The Abbe Refractometer

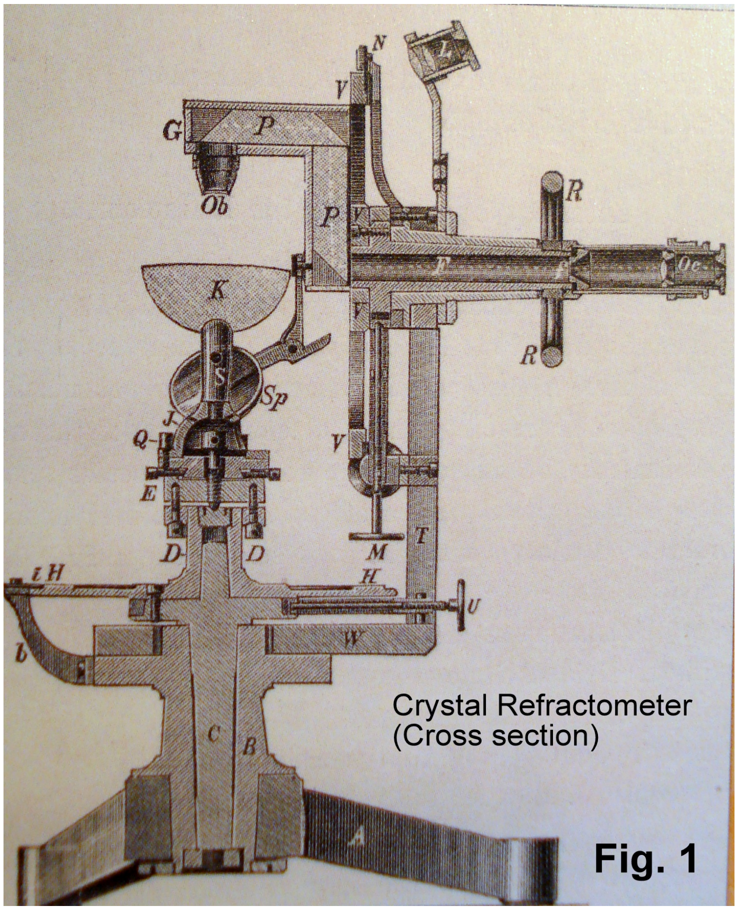
An Overview with Special Reference
to the Instruments in my Collection
by Fritz Schulze

Part I

Carl Zeiss' "*Mechanical Atelier",* his workshop for scientific instruments, established in Jena in November 1846, prospered and grew in the second half of the 19^{th} century from one employee to 250 in 1883, to 500 three years later and to over 1000 by the turn of the century. . Carl Zeiss himself could still celebrate the $10{,}000^{th}$ microscope before his death in 1888.
The business morphed from a traditional trade from the front room in his home to industrial production - instituted mostly by Roderich Zeiss, Carl Zeiss' son - in their own building and later with their own electrical power plant, from one mechanic making the entire microscope (except the lenses) from beginning to end (a most uneconomical method still widely used in England, France and Germany at the time) to "division of labour", where parts were manufactured in series by different departments and then assembled in one final step. This conversion did not go over well with the skilled mechanics whose pride was hurt, but soon financial and social benefits overcame their objections.

The new way necessitated careful quality control and exact measurement of each part to assure the required precision of the final product. To this end Abbe had already designed for internal use certain instruments e..g. the crystal refractometer and the spectrometer for testing glass (Fig. 1 and Fig. 2),, the "Abbe" comparator for precise length measurements of mechanical components (Fig. 3 and Fig. 4), the "Abbe" refractometer for testing fluids like immersion oils (Fig. 5) among others. The fact that there might be a market for such instruments met with other considerations of Abbe, by now a partner of Carl Zeiss: how to preserve the future of the booming company in view of the growing competition. Zeiss was by now already famous for its microscopes, prism binoculars and photographic objectives, but it needed a wider product base. The new "MESS" department, 1890, now the next separate successful production line, soon split into "FE" for "Feinmess", fine mechanical precision measuring instruments (such as comparators and measuring microscopes), and "MESS" for analytical measuring instruments (such as refractometers, photometers and polarimeters). The production of spectacle lenses and geodetical instruments followed soon after.

To realize his plan for the future of the company and secure his succession, Abbe went about attracting and hiring a number of capable scientists and administrators:
Dr. Siegfried Czapski, 1885, CEO and scientific director,
Dr. Carl Pulfrich, 1890, in charge of the MESS dept.(best known for his "Pulfrich photometer"),
Dr. Fritz Löwe, 1899, to develop analytical instruments,
Dr. Moritz von Rohr, 1905, spectacle lenses (Punktal eyeclasses),
Dr. Max Paul Rudolph, 1886, photographic lenses (first anastigmat) and terrestrial telescopes,
Max Fischer, 1890, administration,
Dr. Max Pauly, 1897, astronomy.
Roderich Zeiss, who had headed the Micro-photographic Dept., left the company in 1891 when Ernst Abbe was about to institute the Carl Zeiss Foundation after he became sole owner of the company.. Abbe chose these co-workers not only for their scientific potential but also for their social and ethical views. When he died in 1905 he knew the company in capable hands and aimed in the right direction.



