Safety Standards Applicable to the Installation of Fiber Optic Probes and Flow Cells in Potentially Explosive or Incendive Processes

and

How they Apply to Guided Wave's SST Probes and Multipurpose Flow Cells

GUIDED WAVE (GWI) manufactures and markets numerous fiber optic cables, probes and flow cells for use in process environments which often involve explosive or combustible solids, liquids, and gases. For all practical purposes these devices are intrinsically safe (IS) when deployed using incoherent sources. However, two standards have been created that apply to the deployment of such devices. These are international standard IEC 60079-28 "Explosive Atmospheres - Part 28 Protection of Equipment and Systems Using Optical Radiation"[1] and ANSI/ISA 12.27.01-2003 "Requirements for Process Sealing Between Electrical Systems and Flammable or Combustible Process Fluids"[2]. This note will show that under normal operating conditions, Guided Wave's SST[3], O-SST[4] and Multipurpose Flow Cells[5] meet the requirements of both of these standards.

Guided Wave's fiber optic coupled probes and flow cells are used with either a spectrometer or photometer to measure spectral features of process fluids. The spectral features are then analyzed to determine the chemistry or physical properties of the stream under test. These measurements are typically done on line, in real time with the SST style insertion probe inserted directly into a process pipe or reactor or with the process diverted through a loop to a flow cell. The wetted part of the probe or cell is in direct contact with the sample as is the optical beam which is transmitted through the sample. The external part of the probe is exposed to the surrounding process environment which may be classified as hazardous as well. While under normal conditions, the optical beam is not in direct contact with this external environment unless a break in the fiber (a fault) occurs.

First, it must be stated that the probes and fibers themselves are intrinsically safe containing no electrical hazards. It is only when they are connected to an analyzer that light enters the fibers and is transmitted to the probe tip. Hence if hazardous body certification (ATEX, UL, CSA, IECEx, etc.) is required, it must be done in conjunction with the analyzer. Guided Wave probes have been used with Guided Wave's near infrared (NIR) spectrometers (Model 412, Lab 412, and NIR-O) and photometers (ClearView db) as well as instruments manufactured by others. Most often these third party analyzers are Fourier Transform near infrared (FT-NIR) spectrometers. All of these analyzers use incoherent sources, typically tungsten-halogen light bulbs that operate on the principles of blackbody thermal radiation.

Light from the source lamp is typically imaged into the end of the optical fiber which transmits it to the probe. The probe then sends a collimated beam of light through the sample and injects it back into a fiber which returns the radiation to the analyzer where it is detected. For grating spectrometers, the light may be dispersed prior to entering the fiber (pre-dispersed) or after it returns from the probe (post-dispersed). In the pre-dispersed case (GWI's Model 412), monochromatic light is sent to the sample. We will not analyze this case as it is trivial in comparison to the post-dispersed case where white (broadband) light is sent to the sample (GWI's NIR-O Spectrometer) which we will discuss.

For FT-NIR spectrometers, the light is encoded via an interferometer which also may pre- or post-encoded. In most cases, FT's are pre-encoded to reduce stray light interference. In both cases, however, broadband radiation is sent to the probe. We will investigate pre-encoded case as it is the most common.

In most cases photometers also fall in the post-dispersed configuration with white light being sent out. We will not specifically discuss photometers since they are not significantly different than the two cases above.

We will first examine the IEC standard and then look at the ISA standard.

IEC 60079-28

The IEC 60079-28 standard was primarily developed for laser sources which can deliver significant energy into a fiber optic cable. For these discussions, we are going to limit ourselves to incoherent sources, namely tungsten-halogen lamps that operate on the principle of black or gray body thermal radiation as defined by the well-known Planck Equation[6]. The potential hazard is that the light source could provide sufficient energy to ignite a combustible gas, liquid, solid, particle or droplet. Light from an incoherent source injected into a single strand fiber optic cable does not have sufficient energy to ionize any target, hence the only possible mechanism is thermal heating via absorption of the radiation associated with the hazardous material or any other material in the beam. Some materials are broadband absorbers hence could absorb all wavelengths impinging on them. Others have selective absorption bands and broad regions of spectral transparency. For these calculations, the former case is assumed.

