

On the role of T. J. Seebeck in the discovery of the photoelastic effect in glass

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Abstract. It is shown that Seebeck was the first scientist who systematically investigated the photoelastic effect in annealed and tempered glass articles of different shape. Some of Seebeck's results are analysed and put into the framework of contemporary photoelasticity. Already about two centuries ago Seebeck observed in 3D glass articles interference fringes, which are nowadays the basis of integrated photoelasticity for residual stress measurement in glass articles of complicated shape. Investigations on the photoelasticity of glass made Seebeck famous even before he started investigating the problems of thermoelectricity.

Key words: glass, photoelasticity, birefringence, polarization.

1. INTRODUCTION

Seebeck is mostly known as the discoverer of the thermoelectric effect. His first paper on this topic [1] was published in 1822. However, from 1802 to 1820 he was seriously engaged in research in optics. From 1802 to 1810 he made together with Goethe experiments on the spectrum of light with *camera obscura*. The results of these experiments are described in Goethe's book *Zur Farbenlehre* [2] and in Seebeck's paper [3].

The beginning of the 1810s was a golden era in optics. Malus discovered the possibility of polarizing light by reflection from a glass plate [4] and investigated birefringence in crystals and also in thin slices of plants and animal tissues [5]. Biot found that light that passes obliquely a pile of glass plates becomes polarized [6]. Arago carried out detailed investigations of various crystals in polarized light [7]. He also observed crystal-like behaviour of flint glass plates.

Application of polarized light opened up new possibilities of investigating transparent objects. While most of these investigations were devoted to crystals,

Seebeck decided to investigate glass. Starting his investigations, he was familiar with publications* [4-7]. Following the publications of Malus and Biot he constructed devices that created polarized light both by reflection and refraction. In contemporary terminology he used in his experiments both crossed and parallel plane polariscopes, turning the test object between the polarizing devices. He collected a number of glass plates, cubes, cylinders and specimens of other shapes. He heated the specimens up and cooled them down, some of them slowly and some quickly. He discovered that pieces of glass that were cooled down slowly did not exhibit birefringence. Pieces of glass cooled down quickly showed interference fringes, which depended also on their form. He also discovered that glass did not exhibit any birefringence at high temperatures. He reached the conclusion that observation in polarized light permits to determine how quickly a glass article is cooled down.

Seebeck published the results of these investigations in two papers [9,10]. In the first of them [9] he described in detail his experiments of polarizing light by reflection and refraction and presented also fringe patterns obtained in polarized light for various test objects. In [10] Seebeck gave an interpretation of the obtained interference fringes and investigated the changes of the fringe patterns when the specimens were rotated in a polariscope. He named the interference fringes in glass “entoptical fringes” (*entoptische Farbenfiguren*), evidently following Goethe’s classification of colours into “dioptical”, “paraoptical” and “eoptical” ones [2].

The aim of this paper is to show that Seebeck observed in his apparatus in various glass specimens the basic photoelastic effect, isoclinic and interference fringes, which are used nowadays for residual stress measurement in glass and in other applications of photoelasticity. Somewhat later similar observations were made by Brewster.

2. SEEBECK’S BASIC RESULTS AND THEIR INTERPRETATION

The basic results of Seebeck’s investigations are graphically shown in Figs. 1 and 2, taken from his paper [9]. Figure† 1.1 shows the polariscope where polarization is created by reflection from the glass plate $G-G$. The test object is placed between the plates $G-G$ and $H-H$. If the plates $G-G$ and $H-H$ are parallel to each other, one has a polariscope with parallel polarizing elements (the plane parallel polariscope), if the plate $H-H$ is turned 90 deg around the axis bc , one has a polariscope with crossed polarizing elements (the plane crossed polariscope). Figure 1.2 shows the investigated cube. Figures 1.3 and 1.4 show how piles of glass plates are used to detect the planes of polarization of the light that is passed through a quartz wedge. Figure 1.5 shows a plane crossed polariscope

* This follows from Seebeck’s letter to Goethe of 30 January 1816 ([8], p. 356).

† We use double numbering of the figures: the first number gives the figure number of this paper and the second one the figure number on the Seebeck’s plate of illustrations.

