Abstract: New non contact, in-line coating thickness measurement systems have been demonstrated to improve process control, optimize coating quality and reduce the costs of coating thin films and other substrates. Production data was obtained using a SpecMetrix In-line coating and film thickness measurement system on clear UV hardcoats, laminates and pressure sensitive adhesives. The system uses non-radioactive optical packages to measure coated layers for various coated products in film, packaging, solar thin films, currency, coated metals and specialty web applications. The unique capabilities of SpecMetrix systems for both wet and dry coatings have been demonstrated and measured during extensive system trials at Solamatrix. Multiple layers of thickness were also simultaneously measured on moving webs, with detailed results also presented in this paper.

Background: Thin film layers and coatings are applied to various products to achieve important functional and finish characteristics. In many cases, coatings are applied to improve surface properties of the substrate, such as appearance, adhesion, corrosion resistance, wear resistance, and scratch resistance. Traditional web and coating measurements have been generally accomplished through mechanical sample testing methods or through the use of an earlier generation of in-line coat weight measurement methodologies such as total weight gauges. The current mechanical methods for determining the coating thickness on coated products are not only labor intensive and time consuming, but the selected sample sizes used for taking measurements are insufficient to assure quality across the web and for the length of the coated roll or product. Mechanical methods also face additional challenges when measuring multiple layers of coating or clear coatings applied onto clear substrates.

In addition to the rapidly increasing costs of monitoring, maintaining and disposing of radioactive measurement options, beta and x-ray gauges are often not sensitive enough to precisely measure thinner films and coatings (< 20 microns) and requiring expensive load bearing traversing mechanisms. Coat weight determination using beta, gamma, x-ray or other total weight gauges require a differential measurement wherein a base material is measured along with the combined thickness of the base + coated layers. The difference of the results is then used to calculate the coat weight of the coated layer. While generally accurate if proper
calibration is maintained, this approach requires a minimum of two sensors and scanners, thereby increasing the cost of the measurement solution for manufacturers. Measuring web products with multiple layers using nuclear gauging also adds cost and complexity as additional sensor/bridge combinations may be required at each stage where a layer is applied. Beyond nuclear and other administratively burdensome solutions, in-process measurement techniques such as UV and IR absorption gauges rely on various inferential means for measurement, as opposed to measuring the absolute thickness of a film package or a specific film or coating layer.

Optical interferometric based techniques, on the other hand, are well known for precision and have been proven to be reliable, although their use has been generally limited to laboratory or certain stable and repetitive production environments such as semiconductor wafer and chip fabrication. Although there have been limited earlier attempts to bring optical interference based tools to the production floor, the variability inherent in production environments and product substrates have limited the expansion of these non-contact and non-hazardous techniques from moving webs until recently. New SpecMetrix systems exclusively incorporate a proven ruggedized optical interference technology that has been developed to meet production needs by Sensory Analytics using proprietary algorithms, software and advanced optics to accurately and precisely monitor coating thickness as low as 0.5 microns. The systems are in active production and QA use across the metal packaging, coil coating, aerospace, industrial coating and coated film industries.

SpecMetrix In-line systems use modular designs and are flexibly configured to monitor real-time coating and film thickness measurements. The systems can simultaneously monitor multiple layers of coating on or across a web at up to 20 measurements per second. Since the system only relies on change of refractive index between the coated layer and the substrates, there is no need for dual systems to produce single measurement results, and the evaluation of clear coatings or finishes on clear materials are not treated differently than any other coating or film combination.

**Solar Control Films:** Solar control films are typically designed to be applied to broad window surfaces in automobiles, homes and offices and are characterized by multi-layer plastic laminates interspersed with various functional precision coatings. Product designers choose key components in these laminate constructions to provide both aesthetic and functional performance. Color, optical clarity and uniformity, product thickness and precise management of solar radiation (% reflectance, % absorbance and % transmission) are all key commercial attributes of these films.

