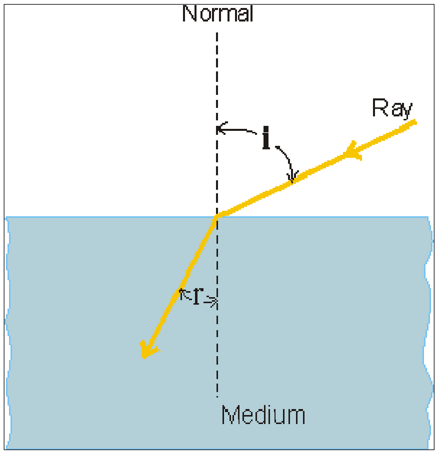

Figure 1: Refraction of light.

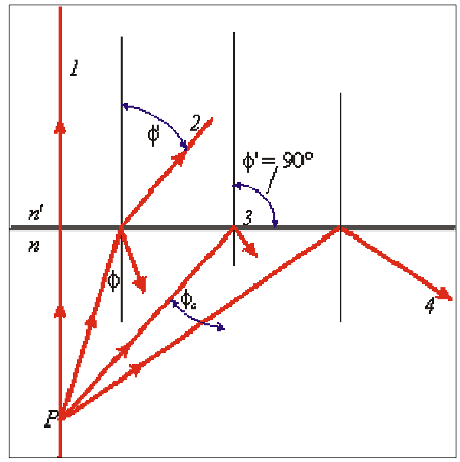

Figure 2: Total internal reflection.

REFRACTIVE INDEX PRINCIPLE

INTRODUCTION

A refractometer determines the concentration of a solution by measuring the optical refractive index. Ernst Abbe is credited with having invented the refractometer in 1874 when he published a description of an apparatus for determining the refractive index of solid and liquid substances.

REFRACTIVE INDEX (R.I.)

The Refractive Index of a transparent isotropic medium may be loosely defined as the "bending" power of the medium for a ray of light obliquely incident on its surface. This bending power is expressed precisely in the form of an equation (Snell's Law).

$$\sin i / \sin r = N_v$$

where i and r are the angles of incidence and refraction (see Figure 1 above) of a beam passing obliquely from a vacuum into the plane surface of the medium. For convenience, it is almost universal practice to refer to air as a standard for refractive indices rather than to vacuum. The refractive index relative to air is denoted by n and is related to N_v by the equation

$$N_v/n = N_{air} = 1{,}00027$$

More exactly, the R.I. is defined the following way: Light travels at different speeds in different media. The denser a medium is, the slower the speed of light in that medium. When light passes from one medium to another at any angle other than 90º it not only changes speed, it also changes direction at the boundary between the two media.

The refractive index (symbolized as n or nD) of a medium is defined as the speed of light in air divided by the speed of light in the medium.

THE CRITICAL ANGLE

K-Patents Process Refractometer utilizes the critical angle of total reflection to measure the refractive index.

Total internal reflection: Figure 2 shows a number of rays diverging from a point source P in a medium of index n and striking the surface of a second medium of index n', where n > n'. From Snell's Law,

$$\sin \varphi' = n/n' \cdot \sin \varphi$$

Since n/n' is greater than unity, sin φ' is always larger than sin φ and evidently equals unity (i.e., φ' = 90º) for some angle φ less than 90º. This is illustrated by ray 3 in the diagram, which emerges just grazing the surface at an angle of refraction of 90º. The angle of incidence for which the refracted ray emerges tangent to the surface is called the critical angle and is designated by φ_c in the diagram. If the angle of incidence is greater than the critical angle, the sin of the angle of refraction, as computed by Snell's law, is greater than unity. This may be interpreted to mean that beyond the critical angle the ray does not pass into the upper medium but is totally internally reflected at the boundary surface. Total internal reflection can take place only when a ray is incident on the surface of a medium whose index is smaller than that of the medium in which the ray is travelling.

Notice carefully that the reflection of light at a boundary surface does not set in suddenly at the critical angle, but that the approach to total reflection is a gradual one. When a ray strikes the boundary surface between two transparent substances at any angle less than critical angle, both reflection and refraction occur.

The critical angle for two given substances may be found by setting φ' = 90° or sin φ' = 1 in Snell's law. We then have

$$\sin \varphi_c = n'/n$$

In Figure 3 we can see the fraction of incident light reflected as a function of angle of incidence. Curve A, index of second medium greater than that of first; Curve B, index of first medium greater than a second.