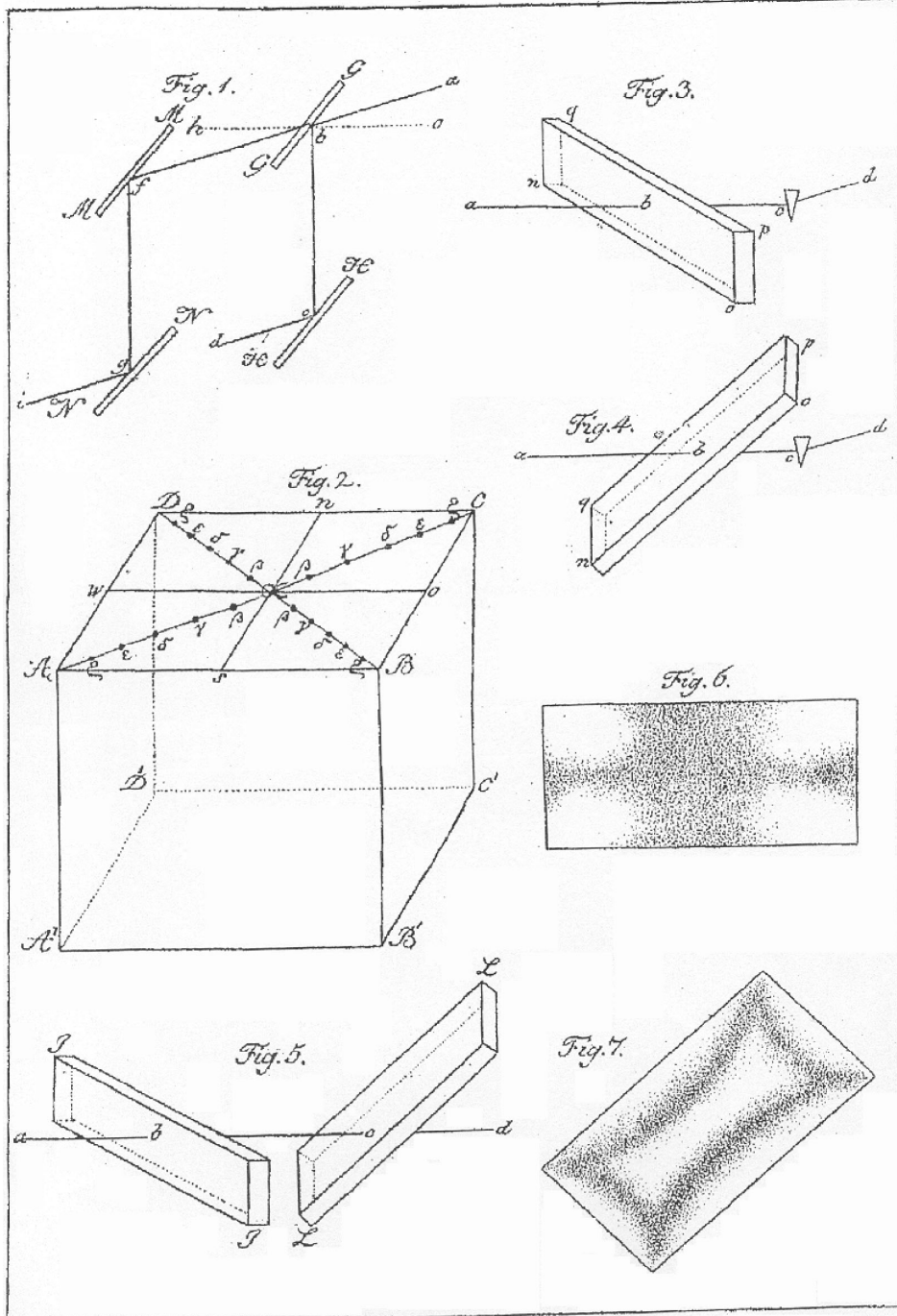


Fig. 1. First plate of illustrations of Seebeck's paper [9].

with piles of glass plates as polarizers. Figure 1.6 shows the optical image of a parallelepiped when polarizing elements are crossed and parallel to the borders of the specimen, and Fig. 1.7 shows the same specimen when it is turned in the polariscope 45 deg.

The fringe patterns drawn by Seebeck are the most interesting in the case of the cube. Figure 2.8 shows the optical image of the cube in the plane crossed polariscope when polarizing elements are parallel to the borders of the cube. The dark cross in the middle is the 0 deg isoclinic. The intensity of light in a plane crossed polariscope I_{\perp} is expressed as [11]

$$I_{\perp} = I_0 \sin^2 2\varphi \sin^2 \frac{\Delta}{2}, \quad (1)$$

where I_0 is the intensity of incident light, φ is the azimuth of the principal stresses and Δ is optical retardation between the light vibrations along the principal directions. Due to the symmetry of the cooling conditions of the cube, we have on the horizontal and vertical axes of Fig. 2.8 $\varphi = 0$ or 90 deg, and $I_{\perp} = 0$. Away from the symmetry axes $\varphi \neq 0$ and the fringe pattern is mainly caused by optical retardation Δ .