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It should also be pointed out that light from the end of a fiber optic cable diverges quite rapidly, thus the energy density decreases significantly with distance. In most cases, fiber optic cables used for process spectroscopy have a numerical aperture (N.A.) of 0.22 which means the light diverges in a 25° cone angle[7]. Thus any hazard decreases rapidly with distance.

For the probe or flow cell to be classified as intrinsically safe per the standard, the optical energy density must be below 5 mW/mm^2 at the point of interaction with the hazardous medium or sample. For both probes and flow cells, the sample flows between two windows, typically made of sapphire. In the region between the windows, a collimated beam of light transits the sample where some or all of the light is absorbed by the sample. For GWI's probes and flow cells this collimated region is approximately 5 mm in diameter. Where the light exists the first sapphire window, the power density must be below the 5 mW/mm^2 requirement.

Let's start at the light source. The source most FT-NIR spectrometers and for GWI's spectrometers is an incandescent lamp whose filament is made of tungsten. The filament is usually maintained near 2800 K. However, to use the worst case scenario, we will assume the lamp is operating at it absolute maximum of 3683 K which is the melting point of tungsten[8]. The power density by a thermal source is given by the Stefan-Boltzmann Law[6] which is:

$$R_e = \varepsilon\sigma T^4$$

Where R_e is the radiant exitance in W/m^2, ε is the emissivity, σ is the Stefan-Boltzmann Constant (5.67×10^{-8} $W/m^2/K4$)[8], and T is the source temperature in K. For tungsten, the emissivity has a maximum of 0.45[9]. Thus for a 3683 K source, Re = 4.69 W/mm^2. From the radiant exitance, we can calculate the radiance (L) which is the power per unit area per unit solid angle or steradian.

$$L = R_e/\pi$$

Hence our source radiance is L = 1.49 $W/mm^2/sr$.

This is the common source for FT-NIR and grating spectrometers. The calculations will now take two paths, one for each instrument. Pre-encoded FT-NIRs, lose half the light in the interferometer. The source optics will also attenuate the beam due to reflection and transmission loses but these values are unknown and depend on the optical geometry of the instrument. Hence the worst case radiance for the FT is L_{FT} = 0.76 $W/mm^2/sr$.

For GWI's NIR-O spectrometer, we know the source optics design. The beam transits through a long pass filter with an efficiency of 80% and through eight (8) other optical surfaces each with an efficiency of 96%. Thus the source is attenuated by $0.8 * 0.96^8 = 0.58$. Therefore the grating instrument radiance is L_g = 0.86 $W/mm^2/sr$.

The amount of light that enters the fiber is determined by the étendu of the fiber. Étendu is frequently referred to as the A·Ω product, where A is the cross sectional area of the fiber and Ω is the acceptance solid angle of the fiber. For the area of the fiber we again have two cases. Typically FT-NIR spectrometers use a 600 µm diameter fiber while GWI uses 500 µm diameter fibers. Both fibers have an N.A. of 0.22 which defines the acceptance solid angle. N.A. is the sine of the half cone angle, θ. The solid angle is defined by the equation:

$$\Omega = 2\,\pi\,r\,(1 - \cos(\theta))$$

For a unit circle, r = 1. Using a standard trigonometric identity and using the definition of the N.A., this equation becomes:

$$\Omega = 2\,\pi\,(1 - (1 - \sqrt{(1 - N.A.^2)}))$$

For both fibers, Ω = 0.154 sr. Thus for these two fiber choices, the étendu is $A\cdot\Omega_{600}$ = 0.044 $mm^2\cdot sr$ and $A\cdot\Omega_{500}$ = .030 $mm^2\cdot sr$.