Crystal Refractometer
(Cross section)

Fig. 1

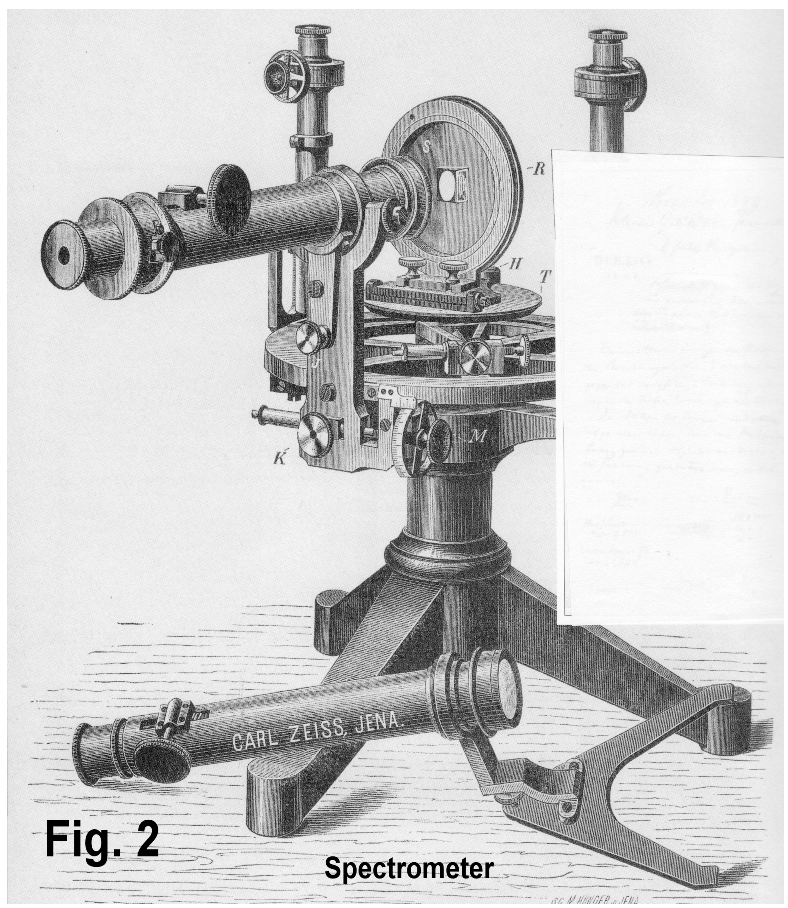


Fig. 2

Spectrometer

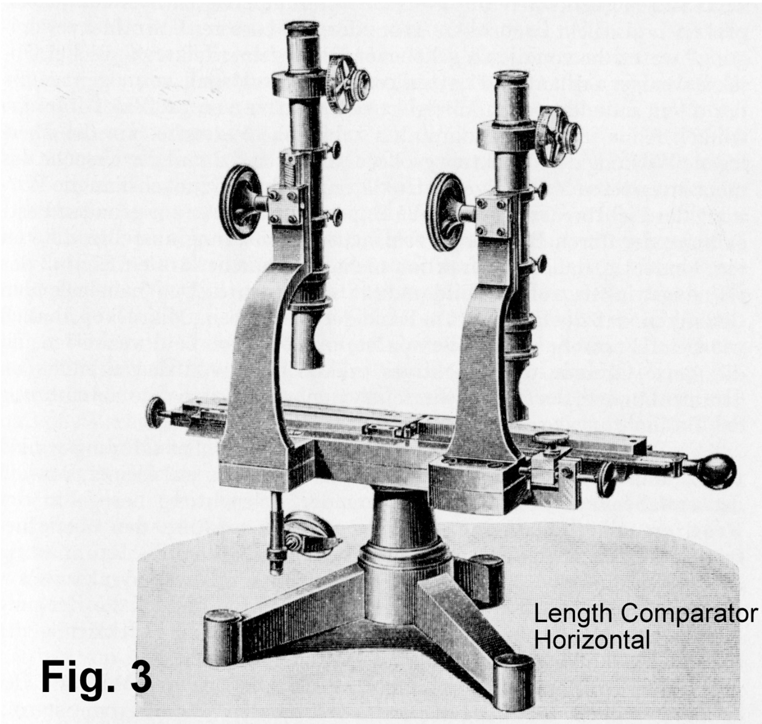


Fig. 3

Abb. 5. Abbescher Komparator für Längenmessungen. „Meß-Apparate für den Physiker". Verlag d. Ges. Dtsch. Naturforscher und Ärzte (1891), S. 88—90.

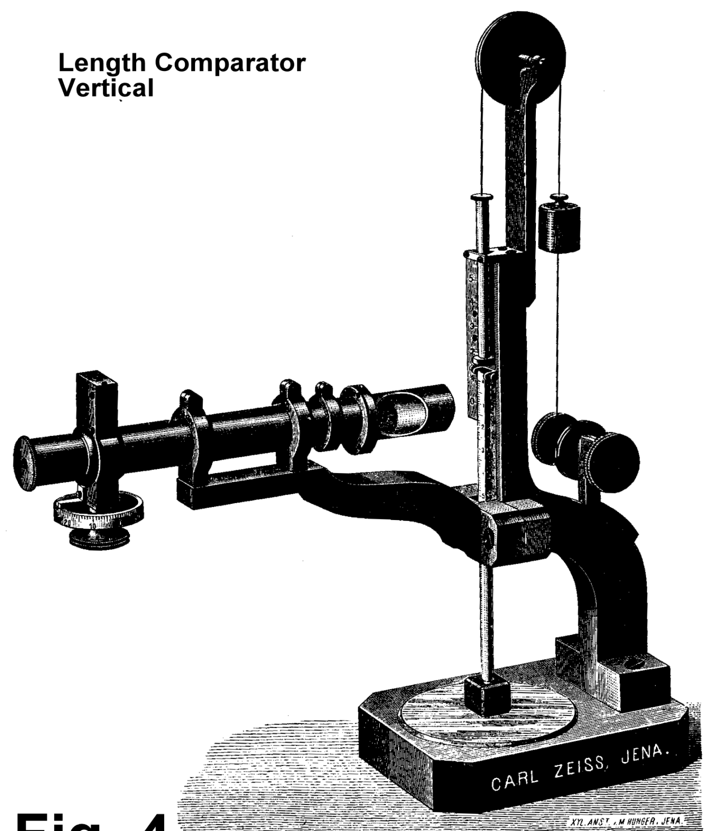


Fig. 4

Fig. 8.
Dickenmesser ($^1/_2$ nat. Grösse).