Figure 2.9 shows the image of the same cube in a plane parallel polariscope. In this case the intensity of light I_{\parallel} is determined as [11]

$$I_{\parallel} = I_0 \left(1 - \sin^2 2\varphi \sin^2 \frac{\Delta}{2} \right). \quad (2)$$

Now the horizontal and vertical symmetry axes appear bright and fringes, determined by Δ , appear near the corners of the image. From Eqs. (1) and (2) it follows that $I_{\perp} + I_{\parallel} = I_0$. In Figs. 2.8 and 2.9 this condition can be well observed.

Seebeck recorded the fringe pattern also in the plane crossed polariscope with polarizing elements parallel to the diagonal of the cube surface (Fig. 2.10). Again we see a dark cross in the centre of the image, supplemented by curved fringes in the areas near the borders of the cube.

Seebeck established also that if the cube was rotated around the axis bc of the light beam (Fig. 1.1), the fringe patterns of Figs. 2.8 and 2.9 repeated themselves after every 90 deg. This follows directly from Eqs. (1) and (2). Similar fringe patterns were observed by Seebeck when investigating eight other glass cubes.

Figure 2.11 shows fringes observed in a cylinder. In this case the dark cross (isoclinic) remains the same when the specimen is rotated around its axis. Figure 2.12 shows fringes in a glass block of complicated shape.

Let us mention that in the cubes investigated by Seebeck the stress field is actually three-dimensional. That is, the stresses vary in the plane perpendicular to the light beam as well as along it. Thus Seebeck actually recorded integrated fringe patterns, which nowadays are used in integrated photoelasticity and in photoelastic tomography for residual stress measurement in glass [12-14].

