2002

Implementation of a modern colorimetry system into an optical thin film coating facility

Jason Barrett

SIMG-503

Senior Research

Implementation of a Modern Colorimetry System into an Optical Thin Film Coating Facility

Final Report

Jason Barrett

Center for Imaging Science

Rochester Institute of Technology

August 2002

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Jason Kajon Barrett

Abstract

Thin films are typically designed to transmit or reflect light based upon spectral performance. The films can be designed with very specific wavelength targets. For Applied Coatings' customers, the wavelengths in question are typically in or around the visible range. Accurate measurements are required for customer satisfaction.

An in-process quality check utilizing a scanning monochromator system has been used successfully for several years. The ability to receive support into the new millennium on the generic system that has been in place has driven a new project. The project, called the Scanning Monochromator Measurement System (SaMMS), is key to Applied Coatings, Inc. continued ability to produce both high quality and volume for the many diverse customers' products.

The SaMMS system was originally designed to offer a Graphical User Interface (GUI) interaction between user and machine where there was previously a menu driven text format. The author of the original code was no longer in Applied Coatings, Inc. employ, the hardware that it ran on was no longer going to be supported by the original vendor, and spare parts were not readily available. A completely new measurement system was needed. I have been involved in development, integration, and installation of the SaMMS software; testing and calibration of the photodiode array spectrophotometers purchased; design, alignment, and testing of the light collection stations; and training, documentation, and justification at all levels for the end user.

This report is accepted in partial fulfillment of the requirements of the course SIMG-503 Senior Research.

Title: Implementation of a Modern Colorimetry System into an Optical Thin Film Coating Facility.
Author: Jason K Barrett
Project Advisor: Dr. Joseph Hornak
SIMG 503 Instructor: Dr. Joseph Hornak

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Acknowledgement

The author would like to acknowledge the family and friends that had demonstrated faith and support throughout this undergraduate experience. Especially in loving memory of John Barrett, who demonstrated what strength and the will to survive truly are.

The author would like to acknowledge the patience and assistance of Dr. Joseph Hornak, Susan Chan, Dr. Anthony Vodacek, Dr. John Arney, Dr. Jeff Pelz, and the Center for Imaging Science as a whole. You have all made the journey of one small-town, young man through your halls that much more valuable an experience.

Lastly, the author would like to acknowledge the guidance and assistance of Eric Alden and Brady Hackleman, the former author's manager that gave him the opportunity to work on this project and the previous author of the program who documented it so well that the author could make the necessary changes, respectively.

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Introduction

The definition of *thin film* is somewhat vague and often refers more to the process used to apply the film, rather than the actual film thickness. The purpose of the thin film application is also often used to describe it. There are porous and protective, conductive and insulating, *hydrophobic and hydrophilic*, and optical films, to name a few. This paper addresses the measurement of an optical thin film, as the others tend to only need spectral analysis to determine their composition, not desired spectral properties. The thin film can be comprised from a simple single layer of coating material up to 60 or more alternating layers of varying materials, called a "stack", even though the stack is too small to see. In 1995 [1], the Thin Films division at Bausch and Lomb (Rochester, NY) was reported to make films that are 60 to 80 nm thick. Optical thin films are widely used in industry for protection from corrosion and heat as well as color correcting and *bandpass* applications. They can be made to reflect some forms of light and other radiant energy while absorbing others.

Thin film technology has been utilized for some time (dating back to the 1800's) [3,5,6,8], but the industry is gaining footholds as new applications are constantly being developed. In 1953, Bausch and Lomb scientists received an Oscar for coating lamps in movie projectors to prevent the movie-film from absorbing heat, so that the light couldn't melt it. Previous to this, aluminized reflectors would reflect all the energy that the bulb would produce equally, including the massive amounts of infrared produced by quartz halogen lamps. The *dichroic* film technology allowed for specific wavelengths of light to be targeted for reflection, even more efficiently than the aluminized reflectors. The Thin Films division of Bausch and Lomb expanded to various applications including opthalmic lenses, medical reflectors, military hardware, and other lighting components.

The division utilized several different methodologies to apply their coatings that are still industry standards today. Among them, *sputtering*, in which tiny drops or particles of coating are sprayed onto a surface from kinetic collisions within plasma, and vapor deposition, in which the coating condenses on the surface like fog on a window after being melted by copious amounts of heat, still are conducted at the Paul Road facility. The primary (determined by sheer volume) method utilized, however, would be referred to as thermal *evaporation* (physical vapor deposition).

The division has since become the acquisition of Applied Image (Rochester, NY) in the late nineties. Applied Coatings (Rochester, NY) produces films according to various customer requirements. The customer specifications are typically based on the spectral characteristics of the film in transmission or reflection, depending upon the final product's application. There are also integrated color measurements and radiometric requirements for some coatings. The units discussed in this paper are not utilized for radiometric measurements, but are capable of the transmission, reflection, and color-measurement capabilities required of them with 1 nm resolution for their designed range. Getting them up and running was my task.

As for basic organization of the text, a few noteworthy methods are being employed. Italicized words can be found in the Definition of Terms at the end of this paper. A numeric reference style is being adopted due to the variety of reference types. A standard scientific method organization of Background, Theory, Methods, Results, Discussion, and Conclusion is employed as well. The background section gives the reader an understanding to the relevance of the project as a whole. The theory section gives an overview of the principles involved in the project. The methods section explains a few of the testing procedures involved in determining the effectiveness of the new system. The results section is an interpretation of the testing. The conclusion summarizes the project's relevance based upon the testing that occurred.

Background

Applied Coatings, Inc. is a world leader in the application of thin film vacuum coatings on various substrates with customer design specifications followed for spectral and/or overall color performance. A quality check is done after each run to ensure the optical film is within the customer's expected performance characteristics and that the process is running as expected. Statistical Process Control is used to diagnose problems that may have occurred during a run that need to be corrected before the beginning of the following one.

Customer specifications are typically wavelength-specific, percent transmission and/or reflection value near or within the visible range. Reflectors are often designed to produce an output color within a given *color box* defined by a given set of X-Y chromaticity coordinates for an ideal source of a given color temperature tolerance. [13]

An industry-accepted standard for determining the optical characteristics of a given batch for thin films involves placing flat *witness pieces* within the chamber that can be easily measured after the run with traditional means to acquire spectral results. This method, however, may not represent the angular effects of a non-flat substrate satisfactorily. The optical design of a given component may not be ideal for uniform film deposition and this must be accounted for.

