Process Control of UV radiation
In the Fiber Optic process industries

Summary

The following describes some recent advances in UV spectroradiometry as required by the optical fiber manufacturing industry. The demands from fiber process engineers have presented some severe challenges in developing accurate and reliable UV measuring instruments. Such instruments are now available to provide both intensity and wavelength data in the form of UV spectral distribution analysis and monitoring in an easy to understand form.

Three state-of-the-art UV spectroradiometers can be used in the following practical ways :-

- **Off line**, without fiber, inside the quartz tube to benchmark the performance of the UV ovens
- **On-line**, with fiber in place, for UV oven manual performance checks and problem diagnosis
- **On-line**, with fiber, automatic radiometric data collection and UV watchdog monitoring.

These different approaches are described, and the practical benefits and drawbacks of each approach discussed. Some real examples of lamp system performance during lamp starting, run up and longer term effects are presented from some typical fiber coloring lines.

Keywords

UV; measurement; spectrum; calibration of UV measurement; fiber processes; UV cured formulation; on-line monitoring; process control.

1 Introduction

High intensity Ultra Violet radiation is a critical ingredient in the manufacturing process for quartz optical fiber and cable in the following four areas:

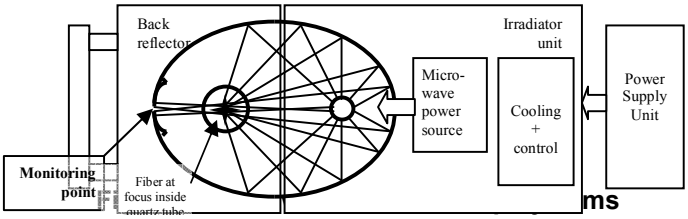
1. fiber draw,
2. fiber coloring,
3. fiber ribbon matrix,
4. fiber cable non-ferrous strength member.

In fact, the absolute intensity and wavelength distribution of the UV reaching the process during manufacture can be a critical limiting factor on process speed, however, fiber draw process speeds in excess of 20m/sec are not uncommon. If it is not taken into account, inadequate UV irradiation during the manufacturing process may lead to inadequate cure, which if not detected can lead to severe product quality in-service problems, premature failure, or loss of performance of the fiber once installed.

But how can one know that the UV radiation reaching the fiber is adequate, or is being sustained at an adequate level during manufacture? This can only be achieved by accurate measurement of the UV itself, both from a quantitative and also from a qualitative standpoint. The essence of good quality control in any of the application areas mentioned is to be able to measure and compare meaningful UV spectral measurements of the photon flux causing the radiation curing of the formulation being applied in the process.

2 The UV cure zone

Quartz fiber optic cable is a remarkable product; a very highly developed and demonading process at the forefront of UV curing. Process engineers are continually pushing the envelope of speed of cure, mechanical handling, and process machine performance. Naturally, to keep the process in control, many paramteres are monitoried to very exacting standards. Recently, spectral monitoring has also been made possible for the UV radiation which is such a critical part of the process.



ms commonly used in fiber processes

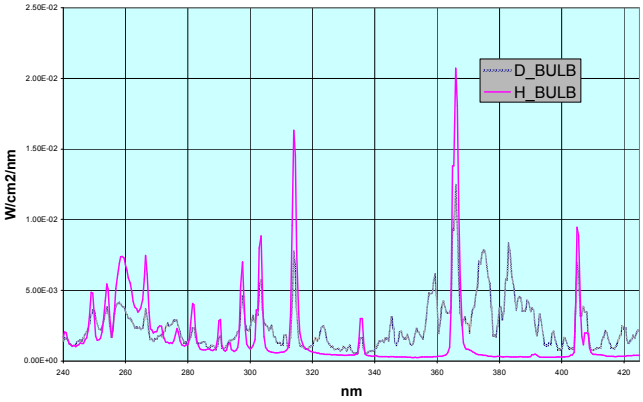
Generally, the lamp used in the fiber process industries is of the form shown in figure 1. Here we have a very highly focused, microwave excited UV lamp with the bulb positioned at one focus of an eliptical reflector, and the fiber product running through the second focus of the ellipse. The fiber product in Figure 1 is running perpendicualr to the the page, and the curing zone of the lamp is typically 250mm long i.e the fiber product is expsed to UV for 250mm of its passage through the quartz tube of one lamp. Often many lamps are arranged vertically, one above the other with the fiber running through one long tube, or several quartz tubes carefully aligned vertically. Sometimes more conventional mercury arc lamps are used instead of the 250mm microwave excitied lamps, but although these are longer in length, they cannot reach the extremely high intesity tight focus the microwave lamp can offer due to its smaller bulb diamter.