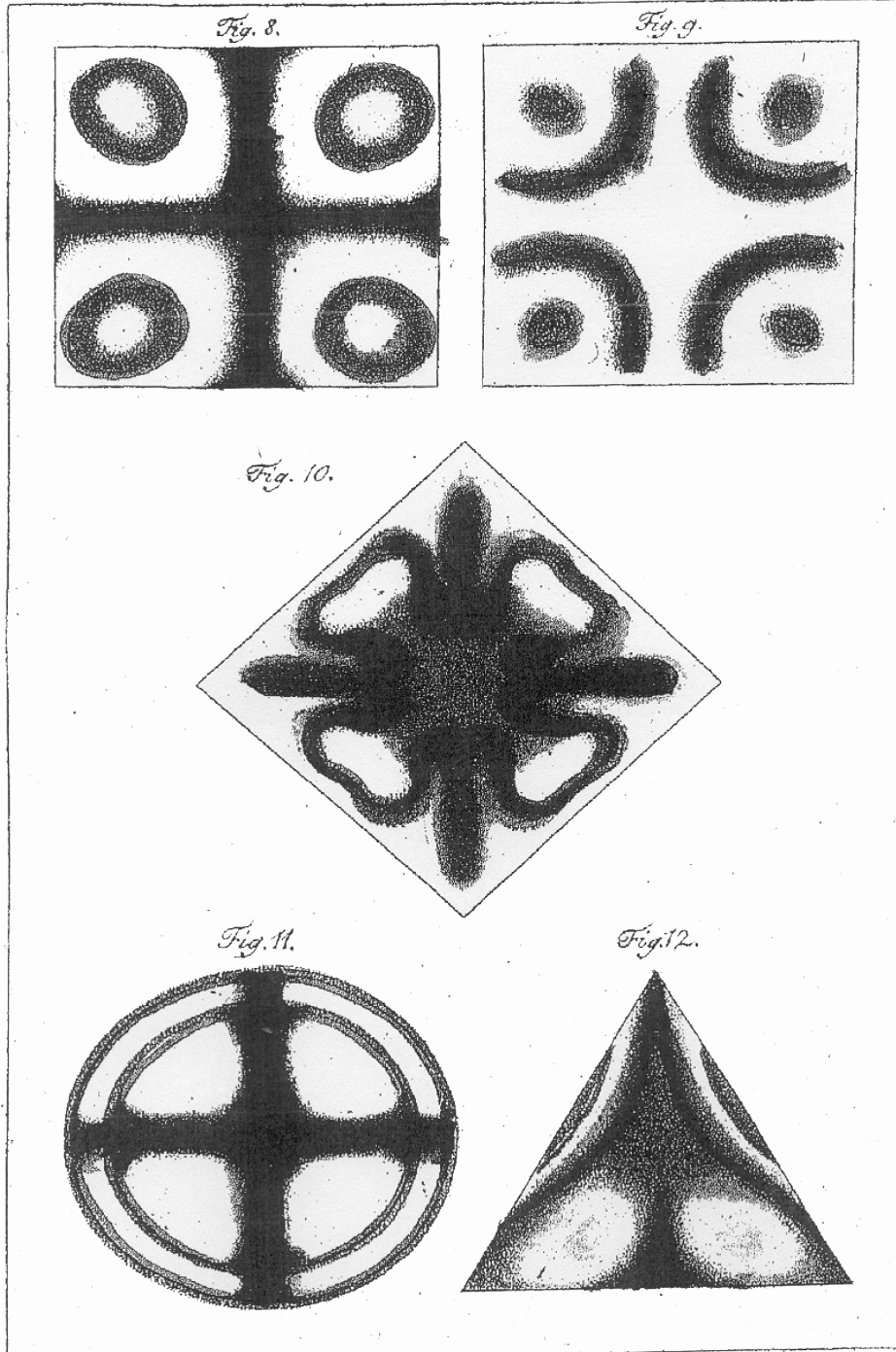


Fig. 2. Second plate of illustrations of Seebeck's paper [?].

Seebeck investigated in his polariscope also a cube made of NaCl, which did not exhibit any fringes. This is understandable as NaCl is a cubic optically isotropic crystal. Seebeck also observed that water does not change polarization of light while ice shows fringe patterns similar to birefringent crystals.

By using for polarization of light a pile of glass plates, Seebeck investigated the influence of the number of plates on the degree of polarization and found that the latter increases with the increase in the number of plates. Seebeck made his test objects from different kinds of glass. In [9] he mentioned that the brightest colours of the fringes were given by French crystal glass and some white Bohemian glasses.

Seebeck gave a detailed analysis of his experimental results in [10]. He mentioned that coloured fringes appeared only if the glass was sufficiently thick. He established that glass plates that did not exhibit fringes could be cut without problems while a piece of glass that exhibited bright coloured fringes broke into many small pieces when cut. He assumed that this phenomenon was characteristic of glasses that are quickly cooled down. He also heated up and cooled slowly down pieces of glass with coloured fringes and observed the vanishing of the fringes after such a treatment. Thus he actually used the two basic ways of thermal treatment of glass – tempering and annealing.

Seebeck observed also fringes in Prince Rupert drops, in small drops of glass cooled down quickly in cold water. An explanation of the fringes in these drops was later given by Neumann [15]. Also in this case fringes characterize stress birefringence in an integrated meaning.

On the basis of the experimental results Seebeck formulated the question [10]: “Do glasses cooled down slowly and quickly have a different internal structure (*innere Bau*)? And if so, can it be related to different forms of crystallization?” Seebeck had no doubts that the answer to the first question had to be positive. However, he was sceptical about the hypothesis about crystallization.

He referred to the hypothesis of Malus [5], according to which annealed glasses crystallize in cubic and octaedic systems and tempered glasses in rhomboedric and irregular octaedic systems. Seebeck investigated fringes in 60 pieces of quartz of different form. He showed that the optical behaviour of quartz is different from that of glasses. Most important is that in the case of quartz the dark (or bright) cross (isoclinic), always present in glasses, never appears. Besides, the form and position of fringes in quartz do not depend on whether the crossed or the parallel polariscope is used, only the colours of the fringes change. In glass the two types of the polariscope give completely different fringe patterns. Thus Seebeck concluded that fringes in crystals (epoptical fringes) have a different origin than entoptical fringes in glass.

Seebeck argued that only glass cooled down quickly (tempered) exhibits fringes. He considered it important to find an explanation how these fringes are formed. Let us mention that this problem has been treated in most of the books on photoelasticity. The fringe formation in integrated photoelasticity is the most

complicated [16-18], but singularities appear in the fringe patterns also in the case of 2D specimens [19].

As a practical result of his investigations, at the end of paper [10] Seebeck suggested that a polariscope should be used for the assessment whether a glass is tempered or not.

