Taking Optical Probes  
into Harsh Environments

The need for optical probes to monitor industrial processes and machinery is undeniable. The question is: How do you protect them from the harsh operating conditions that have barred their use up until now?

**Michael Pollack  
Stephen C. Bates**

**O**ver the last 10 years, the growing use of optical probes and borescopes has increased production yields and enabled the maintenance of processing equipment during the production cycle (see Photo 1). Temperature, pressure, and harsh chemicals commonly used in industrial processes, however, degrade conventional probes quickly. To extend a probe’s life and expand its capabilities in harsh environments, one option is to use a sapphire-window protective shroud.

To appreciate the benefits of these shrouds and the value of sapphire in this application, it helps to understand how standard optical sensors are being used to control and inspect processes involving harsh environments. For example, endoscopes allow remote inspection; optical pyrometers measure temperature; and fiber-optic spectrometers measure chemical composition. New developments in fiber optics are being used to diagnose chemical and physical properties in various process systems. Process instrumentation sensors must be simple and rugged, but standard probes traditionally require relatively clean and mild environments, which greatly limits their usefulness in industrial processes.

**Challenges of Industrial Environments**

|  |
| --- |
| A metal object on a red surface  Description automatically generated |
| **Photo 1.**  Air cooled protective shroud with noble metal brazed sapphire window to 316 stainless steel housing makes it possible for borescopes and optical sensors limited to 100°C to be used in environments with temperatures as high as 600°C. |

**Challenges of Industrial Environments**

Industrial processing involves tremendous variations in the work environment, so diagnostic probes must be able to withstand a wide range of conditions. The basic parameters include:

• Pressure: vacuum of 10-10 torr to pressures of 20,000 psi

• Temperature: 2000ºC to –270ºC

• Chemical: process chemicals that include corrosive acids and bases (e.g., HF to NaOH)

Multiphase flow is also common in many forms, leading to a variety of additional optical and mechanical constraints.

Industrial temperature monitoring, which is the most common diagnostic parameter of interest, is performed by thermocouples and RTDs or by optical pyrometry in extreme cases. Temperature-related degradation mechanisms include:

• Thermal shock

• Thermal cycling

• Thermal stress

• Thermal fatigue

• High heat fluxes

All these factors must be considered in elevated temperature design.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Today’s off-the-shelf in-process probes have limited capabilities. Because the probes use seals made from epoxies, glues, rubbers, or plastics, they can operate only in temperatures from –50ºC to 150ºC, and the probes can’t function in chemically corrosive environments. Fragile optics often limit pressure tolerance to <100 psi, which in turn limits mechanical handling. Abrasive environments and processes that have sediment buildup must also be avoided to prevent obstructing the viewing window or fouling the sensing probe.  Corrosion is a pervasive and complex problem. High temperatures, pressure, and stress accelerate corrosion, speeding the degradation of probes. Stray electrical potentials and dissimilar metals (galvanic reaction) can also induce corrosion. Although oxidation is the most common form of high-temperature corrosion, nitridation, carbonization, and sulfidation are becoming more common in the chemical and microelectronic industries.  The chemical processing industry functions under different constraints than do other industries. A probe’s environment rarely consists of only the gas phase because the mass flows are too small to generate large amounts of product. Often the chemical conditions are harsh, and the fluid flow consists of two and three phases (e.g., solid, liquid, gas). These flows are difficult to diagnose externally and can generate high heat flux, corrosion, and erosion problems.  The chemical environment and temperature are crucial factors. The most common processes are powder processing and boiling liquid; both continually spread small particles throughout the flow. Optical access to these processes is also a common need, as is sampling, although nonintrusive sensing is the current trend.  **Conclusions**  There are a wide variety of commercial probes that could make a major contribution to industrial process control if they could survive the harsh environments of typical processes. Gas-cooled probe shrouds can cost effectively accomplish this. Probe shrouds allow standard, affordable probes to operate in high-temperature, high-pressure, or reactive environments. Gas-cooled designs offer major advantages over water-cooled designs in that they can directly cool and clean the probe tip (see the sidebar “New Features,”).     |  | | --- | | **Heat Transfer Parameters** | | Two methods of heat transfer—convective and radiant—regulate a probe’s temperature in a gas-cooled sapphire shell. Convective heat transfer will dominate the heat transfer to the probe shroud at low temperatures when a fluid at higher temperatures flows past the probe. For laminar flow, the heat transferred to a fluid from a flat plate is defined:  q/A = h(T) (1)  where: q = rate of heat transfer A = unit of surface area h = heat transfer coefficient T =temperature difference between the fluid and the surface of the shroud  The heat transfer coefficient, h, has been defined experimentally:  h = Nu(k/L) (2)  where: Nu = a Nusselt number k = thermal conductivity L = flow length  Different flow and fluid regimes are defined by the dependence of Nu on flow parameters, such as the Reynolds number:  ReL = uL/µ (3)  and the Prandtl number:  Pr = cpµ/k (4)  where:  = fluid density cp = specific heat u = fluid velocity µ = fluid viscosity  It’s not necessary to derive these numbers experimentally because many correlations exist that give Nu for different geometries and fluids. At high temperatures (above ~800ºC) radiant heat transfer becomes the dominant mechanism for heat transfer—in this case, between hot walls and protruding probes. Above this temperature, for every 200ºC temperature increase, blackbody radiation heat loads increase by a factor of 2. Radiation heat loss is defined fundamentally by the Planck function:  eb(,T) = 2phc2/[5(ec2/T – 1)] (5)  where:  = wavelength c1, c2 = constants T = absolute temperature e = speed of light in a vacuum h = Planck’s constant eb = emissivity of a blackbody  which describes blackbody radiation—a body that absorbs all incoming radiation.  The intensity of this radiation in watts,W, as a function of wavelength is described as:  W(l,T) = [c/(5)(ec/T–1)] (6)  Overall radiated power of a blackbody at temperature, T, is given by the Stefan-Boltzmann function:  Wtotal(T) = 5.679 ¥ 10–12 (T4)(W/cm2) (7)  The T4 dependence of the radiated power accounts for the dominance of radiation at high temperatures. For real materials, the total radiated power differs from that of a perfect blackbody by the total emittance, et, such that:  Wreal(T) = et(T)Wblackbody(T) (8)  Total emittances are integrals over wavelength of detailed emissivities that are also wavelength dependent. Total emittances can be quite low, but usually depend strongly on temperature, increasing with temperature. The theoretical descriptions of the optical constants of solid, pure materials are reasonably well known, but the optical properties of materials at high temperatures have not been extensively measured and have to be derived experimentally for specific materials.  