The microwave lamp comproses essentially three different components; a) The **irradiator**, which containes the microwave sources and cavity, the bulb, half of the elliptical relfector, and the cooling and control system for the lamp, b) the demountable **back reflector**, which completes the elliptical relfector, holds the quartz tube containing the fiber and nitorgen inerted atmosphere, and provides UV monitoriing access points, and c) the **power supply**, which is either switchable between low and high power or is continuously variable between typically 25 and 100%.

The other parameter which can be altered is the type of bulb fill used. The most common two types of bulb are reffered to as ‘D’ and ‘H’ and are contrasted in Figure 2 (spectral data are measured using an instrument type described later in this paper).

The D bulb, while having lower peaks in the longer wavelength region, has a higher total integrated power than the H bulb in the region 320 to 400nm. Whereas the H bulb, for the same input power, emits a higher total power in the short wavelegth region, shown here as 240 to 280nm.

Figure 2. Typical fiber curing lamp spectral charts



2.1 Process types

In the fiber cable manufacturing industry, we can look at the four distinct areas where high intensity UV is used as part of the manufacturing process

i) **fiber draw** – the initial manufacturing stage where quartz fiber is drawn from a preform, then coated with a UV cured functional coating;

ii) **fiber coloring** – where the quartz, coated fiber from stage i) is coloured for identification purposes using a dyed, UV-cured lacquer (sometimes stages 1 and 2 are combined into one process);

iii) **fiber ribbon matrix** – where typically 10 or 12 colored fibers are combined into a flat ribbon, for construction into a cable

iv) fiber cable non-ferrous **strength member** – the final cable has many fibers contained within it (often in the form of many ribbons); the cable is given logitudinal stength by the addition of a central spine, or strength member. This strength member is increasingly made of a composite material which is UV cured.

In each of the above processes, the type of UV lamp used is often of the microwave excited type as shown in Figure 1. In order for cure to occur in each process, the UV formulation is applied wet, then the product is passed through one, or more usally, several UV curing lamps inside a quartz tube which has nitrogen gas continually supplied into it. The reason for the nitorgen is to inert the curing atmosphere, more specifically to remove oxygen which would otherwise inhibit the curing process. During each of these processes, temperature will also play an important role in the speed of the procees and the fullness of cure.

3 UV requirements to cure a fiber process formulation

As fiber processes increase in speed, there is demand for just a straightforward increase in the W/cm (or W/inch) output from the lamp. This is a traditional way of speficiying UV lamp systems e.g. 240W/cm, but is somewhat misleading because it says nothing about the actual power reaching the procees – so does not take into account the effect of the reflector geometry, or distance from the lamp system – nor does it say anything about the spectral distribution of the UV irradiance which is so critical to the process. As we know from 'the cure zone' section 2, we can select a bulb type for its higher short (H) or longer (D) wavelength UV output performance. Some fiber processes use a combination of H and D bulbs in series for their better suitability to surface cure, or adhession (through cure) properties respectivlty. However the formulation often is specified as simply needing UV in one or two peak areas e.g. "370nm to 400nm", which obviously correspond to the actual mercury vapour naturally occuring peaks, but say little about the matching of real bulb output (see Figure 2) to the absorption spectra of the UV formulation. Some experimentation is often required to detemine the best lamp number, spectrum and power combination to achieve a specific cure rate.

The reason mutiple lamps are often required is partly due to the speed which the fiber passes through the cure zone. A UV lamp does not have a completely stable 'd.c.' output, but rather fluctuates with the utility supply frequency. Such is the speed of the fiber that if the UV lamp output is going through a minimum as the fiber passes through the cure zone in one specific lamp then inadequte UV dose would be achived with only one lamp. Two or more lamps overcome this phenomena.

Added to this is the almost universal need to exclude oxygen from the curing process area as mentioed in the previous section. The temperature of the fiber as it paases through the cure zone can also play a significant role in the overall cure rate.