Measurement setups that could measure a component that would simulate its use in a final application were necessary. Fixtures were developed for a given product to place it in an optical setup that would capture a final application result. Originally, custom code was written in *Rocky Mountain BASIC* (TransEra Corporation, Orem, Utah) to acquire data from scanning monochromators produced by Optometrics (Ayers, MA) to take these measurements. The program that was developed was written in a time when there was a primary market for the technology with specific requirements. The flexibility of the code was limited and it was not well documented. The user interface was text based and menu driven. Proposals were being drafted to created a *graphical user interface* (GUI) based upon the menu commands and equipment that already existed. The interface system that was proposed was dubbed the Scanning Monochromator Measurement System (SaMMS).

There were other reasons for these proposals, the equipment that was being utilized previous to SaMMS was becoming difficult to maintain and support was no longer available from either a hardware or software perspective. Optometrics would not support instruments that were as old as these were, for instance.

The SaMMS code was developed in C using LabWindows CVI (National Instruments, Austin, TX) to produce a GUI Human-Machine Interface for improved ease of use. Since the purchase of the LabWindows CVI development environment, National Instruments (Austin, TX) has undergone some restructuring and LabWindows is now considered a component of Measurement Studio (National Instruments, Austin, TX). The Ocean Optics (Dunedin, FL) model SD2000 (Ocean Optics, Dunedin, FL) spectrophotometer with its photodiode array was chosen as the replacement for the Optometrics scanning monochromator.

The scope of this project has included becoming the primary software developer, calibrating the acquired units, training and documentation for the system's use, testing of various methods of light collection before complete system implementation into the production environment, and collecting feedback from engineering and production to implement improved system performance.

Theory

Much the way that a prism breaks up a beam of white light into its component colors, a *diffraction grating* can be produced to achieve the same effect. The range of wavelengths that the grating will pass efficiently and at what angle they reflect or transmit is greatly determined by the design of the grating and how it is fabricated. Various methods of grating creation may lead to an optimal selection for the desired response. [10,11,12]

Ocean Optics produces gratings with varying efficiency curves. The predictable change in path of these can be utilized in an optical setup designed to capture a unique wavelength. Different spectrometers utilize different methods of energy capture, but this is the premise that they all utilize.

One common method is referred to as scanning. It requires limiting the light that is detected by use of slits. It is where either the light dispersion element (whether prism or grating) or a detector is rotated about a known position to cause a single wavelength to pass between the two at a calculated time. By knowing the design of the dispersion element, the distances in the optical system, and a rotation speed or position, the spectral component being measured at a given point can be easily determined. The resultant signal is typically translated to wavelength over time for the known scan motion.

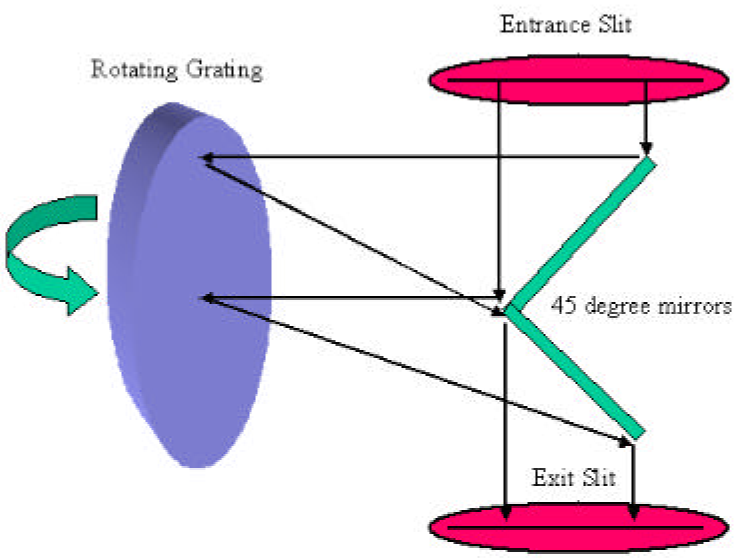


Figure 1 - Scanning monochromator optical setup.

Another method utilizes a fixed photodiode array, or other multi-element detector. Typically it involves all fixed distances and positions for all the elements and utilizes the predictable path change in light to place individual pixels in position to collect particular wavelengths of light. (The Ocean Optics website provides an excellent animation demonstration of how light is collected with the SaMMS system.) The light is again limited with slits or apertures to isolate a single beam to the grating. The beam is separated into the multiple wavelength components that fall upon unique detector elements. The resultant signal is typically translated to wavelength over pixel number, or position, for the known optical path.

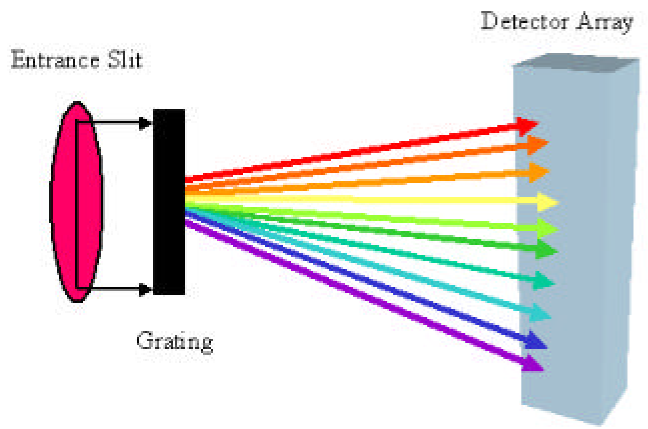


Figure 2 - Simplified diode array optical setup.

Each method has its advantages and disadvantages. When dealing with the various aspects of spectrometry, there are tradeoffs when designating the appropriate design. Desired range, resolution, speed of scan, accuracy, repeatability, signal to noise ratio, are all effected by one's detector and grating choice, collection optics used, data acquisition methodology, light source, processing parameters, cost, and support.