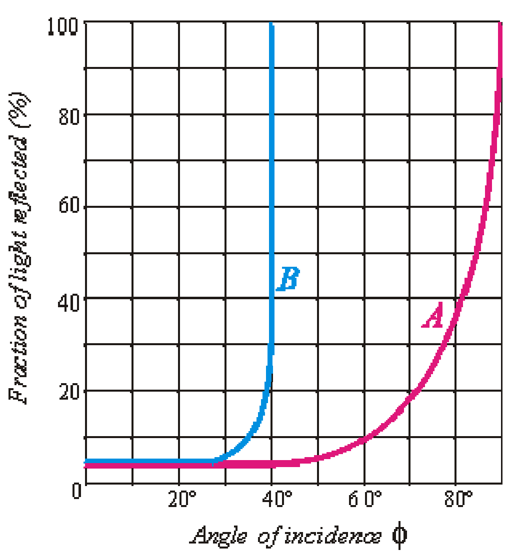

Figure 3: Amount of reflected light

INTERNAL REFLECTION VERSUS TRANSMISSION METHOD

There are two different methods to measure the critical angle:

1. By transmission (light is transmitted through the sample).
2. By internal reflection (light is reflected from the boundary between the sample and the prism).

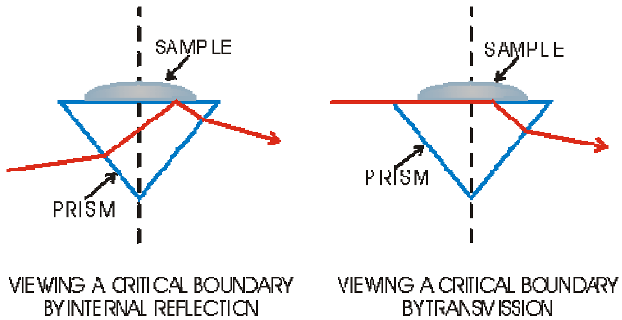

Figure 4: Comparison of Transmission and Internal Reflection Viewing.

IN-LINE MEASUREMENT PRINCIPLE

K-Patents Process Refractometers measure concentrations in-line with the same accuracy as a laboratory refractometer.

The K-Patents in-line refractometer sensor determines the refractive index nD of the process solution. It measures the critical angle of refraction using an LED light source. Light from the light source (L) in Figure 5 is directed to the interface between the prism (P) and the process medium (S). Two of the prism surfaces (M) are act as mirrors bending the light rays so that they meet the interface at different angles.

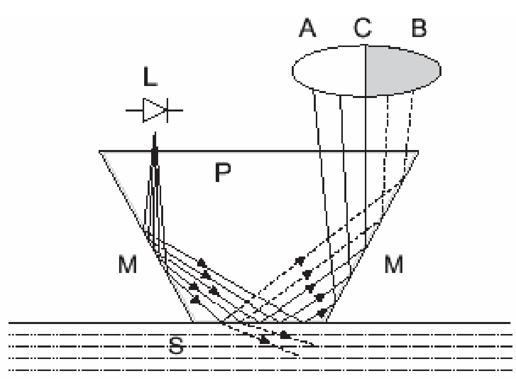

Figure 5: Refractometer principle

The reflected rays of light form an image (ACB), where (C) is the position of the critical angle ray. The rays at (A) are totally internally reflected at the process interface, the rays at (B) are partially reflected and partially refracted into the process solution. In this way the optical image is divided into a light area (A) and a dark area (B). The position of the shadow edge (C) indicates the value of the critical angle. The refractive index nD can then be determined from this position.

The refractive index nD changes with the process solution concentration and temperature. When the concentration changes, the refractive index normally increases, when the concentration increases. At higher temperatures the refractive index is smaller than at lower temperatures. From this follows that the optical image changes with the process solution concentration as shown in Figure 6. The colour of the solution, gas bubbles or undissolved particles do not affect the position of the shadow edge (C).

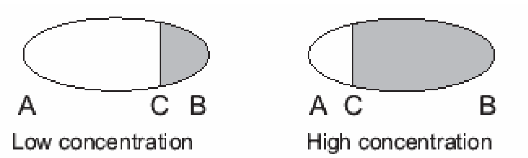

Figure 6: Optical images

The position of the shadow edge is measured digitally using a CCD-element (Figure 7) and is converted to a refractive index value nD by a processor inside the sensor. This value is then transmitted together with the process temperature via an interconnecting cable to the Indicating transmitter for further processing, display and transmission.

