Refractometers & Polarimeters
THE FIRST 100 YEARS IN THE SUGAR INDUSTRY

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a xylem brand
Refractometers

A refractometer is a handheld or bench optical instrument for the measure of the Refractive Index. This is a measure of how light bends or refracts as it passes through a sample.

This will be explored further in the paper.
The Abbe Refractometer

Principle of Operation

The Abbe refractometer is used to measure the Refractive Index.

The refractive index determines how much light is bent, or refracted, when entering a material. This is historically the first use of refractive indices and is described by Snell's law of refraction.

By measuring how the light is refracted we can apply a scale which can determine the concentration of a solution.

The refractive index varies with the wavelength of light. This is called dispersion and causes the splitting of white light into its constituent colors in prisms and rainbows, and chromatic aberration in lenses. Light propagation in absorbing materials can be described using a complex-valued refractive index. The imaginary part then handles the attenuation, while the real part accounts for refraction.

The majority of people will use Sodium wavelength 589nm.
**Temperature**

Temperature also plays a critical role when measuring the Refractive Index.

The reading will vary with a change of temperature, in some cases the differences can be large with liquid oils for example others materials the change is far smaller quartz for example.

Throughout its life measures have been taken to add temperature control to the instrument. In the past this was achieved by using a water bath which would be connected to the instrument and have water pumped around the prism and prism head to maintain a stable temperature.

Modern instruments use an electronic device called a Peltier which will be covered later in this paper.

The majority of measurements are taken at 20°C, although in some cases other temperatures are preferred.

An example of a temperature correction table is shown on the next page.
Temperature correction values for sucrose samples

Correction values for sucrose solutions measured on the Brix (% Sucrose) scale are shown in the table below. The correction values should be added to the scale reading.

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<th>Scale reading °Brix</th>
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Example: An Abbe 5 gives a reading of 35.4 °Brix at a temperature of 32 °C

Scale reading of instrument = 35.4
Correction = 0.99
Equivalent value at 20°C = 36.39
which should be realistically rounded to 36.4
1869

The Abbe refractometer was first invented by Ernst Abbe.

Working for the Zeiss Company in Jena East Germany, the company was established in 1846 manufacturing multiple optical instruments. But particularly known for its development of high performance photographic lenses and prismatic binoculars.

Abbe first discussed the theory and described the instruments he had developed for the measurement of refractive index using prisms and by total reflection in Neue Apparate in 1874.

This instrument included Amici prisms similar to those used in modern instruments but without the water jackets.

In the Abbe’ refractometer the liquid sample is sandwiched into a thin layer between an illuminating prism and a refracting prism. The refracting prism is made of a glass with a high refractive index (e.g., 1.75) and the refractometer is designed to be used with samples having a refractive index smaller than that of the refracting prism. A light source is projected through the illuminating prism, the bottom surface of which is ground (i.e., roughened like a ground-glass joint), so each point on the surface can be thought of as generating light rays traveling in all directions. A detector placed on the back side of the refracting prism would show a light and a dark region. This is known as the borderline, the position of this border line on the detector would indicate the Refractive Index value.
1910
Carl Zeiss introduce the sugar refractometer

To satisfy a growing need from the sugar industry for an accurate instrument for determining sugar concentrations, this instrument has a narrower range 1.33 – 1.55 allowing the use of harder glass. This instrument was different because both the scale and the refractive index border are visible at the same time.
1914

Leonard Bellingham and Frank Stanley met and formed Bellingham + Stanley Ltd.

Began supplying the market with Abbe refractometers focused on the sugar market but also food and pharmaceuticals.

1920

Bellingham + Stanley release an improved Abbe refractometer.

This instrument had the scale on glass externally so could be read easily and accurately.
1950’s

Bellingham + Stanley release a Sugar Specific Instrument,

Extract from advert
“The accompanying illustration shows the Bellingham and Stanley sugar refractometer. It provides a direct reading of sucrose percentage and because the flat prism face is horizontal, the solution will not drain or evaporate readily. Transmitted light can be used. An automatic temperature correction device is available”

This instrument again was designed for ease of use and specifically for the sugar industry.