ABBE, Gesammelte Abhandlungen. II. 14

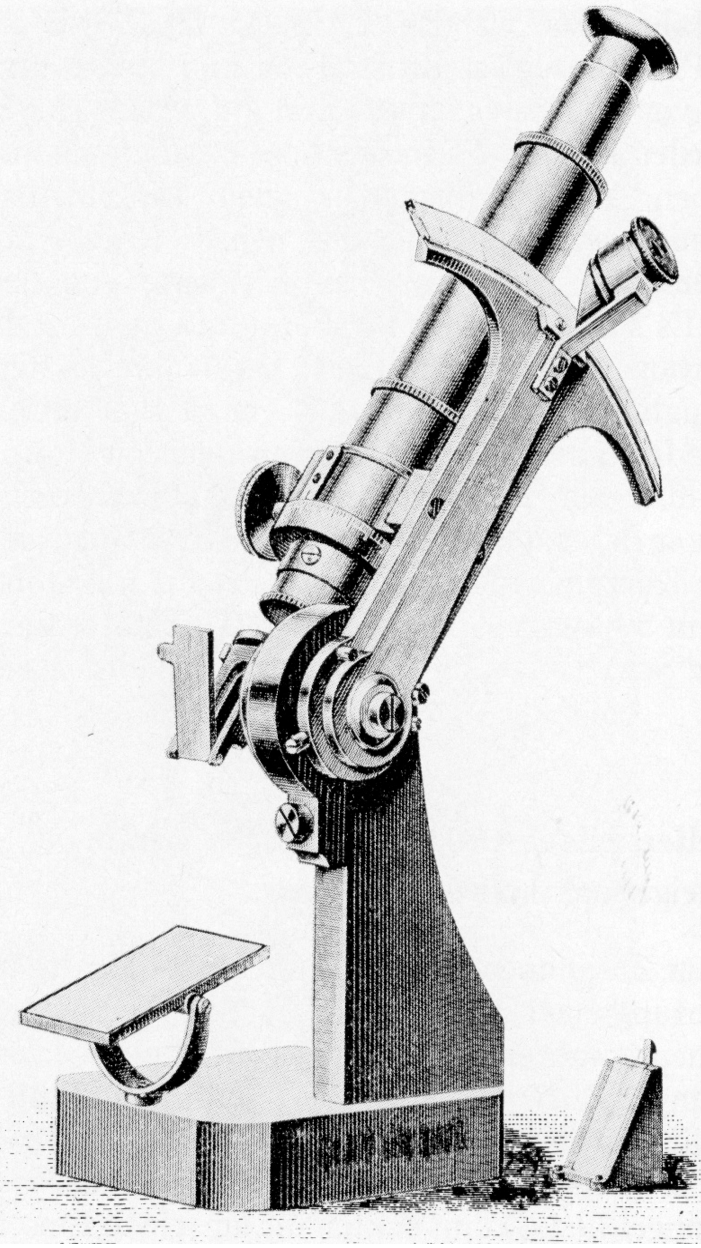


Fig. 5

Abb. 4. Abbe-Refraktometer 1869. „Jenaische Zeitschrift f. Naturwissensch." Band 8 (1874), S. 96—174.

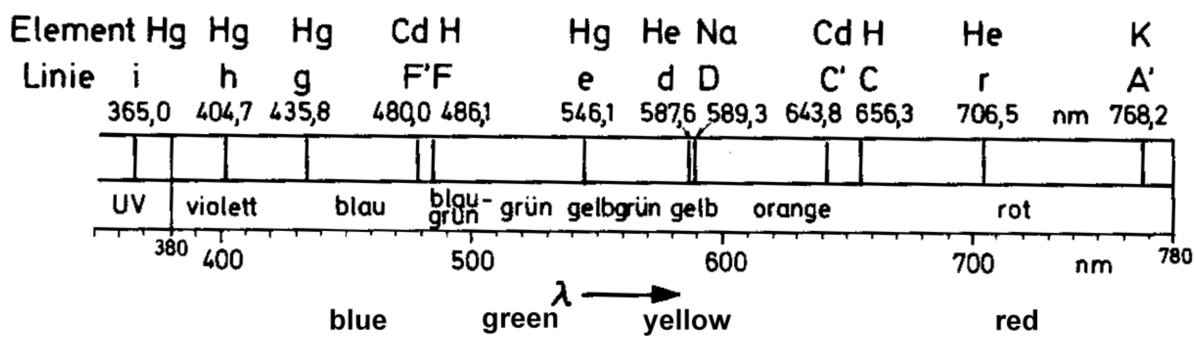
Refractometer

Part II

The Refractometer is an instrument to measure the *refractive index n_D* (R.I.) of liquids and, in some cases, solids. The R.I. can be used to determine the concentration of solutions, for example, sugar in a juice or water in milk, therefore, refractometers are widely used in industry and trade. The R.I. is defined as the ratio of the velocity of light in a vacuum c_o (for practical reasons conventionally air $n_D = 1.0003$) to the velocity in the substance concerned c_n:

$$n = \frac{c_0}{c_n} = \frac{\lambda_0}{\lambda_n}.$$

The R.I. also depends on the wavelength λ, conventionally that of the Fraunhofer D line in the spectrum (sodium 589.3 nm, I suppose because originally the yellow sodium light was most easily obtained by adding salt to the flame of a bunsen burner), hence the "D" of the n_D.