For the SaMMS system, two channels are used to achieve the desired optical resolution and bandwidth to perform the product specific measurements not possible with a single channel. The grating/entrance-slit combinations chosen for the system provide one nanometer spectral resolution rather than the "step dependent" resolution associated with scanning units. Different grating/slit combinations will offer resolution values that are different as well. Each channel can take acquire 2048 measurements simultaneously, reducing scan time. Up to 8 channels are simultaneously acquired with a data acquisition card to increase resolution to a specific bandwidth of the spectrum. A reference scan is taken with an uncoated substrate for transmission or aluminized part for reflection to determine the coating’s response. It is assumed that all deviation from this "ideal" part can be attributed to the thin film coating and all sample measurement values are divided by the reference for a transmittance or reflectance value. A baseline measurement is taken to subtract out any dark current noise or ambient light that may leak in from the surround.

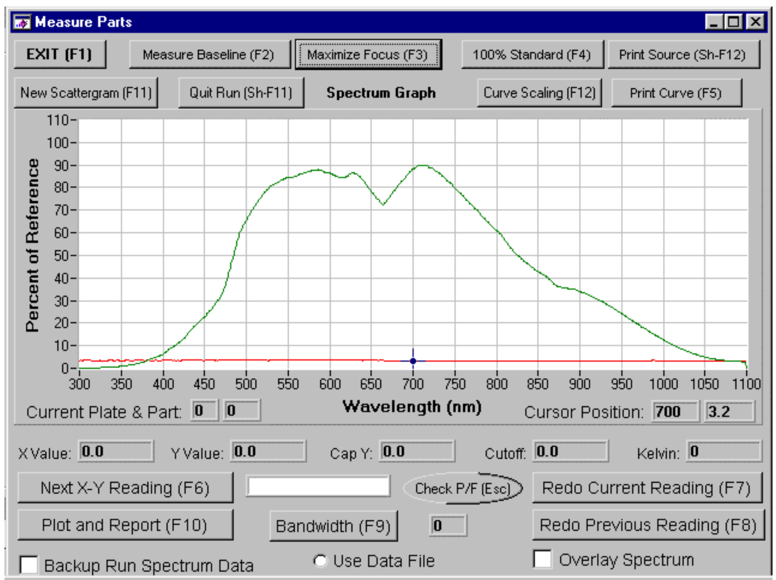


Figure 3 - SaMMS system Measurement Screen illustrating the reference and baseline scans.

Third party software and instrumentation is fully capable of attaining this sort of measurement. As a matter of fact, the vendor we acquired the instrumentation from has this sort of capability with a variety of software packages they can provide. The strength, and necessity, of the SaMMS system comes when the spectral measurement undergoes processing to determine if a given set of test criteria has been satisfied. Test criteria may include the following for a given scan: Maximum, Minimum, 50% Cutoff, or Average Percent of Reference values.

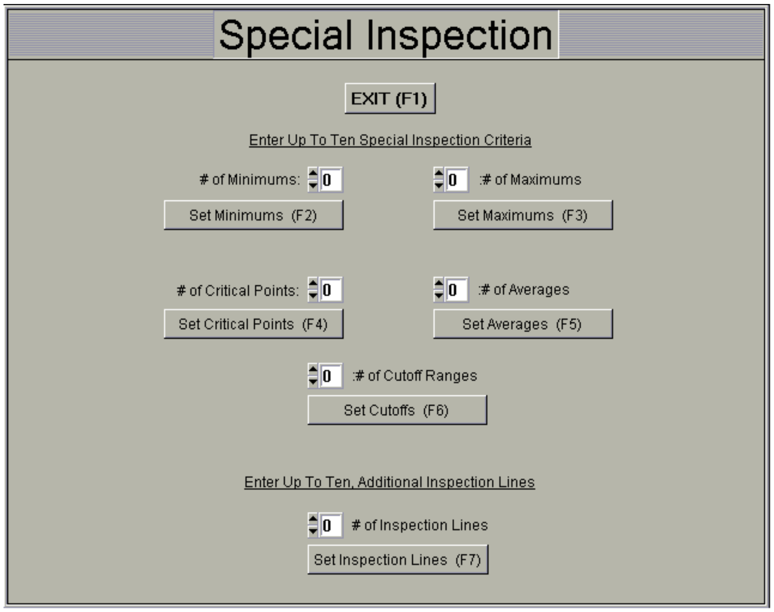


Figure 4 - SaMMS system Special Inspection screen.

The specification criteria may be stored within individual product files without the user having to worry about reconfiguring the instrument. All the user has to know is which product file they are utilizing for a given part, how to fixture the particular optical element, and how to run the software. The pass/fail judgement is determined by the software's interpretation of the spectral curve, not an observer's objective gaze.

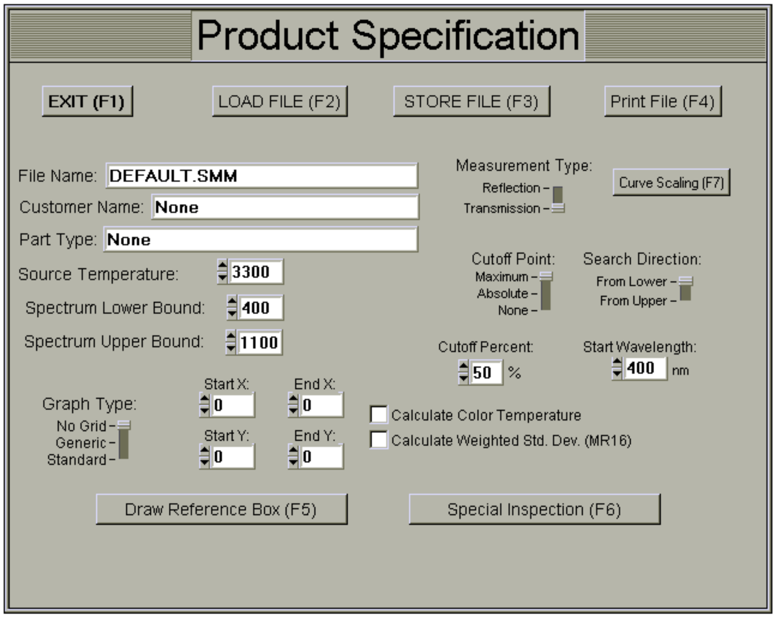


Figure 5 - SaMMS system Product Specification screen.

Color calculations are based upon a given blackbody color temperature. A "Color Box", chromaticity coordinate limits, can be set to determine if the light output measured integrates into a desired color, based on CIE 1931 Color Space. The color box defines the range of acceptable limits that the customer would consider for a particular color (whether it is red, green, amber, blue, or even white) much more accurately than a subjective observer would.