1956

Bellingham + Stanley begin redesign of the new Abbe 60 with new features and designs to make the instrument easy to use compared to its predecessors,
Current day

To the current day the Abbe type refractometer has not changed a great deal, the introduction of Digital Refractometers decreased the use of the Abbe for general use but it is still widely used in research, education and pharmaceutical applications.
The Arrival of Digital Refractometers

With the digital age growing demand was high for a refractometer that would give a reading at the push of a button, rather than relying on operators to use their judgement of a border line to obtain the value.

Digital Refractometers

Principle of operation

The digital instrument works in a different way to the classic Abbe type instrument.

Total Internal Reflection is used.

The sample is placed on a prism with known optical qualities. An internal light source is then filtered (in the RFM80 it was a Quartz Halogen Lamp), provides a cone of illumination via the prism to the sample.

The samples refractive index is determined by measuring the angle of incidence (Critical Angle) which causes total internal reflection, using a photocell assembly which detects the position which light cut-off (Shadow Edge) occurs. All positional calculations are then electronically converted to readout directly as Sugar concentration levels.

A graphic image is shown below
**1980’s**

Bellingham + Stanley release the first to release a successful digital instrument.

The instrument was designed for ease of use and used across many industries including,
- Sugar
- Soft Drinks
- Coffee
- Tomato Puree
- Confectionary
- Pharmaceutical
- Plus many more

The instrument used a detection system on a carriage that moved up towards up to the reflected ray, this in conjunction with a potentiometer would tell us the position of the critical angle, which can then be used to calculate the Refractive Index.
Some examples of customers using refractometers as part of their production below.

(All trademarks recognised)
1992

Bellingham + Stanley release the RFM300 Series refractometer
A refractometer with no moving parts and an LED light source.
With a static detector array and the LED light source the instrument was very low maintenance making it perfect for industry

This is to date Bellingham + Stanley’s most successful instrument, with thousands being shipped worldwide.

The instrument was easy to use and very robust

With the onset of digital age connectivity was becoming a must and the RFM300 had the ability to connect to computers and process data.
1996

Peltier Temperature control introduced,

Historically refractometers were temperature controlled by circulating water from a temperature controlled water bath through a jacket around the prism. Peltier systems achieve the same thing but work with electrical circulation. When passing an electrical current through a peltier device one side of the element rises in temperature and the other side falls. By placing peltier elements against a refractometer prism and controlling the amount and direction of the current one can determine whether the prism heats or cools and to what degree.

It is believed Index Instruments released the first successful Peltier temperature controlled instrument. Overcoming the need to connect a water bath.

Although this instrument did not sell in vast numbers and at the time water baths were more popular, it did pave the way for future refractometry with many other instrument manufacturers, including B+S introducing Peltier controlled instruments to the market.
2008

Bellingham + Stanley release the RFM300+ Refractometer.

This instrument again answered the call of the markets who were asking for a factory friendly temperature controlled instrument.

The basic instrument was designed on the RFM800 with some vast improvements based on mostly customer feedback,

- The prism dish was flattened to improve ease of cleaning.
- The temperature control was improved and made faster.
- The presser was made light weight and non-contact to improve cleanliness.
- Software additions were made to look for stable results before displaying to improve results.
- Computer connections were improved.

Today the RFM300+ is still sold and has recently been further updated with a colour display, Ethernet + USB connectivity and software additions allowing results to be stored as PDF’s. Amongst other advantages.
Conclusion

Over the past years refractometry has come a long way, from the initial concept of measuring refracted light, to the study of temperature affects.

Industry has heavily relied on the refractometer to maintain quality, improve manufacturing yields, reduce wastage and increase profits for many a decade.

But they have also helped to make sure the food we eat is as it should be. The beverages we drink are at the correct concentrations, the drugs created are contamination free and after we have, or the industry has used water it is returned to the land without contamination.

The digital age vastly changed how the refractometer was used in the field and on the bench taking away the need for users to judge a border line, but also making them usable by unskilled workers.