The measuring process itself takes advantage of the effect of *total reflexion* which occurs when a beam of light reaches a substance at an angle where, instead of passing through, it is reflected.

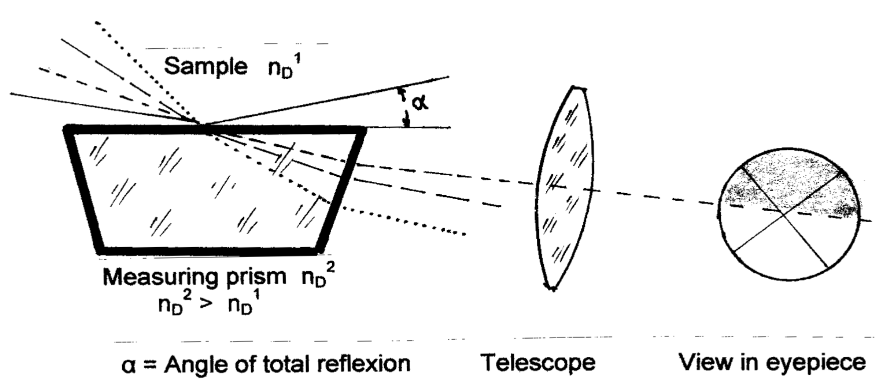


Fig.1

Fig. 1 shows both the principle of total reflexion as well as the function of the refractometer. The boundary line is observed through a telescope and read off the calibrated R.I. scale. Other values, such as sugar concentration (Brix), require a different scale or the use of a conversion table.

Unless light of λ = 589.3 nm is used, a spectrum occurs at the boundary line which makes precise reading impossible. Hence, compensating prisms are employed which eliminate this spectrum and leave a clear boundary line. The entire process is based on a standard temperature of 20ºC and all refractometers have provision of temperature control by water circulation.