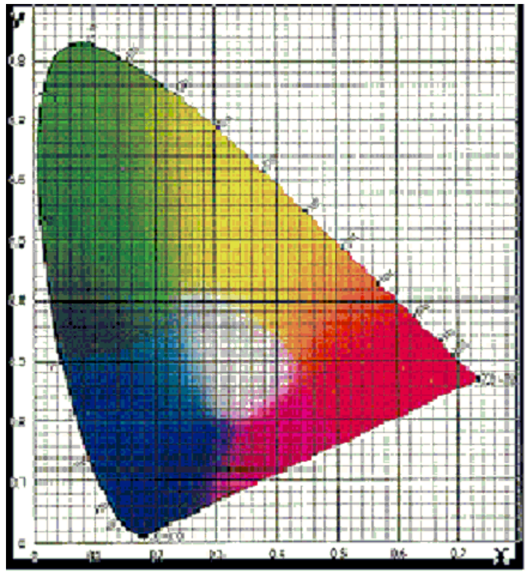


Figure 6 - CIE 1931 chromaticity diagram

Methods

Testing of the SaMMS system included comparison tests between Ocean Optics diode array spectrophotometer and the Optometrics scanning monochromator, two different Perkin Elmer (Perkin Elmer Analytical Instruments, Shelton, CT) dual beam spectrophotometers, a LMT (LMT Lichtmesstechnik, Berlin, Germany) colorimeter, NIST traceable standards, and trained human inspectors with visual inspection techniques.

Repeatability and reliability (R&R) experiments were used as well as design of experiments (DOE) to determine optical performance previous to the purchase of the necessary units for plant-wide implementation.

Figure 7 shows how the didymium filter produced aggressive absorption peaks that allowed for checking tolerances for calibration as a secondary standard against a dual beam instrument. The green curve was taken with a SaMMS system to compare with the same filter measured with the dual beam instrument after the former was found to fail the didymium filter "product specification file". The failure was from falling out of a theoretical "color box" specification which has proven more rigorous a test than most spectral limits. Fortunately, the poor UV signal detected while using a tungsten-halogen bulb does not contribute much to this part of the specification. The spectrometer was found to be out of calibration in the slave one channel, which corresponded to approximately 650 nm and above. It can be seen where the green curve pulls ahead of the blue one in this range.

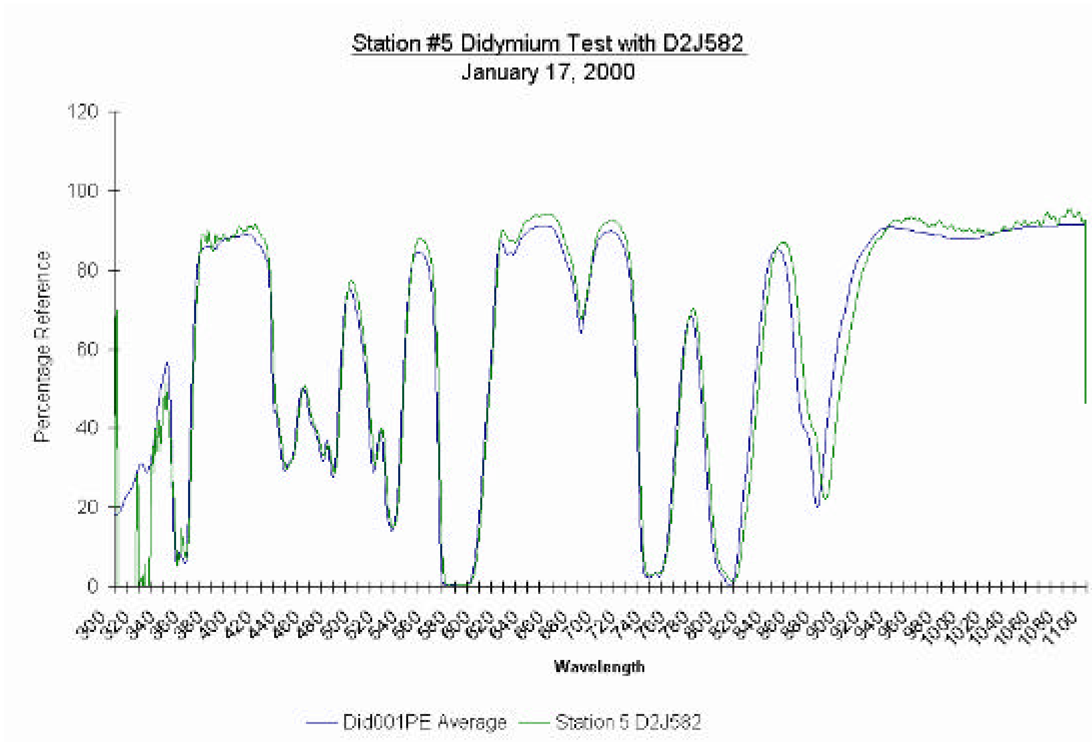


Figure 7 - Spectral accuracy testing demonstration.

Figure 8 shows the result of a didymium filter comparison between two transmission stations with the dual beam instrument results. The shift found at the 537 nm minima for the filter for both stations was not as much an issue as the 3- and 4- nm shifts found at the 618- and 654- nm peaks for Station #3, respectively.

Recalibration on each of nine SD2000 units was performed utilizing a mercury-argon (HgAr) source of known spectral composition, a published procedure provided by Ocean Optics, and their OOIBase32 (Ocean Optics, Dunedin, FL) software package which provided pixel number as well as calculated wavelength information. Through the manufacturer, there also is an available NIST-calibrated Tungsten Halogen source that would allow for the measured light level to be calibrated radiometrically as well.