B+S have been at the forefront of product innovation and continue to develop instruments to fit user needs of today and the future.
Different Refractometers from the past

The Pulrich Refractometer

A critical angle refractometer,
**Jamin Refractometer – 1950’s**

An instrument for measuring the index of refraction of a gas in which two light beams from a common source are each passed through an evacuated tube and recombined, and the displacement of interference fringes is noted as gas is slowly admitted into one of the tubes.
Immersion Refractometer 1930’s

This instrument was used by dipping the nose of the prism into the beaker of liquid that needed to be tested. This was a very popular instrument in the brewing industry.

This was the most accurate but practical instrument ever built. It had a Zeiss linear scale with interchangeable prisms.

The linear scale takes out the error at the bottom end of the refractive index scale which is compressed at the most interesting lower part of the scale for beverage.

The introduction of flow cells made this a very popular model.
Handheld Refractometers

1930

Bellingham + Stanley were visited by Mr Noel Deer, a sugar chemist.

At that time in sugar plantations it was common practice for a sample of the cane to be taken from the field back to the lab for testing on an Abbe refractometer for ripeness.

The sample was taken by inserting a small tube into the cane.

Mr Deer challenged Bellingham + Stanley to make a small instrument that could be carried into the field.

Bellingham + Stanley began development of the Pocket Refractometer which was sold combined with a sampling tool.

As far as we are aware we were the first company to design a hand held refractometer.

Different versions are now manufactured all over the world for multiple markets.

Current Day

A varying range of instruments are now manufactured worldwide, optical and digital are available for almost any need.
**Polarimeters**

A Polarimeter is used to measure the angle of rotation caused by passing polarized light through an optically active substance (i.e. Sugars, Pharmaceuticals and Chemicals).

**Polarimeters / Saccharimeters**

**Principle of operation**

Some chemicals are optically active, as the polarized light passes through the sample the light will rotate either clockwise or anti clockwise. The amount the light is rotated is measured and is known as the angle of rotation.

Polarimeters are used in many industries including

- Sugar, for the measurement of purity
- Pharmaceutical, for concentration and contamination measurements
- Research
- Amongst many others
Temperature

As with refractometry temperature plays a role when measuring the optical rotation, this is product specific and can be combated in a number of different ways.

Since early times people have added temperature control to their polarimeters to ensure an accurate measurement, this has typically been done with a water jacketed tube, water is circulated around the tube to stabilise the temperature and the reading is taken.

Another method is to use temperature correction, this is where a measurement of the optical rotation and the temperature is taken. A calculation is then applied to correct the result back to 20°C (typically) ICUMSA came up with a standard method for sucrose sugar.

Modern instruments now also use Peltier systems to control the temperature.
Huygens first discovered polarization of light while repeating Bartholinus' experiments to discover the double refraction in Icelandic Spar.

**1766 – 1777**

M. L'Abbe Alexis Marie Rochon uses doubly refracted prisms and perfects a device for measuring small angles and measures the diameter of the sun. Rochon perfects the device for astronomical and nautical measurements.

**Early 1800's**

Arago begins to use the instrument to study polarised light, and discovers that polarised light rotated as it passes through quartz cut perpendicular to the optic axis.

**1812**

Biot discovers the rotation changes with the thickness of the quartz, and designs an instrument to measure the affects.

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**Figure 3.** One form of Biot's original apparatus.
1815 – 1840

Biot formulates the majority of the fundamental laws of polarimetry, recognising liquids could also be optically active and each different kind of optically active sample had a different characteristic of rotary power. And also that concentration affected the rotation.

Approx. 1840’s

Ventzke improved the Biot Design using two nicol prisms.
Late 1800's

Various manufactures and scientists work making improvements to prisms, filters and accuracy including,

- Mitscherlich
- Duboscq
- Laurent
- Lippich
- Landolt

Figure 7 (Continued.—Early polariscopes.
Late 1840’s

Research and development goes into the Saccharimeter, which could be used to determine the rate at which a sucrose sugar solution would rotate the light. These instruments allowed the use of white light due to the use of a quartz compensator. This idea took off and the majority of manufacturers moved to this design.

After this point various changes are made to the instrument but none that are dramatic.

Later ICUMSA will introduce the International Sugar Scale that will be implemented into the Saccharimeter.
1950's

Bellingham + Stanley release the Model A Polarimeter.