Once the UV lamp number + spectrum + power and process speed formula are determined, it is necessary to ensure that this lamp array continues to deliver the required power and spectra for a sustained period, and to have the ability to diagnose problems if they occur.

4 Effects of inadequate cure on fiber processes

What are the dangers associated with inadequate cure, and how can it occur ? Break outs (quartz fiber breaking out of coating during handling), in-system failures, or loss of performance of the installed fiber are the main problems. Also mechanical problems can become evident with the preparation of the fiber during installation whereby the buffer coating cannot be stripped reliably, thus making the fiber difficult to use.

With colored fiber, the actual dye color can have a major bearing on the effectiveness of cure, with some colors e.g. orange, being more difficult to cure reliably with a greater tendency for break outs. Better matching of UV emission spectra to absorption spectra of colored UV coatings can help here, as well as process speed modification.

As already mentioned, the fiber process is a complex with many elements contributing to a successful and reliable result. However we will concentrate on the UV radiation necessary for cure, which is clearly a critical element with different parts of the spectrum being generally associated with different effects.

Figure 3 shows the effect of different portions of the UV spectrum. For convenience the diagram depicts the effect of short (UVC), medium (UVB) and long (UVA) wavelengths where it is generally understood that the shortest wavelengths

are absorbed near the surface of the coating, so are associated with surface cure effects, while the longer wavelengths penetrate further and are associated with depth of cure, or adhesion between the coating and the fiber.

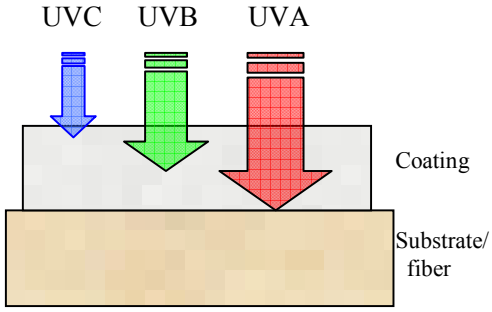


Figure 3. Penetration dependance on UV wavelength

5 What can go wrong ?

In providing UV radiation to the fiber process we have a high power optical system. Although the lamp systems are generally very reliable there are nevetheless factors in the process itself which can contribute to the deterioration of the optical surfaces involved, some of which are breifly reviewed below.

5.1 Quartz tube fogging

The most common problem is the so-called 'fogging' of the quartz tube used in the lamp system shown in Figure 1. In severe cases during run up, a quartz tube can become quite dark due to a little uncured coating or dye becoming deposited on the inside surface, then becoming 'baked on'. This darkening can have a dramatic effect in the UV reaching the process. Fortunately, the monitoring points shown in figure 1 allow a UV measuring probe to be postitioned to see the effect of two thickness of quartz in front of the bulb, so this problem can be detected fairly easily with the manual or automatic monitoring systems described later.

5.2 Bulb overheating

The cooling air-flow provided to the bulb when the lamp system is turned on must be maintained above a certain level. If the air flow is inadequate then the bulb can overheat. The effects of this can be to alter the bulb output spectrum or the bulb actually expanding so effecting focus. Some increase in bulb output may be obtained over a shortened period, as we will see later, but the consequence will ultimately be the bulb failing prematurely.

5.3 Wrong bulb

It is reltively striaghtforward to check that the correct bulb type is being put in the lamp system by checking its marking during routine maintenance. However, once in service, it is not easy to check the bulb type without disassembly of the lamp. A quick check on the bulb's spectrum in operation verifies the correct type is fitted.

5.4 Low power setting

The spectrum of a D bulb will look quite different – more like that of an H bulb – if it is operated at low power (see figure 2). Not only is the output of the bulb a lot lower, the spectral matching of the bulb output to the chemistry of the UV formulation is no longer optimised. Experience shows that power settings in multiple lamp systems may not always be set correctly. The output power and spectral distribution 'signature' of the lamp can reveal whether it is operating correctly, by comparison with previously recorded spectra.

5.5 Lamp maintenance requirement

Nomally a UV lamp system will give thousands of hours of trouble free use if it is looked after properly. As we have described above, if the lamp system has for example a poor air flow, the bulb will behave abnormally and can fail after only hundreds of hours.