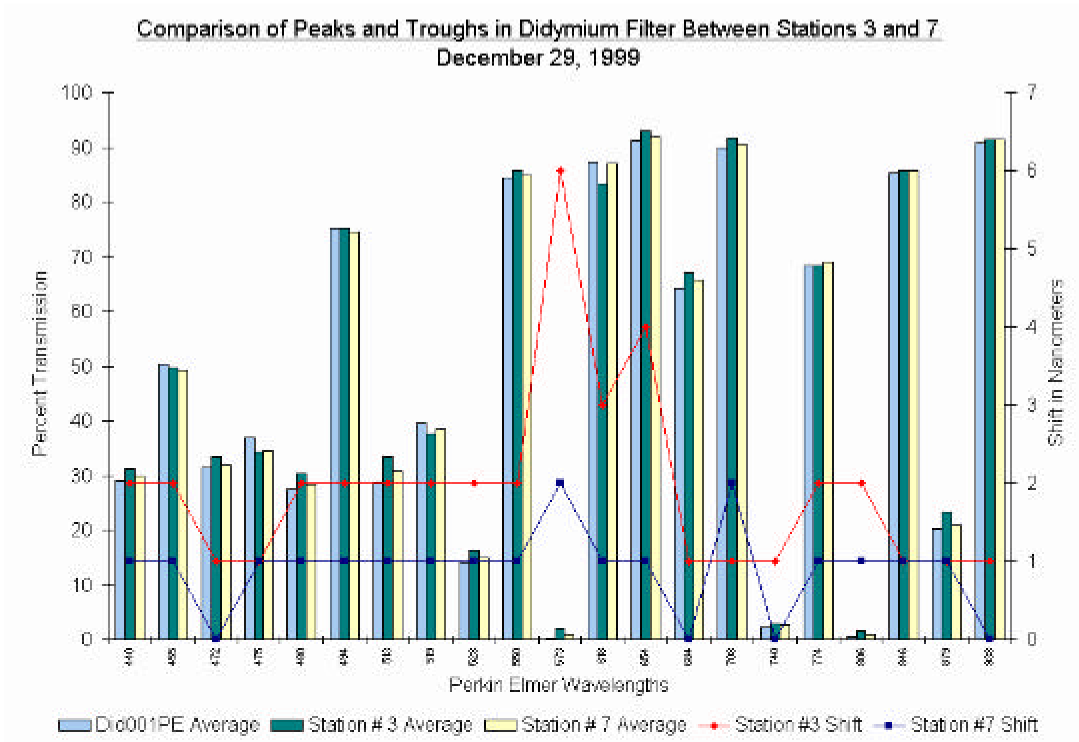
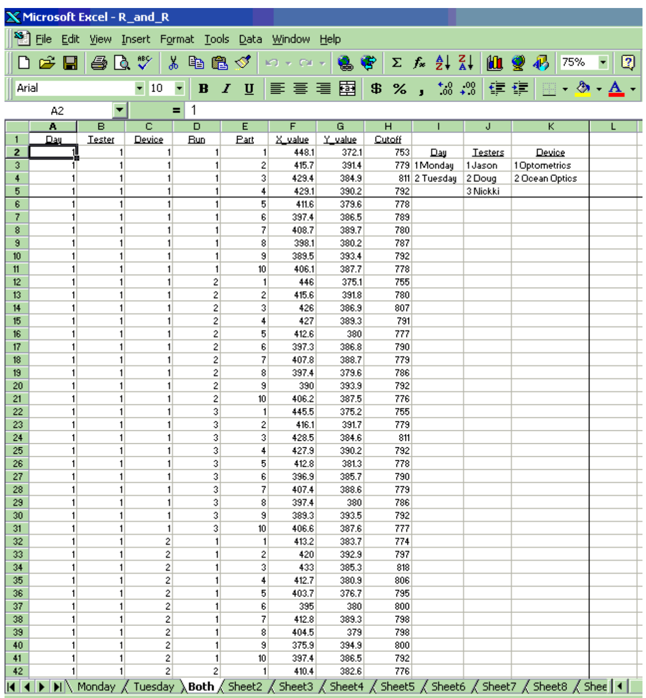


Figure 8 - SaMMS station spectral accuracy comparison.

Each of the seven stations that have been currently upgraded to the SaMMS systems have undergone rigorous R&R testing against the Optometrics systems they were to replace until a "level of comfort" was found. The measuring of large, curved products is not possible with the highly accurate Perkin Elmer units, limiting to this method of testing.

Results

An example of the resultant data from the first Repeatability and Reliability study conducted by the researcher can be seen in Figure 9. The two different devices (scanning monochromator and photodiode array) proved to have consistent results between all of the testers. Initial variation between the two averages for cutoff was an issue of concern. After further study this variation between instruments was attributed to the difference in collection optics. The scanning monochromator was taking light directly from an entrance slit while the photodiode array had a cosine-corrector diffusing optic in place. The level of consistency allowed for an adjustment of film design due to the nanometer differences in cutoff without concern. Variability in the film batches was greater than the difference between instruments.



	A	B	C	D	E	F	G	H	I	J	K
1	Day	Tester	Device	Run	Part	X_value	Y_value	Cutoff			
2	1	1	1	1	1	448.1	372.1	753	Day	Testers	Device
3	1	1	1	1	2	415.7	391.4	779	1 Monday	1 Jason	1 Optometrics
4	1	1	1	1	3	429.4	384.9	811	2 Tuesday	2 Doug	2 Ocean Optics
5	1	1	1	1	4	429.1	390.2	792		3 Nickki	
6	1	1	1	1	5	411.6	379.6	778			
7	1	1	1	1	6	397.4	386.5	789			
8	1	1	1	1	7	408.7	389.7	780			
9	1	1	1	1	8	398.1	380.2	787			
10	1	1	1	1	9	389.5	393.4	792			
11	1	1	1	1	10	406.1	387.7	778			
12	1	1	1	2	1	446	375.1	755			
13	1	1	1	2	2	415.6	391.8	780			
14	1	1	1	2	3	426	386.9	807			
15	1	1	1	2	4	427	389.3	791			
16	1	1	1	2	5	412.6	380	777			
17	1	1	1	2	6	397.3	386.8	790			
18	1	1	1	2	7	407.8	388.7	779			
19	1	1	1	2	8	397.4	379.6	786			
20	1	1	1	2	9	390	393.9	792			
21	1	1	1	2	10	406.2	387.5	776			
22	1	1	1	3	1	445.5	375.2	755			
23	1	1	1	3	2	416.1	391.7	779			
24	1	1	1	3	3	428.5	384.6	811			
25	1	1	1	3	4	427.9	390.2	792			
26	1	1	1	3	5	412.8	381.3	778			
27	1	1	1	3	6	396.9	385.7	790			
28	1	1	1	3	7	407.4	388.6	779			
29	1	1	1	3	8	397.4	380	786			
30	1	1	1	3	9	389.3	393.5	792			
31	1	1	1	3	10	406.6	387.6	777			
32	1	1	2	1	1	413.2	383.7	774			
33	1	1	2	1	2	420	392.9	797			
34	1	1	2	1	3	433	385.3	818			
35	1	1	2	1	4	412.7	380.9	806			
36	1	1	2	1	5	403.7	376.7	795			
37	1	1	2	1	6	395	380	800			
38	1	1	2	1	7	412.8	389.3	798			
39	1	1	2	1	8	404.5	379	798			
40	1	1	2	1	9	375.9	394.9	800			
41	1	1	2	1	10	397.4	386.5	792			
42	1	1	2	2	1	410.4	382.6	776			