Thin plastic sheeting ranging from around 12 to 50 microns shapes the backbone to these solar control products. The dominant plastic of choice in the industry is a weather-resistant, optically clear PET commercially available in a wide variety of thicknesses, surface treatments and quality grades to suit the very broad spectrum of customer needs. Specialty additives such as UV absorbers and colorants can be incorporated directly into the plastic sheeting at additional cost.
The release liner protects the pressure sensitive adhesive and will be removed upon film installation. The liner is typically a silicone coated PET or uncoated polypropylene substrate.

A representative product schematic for these types of films is shown in Figure 2 below:

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**Figure 2**: Representative structure of a multi-layered solar control film

The coatings provide far more than basic glue to hold the laminate sheets together. Each coating imparts its own set of performance characteristics to the product and great care needs to be taken to assure consistent, uniform application of these layers during manufacturing. Coating non-uniformities, layer thickness variability or off-aim coating weights can easily result in:

- Degraded layer physical and optical performance
- Unbalanced product solar performance MD and TD
- Off-aim product solar performance
- Coating machine processing problems (fluid application and drying)
- Unintentional product cost increases if target coat weights are exceeded.

The thickest of the three coated layers described in the schematic above, the pressure sensitive adhesive layer, represents the product interface with the glass surface. It must therefore provide a strong bond to the window pane, excellent long-term cohesive strength to hold the mounted film laminate in place, optical clarity once installed and be very light stable. Choice of polymer(s), additives and fluid application method are all critical to achieving these goals.

The laminating layer is called upon to fulfill both the traditional roll of adhesive and, in the case of Solamatrix, deliver colorants which contribute significantly to overall solar performance.
Therefore, apart from requirements common to the pressure sensitive coating layer, the laminating layer must also conform to requirements consistent with the manufacturing of color filters. Tight control of coated layer uniformity is required for product color and density fidelity, especially in darker products.

The top layer and thinnest of the depicted layers is the scratch resistant surface. Exposed to the elements and subject to manual cleaning, this layer needs to be durable, adhere well to the substrate and not generate color upon aging. UV cure coatings typically provide this type of performance in solar control products. Because many of the wide variety of performance requirements demanded of this special layer are coat weight dependent, coating uniformity and adherence to strict coat weight tolerances is paramount. Unlike the two other coated layers, the chemical resistant UV cure layer does not lend itself to traditional off-line layer-removal gravimetric coat weight analysis.

System Demonstration and Test Results: Over two months of system demonstration testing and trials were performed over different coatings on solar control products at the Solamatrix facility located in St. Petersburg, Florida. The film and coating thickness measurement data obtained during on-line and QA Lab trials have been provided within this section. The principal objectives of the trials were to determine the applicability and effectiveness of the SpecMetrix instrument to monitor the coating thickness of thin UV hard coat layers and other film packages that have proven difficult for more traditional measurement technologies currently in use within the film packaging industry.

Instrumentation and Software: The following system configuration was utilized for the presented demonstration and test effort and forms the basis for the significant number of SpecMetrix systems in active production use at global coated product manufacturers.

Instrumentation: The principle hardware components used within the SpecMetrix instrument are custom light Sources, spectrometers and optical packages. The light sources used are stabilized Halogen light sources that are selected for use over a broad range of wavelengths (400 nm to 2400 nm). The advanced optical package used in the proprietary SpecMetrix design enable extremely rapid capture of reflectance data within short time intervals; thereby enabling the system to take up to 20 measurements per second. Multiple fixed points on the web can be inspected and measured for coating thickness simultaneously and continuously through the use of multi- channel SpecMetrix systems. Alternate single frame scanning bridge configurations can be used to enable a single lightweight SpecMetrix probe to quickly and accurately scan the moving web and provide a manufacturer with real-time coating and film measurement data.

Software: The system software and user interface options have been designed for maximum flexibility, ease of use and for minimal actions required for an operator. The software includes a customer database of coating recipes that are periodically updated with new coatings as the need arises. The system operator simply selects the coating or film package from the drop down list
and presses the Start button. The system then continuously display thickness readouts along with a moving average trend that visually indicates the applied coating thickness and continuously monitors whether it falls within the desired quality control limits. Thickness readings are color coded to differentiate measured thicknesses in or out of specification and other identified production tolerances. Below is a sample screenshot showing the display of the measurements from a coated web.