Two methods of heat transfer—convective and radiant—regulate a probe’s temperature in a gas-cooled sapphire shell. Convective heat transfer will dominate the heat transfer to the probe shroud at low temperatures when a fluid at higher temperatures flows past the probe. For laminar flow, the heat transferred to a fluid from a flat plate is defined:  q/A = h(T) (1)  where: q = rate of heat transfer A = unit of surface area h = heat transfer coefficient DT =temperature difference between the fluid and the surface of the shroud  The heat transfer coefficient, h, has been defined experimentally:  h = Nu(k/L) (2)  where: Nu = a Nusselt number k = thermal conductivity L = flow length  Different flow and fluid regimes are defined by the dependence of Nu on flow parameters, such as the Reynolds number:  ReL = ruL/µ (3)  and the Prandtl number:  Pr = cpµ/k (4)  where: r = fluid density cp = specific heat u = fluid velocity µ = fluid viscosity  It’s not necessary to derive these numbers experimentally because many correlations exist that give Nu for different geometries and fluids. At high temperatures (above ~800ºC) radiant heat transfer becomes the dominant mechanism for heat transfer—in this case, between hot walls and protruding probes. Above this temperature, for every 200ºC temperature increase, blackbody radiation heat loads increase by a factor of 2. Radiation heat loss is defined fundamentally by the Planck function:  eb(l,T) = 2phc2/[l5(ec2/lT – 1)] (5)  where: l = wavelength c1, c2 = constants T = absolute temperature e = speed of light in a vacuum h = Planck’s constant eb = emissivity of a blackbody  which describes blackbody radiation—a body that absorbs all incoming radiation.  The intensity of this radiation in watts,W, as a function of wavelength is described as:  W(l,T) = [c1/(l5)(ec/lT–1)] (6)  Overall radiated power of a blackbody at temperature, T, is given by the Stefan-Boltzmann function:  Wtotal(T) = 5.679 ¥ 10–12 (T4)(W/cm2) (7)  The T4 dependence of the radiated power accounts for the dominance of radiation at high temperatures. For real materials, the total radiated power differs from that of a perfect blackbody by the total emittance, et, such that:  Wreal(T) = et(T)Wblackbody(T) (8)  Total emittances are integrals over wavelength of detailed emissivities that are also wavelength dependent. Total emittances can be quite low, but usually depend strongly on temperature, increasing with temperature. The theoretical descriptions of the optical constants of solid, pure materials are reasonably well known, but the optical properties of materials at high temperatures have not been extensively measured and have to be derived experimentally for specific materials. |   **of Protective Shrouds**  Cost-effective, rugged protective shroud shells make it possible for you to use standard probes in harsh environments, greatly expanding the availability of sensing techniques for process control. Increased diagnostic capabilities lead to better process control. You can use one probe shroud with multiple diagnostics, and commercial availability of these shrouds allows more cost-effective, safer, and **Benefits** simpler upgrades of probes already in use. Internal and external gas flows provide simple, stable, and inexpensive cooling, insulation, and surface cleaning. Special materials and coatings provide corrosion protection and additional thermal protection. Insulation and cooling provide complete thermal protection. Fluid jets at the probe tip prevent the process from fouling the sensor inputs.  An optical shroud must consist of a corrosion-resistant body hermetically sealed to a window at the end of the shroud. An ideal shroud is an inexpensive and rugged shell, marginally larger than the probe, that provides auxiliary sensing. The shroud design must address the problem of operating temperature and heat flux to the shell. Other concerns are the operating temperature of the probe, the internal diameter of the shroud, and the outside diameter of the enveloped probe. The type of access to the environment and how the shell is cooled are also important. External constraints consist of the port size, directness of the access, reactivity and temperature of the environment, period of use, and optical requirements.  The shroud material not only has to survive the environment, but it has to be compatible with the thermal expansion of the window and the joining or sealing technique. Possible window material candidates are sapphire, glass, quartz, and diamond. Sapphire’s physical strength, chemically inert characteristics, andoptical properties are desirable when a probe is used under hostile conditions.    **The Sapphire Advantage**   |  | | --- | | A graph with a red line  Description automatically generated | | **Figure 1.** Sapphire windows that are 0.080 in. thick permit safe operation at pressure loads from 100 to 6000 psi over diameters ranging from 2 to 0.25 in. (A). Sapphire windows of 0.0500 in. dia. resist pressures from ~100 psi at 0.020 in. thickness to ~7500 psi at 0.200 in. thickness (B). |   Synthetic sapphire windows brazed to a mounting fixture for viewports into high-temperature or high-pressure environments offer many advantages. Sapphire with an optical finish can be brazed into a variety of sealing flanges that incorporate either a weldable seal or metal ring seal for pressure vessels. New bonding and brazing techniques permit the use of a wider choice of body materials, such as stainless steel, Hastelloy, and high-purity alumina ceramic.  Sapphire provides superior electromechanical, thermal, and chemical properties compared with glass or quartz. Sapphire’s properties include extreme hardness, high strength, good thermal characteristics, and chemical inertness. On the Mohs scale of hardness, which assigns a unit of 10 to diamond, sapphire is rated at 9, quartz at 7, and glass at 4.5–6.5. In contrast to other available light-transmitting materials, sapphire offers maximum resistance to abrasion and scoring. It also provides a durable surface with a low coefficient of friction that minimizes the accumulation of undesirable bubbles and process scum.  