The lamp system is complex, and whilst essentially very reliable, may develop in-service operation issues effecting its output. While these issues are normally avoided by routine mainteneance, it can happen that the maintenece itself can create a operational abnormality if the lamp is not reassembled quite correctly.

Mangnetrons are used to generate the necessary microwave energy to power up the bulb shown in figure 1. These magnetrons have a finite life, and usaully there are two. If one half of the bulb has lower output than the other then it may suggest one magnetron is nearing the end of its service life before the other.

6 UV measurement for fiber industries

6.1 Industry needs

The primary reqirements for UV monitoring in the fiber process industries are firstly, consistency of measurement. It is very desirable to be able to provide reliable specifications for the UV being delivered and methods of comparing measurements between different machines, and different sites. If measurements are consistent and reliable and have absolute calibration traceability [1] across a broad spectrum, then the end user and UV coating formulator are able to speak the same language, and it is possible to 'close the loop' on formualation development and end user requirements for process performance and UV quality control.

6.2 Generic types of measuring device

It is outside the scope of this article to exhaustively compare different methods of UV measurement, but essentially there are two types of physical devices most commonly used for UV measurement [1], where the signal conditioning and amplification electronics are attached to some form of display device, viz. a viz. a) Radiometers or b) Spectroradiometers. The essential differences are summarized in Table 1

Table 1 - The differences between radiometers & spectroradiometers

Radiometers	Spectroradiometers
Low to Medium cost	Medium to High cost
Broad band devices, comprising photodiode and optical filter combinations	Narrow wavelength discrimination, hence irradiance units in $W/cm^2/nm$ (1 nm resolution)
Intensity information in pass band of filter	Intensity and wavelength information, and calibration across wide spectrum
No precise wavelength information	Precise intensity vs. wavelength plot
Only calibrated for one type of light source spectrum, specified at time of ordering	General calibration 'flat response'; purpose is to show calibrated differences in spectra
Gives a **number** as an irradiant Power (P) in W/cm^2	Gives a **Graph** – a picture of spectral distribution, with calibrated units as :- X axis = nanometres (nm) Y axis = $W/cm^2/nm$ Irradiant power can be calculated by 'integrating under the curve' of the spectral distribution over programmable ranges.

As mentioned in the table, radiometers comprise an optical band-pass filter, and a photodiode, both of which are subject to manufacturing tolerances. The optical filter can also suffer from temperature effects and its characterstics can change with time as the filter deteriorates, or 'solarises', in the presence of high intensity UV radiation. The radiometer's combined effect of the filter and diode in series cannot actually be known at the time of manufacture (unless each radiometer is painstakingly characterised nanometer by nanometre, using a spectroradiomter as a reference measuring insturment). The normal procedure to overcome this difficulty in not knowing the combined response, is for the radiometer to be calibrated in front of a particular light source of known power and spectral distribution against a reference radiometer calibrated by a standards institution (e.g. the NIST in the USA, NPL in UK, or PTB in Germany).

The result of this process is that the calibration of the radiomter can only be relied upon for one type of light source, that which it was calibrated against. If the spectral distribution of the light source to be measured differs substantially from the calibrating light source then the radiometer readings are effectively uncalibrated and can only be used as relative readings. Indeed, it will often be found that one radiometer reading cannot be compared against another radiometer because of the unknown nature of the combined response effect of the filter and diode mentioned in the previous paragraph. The radiometer is however useful as a reletive measuring device when these considerations are taken into account.

By contrast, the higher cost spectroradiometer is designed to be able to judge the relative height, or contribution of one part of the spectrum against another part with equal weight (or indeed with an absorption spectra applied to provide 'effective irradiance' measurements). The whole point of the spectroradiometer is that it can be calibrated to give absolute measurements across a wide spectral range, from a wide range of UV lamps, and then to be able to display the spectral distrbitution faithfully in absolute units.

The spectroradiometer can then be relied upon to give both quantitive and qualitive checks, to allow the user to make judgments about the state of the UV lamp system e.g. whether the spectrum is correct, whether the short wavelength UV has deteriorated – possibly as a result of contamination on one of the optical surfaces – or whether the overall power level in one installation matches another in absolute units.