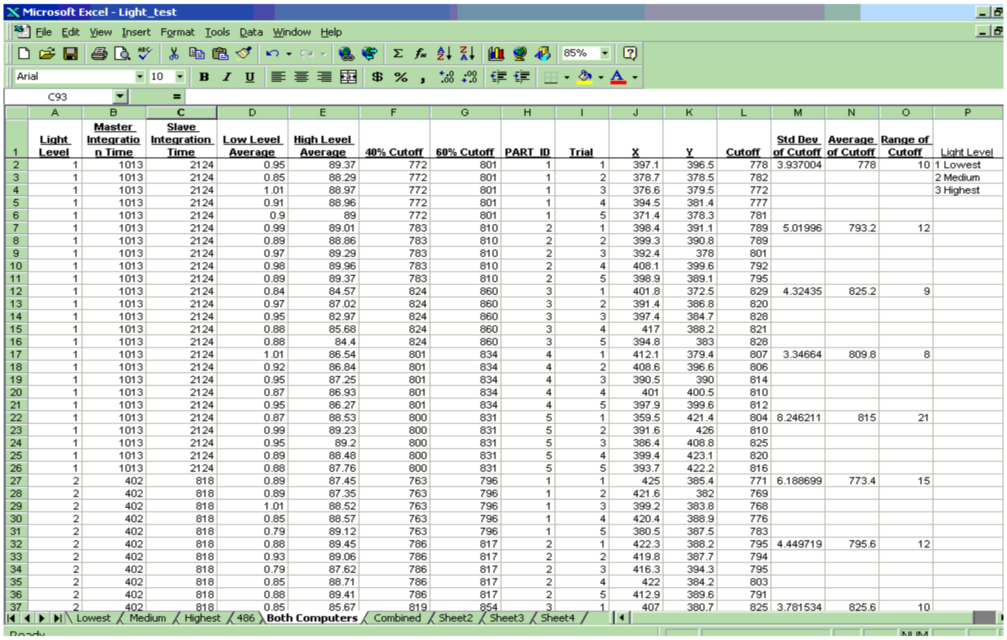
Figure 9 - Repeatability and reliability data from initial phase of testing.

Due to the consistency of the results between operators, it was believed that operator was not a determining variable in the testing. The next R & R study utilized a single subject for the two types of devices to confirm the previous results once in production. Figure 10 shows an example of testing results from this experiment. The same test pieces were utilized from the previous test. Positioning the pieces in the fixture with the same orientation each time eliminated uniformity issues of the coating.

	A	B	C	D	E	F	G	H
1	Instrument	Part	X	Y	Cutoff	Average	Stdev	
2	1	1	430.1	385.8	771	771.6	0.89	
3	1	1	429.9	383.5	773			1 Ocean Optics
4	1	1	431.6	387.9	772			2 Optometrics
5	1	1	430.7	385.8	771			
6	1	1	434.8	393.4	771			
7	1	2	449	396.5	821	820.6	1.52	
8	1	2	449.1	398.6	819			
9	1	2	452.1	402.8	823			
10	1	2	447.4	396	820			
11	1	2	448.2	396.2	820			
12	1	3	431.9	389.8	805	806.6	1.67	
13	1	3	434.5	396.7	807			
14	1	3	428.9	395.4	805			
15	1	3	434.2	395.8	807			
16	1	3	431.2	395.7	809			
17	1	4	414.3	394	791	791.2	0.45	
18	1	4	414.4	393.1	791			
19	1	4	415.4	398.3	791			
20	1	4	417.3	396	792			
21	1	4	421.8	402	791			
22	1	5	422.4	405.5	795	794.8	0.84	
23	1	5	425	408	794			
24	1	5	423.7	408.1	795			
25	1	5	421.5	405.2	796			
26	1	5	420	403.8	794			1.07
27	2	1	446.8	374	753	756.2	1.92	2.45
28	2	1	441.5	379.3	757			
29	2	1	440.1	378.9	757			
30	2	1	439.3	379.5	758			
31	2	1	440.5	378.1	756			
32	2	2	434.9	389	808	809.4	4.10	

Figure 10 - Repeatability and reliability test data from day two.

Once the dual-channel independent integration time was developed, there was concern over the method of adjusting light that had been utilized with the scanning monochromators. The different light levels had to be tested to prove if the measurements were independent of aperture setting. Figure 11 shows an example of light level testing data.



