Of Acoustics and Instruments*

Memoirs of a Danish Pioneer – Part 2

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This is the final part of this two-part series of articles. The first part was published in the February 2008 issue of *Sound & Vibration*. A short biography of Dr. Per V. Brüel precedes Part 1. Part 2 covers the period from 1942 to 1954. Acoustical research in Sweden during the final years of World War II, early production of electronic instruments at Brüel & Kjær, development and production of the first acoustical measurement instruments and development of measurement standards are discussed.

To Sweden

At the end of 1942, all the acoustical studies at the Radiohuset (Danish broadcasting house in Copenhagen) were completed and were being used. The Studio 1 concert hall was not finished, but it was decided that it should not be done until after the war. Quite sensibly one would not wish to inaugurate the Radiohuset until the Germans were out of the country. Thus Nøkkentved and I were no longer involved with the Radiohuset. I had almost completed my doctoral dissertation and only a few more measurement results from the Radiohuset had to be included.

The Brüel & Kjær company was doing rather well but it was difficult to find materials and components. For example, we did not have enough tinned copper wire for fabricating electronic circuits. Also there was a shortage of vacuum tubes. Fortunately, we received a huge order for vacuum-tube voltmeters from Philips in Holland. The factory in Eindhoven had been bombed and destroyed completely. The delivery time was scheduled for the end of the war. Philips helped with the vacuum tubes, and one of our good friends, engineer Ole Remfeldt, had surreptitiously acquired some excellent wire for us from a German telephone communications link (see Svend Gade's editorial in this issue).

In August 1942, I was visited by Peer Gummeson, the managing director of the Höganäs company in Sweden. Höganäs had just bought the Billesholm glasswool factory, and Gummeson wanted to see some acoustical applications for glasswool. We talked about acoustics technology for hours. Among other projects, I had just finished a number of experiments to estimate the savings one could achieve by placing mineral wool spaced away from a supporting surface rather than being affixed directly as shown in Figure 1. As a result of this discussion, I was employed in December 1942 in Stockholm as an engineer in one of the subsidiaries of Höganäs. They manufactured and sold acoustical absorbers that were made from both plaster of Paris and wood with glasswool coverings. These activities were extended to Finland, where I had also visited several times. I got my visa through Kryger A/S, which had several water treatment projects in Finland. So my visa was valid for Finland by way of Sweden. This allowed me to make multiple entries into both Denmark and Finland. The interest in acoustics and sound insulation almost exploded in Sweden and especially in Finland in the years that followed. In Finland, it was widespread building construction and new electronic industries that were responsible for their interest in acoustics. Much had to be built from the ground up because of extensive destruction. Swedish companies became involved in the construction of houses in Europe after the war. Building elements had to be developed that were both heat insulating and sound isolating.

Although a number of exciting projects could be noted here, they shall not be mentioned, since this article deals only with topics that concern Danish acoustics. I became head of a newly started acoustics laboratory, that was affiliated with the building technology section at Chalmers Technical High School (now university) in Gothenburg. Volvo and Götaverken sponsored the laboratory. This generated many projects for the auto- and ship-building industries. In addition, we had much work for the Swedish bearing manufacturer SKF. Over a long period of time, I went to Stockholm every Monday to attend meetings at the Byggnadsstyrelsen (Building Committee). I was offered and accepted a limited-time associate professorship to which I was committed until 1947. It was a turbulent time around 1944, since everyday there was something new. There were many other jobs apart from the purely acoustical projects. For example, the fact that I could travel to Denmark was of importance to the Danish police force. We tried to establish an infrared telephone connection between Skodsborg, Denmark and Sweden. The Germans had become very clever in locating Danish radio links. I worked on the infrared link with light expert Professor Weber, among others, but the technical difficulties were overwhelming and we gave up the idea.

We received unexpected assistance at Chalmers from a number of well-educated Danish people from various walks of life. They were all of Jewish descent who escaped to Sweden prior to the Nazi persecution of Jews in Denmark. Hitler had ordered all Danish Jews to be sent to concentration camps in Germany. Those who had an academic background were placed at universities and other state institutions. At Chalmers we had 12 of these refugees in the new acoustics laboratory – all well educated and proficient in their work. They were bankers, stockbrokers, painters, office workers, shop owners and craftsmen. They helped make many excellent measurements for the Building Committee.