![Sample Screenshot](image)

**Figure 1: SpecMetrix In-line dual-channel software screen configuration**

All thickness measurements herein were recorded by the system on-line immediately after the coating is applied and also after the coating was cured. Excellent correlation was obtained between wet and the dry coating thicknesses based on the specific gravity and the solids information of the applied coatings. The ability of the system to monitor wet coating thickness enables production personnel to adjust the coating application earlier in the coating process and to accurately determine dry coating thickness from the measured wet coating thickness. The various testing efforts and results from the SpecMetrix system trials at Solamatrix follow below:

**UV Hardcoat:** The UV hard coat layers were selected for initial evaluation because they are particularly thin and have tight adherence to substrates, thereby making them difficult to separate for weigh strip weigh measurements. Even though UV hardcoat layers are challenging for many other tools, the optical properties of UV coatings are favorable for SpecMetrix systems. Precise thickness measurements were recorded for wet coating directly after it was applied and measurements were then obtained after the coating is cured. The thicknesses reported in Table 1 represent an average value of coating thickness recorded by SpecMetrix over a period of time. A
strong correlation was noted between the wet and the dry coating measurements, with the correlation factor being proportional to the specific gravity and solids percentage in the wet coating solution.

<table>
<thead>
<tr>
<th>Meas #</th>
<th>Wet Thickness</th>
<th>Dry Thickness</th>
<th>Correlation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wet(µ)</td>
<td>dry(µ)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18.20</td>
<td>3.75</td>
<td>4.85</td>
</tr>
<tr>
<td>2</td>
<td>21.66</td>
<td>4.45</td>
<td>4.87</td>
</tr>
<tr>
<td>3</td>
<td>22.20</td>
<td>4.52</td>
<td>4.91</td>
</tr>
</tbody>
</table>

Table 1: Wet and dry UV coating measurement results using SpecMetrix In-line systems

**Multiple Layer Measurements:** Simultaneous thickness measurements on more than one layer were also observed to be accurately taken using the SpecMetrix system. On multi-layered structures, reflected rays of light are generated from each boundary surface and the resultant interference spectrum yields multiple frequency modulations that are used to determine the thicknesses of various layers. A coated product with a generic structure shown in Figure 2 was measured with the results provided in Table 2 below. Measurements were taken using the SpecMetrix In-line system for the scratch resistant coating, dyed laminate adhesive and the pressure sensitive adhesive.

<table>
<thead>
<tr>
<th>Meas#</th>
<th>DL Adhesive thickness(µ)</th>
<th>Scratch Resistant thickness(µ)</th>
<th>PS adhesive thickness(µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.17</td>
<td>1.6</td>
<td>6.88</td>
</tr>
<tr>
<td>2</td>
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</tr>
<tr>
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<td>3.26</td>
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<td>6.89</td>
</tr>
<tr>
<td>5</td>
<td>3.27</td>
<td>1.61</td>
<td>6.87</td>
</tr>
</tbody>
</table>

Table 2: Measurement results on three layers of coating on final film package

Below in Figure 3 is a snapshot of the SpecMetrix software showing the multiple thickness peaks on the multi layered sample measured above. The demonstrated ability of the system to measure multiple layers simultaneously and individually is significantly more helpful than most alternate methodologies in improving the quality and process control as it gives far more information than
the total thickness of the combined film package, which may mask underlying problems with a particular layer within the film stack.

Figure 3: Thickness peaks for multiple layers and sum combinations of various layers

**Day-to-Day Measurement Stability:** Thickness measurements were taken on a multi-layer product over a period of several days in order to verify the measurement stability of the system. Table 3 below shows the results of measurements of three different layers over a period of five days. The measurements taken over 5 days on the various layers turned out to be very consistent. The spot size or area of measurement of the instrument is between 1 to 2 millimeters, so even though the measurements were taken on the same sample each day, it is very unlikely that the same exact measurement spot was measured each day. Therefore, the coating thickness variability within the sample is the most likely contributing factor in the slight amount of variation observed in the measurements from different days.