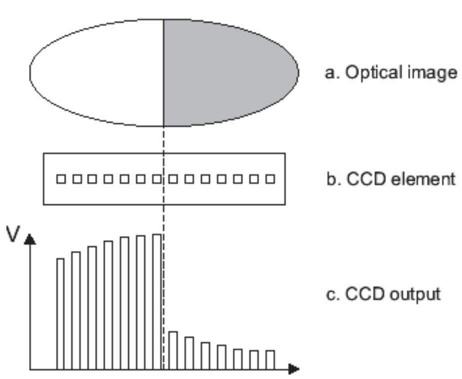

Figure 7: Optical image detection

FACTORS INFLUENCING THE MEASUREMENT

In general, the refractive index of a substance decreases with increasing temperature and with increasing wave length of the illuminating ray. Because of this variation, it is necessary to specify these quantities and to adopt a conventional temperature and wave length for all measurements. The measurement has then to be adjusted considering the selected wavelength and temperature.

The wavelength has to be well defined: K-Patents Process Refractometer uses a sodium yellow light source with a visible yellow light, the wavelength is 580 nm.

In view of the considerable change of refractive index with temperature, it is important to observe suitable precautions in controlling this variable.

Determination of the average temperature coeffient permits estimation of refractive index of liquids over a liquid, and in more precise work must be computed from a number of experimental determination. The variation of refractive index with temperature is nearly linear of a limited range.

In K-Patents Process Refractometer, the temperature is measured near the prism, and an automatic temperature compensation is made by the microprocessor. In critical cases a non-linear temperature compensation is used.

For automatic temperature compensation, the sensor tip contains a process temperature probe. The microprocessor applies an edge-detecting algorithm to the optical image, and determines exactly the position of the shadow edge. When this position is known, the critical angle is known.

Generally concentration scale is a nonlinear function of the critical angle and the refractive index (R.I.).

Figure 8 shows the concentration in percent of the weight of a sugar solution (BRIX) as a function of the refractive index (R.I.): The microprocessor in the electronic assembly performs complete linearization, temperature compensation and various functional tests.

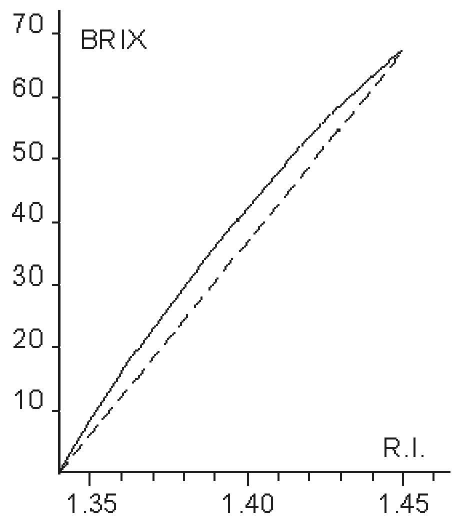

Figure 8: The BRIX diagram.

Figure 9 shows schematic a cut-away picture of a PR-23 inline refractometer sensor.

The measurement prism (A) is flush mounted to the surface of the probe tip. The prism (A) and all the other optical components are fixed to the solid core module (C), which is spring loaded (D) against the prism gasket (B). The light source (L) is a yellow Light Emitting Diode (LED), and the receiver is a CCD element (E). The electronics is protected against process heat by a thermal isolator (K) and cooling fins (G).

The sensor processor card (H) receives the raw data from the CCD element (E) and the Pt-1000 process temperature probe (F), then calculates the refractive index nD and the process temperature T. This information is transmitted to the Indicating transmitter.

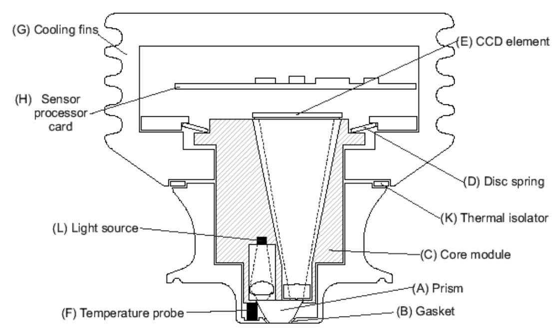

Figure 9: K-Patents PR-23 Sensor cut-away.