The total power, Pt, entering the fiber is the product of radiance and étendu of the fiber. Thus

$$P_{tFT} = L_{FT} \cdot A\cdot\Omega_{600} = 32.5 \text{ mW}$$

$$P_{tg} = L_g \cdot A\cdot\Omega_{500} = 26.1 \text{ mW}$$

There is one last correction that must be applied. Fused silica fiber attenuates all radiation beyond 2300 nm quite strongly, > 1000 dB/km over 90% attenuation for a 10 m fiber run. We will assume the FT-NIR transmits all light from the visible to this wavelength. Integrating the Planck Equation from UV to 2200 nm for a 3683 K source gives us only 87.5% of the total energy, thus P_{tFT} = 28.4 mW. The same long wavelength cut off also applies to the grating spectrometer but as we noted above, there is a long pass filter in the beam. This filter cuts off all radiation below 950 nm. Thus the integral is only from 950 nm to 2200 nm which is about 48.5% of the available light. Thus the power in the grating spectrometers fiber is P_{tg} = 12.7 mW.

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Assuming the fiber is lossless to the probe, we can know calculate the energy density in the optical beam through the sample. The beam for both SST probes and flow cells is about 5 mm in diameter, hence the power density (power per unit area) is:

$L_{pFT}(3683\ K) = 28.4\ mW/19.6\ mm^2 = 1.45\ mW/mm^2$

$L_{pg}(3683\ K) = 12.7\ mW/19.6\ mm^2 = 0.66\ mW/mm^2$

Recall that the intrinsically safe power density is 5 mW/mm^2. Obviously both cases meet the specification as IS at the sample interface for this worst case scenario.

Had we used a more realistic blackbody temperature of 2800 K the values would have been:

$L_{pFT}(2800K) = 0.43\ mW/mm^2$

$L_{pg}(2800K) = 0.28\ mW/mm^2$

Both cases at this realistic temperature are an order of magnitude below the safe value.

One other aspect of the IEC standard is that the total power in the fiber be below 35 mW in case there is a break in the fiber. Again for the worst case scenario, the total optical power in the fiber is P_{tFT} = 28.4 mW and P_{tg} = 12.7 mW, both well below the 35 mW requirement. For a 2800 K lamp, these values drop to 9.4 mW and 5.4 mW respectively. ***Thus we can conclude that GWI's SST probes and flow cell satisfy the IEC 60079-28 standard for inherently safe (op-is) operation when used with a pre-encoded FT-NIR spectrometer or GWI's post-dispersed NIR-O spectrometer even in the case of two faults, lamp over voltage to burnout and a broken fiber or failed conduit.***

ANSI/ISA 12.27.01-2003 Requirements for Process Sealing Between Electrical Systems and Flammable or Combustible Process Fluids

ISA 12.27.01-2003 basically calls for a secondary seal between the primary process seal and any conduit connections to the probe. This is to prevent process fluid from migrating into the conduit system should the primary seal fail. For GWI probes and flow cell, the primary seal is at the sapphire windows. This seal may be an o-ring or a gold alloy braze between the window and the stainless steel probe body.

In the case of the SST probe and the O-SST probe, the fiber exits the probe at an SMA connector. These connectors are sealed to the probe body by either o-rings or adhesives. Both probe designs have had this seal mechanism tested to greater than 3 times the probe's pressure rating. Thus the sealing method qualifies as a secondary seal under the ISA standard.

The construction of the flow cells is different. The primary seal is a double set of o-rings on the sapphire windows. The windows are held in place by the lens holders. Each lens holder has o-rings that provide a seal between the lens holder and the cell body plus an o-ring around the lens itself. This combination makes up the secondary seal. It too has been proof tested to greater than 3 times the pressure rating of the cell.

Hence GWI's SST probes and O-SST probes plus GWI's Multipurpose Flow Cells meet the ANSI/ISA dual seal requirement.

References:

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