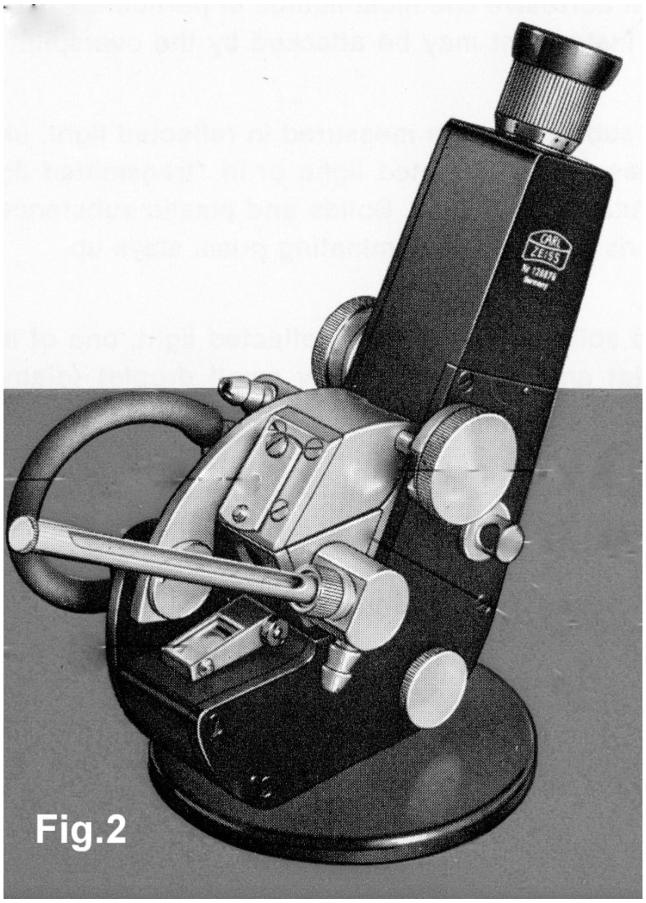


Fig.2

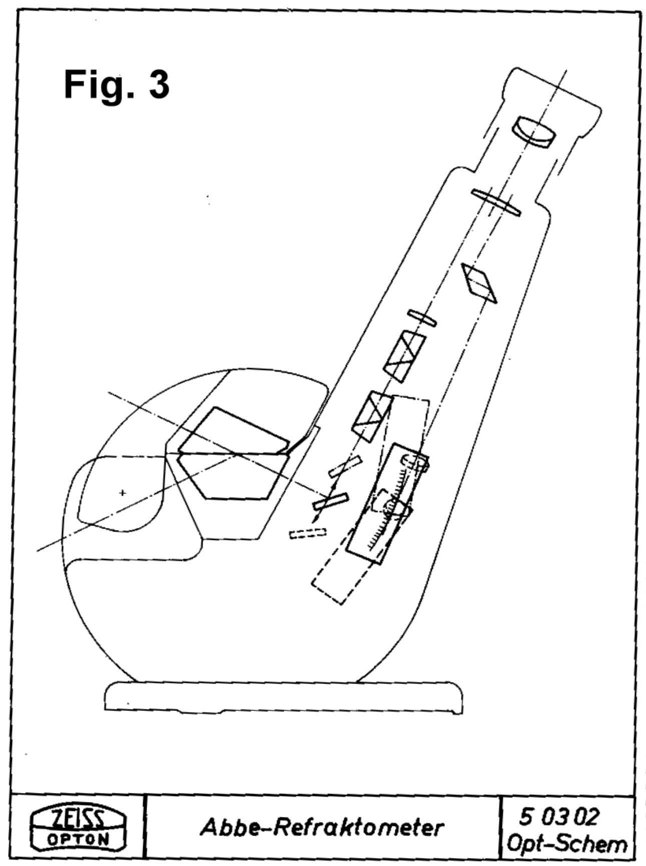


Fig. 3

Above the first modern Abbe Refractometer made by Zeiss Opton, later Carl Zeiss, Oberkochen, in West Germany in 1957. Next to it a schematic of the optical system. Clearly visible are the two compensating prisms. This particular model proved to be extremely successful and has been copied often as the many offers from India and China on eBay prove.

The small mirror in front of the lower, measuring prism can be used as a shutter when the shutter at the upper illuminating prism is opened for the light to enter for normal measurements. Samples of high absorption, such as molasses, are measured with the light entering from below. The large knob on the right secures the illuminating prism and also lifts it off.

Right: an impression of the view through the eyepiece with the boundary line and two scales, R.I. and 0 - 100 % sugar. The normal measuring range of the Abbe Refractometer is n_D = 1.30 -1.71. Extra prisms with corresponding conversion tables were available for n_D = 1.17 - 1.56 and 1.45 - 1.8.

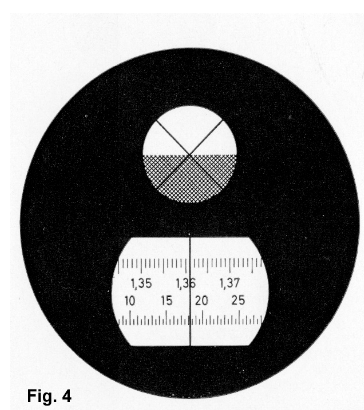


Fig. 4

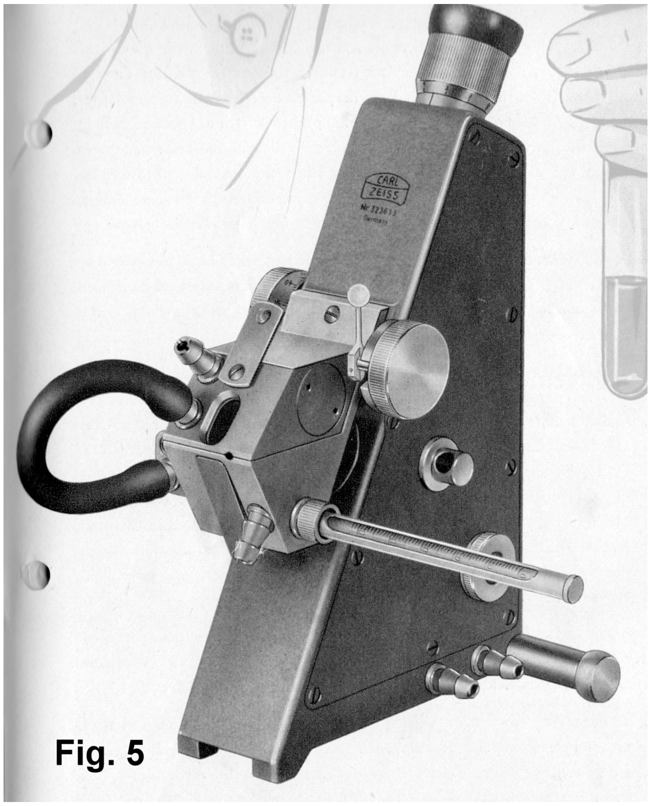


Fig. 5

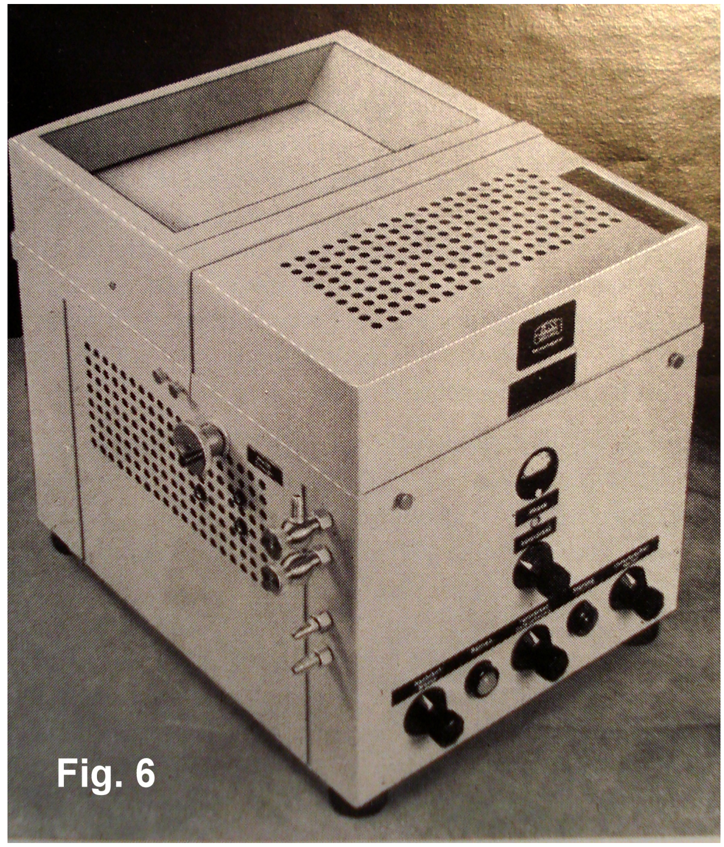


Fig. 6

Above, Fig. 5. shows the industrial version, which is completely water-proof, with all major parts made of stainless steel. Fig. 6 is a *Refractograph* for industrial continuous processes. Both these two version were made in the same period. The entire line of refractometers was discontinued when Carl Zeiss/Oberkochen closed the Dept. MESS (analytical instruments) in the 1970/80s.