<table>
<thead>
<tr>
<th>Product</th>
<th>Days</th>
<th>Layer1</th>
<th>Layer2</th>
<th>Layer3</th>
</tr>
</thead>
<tbody>
<tr>
<td>302398</td>
<td>Day1</td>
<td>1.630</td>
<td>3.250</td>
<td>6.750</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>1.610</td>
<td>3.310</td>
<td>6.750</td>
</tr>
<tr>
<td></td>
<td>Day3</td>
<td>1.630</td>
<td>3.220</td>
<td>6.770</td>
</tr>
<tr>
<td></td>
<td>Day4</td>
<td>1.650</td>
<td>3.180</td>
<td>6.800</td>
</tr>
<tr>
<td></td>
<td>Day5</td>
<td>1.630</td>
<td>3.270</td>
<td>6.880</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Standard Deviation</strong></td>
<td>0.014</td>
<td>0.049</td>
</tr>
<tr>
<td>302386</td>
<td>Day1</td>
<td>1.590</td>
<td>3.240</td>
<td>6.850</td>
</tr>
<tr>
<td></td>
<td>Day2</td>
<td>1.570</td>
<td>3.250</td>
<td>6.800</td>
</tr>
<tr>
<td></td>
<td>Day3</td>
<td>1.560</td>
<td>3.240</td>
<td>6.840</td>
</tr>
<tr>
<td></td>
<td>Day4</td>
<td>1.610</td>
<td>3.280</td>
<td>6.800</td>
</tr>
<tr>
<td></td>
<td>Day5</td>
<td>1.630</td>
<td>3.270</td>
<td>6.880</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Standard Deviation</strong></td>
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<td>0.016</td>
</tr>
<tr>
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<td></td>
<td>Day2</td>
<td>1.470</td>
<td>3.360</td>
<td>6.220</td>
</tr>
<tr>
<td></td>
<td>Day3</td>
<td>1.530</td>
<td>3.230</td>
<td>6.310</td>
</tr>
<tr>
<td></td>
<td>Day4</td>
<td>1.550</td>
<td>3.300</td>
<td>6.200</td>
</tr>
<tr>
<td></td>
<td>Day5</td>
<td>1.590</td>
<td>3.280</td>
<td>6.160</td>
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<td></td>
<td><strong>Standard Deviation</strong></td>
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<td>302558-2B</td>
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<td>3.200</td>
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<td>Day2</td>
<td>1.540</td>
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<tr>
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<td>Day3</td>
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<td>3.210</td>
<td>6.160</td>
</tr>
<tr>
<td></td>
<td>Day4</td>
<td>1.500</td>
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<td>6.000</td>
</tr>
<tr>
<td></td>
<td>Day5</td>
<td>1.510</td>
<td>3.220</td>
<td>6.170</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Standard Deviation</strong></td>
<td>0.024</td>
<td>0.051</td>
</tr>
</tbody>
</table>

Table 3: Day to Day Measurement Variations
**Pump flow rate versus film thickness measurement:** In order to determine whether the SpecMetrix system can detect differences in coating thickness real time when slight amounts of adjustments are made to the Pump flow rate on a slot die system, pump flow rates were marginally increased and decreased with the average thickness measurement results recorded over a period of 2 minutes at each flow rate. The data obtained at the different values of pump flow rate correlated linearly with the resultant thickness data measurements, as shown in Figure 4 below. These results indicate that a highly advanced and desired feedback control loop could be established between the SpecMetrix measurement system and the slot die pump flow system.

