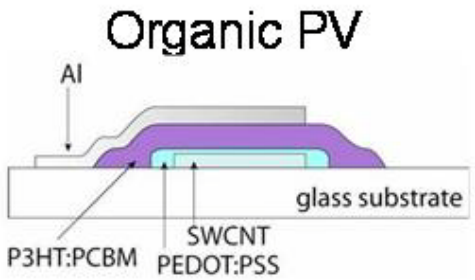


New Material Integration into PV

- Successful trials of Eikos CNT coatings integrated in to CdTe PV device resulting in a cell efficiency of 12%.
- Successful trials of Eikos CNT coatings integrated in to multiple OPV devices resulting in a cell efficiency of 3%.
- Currently developing AR binders to 'level out' roughness from the CNT layer and in so doing replace PEDOT/PSS layer with material that will allow for better cell perfomance.



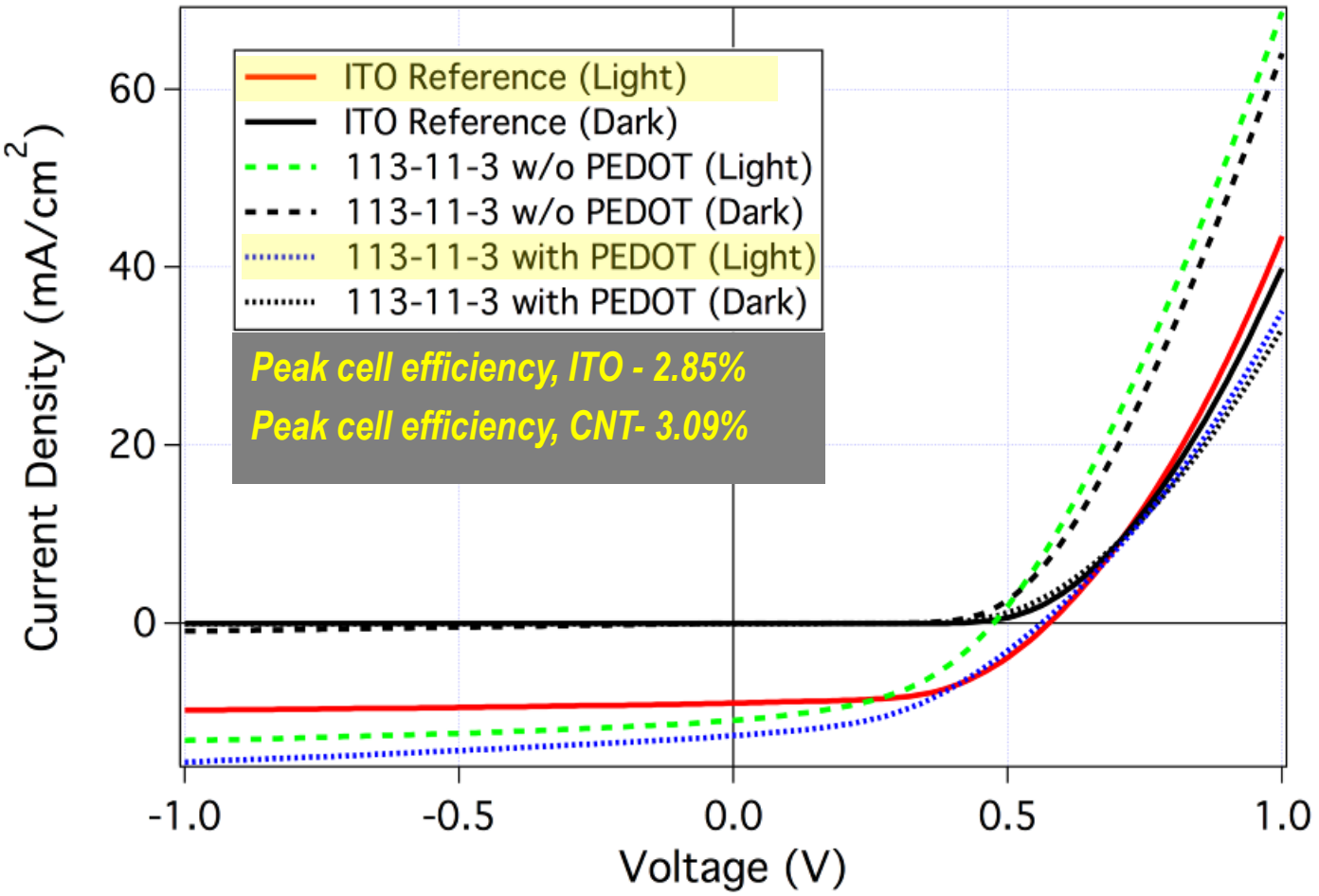
CNT Replaces ITO: 12% Efficient



CNT Replaces ITO: 3% Efficient

New Material Integration into PV, Cont.

OPV cells made with Eikos CNT TCC compared to ITO in a recent study by NREL



Collaborations

For this project Eikos subcontracted work to NREL fulfill some project goals. Based on collaboration with TPOC Teresa Barnes support is provided by NREL in three areas.

1. Characterization of Materials
    1. Compositional
    2. Optical
    3. Electrical
2. Device Development
    1. Incorporation of Invisicon® into thin film Solar Cells
    2. Trouble shooting new cell processing and design
3. CNT Research
    1. Compiling a database of CNT's for use as Transparent Conductors
    2. CNT separation/purification to improve RT performance

Summary

Eikos has made notable progress toward all stated technical objectives of this program.

- Formulated inks for deposition of transparent and conductive CNT coatings.
- Developed multiple coating methods with the ability to deposit complex patterns.
- Integrated CNT/binder TCCs into PV devices using common commercial deposition techniques.

Summary Table/Program Status

Performance Metric (Technical Objectives)	Status in FY09 (% complete)	Result in FY10 (% complete)
Survey of TCCs for Energy Applications	50%	90%
Development of Novel Nanomaterials	20%	85%
Formulation of Inks and Dispersions from Novel Nanomaterials	15%	60%
Coating/Deposition Development	8%	50%
Binder Process Development, Formulation and Characterization	5%	50%
Durability Testing	0%	15%

Future Plans (FY 2011 and beyond)

Work with NREL will be focused on development of CdTe and OPV type cells, with Eikos activity centered on preparing coatings and NREL testing new cell constructions.

- Optimize CNT/Binder coatings by improving formulation, deposition and post deposition processing methods.
- Continue to integrate our binder coatings into thin film organic and polycrystalline PV. Eikos will formulate and apply CNT and binder to a substrate that will then be integrated into OPV, CdTe and other PV cells by NREL.

Eikos will continue to pursue commercial applications where optical transparency and electrical conductivity are required: LCDs, touch screens, energy efficient architectural lighting devices, ‘smart windows’, and for a variety of other emerging commercial applications.