Leonard Bellingham invented a new polarising filter specifically for the instrument, and with addition of unique features by Frank Stanley the instrument was a considerable advance on comparable instruments of the time. The modifications made the instrument easier to use, more robust and highly accurate.
1958

Bellingham + Stanley release the first electronic Polarimeter,

This instrument was designed to fill the need for the investigation into DNA and anomalous dispersions of proteins and steroid chemistry.

This instrument was also used in preliminary research of the birth control pill.
1960’s

Bellingham + Stanley release its Saccharimeter

This instrument was designed specifically for the tarehouse, it was manufactured to conform with ICUMSA recommendations.

It also had external features which made it easy to use and maintain, with a large base to stabilise temperature quickly and with minimum crevices to trap spilt sample.
1970's

Bellingham + Stanley introduce the P70 Automatic Polarimeter.

This had considerable advances in electronics to make it far more reliable than its predecessors and competition.
1994

Bellingham + Stanley release the ADP220,

This was the first polarimeter to use LED instead of a halogen bulb. This combated multiple issues including, temperature errors due to heat emitted from the bulb. And increasing the lifespan of the instrument as the LED did not need to be changed.

2000’s

It is believed Rudolph Research produce the first Peltier temperature controlled automatic Polarimeter.

However prior art for the concept can be traced back to 1987 when a patent was filed by Ulphric Schmidt.
Current Day

There are many instruments available on the market, but all still hold to the original principles.

Below are some examples of modern optical and digital instruments.
Conclusion

Again polarimetry has come a long way since its initial discovery.

Polarimeters are still heavily relied on within many industries for quality control, production control and research.

The biggest change in the past years has been the introduction of digital technology with automatic readings; this has allowed the use of polarimetry by unskilled operators.

Again Bellingham + Stanley have been at the forefront of product innovation and continue to develop instruments for the current and future industrial needs.
A Brief History of Bellingham + Stanley

- Leonard Bellingham + Frank Stanley met working for Adam Hilger Ltd in North London 1914.
- They began to develop instruments in Frank Stanley’s living room at home.
- Leonard Bellingham’s father died leaving Leonard some money, which they use to purchase the first home of Bellingham + Stanley No 71. Hornsey Rise, London.
- War was declared as Bellingham + Stanley opened their doors for business.
- The war proved to be a catalyst for Bellingham + Stanley and their business, their major competition Zeiss and Schmidt + Haensch were both located in Germany which restricted their global movements.
- Also many of the optical suppliers from abroad were prevented from entering Great Britain, this left Bellingham + Stanley as a major supplier to the UK and the USA and rest of the world.
- Although the main part of the business was to supply refractometers and polarimeters to the sugar, food and pharmaceutical industry.
  - Bellingham + Stanley also made prismatic binoculars for the Ministry of Defence
  - Also assisted the MOD with optical detection of submerged U-Boats from aircraft
- During the 1930’s the company was expanding and the Hornsey Rise residence was rapidly becoming too small. And some production was sub contracted A.E Davidson in Tunbridge Wells, a company set up in an old dance hall.
- World War II broke and again Bellingham + Stanley took on additional responsibilities for the war effort making
  - Range finders
  - Periscopes
  - Special items for Coastal Command
- After WWII Bellingham + Stanley were the major supplier of optical instruments to Europe, as European capacity for providing the instrumentation had been destroyed.
  - During this period demand was so high that delivery times stretched out to 2 years.
- In 1961 Building began on the Tunbridge Wells Factory where Bellingham + Stanley still are to this day.
- In 2007 Bellingham + Stanley were acquired by Nova Analytics who grouped the company with other analytical brands such as WTW, SI Analytics and ebro.
- In 2010 Nova Analytics were purchased by ITT Corp.
- In 2012 ITT split into 3 companies and Xylem Inc. was formed. Bellingham + Stanley are now part of a strong analytical group servicing the world with their instruments.


Acknowledgements, References + Disclaimers

Disclaimers

This paper has been constructed for the BSST Autumn Technical Meeting; this paper may not be copied or distributed without prior consent of Bellingham + Stanley Ltd or Xylem Inc.

Although every effort has been taken to ensure the accuracy of the content Bellingham + Stanley Ltd cannot guarantee the accuracy of the content and assume no responsibility for errors contained.

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