So there are clear advantages to using a spectroradiometer if absolute UV measurement accuracy is required.

6.3 The ideal ?

What are the factors which can have a significant effect on UV measurements for high power lamp systems? They can be summarized as follows :-

- Position – is the probe + spectroradiometer combination being accurately and repeatably placed ?
- Probe effects – has the attenuation of any optics been taken into account ?
- Spatial response – the angular response effects
- Calibration – is the instrument properly calibrated ?
- Scan time – is the time to make a measurement too short / too long ?
- Stray light – which out of band radiation effects could effect the measurement ?
- Temperature – could effect the electronics or the optics performance

In order to make accurate and meaningful UV spectral measurements in a high power curing process, first of all we need to be able to insert our measuring instrument entrance as close as possible to a representative position, or positions, seen by the process. To do this, it is convenient to use a probe of some type capable of withstanding the high temperatures and extreme UV intensity normally found from a lamp system (bulb + reflector combination). In the case of the lamp configuration in Figure 1, we are unable to position our probe in exactly the same postion as the fiber while the process is running, so next best is at a defined postion which will take into account most of the contributing factors to the lamps system's performance. Indeed, some lamp manufacturers have provided this type of monitoring points at stategic positions exactly for this purpose.

6.4 Robust miniature UV Spectroradiometers

Since their introduction some 8 yeras ago to the radiation curing industry, the development of robust, miniature battery operated UV spectroradiometers has been continuing. These devices are based on a miniature, monolithic, single diffraction grating spectrograph, optimised for UV spectroradiometry [1]. They comprise a self scanned UV enhanced array of typically 512 photodiodes, mounted on focal plane of the spectrograph. A wide range of wavelengths in the UV can be collected in one (or a few) rapid scan(s), with typically a 1nm bandwidth; so that spectral lines of typically 2nm spacing can be resolved.

Current wavelength ranges from such instruments range down to the short wavelength UVC (below 240nm), to well into the near visible, stopping at typically 470nm.

Such UV spectral intensity measurement devices are available as hand-held, battery operated instruments with a graphical display able to show UV lamp spectra, and with colour display versions to compare one spectra with another directly.

More recently, simpler, lower cost devices, based on the same type of core UV spectrograph technology, have come along in the guise of 'programmable UV-near-visible radiometers' with the purpose of being used in a production environment as a simple go/no go check on the output from a UV lamp system on, for example, a fiber optic cable draw tower. Such devices are able to store a complete UV reference spectra, and to allow comparison of this with the latest reading to establish whether a lamp may have lost power in part of its output spectra e.g. due to a contaminated quartz tube. A simple traffic light arrangement can tell an unskilled operator in seconds the condition of his lamp system.

All of the above types of instrument are usually used in radiation curing measurement application with a UV probe, capable of withstanding the high temperatures and UV intensities found in such applications. As already mentioned, there is a requirement to position the probe in the same position every time a measurement is taken, so accurate location methods providing very good repeatability have needed to be developed, and are available for the types of microwave excited lamps used in the fiber optic industry, shown in Figure 1.

In addition, small radiometer devices have been developed to provide complete system for on-line monitoring of UV spectra with, for example up to 32 lamps under continuous monitoring [3].

6.5 Probes

An example of a typical, elevated temperature (to 250^{o}C) withstanding UV measurement probe is shown in the photograph Figure 4.

Figure 4. The original UV probe and precision location system

It has only a 1 mm entrance aperture so is able to be very accurately positioned in the irradiant field of the UV lamp system. To the left of the photo is a locating mechanism for the probe. This is normally mounted on the machine or UV lamp system and provides accurate (to within 0.5mm) and very repeatable positioning of the UV probe for taking measurements. A sprung loaded flap on the locator ensures that UV light is not allowed to escape from the locator when the probe is not inserted.

Other larger diameter probes capable of being operated at temperatures up to 350^{o}C have been successfully manufactured with a built in diffuser in order to extend the spatial response of such probes to an approximation to a cosine response which can be used actually inside the quartz tube off-line with no fiber running through.

Figure 5. The probe of figure 4 in position in a microwave excited lamp's back reflector

6.6 Monitoring approaches for fiber industries

Varuous approaches have become avaialable for the fiber process industries to allow a range of choices for both checking and monitoring the operation of the UV lamps capability to deliver the expected spectral distribution and power levels necessary to achieve cure at the required process speed. These approaches are breifly described below.