The compressive strength of sapphire is 300,000 psi, nearly double that of quartz. Its modulus of elasticity (Young’s modulus) is 50–56 at 106 psi—five times that of quartz. Sapphire is an ideal material for windows that must withstand great pressure or vacuum. Empirical hydrostatic burst data for sapphire (which includes a safety factor of 3) has been calculated for circular window diameters from 0.125 to 2.000 in. and over a range from 0.020 to 0.200 in. thick (see Figure 1).  Three E Labs, Inc., and Thoughtventions Unlimited have developed enhanced sapphire windows with mounts that extend these parameters greatly. Windows 0.020 in. thick by 3.5 in. in diameter have been failure tested to >5 atm.   |  | | --- | | A diagram of a uv light  Description automatically generated | | **Figure 2.** The approximate transmission bands of standard- and UV-grade sapphire are plotted for a window thickness of 0.039 in. |   Sapphire’s melting point of 2040ºC lets it survive in a wide range of thermal environments. Very thin sapphire windows don’t break, even when operating at 400ºC and sprayed with water. Sapphire’s chemical inertness in the presence of a wide variety of reagents at temperatures greater than 1000ºC make it ideal for chemical industrial applications. For example, silica becomes soluble in hydrofluoric acid at room temperature, but sapphire exhibits no solubility in alkalies or acids, including hydrofluoric acid. At elevated temperatures, other acids (e.g., hydrochloric acid and nitric acid) attack silica, but not sapphire.  The sapphire used in shrouds comes in standard and UV grades. The standard grade of single-crystal synthetic sapphire provides an optical transmission >80% from a wavelength of 0.25 nm in the UV range to the visible range of 0.4–0.7 nm in the IR range. Figure 2 (page XX) shows the transmission band of a window 0.039 in. thick. In the 0.3–0.4 nm UV range, standard-grade windows up to 0.39 in. thick provide a uniform transmission of 85%.  The perfection and purity of the UV-grade sapphire crystals offer a transmission capability superior to that of standard-grade sapphire. For example, measurements of ultraviolet light transmission through a 0.39 in. thick window vary from 75% to 80% at a wavelength of 0.19nm to ~85% at 0.27 nm. The upper limits of transmission specified for UV-grade sapphire at a wavelength of 0.20 nm range from 70% for a window 1.6 in. thick to 60% for a window 3.5 in. thick.  Unlike the various IR grades of silica and glass, sapphire is free of intrinsic absorption bands and permits an optical transmission >85% in the 1–4 nm IR wavelength. The strength of sapphire permits the use of thin windows. A transmission of 75% can be obtained for a 0.39 in. thick window at a 5.5 nm wavelength, and at 6 nm, the transmission is 50%.  Many optical sensing applications require IR transmission, especially for thermal optical sensing. Most broadband IR window materials don’t tolerate even moderate temperatures and are hygroscopic at high temperatures. As they absorb water, they become less efficient at transmitting IR light. The use of sapphire avoids these problems. Sapphire’s lower surface scattering losses at IR wavelengths also translate into less rigorous surface finish requirements. This allows sapphire to be priced competitively for use in commercial and experimental applications.   |  | | --- | | **New Features** | | Focused Sapphire Fiber-Optic Probes. New fiber-optic probes from Three E Laboratories feature integral focusing onto a protected fiber tip behind a brazed sapphire window. The new FOCUS-PROBE offers a maximum light collection for sensitive optical detection combined with durable environmental protection. Probe tips can be designed for parallel beam, wide area, or focused spot detection. Typical uses for the new probe tips include inline spectroscopic monitoring of chemical process furnaces and temperature monitoring. The new probes incorporate high-purity sapphire rods as light carriers, which permit their use in corrosive, high-temperature, and high-pressure environments.  Probe-Cam. Instead of using a long and expensive lens train to gain video access to a high-temperature site, a protective cooled shroud allows a camera to be placed at the site. This eliminates the need for a long lens train, which not only saves money but also allows the camera to operate under lower light conditions. Miniature video cameras offer an inexpensive way of placing a wide viewing angle in a processing chamber.  Multisensor Probes. You can also use a protective shroud to house multiple probes. This saves you money by reducing the number of shrouds needed to protect all the probes in the sensing system. A multiple probe shroud also requires only one port into the chamber to accommodate several sensing probes, greatly reducing installation costs and increasing reliability.  Low-Absorption Window Shells. Sapphire windows are offered as thin as 0.013 in., resulting in low absorption beyond the normal bandwidth of sapphire. The windows can survive high pressures for apertures greater than 1 in. in diameter. |   **Sealing Design**  A critical aspect of joining windows to probe shells is how the seal withstands cycling between room and operating temperatures without degradation. Three E probes and shrouds have been successfully tested at 600ºC for hundreds of cycles, and newly developed brazing techniques are available for operating temperatures to 750ºC.  