Fig. 7

Interestingly, for a comparison, the Abbe Refractometer of the same period manufactured in the VEB Jena factory in the GDR (Fig.7). As most major researchers of the Zeiss factory had been moved to the West by the Americans at the end of the war, the remaining Zeiss people in their effort to start production again, simply modernized the well known pre-war instruments, in this case by encasing the scale. In all other aspects the instrument resembles the traditional model. It is also 10 cm taller than the compact Oberkochen one. The designers in the West, unencumbered by any historical considerations, were able to introduce modern ideas they had already pondered about. This fact contributed greatly to the success of the new Zeiss factory in Oberkochen.

Part III

I come now to the instruments in my collection. The oldest one is the **Butter Refractometer** dated 1909 with the serial Nr, 6102 (Fig. 1), which would indicate that by that time already a considerable number of such instruments had been manufactured and sold. My particular model was originally sold to a customer in Frankfurt, but I bought it on eBay from a seller in the US. The oldest illustration of this instrument I found in Felix Auerbach's *Das Zeiss Werk und die Zeiss Stiftung in Jena,* 1907. It shows the instrument slightly different: the telescope and prisms mounted on the stand rotated 90º from mine.

At the time watering down milk and butter was a common problem. The arrival of the butter refractometer was welcomed by the dairy and fruit industry and put an almost immediate stop to this problem.

In the instrument's eyepiece the boundary line and measuring scale are superimposed, the scale reads 0 -100. The small knob on the side with a scale of 0 - 10 is intended for precise testing and adjustment with a standard solution. Incidentally, my refractometer came in a fitted wooden box and included a small bottle with a “Standard Solution” (no details on label) and the thermometer missing.

A small tiltable mirror directs the light into the measuring prism which is insulated against the stand acting as a heat sink by a layer of red hard rubber (?). Both prisms have provision for temperature control by circulating water with a port for the thermometer. Lastly, on the square base is a post to stop the illuminating prism from swinging uncontrollably down. The thin layer of sample between the prisms causes a considerable amount of cohesion which makes the opening or separating the prisms after a measurement problematic. This is why the newer and modern instruments feature a knob design that forces the prisms apart when opening them. Both prisms have a matching “funnel groove” at one corner for filling with a liquid sample

I tested my butter refractometer with a sample of Gay Lea unsalted butter, but found the boundary line indistinct - between 50 and 60, Mazola canola oil, however, yielded a clear boundary line at 67 with a bluish spectrum (at room temp. of 21ºC). My effort to introduce the oil via the “funnel groove” at the edge of the prisms failed with a big mess, I ended up dropping the oil on the opened illuminating prism.

The second in my line of refractometers is the **Abbe Refractometer** serial Nr. 37533 and dated 1932 (Fig. 2 and Fig. 3 with opened pisms). This instrument also ended up in the United States. It is a considerable improvement compared to the first one made in 1869, but the main features are the same. The measuring range as engraved on the arch with the scale is n_D = 1.3 - 1.7 and 0 - 100% at 20ºC (so engraved). Both prisms are temperature controlled by circulating water with a port for the thermometer (got lost!), are insulated against the stand by a layer of brown non-metallic material, and allow measurement both in transmitted and reflected light. The telescope for observing the boundary line has the necessary crosshairs. At the prism end sits the graduated compensator (0 - 60 - 0) for eliminating the spectrum of the boundary line, operated by a convenient knob. The key-like lever to both lock and “open” the illuminating prism is designed in such a way that it automatically separates the prisms before folding the latter down. The prisms also have the above-mentioned filling “funnel groove”. A mirror, mounted on a lockable arm, directs the light from below into the illuminating prism, neither prism has a shutter for its window (although I saw one illustration in a book where the window of the measuring prism was covered with a cap).

A knurled knob tilts the prisms relative to the telescope by means of a rack on the scale arch. After the boundary line is thus set to the crosshairs, the value is read by means of a magnifier in a focusing sleeve. The magnifier.has a glass plate at 45º at its end to reflect light onto the scale, the index line is on a thin glass plate just above the scale. The instrument initially always included the thermometer 0-50ºC, a testing prism (a small glass block with engraved n_D) and a small bottle with immersion liquid (*monobromnaphthalene* n_D = 1.568). For calibration the testing prism, which has two polished surfaces at right angle, is attached to the open measuring prism with a small drop of the immersion liquid and the light directed into its polished front side. The calibration value is then set on the scale and the prism block reset on its axis until the boundary line meets the crosshairs (I assume so, I found no obvious means for this adjustment except perhaps one screw on the axis of the tilting assembly, by comparison, my Spencer/Buffalo Abbe Refractometer “copy” has a neat arrangement for this adjustment).