<table>
<thead>
<tr>
<th>Meas #</th>
<th>Pump Flow (flow rate)</th>
<th>Thickness (µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48.60</td>
<td>2.08</td>
</tr>
<tr>
<td>2</td>
<td>51.30</td>
<td>2.13</td>
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<tr>
<td>3</td>
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<td>2.26</td>
</tr>
<tr>
<td>4</td>
<td>56.70</td>
<td>2.39</td>
</tr>
<tr>
<td>5</td>
<td>59.40</td>
<td>2.52</td>
</tr>
</tbody>
</table>

Table 4: Pump flow rate versus thickness measurements

A positive displacement gear pump from Zenith with a gear ratio of 11 to 1 was used for this test effort. The thickness increased linearly with the changes in the pump flow and the slight amount of deviation from the linearity is probably due to relatively modest two minute interval over which the thickness was recorded. If the interval were increased to a longer period at a given pump flow rate, then more linearity would be expected to be observed in the graph.

A pump flow rate of 59.4 was used at three different times during the study to verify the repeatability of the measurements at a given pump rate. Table 5 below summarizes the results of those tests. The thickness measurements recorded by the SpecMetrix system were shown to be almost identical at a given pump speed. The extremely small amount of difference in coating thickness (maximum difference of 0.05 microns) can be easily attributed to variations in coating thickness.
### Table 5: Measurement repeatability at a given pump rate

<table>
<thead>
<tr>
<th>Meas #</th>
<th>Pump Flow (flow rate)</th>
<th>Thickness (µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59.40</td>
<td>2.52</td>
</tr>
<tr>
<td>2</td>
<td>59.40</td>
<td>2.47</td>
</tr>
<tr>
<td>3</td>
<td>59.40</td>
<td>2.50</td>
</tr>
</tbody>
</table>

**Thickness results on coated metalized film:** A coated metalized film having a higher coat weight in the middle section of the film was tested with SpecMetrix as it was observed by the Solamatrix team that the beta gauge used for this thin coat weight sample produced a noisy cross web profile analysis that did not indicate to the operators a significant coating profile. The same sample was then measured using the SpecMetrix system for comparison purposes. The SpecMetrix system was uniquely able to clearly distinguish the subtle coating differences between the different sections of the film as shown by the thickness profile in Figure 4.

![Thickness profile of the coating on a metalized film](image)

**Figure 4: Thickness profile of the coating on a metalized film**

**Cross Section data compared to SpecMetrix results:** In order to validate the thickness measurements generated by the SpecMetrix system on UV hard coat layer, cross sections of the samples were performed with a digital microscope and compared with actual thickness results obtained. Samples were generated with different levels of coating thickness to assess the linearity of the SpecMetrix measurement system. The area of interest of the SpecMetrix system probes are between 1 to 2mm while the area of interest under a microscope is approximately 500 microns (0.5mm). Additionally, the SpecMetrix system has a resolution of .001 microns whereas the microscope has a resolution of approximately 0.5 microns. As a result, the measurement comparison is not straight forward. Both these factors contributed to the differences seen between the microscope data and the SpecMetrix system measurements in Figure 5 below:
Conclusion: The critical importance of continuous process improvement and cost-reduction efforts and the growing need to move to greener production processes are impacting manufacturers and converters and creating the need for new tools to facilitate those valuable efforts. Inefficient coat weight measurement methodologies that involve time-consuming checks at the beginning and the end of rolls do not guarantee the coating application throughout the entire coating run. There are even greater measurement challenges involved if the manufactured product package includes thin coated layers or clear layers. Total weight solutions require major capital equipment expenditures that strain capital equipment budgets and create challenging ROI justification efforts.

The presented in-line coating and film thickness measurement solution is a proven and cost-effective new means to generate real-time coating process data in a non-contact, non-destructive and non-radioactive manner on a wide variety of substrates. Data obtained during the test and demonstration trials using the SpecMetrix In-line system at the Solamatrix facility confirmed that manufacturers and converters of coated film, foil and extruded products now have an enhanced capability to monitor and precisely control their coating application processes to better assure their end product quality. More precise coating thickness measurements can be accurately taken on wet and dry coatings, to include the simultaneous thickness measurement of multiple film or coating layers. The new capability to measure coatings on individual film package layers, to include UV and adhesives, will provide product manufacturers with added process control and an important new tool to help verify product quality, avoid customer claims and to reduce production costs.