	Light Level	Master Integration Time	Slave Integration Time	Low Level Average	High Level Average	40% Cutoff	60% Cutoff	PART ID	Trial	X	Y	Cutoff	Std Dev of Cutoff	Average of Cutoff	Range of Cutoff	Light Level
2	1	1013	2124	0.95	89.37	772	801	1	1	397.1	396.5	778	3.937004	778	10	1 Lowest
3	1	1013	2124	0.85	88.29	772	801	1	2	378.7	378.5	782				2 Medium
4	1	1013	2124	1.01	88.97	772	801	1	3	376.6	379.5	772				3 Highest
5	1	1013	2124	0.91	88.96	772	801	1	4	394.5	381.4	777				
6	1	1013	2124	0.9	89	772	801	1	5	371.4	378.3	781				
7	1	1013	2124	0.99	89.01	783	810	2	1	398.4	391.1	789	5.01996	793.2	12	
8	1	1013	2124	0.89	88.86	783	810	2	2	399.3	390.8	789				
9	1	1013	2124	0.97	89.29	783	810	2	3	392.4	378	801				
10	1	1013	2124	0.98	89.96	783	810	2	4	408.1	399.6	792				
11	1	1013	2124	0.89	89.37	783	810	2	5	398.9	389.1	795				
12	1	1013	2124	0.84	84.57	824	860	3	1	401.8	372.5	829	4.32435	825.2	9	
13	1	1013	2124	0.97	87.02	824	860	3	2	391.4	386.8	820				
14	1	1013	2124	0.95	82.97	824	860	3	3	397.4	384.7	828				
15	1	1013	2124	0.88	85.68	824	860	3	4	417	388.2	821				
16	1	1013	2124	0.88	84.4	824	860	3	5	394.8	383	828				
17	1	1013	2124	1.01	86.54	801	834	4	1	412.1	379.4	807	3.34664	809.8	8	
18	1	1013	2124	0.92	86.84	801	834	4	2	408.6	396.6	806				
19	1	1013	2124	0.95	87.25	801	834	4	3	390.5	390	814				
20	1	1013	2124	0.87	86.93	801	834	4	4	401	400.5	810				
21	1	1013	2124	0.95	86.27	801	834	4	5	397.9	399.6	812				
22	1	1013	2124	0.87	88.53	800	831	5	1	359.5	421.4	804	8.246211	815	21	
23	1	1013	2124	0.99	89.23	800	831	5	2	391.6	426	810				
24	1	1013	2124	0.95	89.2	800	831	5	3	386.4	408.8	825				
25	1	1013	2124	0.89	88.48	800	831	5	4	399.4	423.1	820				
26	1	1013	2124	0.88	87.76	800	831	5	5	393.7	422.2	816				
27	2	402	818	0.89	87.45	763	796	1	1	425	385.4	771	6.188699	773.4	15	
28	2	402	818	0.89	87.35	763	796	1	2	421.6	382	769				
29	2	402	818	1.01	88.52	763	796	1	3	399.2	383.8	768				
30	2	402	818	0.85	88.57	763	796	1	4	420.4	388.9	776				
31	2	402	818	0.79	89.12	763	796	1	5	380.5	387.5	783				
32	2	402	818	0.88	89.45	786	817	2	1	422.3	388.2	795	4.449719	795.6	12	
33	2	402	818	0.93	89.06	786	817	2	2	419.8	387.7	794				
34	2	402	818	0.79	87.62	786	817	2	3	416.3	394.3	795				
35	2	402	818	0.85	88.71	786	817	2	4	422	384.2	803				
36	2	402	818	0.88	89.41	786	817	2	5	412.9	389.6	791				
37	2	402	818	0.85	85.67	819	854	3	1	407	380.7	825	3.781534	825.6	10	

Figure 11 - Design of experiments test data utilizing change in light level as a variable.

Discussion

The SaMMS system has already proved its worth in diagnosing a software driver upgrade issue in another device as well as eliminating some of the subjective error of human observers with visual color comparators. Further implementation of newly customized software developments will only increase the system's usefulness at Applied Coatings.

Repeatability and Reliability testing has shown that the SaMMS system has better repeatability with the Ocean Optics SD2000 without any moving parts over the Optometrics scanning monochromator system. The scanning monochromator uses a stepper motor with no encoder and has too be "homed" when it gets "lost". Should the stepper motor lose track of the number of pulses it has sent out or if the motion system gets upset in a way that is not registered by the controller, it is not possible to correlate the current position to a wavelength.

The system has been found to be within one nanometer of spectral resolution for the same measurements taken on flat pieces using the much more expensive Perkin Elmer dual beam devices. The SaMMS system also took far less time for a given scan while being far friendlier for user interaction. It also offers the customizable Pass/Fail results that the Chemistry-minded Perkin Elmer units do not have.

Transmission fixtures were designed for consistent measurement of curved parts. It was found that the mechanical tolerances went beyond the placement of the part, but also included the detector, bulb, and lens positioning that could cause a discrepancy between two stations. Consistency of measurement between units improved when these factors were accounted for.

Recalibration of the SD2000 spectrophotometers upon receipt, despite the careful packaging of the shipment, proved to increase spectral accuracy to within a calculated two tenths of a nanometer. The significance of this level of accuracy is appreciated more when one device was found to be seven nanometers off for a given wavelength of the HgAr spike upon receipt. Figure 12 demonstrates how three instruments benefited in performance from this level of inspection. Using a didymium filter, with its aggressive absorption peaks, has proven an effective test for a unit's calibration status. These filters traditionally have been used on the scanning monochromator units to determine calibration as well.

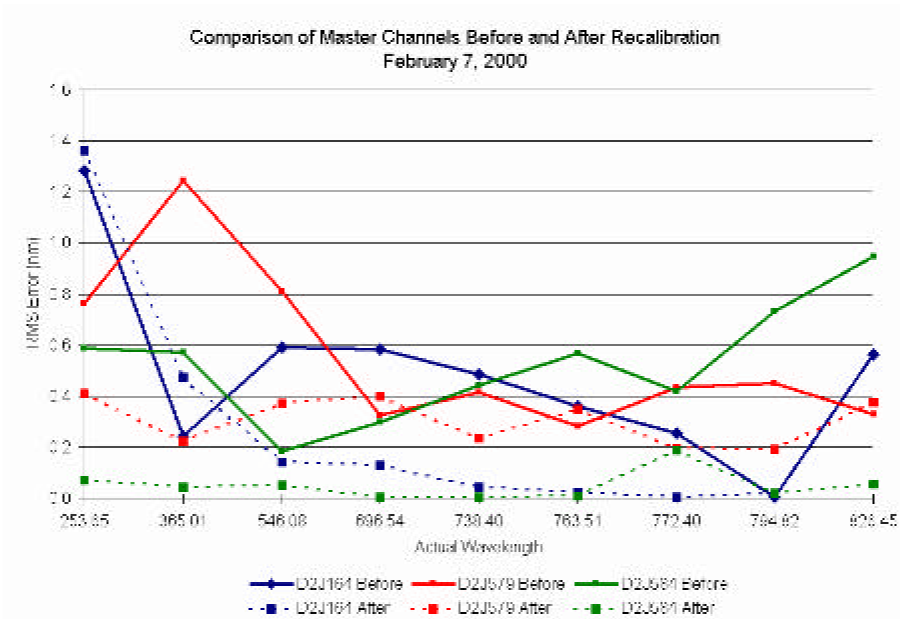


Figure 12 - Calibration of instruments upon receipt showed improved spectral accuracy.

Conclusions

Given the availability of support for the Optometrics scanning monochromator systems, the SaMMS project was a necessity. There was concern as to whether the old units' controllers were even Y2K compatible. Although there are other commercially available systems, the Ocean Optics' spectrophotometer solution has proven to be effective and economical.