The third instrument of my collection is a Zeiss **Butter Refractometer** with the serial Nr. 66372 (Fig. 4). According to the Zeiss Archive it was manufactured in 1939 and shipped to the US in 1940. It has no similarity with the other butter refractometer and must have been a revolutionary design in the 1930s.

The instrument is fully nickel-plated, the upper, illuminating prism has a spring clip to “close” it, its weight being sufficient (Fig. 5). Again, both prisms are equipped for temperature control with a port for a thermometer. The upper prism has a window for the light to enter from above, there is no mirror. At the lower end of the telescope is a peculiar arrangement: a large knurled ring that can be turned about 90º, its range limited by two stops and graduated 0 - 10. A smaller concentric knurled ring with a locking lever allows this range to be moved within these 90º. Rotating the larger ring moves the scale by about 2 intervals for adjustment. A previous owner must have felt confused by this arrangement for it seems the small knurled ring has been “attacked” with a plumber's pliers! (Fig. 6).

Boundary line and scale are superimposed in the eyepiece and it requires quite some acrobatics to see the ends of the scale. A measurement with butter resulted in a rather blurry boundary line reading about 62 while the Mazola oil read 68 with a clear boundary line, although having a beautiful spectrum! I assumed the butter refractometers to be equipped with a yellow filter to eliminate the spectrum. This is not the case, however. Not having a user's manual, I don't know if there is a requirement that a sodium light source be used. Unusual is the base of the instrument: a trumpet shaped foot of blackened brass on a round pine-wood base, unusual perhaps, but easy to grip for transport.

I add a picture of a Zeiss **Sugar Refractometer** (Fig. 8) of about the same period as the 1939 Butter Refractometer, the similarity of the design is obvious.

Finally, my **Spencer/Buffalo refractometer** Nr. 274 (Fig. 7) is in all essential features a copy of the Zeiss Abbe Refractometer with the exception that the mirror can slide back and forth on a dovetail, and it has less nickel-plated parts, being mostly painted black. It came to me in a wooden box together with a calibration prism $n_D = 1.5176$ and a small glass-stoppered bottle with a tiny amount of *alpha-bromnaphthalene.* Again, the thermometer was missing.

When looking at Fig. 7 in Part II (or Fig. 8 here, the VEB Jena 1955 Abbe Refractomerer) you can understand why some uninformed sellers on eBay advertise the Abbe Refraktometer as a "strange binocular microscope", one even added: "although I cannot perceive a stage".