6.6.1 Off line, without fiber, for UV lamp system performance benchmarking

The first approach allows the UV lamp system to have measurments made directly insidee the usual quartz tube, as shown in figure 6.

Figure 6 – measuring off-line inside quartz tube

Here the operator is able to use, for short periods, a specially desinged quartz probe protected inside a thick stainless steel tube which can be inserted inside the quartz tuber of the secondary reflector illustrated in figre 1. Once inserted inside the tube with the lamp on at full power, the quartz probe is deisigned to be able to 'look' sideways, at 90^{o}, either directly at the bulb, or at the refelctor to be able to judge the condition and operation of the varuous system components, from the spectral distribution observed, depending on the rotation of the probe Also, by observing differences at one part of the tube compared to the another, it is possible to judge whether there is an even

spectral power distribution along the length of the bulb. If there is a marked difference one end to another, then it is possible that a magnetron may need attention.

Figure 7 – Compact spectroradiomter based checking device, with high temperature probe for use inside quartz tube.

A recent self contained hand held instument with detachable probe for use inside the quartz tube is shown in figure 7. Both insturments in figure 6 and 7 can provide valuable lamp system diagnoses when the lamp is demounted from the machine in, for example, a maintenance department. The UV output of the lamp can be thoroughly checked before being brought back in to service after being maintained.

Because it is used right inside the quartz tube, this measuring option gets very close to measuring what the fiber actually 'sees' while passing through the quartz tube, however, it has the disadvantage that it cannot be used for checking the lamp during fiber manufacture, so is described as 'off line'.

6.6.2 On-line manual, with fiber, for UV lamp performance checks and problem diagnosis

As we have seen in figure 4 and 5, probe locators can be fitted to the lamp to take advantage of the monitoring points provided by the lamp manufacturer to allow measutments to be taken 'on-line', either before or during a fiber manufacturing run.

Figure 8 – New compact spectroradiometer based sensor with fine probe for use with probe locator on lamp system

Fiugre 8 shows a more recent version of the same type of probe illustrated in figure 4 and 5 for allowing measurments to be taken at the monitoring points shown in figure 1 while fiber is running through the process. This system provides absolute calibrated measurements at an exact point in the lamp system which is defined mechanically with very precise positional accuracy. This type of probe can be manually moved from monitoring point to monitoring point to take and compare measurments easily. It can also be left 'in-situ' to allow permanent on-line monitoring measurements to be taken.

The probes and sensors of figure 7 and figure 8 are interchangeable and each contrain their own calibration data to take the probe charactersitics into account. The probe should always be calibrated on the sensor it is intended to be used with.

6.6.3 On-line, cautomatic for data continuous data logging and UV watchdog monitoring.

Figure 9 – On-Line ARAD100 Continuous Sensor

The UV measurements systems so far described are essentially manually operated where an operator or engineer must physcially take the measurment, and store the data in the instrument. Complete, multichannel on-line UV spectral monitoring systems are also available. The Radiometer for this is shown in Figure 9. It can be networked with up to 32 other sensors in a digital network for continuous reporting of all lamps on a process. This ARAD100 radiometer also has the unique advantage of being able to communicate with the Sola-Check miniature spectroradiometer. This enables the operator to cross-calibrate the on-line sensors against a traceable standard via the Sola-Check.

This system can be connected to a PLC or PC to provide automatic continuous monitoring and control of one, or several fiber process machines. The advantage is that it provides completely automatic moitoring of the UV lamps, and can be programmed to provde warning and alarms of UV lamps operating outside defined limits. The following graph is a typical plot of the output from an ARAD100 on-line sensor. It clearly demonstrates the decreasing UV output during a fibre draw.