Scan time has been reduced, improving throughput, without sacrificing accuracy in measurements. The improved manageability of the GUI software has made setting up new products easier than the older text interface. The devices have no moving parts prone to wear and only need a single cable to interface with an A/D card rather than one for the detector head and another for stepper control. A bifurcated fiber optic line enhances flexibility in positioning and can accommodate both channels simultaneously with a single probe for measuring light levels, making it a superior setup. The PC's that the SaMMS software runs on are network accessible as well as the data they produce, unlike the older units.

Applied Coatings owns the SaMMS software. It is written in C and is part of a National Instrument's LabWindows project that can be customized at any time without outside assistance. It will continue to change as automation is implemented with a future project. LabView (National Instruments, Austin, TX) is another development environment that allows for ease of integration into LabWindows (by creating DLL's) with less development time than using the C language.

Ocean Optics has multiple gratings that can be put into their optical bench, as well as coatings of their own which provide for increased UV or IR sensitivity beyond the silicon detector's wavelength response curve. This may prove useful in configuring a spectrophotometer with more bandwidth for development purposes. The limitation of the IR coating is in linearity of response, however, so the manufacturer warns that it may not serve as a useful NIR instrument due to aggressive absorption bands. However, they currently have a model NIR512 InGaAs instrument available that could possibly be implemented to cover longer wavelengths.

The SaMMS Colorimetry project was necessary and will serve Applied Coatings into the new millennium with repeatable, reliable, and accurate spectral assessment of their process.

References

1. "B&L Coats the World with Thin Films" by P. Ebersole, Democrat and Chronicle / Times Union, May 22, 1995

2. G.V. Planer and L.S. Phillips, Thick Film Circuits, Butterworth & Co. Ltd, London, 1972

3. Kasturi L. Chopra, Thin Film Phenomena, McGraw-Hill, Inc., New York, 1969

4. Characterization of Coatings - Physical Techniques, Marcel Dekker, New York, 1969
"Infrared Spectroscopy" by Clara D. Smith p.429-498
"Ultraviolet and Visible Spectroscopy" by Edward R. Scheffer p.501-562

5. Thin Films, American Society for Metals, New York, 1964 "Mechanical Properties of Thin Films" by R. W. Hoffman p.99-134

6. H. Angus Macleod, Thin-Film Optical Filters, Institute of Physics Publishing, London, 1986,2001

7. Robert W. Boyd, Radiometry and the Detection of Optical Radiation, John Wiley & Sons, Inc., New York, 1983

8. Milton Ohring, The Materials Science of Thin Films , Academic Press, New York, 1992

9. Eugene Hecht, Optics - 3rd ed., Addison Wesley Longman, Inc., New York, 1998

10. "The Optics of Spectroscopy" a tutorial by J.M. Lerner and A. Thevenon courtesy of the Jobyn Yvon website : http://www.isainc.com/systems/theory/oos/oos.htm

11. "Interactive Computer Models for Analytical Chemistry Instruction" by Tom O'Haver courtesy of Department of Chemistry and Biochemistry at the University of Maryland at College Park website :
http://www.inform.umd.edu/EdRes/Topic/Chemistry/ChemConference/Software/Spreadsheets/WWW/index.html

12. "Holographic Imaging Spectrograph" found on the Kaiser Optical Systems, Inc. website :
http://www.kosi.com/technotes/main.html

13. Lighting Handbook, Illuminating Engineering Society of North America, New York, 1993

14. Agilent Technologies Measurement Products Unit web site
http://ftp.agilent.com/pub/mpusup/pc/hbw/hbwnotes/bw01_ovr.html

15. TransEra web site support reference http://www.htbasic.com/transition/index.html

16. HTBasic (TransEra Corporation, Orem, Utah) web site reference
http://htbasic.com/htbwindows.html

Appendix: Definition of Terms

bandpass - Term referring to either designing a filter to allow only a specific range of frequencies or wavelengths to transmit through it while blocking others.

chemical vapor deposition - Method of film coating that utilizes the chemical reactivities of the deposited substance, substrate, and a chemical medium through which the two react to achieve the desired results. This method can be further divided into Electrolysis, Anondization, Pyrolysis, Hydrogen Reduction, Disproportionation, Transfer Reaction, Polymerization, and Electroless Solution.

color box - Boundary area, typically in CIE 1931 x,y color space, based upon isotemperature lines for a given range of blackbody radiators and distance from the Plankian locus or limits in chroma, for measured color tolerance from a target value.

dichroic - Consisting of alternate layers of optical material with varying high and low indices of refraction utilized with varying thickness to target specific wavelengths.

diffraction grating - A dispersive optical element designed to operate with diffractive rather than refractive methods. [10]

evaporation - Method of thin film coating in which the substrate has the material deposited upon it from a heated source where the evaporant collects on the cooler substrate. This method can be further divided into Resistive Heating, Multisource, RF Heating, Electron Beam, Flash, Arc, Laser, and Exploding Wire methods.

graphical user interface - A software environment within which the functionality is enhanced to the point where the user can select items that are represented with graphics rather than having to type in instructions from a given set of commands.

hydrophilic - Prone to wetting, where there is a high surface energy that will allow adhesion of water and cause it to spread about the surface or be absorbed.

hydrophobic - Prone to beading, where there is a low surface energy that will prevent the adhesion of water and cause droplets to form.

Rocky Mountain BASIC - A dialect [14] of the BASIC software language for workstations that is no longer supported by its creators [15] and is being replaced with HTBasic. [16]

sputtering - Method of deposition utilizing a ionic charge to release atoms from a target between substrate and source in some configuration to adhere evaporants. This method may be broken up further into Glow Discharge, Ion Plating, Asymmetric AC and DC bias, Getter, Triode (assisted ionization), RF, Ion Beam, and Reactive methods.

thick films – films thicker than a micron, which is more than 1/25,000th of an inch – are often incapable of the adhesive qualities of thin films and are more susceptible to mechanical or thermal stresses, but are less costly and more easily produced.

thin films - The films are deposited in vacuum chambers where the atmospheric pressure is measured in μ-torr often with intense heat measuring upwards to 500° C. The boiled material under reduced pressure is allowed to deposit onto a substrate. Much more costly and difficult to produce than *thick films*, but create many desired effects that thick films cannot.

witness pieces – Low-cost, flat substrates that are small enough to measure within a traditional dual beam spectrophotometer's sample compartment with the vendor's own accessories.