Fig. 1

Fig. 2

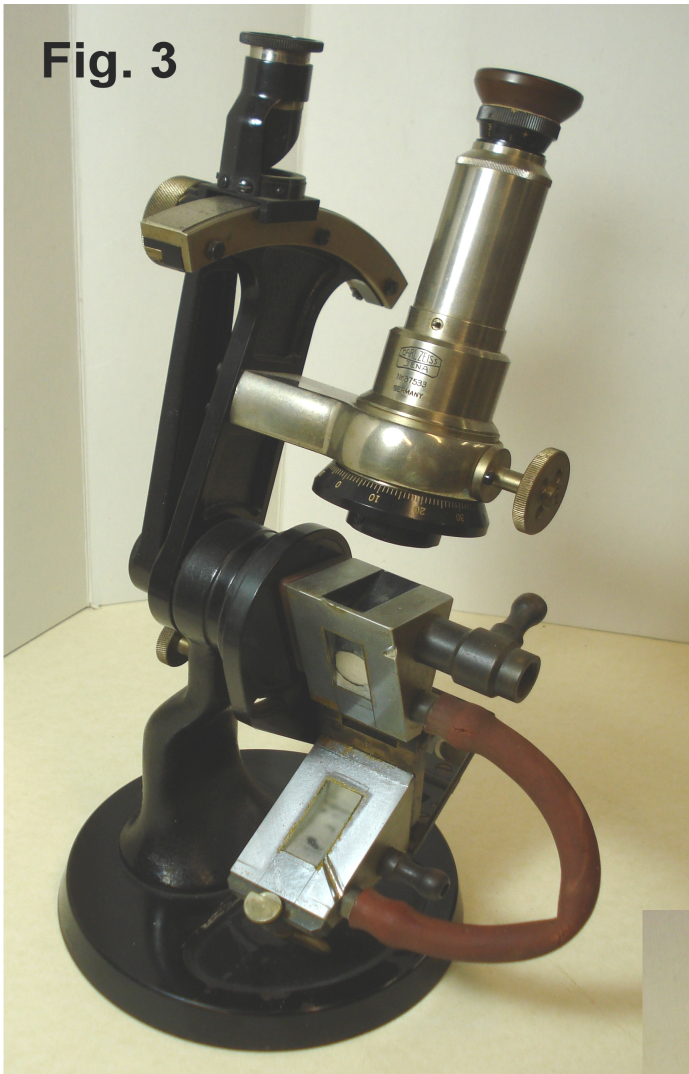


Fig. 3

Fig. 4


Fig. 5

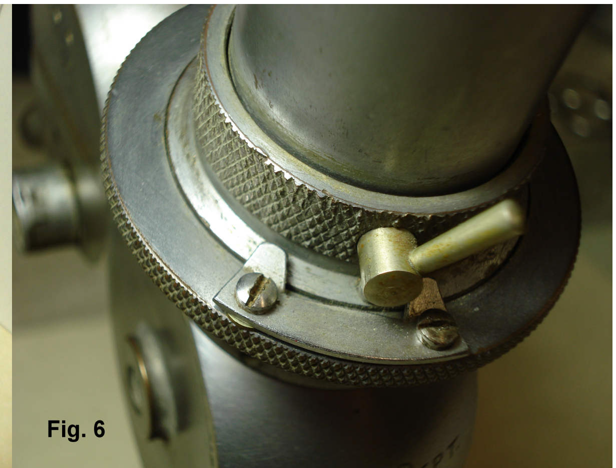


Fig. 6


Fig.7


Fig. 8

Part IV - Stymied

Before writing about my Zeiss Abbe Refractometer I decided to test it for proper function. Immediately I was puzzled because I could not find the cross hairs when looking into the eyepiece. These are needed to set the boundary line. No matter what I tried, no cross hairs. I unscrewed the telescope (Fig. 1) but could not find anything obviously wrong or out of place. When I looked with a magnifier into the telescope tube after the eyepiece had been removed , I could see the cross hairs, so I knew they were there. At the bottom of the tube was a lens mounted in a ring with two key holes (Fig. 2). At first sight it appeared to be screwed in, leaving about 5mm of thread free. But turning the mounted lens did nothing: it was friction mounted. The key holes were obviously for orienting the crosshairs properly in relation to the boundary line.

Then I had a brain wave (that happens occasionally!): I held the eyepiece like a magnifier over a fine print and found the focal point only 10mm from the edge. The mounted lens with the reticle in the tube was, however, at least 40mm distant! Closer examination found that the threads at both ends of the tube were identical, so a previous owner of the instrument, who tampered with it, could be excused for screwing the telescope tube together the wrong way. Once the eyepiece was secured at the end of the tube with the lens in it, the cross hairs were clearly visible. A quick adjustment of the keyed mount brought the crosshairs into the correct 45º position. Eureka!

During this whole procedure the small eyepiece lens with the hard rubber eyecup came off. It was mounted on a brass sleeve with a helical thread for focusing (Fig. 3), but always came loose when turning it. Normally such combinations are secured against loosening by a locking screw on the periphery, but I could not find one, even when examining the parts under a stereomicroscope. Eventually I spied the sharp tip of a grub screw (Fig. 4), however it was not axially arranged as is the custom, it impinged on the narrow **edge** of the brass tube with the helical focusing thread (Fig. 6). I had never seen anything like this before. When I examined the other end of where this screw was supposed to be, nothing. I then scratched the black paint off and, lo and behold, there was the slotted end of the locking screw (Fig.5)! It had been painted over with matte black paint. Carefully reassembling the parts and tightening the tiny locking grub screw and resetting the diopter ring solved this frustrating problem. I always considered myself “experienced”, but this repair taught me that there is always still a lot to learn.

Fig.1

Fig. 2

Fig.3

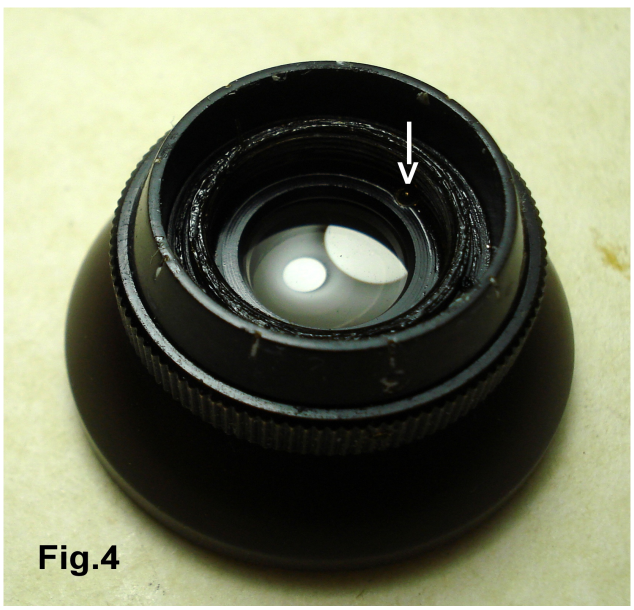


Fig.4

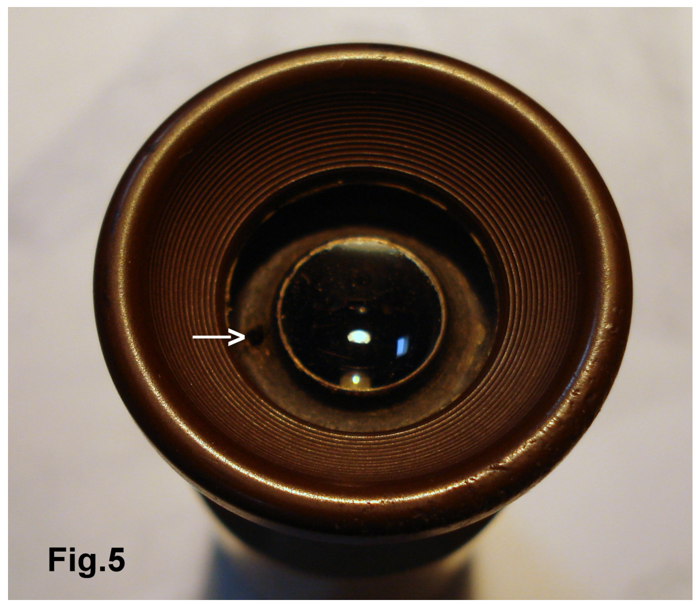


Fig.5

Fig.6

All illustrations and pertaining information I found in a number of publications dealing with Carl Zeiss, Ernst Abbe, and the Zeiss Works, all with the exception of one, in German. Therefore, I think I will abstain from listing all the relevant literature in order not to bore the reader. However, I shall happily share these references with any interested party upon request.

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