Here it is opportune to explain the difference of birefringence in crystals as compared to glass. In crystals the difference of the main refraction indices in the principal directions is usually of the order of 0.1 to 1. That is why we see in crystals the effect of double refraction and doubled images. In glasses the magnitude of birefringence is of the order of 10^{-3} . This is the reason why in stressed glass we observe interference colours, but no visible doubling of the images. This phenomenon was first noticed by Arago [7]. The case of weak birefringence has been thoroughly treated in publications on integrated photoelasticity [12,13,20].

3. INVESTIGATIONS OF BREWSTER

Independently of Seebeck, in 1814 English physicist David Brewster started investigating birefringence in glass caused by inhomogeneous heating. He also investigated the effect of sudden cooling of heated glass and discovered that in broken glass birefringence vanishes. Brewster considered his discovery so important* that he hastily published a paper, in which he only verbally described the creation of birefringence in glass by heat [21].

In 1815 Brewster discovered the classical photoelastic effect: "... I have been led to the discovery of a remarkable property of soft transparent solids, in virtue of which they exhibit, by simple pressure, all the optical qualities of doubly polarizing crystals" ([22], p. 60). This discovery was briefly published also in [23].

In [24] Brewster describes numerous investigations of birefringent glass. While Seebeck related birefringence of glass to its internal structure, Brewster considered heat as the cause of birefringence. Paper [24] is a very thorough investigation of birefringence in glass with numerous examples. To illustrate, Fig. 3 shows photoelastic patterns of a thick quadratic plate (Figs. 29 and 30 from paper [24]).

Brewster actually comes close to the real reason of birefringence in glass: "... I have discovered that glass, and all other substances that have not the property of double refraction, are capable of receiving it from mechanical pressure, and that a compressing force always produces the structure which gives the exterior fringes in crystallized glass, while a dilating force produces the structure which develops the interior fringes" ([24], p. 105).

Brewster suggests that glass should be carefully examined by polarized light before it is purchased.

* "... the results which I have described must be considered as of the utmost importance, ... as opening a new path to the solution of the great problem of double refraction" ([21], p. 439).

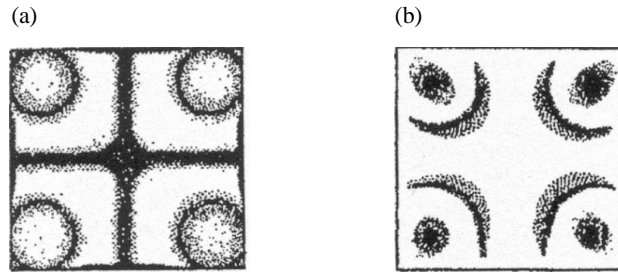


Fig. 3. Photoelastic patterns of a thick quadratic glass plate in a plane crossed (a) and parallel (b) polariscope, obtained by Brewster ([²⁴], Figs. 29 and 30). Compare with Figs. 2.8 and 2.9.

Paper [²⁴] is an excellent study on the photoelasticity of glass. However, many results presented in this paper were earlier obtained by Seebeck and published in [^{9,10}].

A considerable contribution to understanding the photoelasticity of glass is paper [²⁵], in which Brewster attempts to find mathematical relationships for describing the birefringence in different glass objects.

In 1815 the Institut de France decided to divide the prize for best results in the field of general physics (3000 francs) between Seebeck and Brewster. Both were awarded also a gold medal with the name of the recipient.

4. ON PERSONAL RIVALRY BETWEEN SEEBECK AND BREWSTER

As most of the great scientists, both Seebeck and Brewster were sensitive to attempts to diminish the originality of their research results. They were aware of each other's research areas, but not always well informed about each other's publications.

How both of them claimed to have discovered the birefringence effect in glass is most vividly shown by their own comments on their competitor's results. We bring here their statements as a curious illustration of the history of a discovery.

In a footnote of his paper [²⁴], p. 114, Brewster writes:

"I have learnt that M. Seebeck has published in a German Journal for Dec. 1814, an account of some experiments similar to those contained in Sect. II. of this Paper. As there is, so far as I know, only one copy of this Journal in England, in the possession of Dr. Thomson, I have not been able to obtain a sight of it, in order to compare M. Seebeck's results with mine. I understand, however, that he has discovered the fact, that a plate of red hot glass often acquires, in cooling, the depolarising structure, and that the tints depend upon the mode of cooling the glass. This result, however, has no connection whatever with the new properties of heat unfolded in the first Section of the preceding Paper, and does not anticipate the development of the phenomena contained in the Second Section.