It’s important to align the c axis (i.e., the axis parallel to the growth direction of the sapphire bohle) of a sapphire window with the probe axis to avoid nonuniform expansion and to minimize optical birefringence.  Thoughtventions is developing sealing techniques for use at temperatures above 1200ºC. Glass frits that bond sapphire to sapphire have been consistently cycled to 1200ºC. Sapphire-to-alumina seals have been developed to decrease the cost of probe shells with ceramic exteriors.  Requirements above 1200ºC can be met by the use of probe tips made entirely of sapphire. This design is in limited use because of the expense involved in the machining of sapphire in small quantities. As the need for higher production quantities grows, these costs should come down.  **Probe Shell Cooling Design**   |  | | --- | | A diagram of a liquid tube  Description automatically generated | | **Figure 3.**This diagram depicts a typical water flow design that has been used in various temperature extremes, high pressures, and chemically abusive environments. | | A diagram of a liquid tube  Description automatically generated | | **Figure 4.**An important factor in internal cooling design is to keep the thermal boundary layer between the inner wall of the shroud and outer wall of the probe separated by the moving coolant. Doing this significantly adds to the effectiveness of heat removal. |   The heat transfer to a shell is determined by external fluid and radiant surface parameters. The capacity for shell cooling is determined by the:  • Penetration length required  • Linear shape of the probe  • Shell’s outer diameter  • Probe’s outer diameter  • Flow path and turning geometry  • Internal supporting structure  • Pressure supplied to the cooling fluid  • Roughness of the internal surfaces  Two basic coolant fluids are water (see Figure 3) and air (see Figure 4), but other fluids are also used. Inert gases (e.g., nitrogen and argon), which can be recirculated, may be considered in cases in which oxygen will lead to corrosion. Gaseous helium is an excellent cooling fluid because of its superior heat transfer properties and its chemical inertness. Steam is also outstanding as a gas coolant at higher temperatures, with the advantage of the great amounts of heat that can be removed outside the probe by condensation. Water is such a superb and common fluid that it is recommended for most liquid-cooled applications. Water can induce corrosion, but there are many corrosion inhibitors available. Other fluids with a higher boiling temperature can be used in high-value applications where water flow is inadequate.  Industry uses water cooling as a standard practice with probes inserted into hot environments. Manufacturers add cooling shrouds to basic probes to send and return water to the end of the probe. The volume of water flow is determined by the maximum possible heat flux that must be absorbed and carried away by the water, plus a large safety factor is desirable to avoid boiling thermal runaway.  The problem of boiling thermal runaway for water-cooled probes begins when a local hot spot develops. If the heat flux generated at the spot is greater than the cooling rate of the liquid, the extra heat will vaporize some of the liquid and create a bubble. The bubble immediately lowers the heat transfer at the hot spot. Boiling is an even more severe problem for the internal coolant flow in a shroud. Here the formation of a vapor bubble creates a high local pressure that blocks the internal flow, sometimes leading to a catastrophic failure of the entire system.  An attractive alternative is gas cooling.A basic gas cooling design for an optical probe, as shown in Figure 4, consists of three concentric tubes:  • A small-diameter outer trace tube at the end of the shell to supply and contain a flow for tip cleaning/cooling  • An outer shroud shell tube with a thin window sealed on the end  • An internal flow separator tube  At the center of the shell, the probe defines the inside of the outward flow channel. The tubes are sized to provide enough flow for cooling.  Gas cooling is a thermally stable process. When a local hot spot occurs, the heat transfer from the hot spot simply increases with the temperature difference and the heat transfer to the cooling fluid (see the sidebar “Heat Transfer Parameters,” page XX). Another effect stabilizes the heat transfer for global heating for gas cooling. In this case, the gas temperature increases, its density decreases, and because the mass flow rate must be conserved, the gas must speed up, increasing heat transfer.  **Conclusions**  There are a wide variety of commercial probes that could make a major contribution to industrial process control if they could survive the harsh environments of typical processes. Gas-cooled probe shrouds can cost effectively accomplish this. Probe shrouds allow standard, affordable probes to operate in high-temperature, high-pressure, or reactive environments. Gas-cooled designs offer major advantages over water-cooled designs in that they can directly cool and clean the probe tip (see the sidebar “New Features,”). |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| |  |  |  |  | | --- | --- | --- | --- | | |  |  |  | | --- | --- | --- | |  | [Home](http://www.sensorsmag.com/) | [Contact Us](http://www.sensorsmag.com/contact-us) | [Advertise](http://www.sensorsmag.com/about-sensors) | © 2009 [Questex Media Group, Inc..](http://www.questex.com/) All rights reserved. Reproduction in whole or in part is prohibited. Please send any technical comments or questions to our [webmaster](mailto:sensorswebmaster@questex.com). | | |