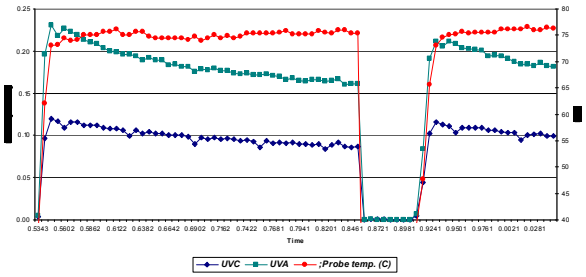


Figure 10 – time series of UVC and UVA showing decreasing UV output during a fibre draw

6.7 Calibration

All of the UV spectroradiomter systems described are calibrated according to the same methods. Although at the time of writing there are no international standard methods of calibrating UV

Spectroradiometers (neither is there for UV radiometers) the steps used can be summarised as:-

1. Define geometry of light sources and the collection optics to be involved in the calibration and field measurement
2. Perform wavelength calibration using Mercury and other 'pen-ray' lamps
3. Perform system response 'shape' characteristics calibration using special smooth continuum lamps (especially Deuterium & tungsten lamps) traceable to national standards
4. Set final overall level, at representative power level e.g. Curing Lamp (undoped Mercury medium/high pressure preferred) – for industrial applications

There is a growing body of work [1][2] in the international arena to move towards standardisation of UV measurements, particularly with the use of spectroradiometers which do not suffer from the disadvantages of radiometers outlined in section 6.2

7 Practical application of spectroradiometers in a production environment

The above described spectroradiometer instruments and high temperature probes have been in use in the various applications in the UV radiation curing industry for several years. During that time ways have needed to be found to make measurements as easy and error free as possible, but with such instruments, UV probes, and probe locators it is possible to :-

- Collect UV spectral data regularly with date and time stamping
- Position spectroradiometer / probe combination in the same place each time a reading is to be taken
- Compare calibrated readings
- Compare intensity with pre-established baseline data
- Check lamp spectra are correct
- Check short/long wavelength ratios – *see figure 7*

By following this discipline it is possible to diagnose a situation where a UV process is failing to cure, and decide if there is a lamp issue, or whether one need to look somewhere else for the cause of the problem.

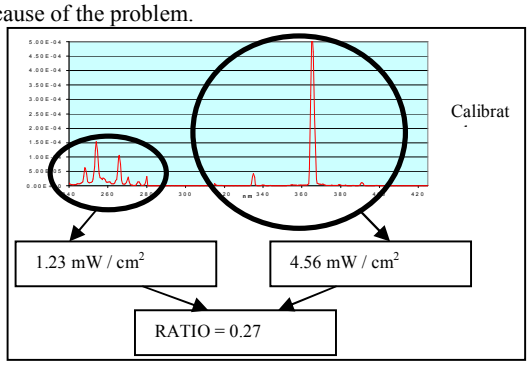


Figure 10 - integrate power in two ranges

Figure 10 shows how different parts of a typical UV spectrum from a curing lamp can be compared as a ratio between short wavelength and long wavelength data to form a ratio between the two. Should the short wavelength power fall off as a ratio of the long wavelength power then the bulb may be nearing the end of its life, particularly if it is an arc lamp, may be dirty, may have a dirty reflector, or contaminted quartz tube.

In addition to lamp diagnostics, it is possible by following a rigorous calibration process with UV Spectroradiometers [1] to allow valid comparisons using absolute power measurements (over specified waveranges) to be made between lamps, between different lamps system or machines, between different processes and between different plant locations. Such absolute calibration ability also points the way for new and better methods of process specification.

8 Examples

There now follow some examples of data collected from real UV lamp systems used in the fiber process industrieis. The typical application is in fiber coloring. In each case we are monitoring 'D' type bulb (as shown in Figure 2 spectral plots). As described above, we can integrate using a UV spectroradiomter over a defined specal range. We have defined two spectral ranges 300 to 425nm (A1), 280 to 320nm (A2), and also have plotted the behaviour of one specific Mercury line, that at 313nm. The traces have been normalised to show their behaviour one against another.