The discovery of the new property of heat was made by me early in 1814, and an account of it was read before the Royal Society on the 19th of May, 1814. See *Phil. Trans.* 1814, p. 436.”

A year later, in his letter to Goethe, Seebeck explains his attitude towards Brewster’s works as follows* ([⁸], p. 379):

“I would like to point out that Mr. Brewster has not made the discovery at the same time with me, as he seems to hope (see *Göttingen Gelehrte Anzeigen* 1816, No. 176), but he has $\frac{3}{4}$ years later, after my 1st paper was already known in London and Paris, started investigations of coloured fringes in glass specimens and crystals. Also the Institut de France has awarded him half of the prize for two other discoveries and for the development of the phenomena, which were discovered by me; this you can find in *Moniteur* 1816, No. 10. I have no information about these developments yet. That formation of the fringes in glass depends on the way it is cooled down and how it is possible to create and to do away with entoptical fringes, I have hopefully first completely explained as it has been recognized also by the Paris Institute.”

5. GOETHE’S INVOLVEMENT IN SEEBECK’S DISCOVERY

Seebeck informed Goethe about the prize of the Institut de France in a letter of 30 January 1816 ([⁸], p. 356). In his reply of 6 February 1816 ([⁸], p. 359) Goethe congratulated Seebeck and expressed his interest in Seebeck’s discovery. Goethe asked Seebeck to send him specimens of crystal and glass, because “... I would like to repeat all the series of your discoveries...” ([⁸], p. 360). Goethe’s diary shows that he indeed constructed a polariscope and repeated many of Seebeck’s experiments [⁸].

In a letter to Schopenhauer Goethe underlined the importance of Seebeck’s discovery and referred to the need to rewrite his presentation about dioptric colours ([⁸], p. 360). In his answer to Goethe Schopenhauer expressed interest in learning more about Seebeck’s discovery and was satisfied with Goethe’s intention to start experimenting with polarized light ([⁸], p. 361).

In his letter to physicist C. C. F. Schulz of 11 March 1816 Goethe writes that he can not dismantle his simple polariscope at the window because he wants to demonstrate to his friends and visitors “this extraordinary phenomenon” ([⁸], p. 361). Goethe also mentions that there is a need to add to the known optical phenomena, reflection and refraction, a third one. He finishes his letter: “For me this situation is similar to that of a geographer who has discovered a new island.”

* Translated from German by the author.

6. CONCLUSIONS

In the discovery of the photoelastic effect in glass at least three scientists – Arago, Seebeck and Brewster – played an important role. Arago was the first to observe birefringence in glass [7]. Seebeck was the first to investigate systematically birefringence in glass specimens of different shape with different thermal treatment [9,10]. Brewster started his investigations somewhat later, but among his papers [22–25] one [24] is the most profound treatment of the problem. However, by explaining the decision about awarding the prize of 1816 to both Seebeck and Brewster, the Institut de France mentioned among other achievements of Brewster also* “... development of the phenomena discovered by Seebeck”. Thus the Institut de France gave the priority in discovering the photoelastic effect in glass to Seebeck.

In most of the encyclopaedias the investigations of Seebeck on optics are either ignored or only briefly mentioned. However, in 1818 he was elected a member of the Berlin Academy of Sciences for his works on optics. Thus Seebeck was a famous scientist already before he started investigations on thermoelasticity. It is not possible to overestimate the practical meaning of the discovery of the photoelastic effect in glass to the development of glass manufacturing. Application of this discovery started already in the 19th century. Nowadays modern photoelastic equipment is widely used in the glass industry for quality control and for the development of new efficient technologies for the manufacturing of glass containers and architectural and automotive glass [13,25–27].

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* Seebeck’s letter to Goethe of 30 January 1816, ([8], p. 358).

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T. J. Seebecki osast klaasi fotoelastsusefekti avastamisel

Hillar Aben

On näidatud, et Seebeck uuris esimesena süstemaatiliselt fotoelastsusnähtusi karastatud ja lõõmutatud klaasis. On analüüsitud Seebecki eksperimentaalseid tulemusi ja antud nende interpretatsioon nüüdisaja fotoelastsuse seisukohalt. Tulemused klaasi fotoelastsuse valdkonnas tõid Seebeckile kõrge tunnustuse juba enne seda, kui ta asus uurima termoelektrilisi nähtusi. Klaasi fotoelastsusomadused on aluseks klaasi kvaliteedi kontrolli meetoditele, mida kasutatakse laialdaselt tänapäeva klaasitööstuses.