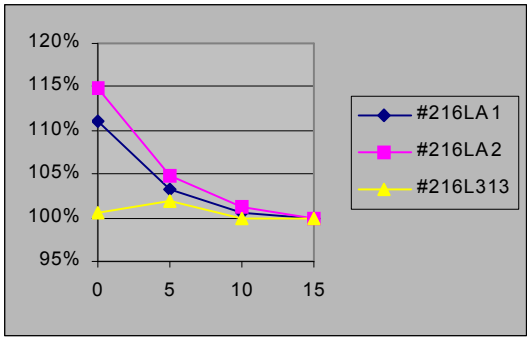


Figure 11 – typical D bulb cold start-up

Figure 11 shows a typical lamp startup recorded automatically every 5 minutes. The 100% normalisation level has been set at 15 minutes since the lamp is turned on from cold. It is interesting to note that the total UV spectral output in A1 and A2 start at a higher level, approximately 10 to 15% above their settled level, and take about 10 to 15 minutes to settle to steady state. The 313nm spectral line, being derieved from pure mercury settles to its 100% level much faster. This phenomena can be explained by the different behavuour of the pure mercury and the additives in the D bulb which modify the spectral distribution of the bulb ouput. The D bulb is more input power and envelope temperature dependant than a straigthforward mercury H bulb, as we noted above.

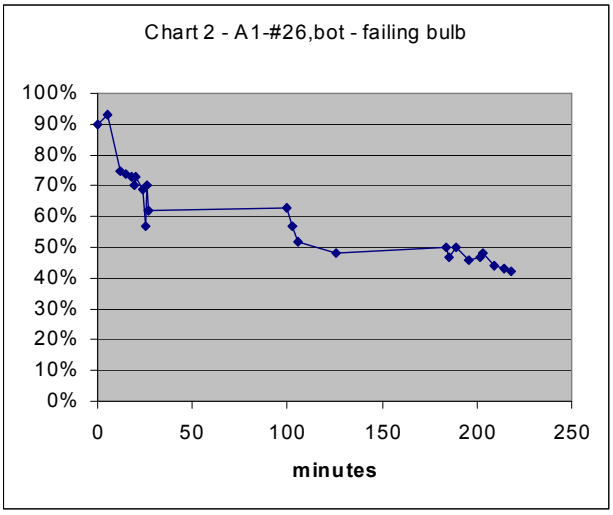


Figure 12 – failing bulb due to overheating (inadequate airflow)

If we have a faulty bulb –in this case due to lack of airflow – the bulb overheats and fails quite rapidly. In this case we can see with three sucessive coloring runs that the bulb deterirates each time it is used, falling to below 50% of its original power level when monitoring started.

After this was noticed, the bulb was changed for a new one, the lamp system serviced and then run again, and chencked more frequenlty, as shown in Figure 13.

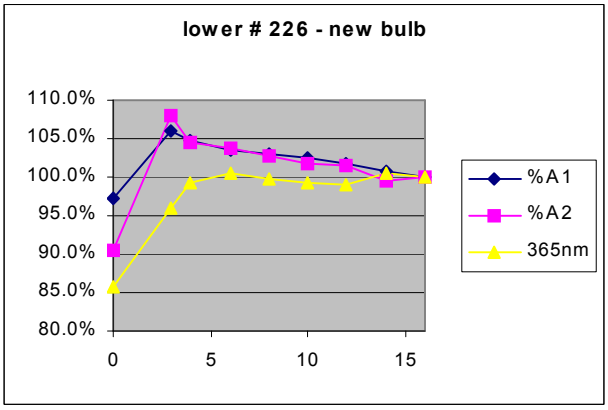


Figure 13 – new D bulb start up

Figure 13 has sampling points collected more freqnetly (every 2 minutes) and shows the different behaviour more clealry of the mercury and addtitive performance after start up. The initial sample point is taken almost immediately after turn on so the microwave lamp's very rapid turn on behaviuous is exhibited very well.

9 Conclusions

Such UV spectral measurement instrumentation as described in this paper is increasingly being used throughout the fiber process industries to reduce uncertainty about the quality of the UV power being delivered to the process during manufacture. Regular, accurate manual UV spectral measurements, and automatic on-line monitoring have shown themselves to be worthwhile activities across many manufacturing sites, and during process development.

10 References

1. '**Accurate, High Power UV Spectral Measurement**'– Andrew Ridyard, 4D Controls Ltd. RadTech USA 2000 (Baltimore) proceedings.

2. '**Reliable Spectroradiometry**' - Henry J. Kostkowski, published 1997 by Spectroradiometry Consulting, MD, USA. ISBN 0-9657713-0-X

3. '**A UV lamp spectral measuring multi-point on-line monitoring system for Radiation Cured processes**' – Andrew Ridyard, 4D Controls Ltd. RadTech USA 98 (Chicago) proceedings.