Unfortunately it became very difficult for me to travel back to Denmark and I managed to complete only two trips after the Jews arrived in Sweden. The last trip in 1944 was unpleasant. I was often the only passenger on the Helsingborg-Helsingør ferry, and a German would examine my papers when I landed. But now there was a German soldier on the Danish ferry. The Germans had become very nervous and accordingly unpleasant. The resistance movement had become active. As usual I had a number of brief messages for my Danish colleagues. I indicated that I could not use envelopes for these messages and that everything had to be written on letter-size paper so that they looked similar to my own manuscripts. There could well be a meaningless differential equation on the messages. These messages were placed together with the manuscript for my doctoral dissertation that was to be defended the day after. The German on board the ferry stared at me viciously and ruffled all the papers so that they flew around the cabin. I admit that I was afraid. He then looked at one of my shoes, which had a crack in the heel. He ripped off the heel and, to be sure, the other shoe also got the same treatment. So I turned up in my father's tuxedo and shoes with glued-on heels at the assembly hall at Sølvtorvet for my dissertation.

My dissertation took a very long time, partly because Professor Ingerslev of the examination committee was more thorough than usual and partly because an air-raid siren sounded in the middle of it all. That was the last time I could come to Denmark before the war ended. I was just in time to see Professor Nøkkentved at the hospital. He died a couple of months later. Nøkkentved was the chairman of the Lydteknisk Laboratorium (Sound Technology Laboratory).

Research in Sweden

Since Sweden is much larger than Denmark and has many in-

*This article is based on "Episoder og Resultater inden for Akustikken för 1954" (Episodes and Achievements in Acoustics before 1954) by Dr. Techn. Per V. Brüel. Translated from the original Danish by Harry K. Zaveri. It was originally prepared by Dr. Brüel for presentation at the 50th Anniversary of the Danish Acoustical Society in 2003.

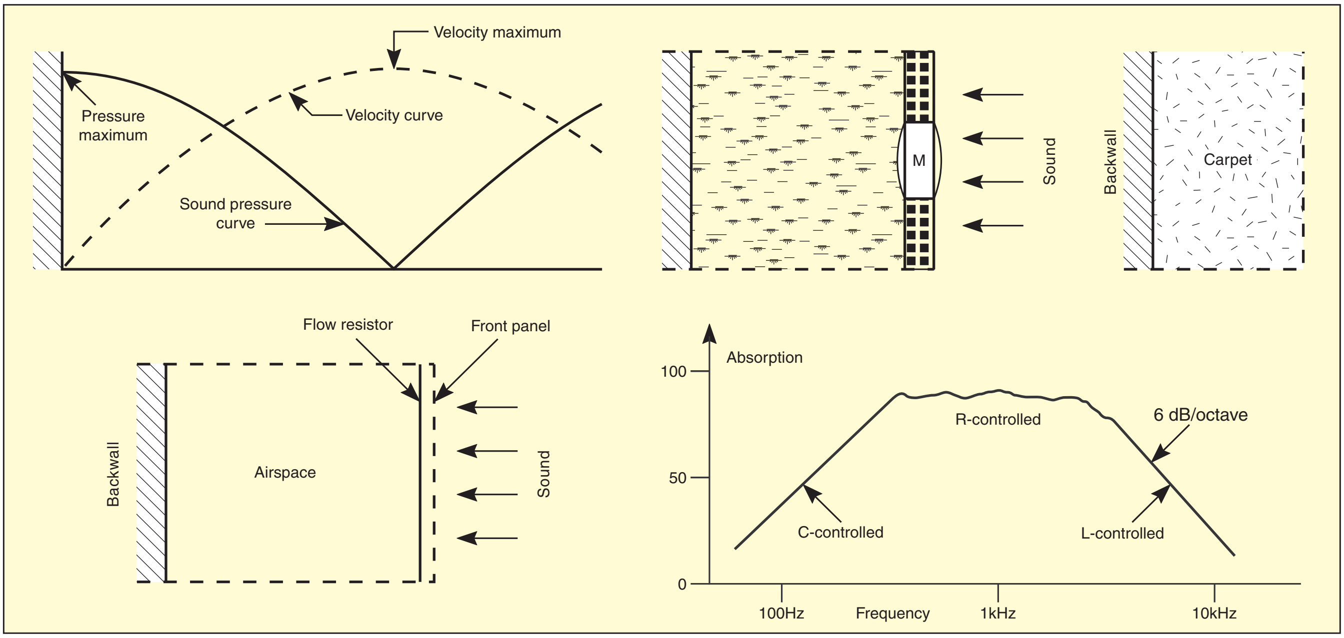


Figure 1. We made a few experiments for the Radiohuset project to see if we could optimize an acoustic absorber with a minimum of material. The main idea is to not have the absorbing material close to the wall, where the particle velocity is minimum. It's simple, but at that time everyone put rockwool mats close to the wall behind a perforated plate. Later at Chalmers, we developed this idea further. Today you still see acoustic plaster only 1 cm thick on walls. The high frequencies are absorbed well, but there is minimal absorption at low frequencies.

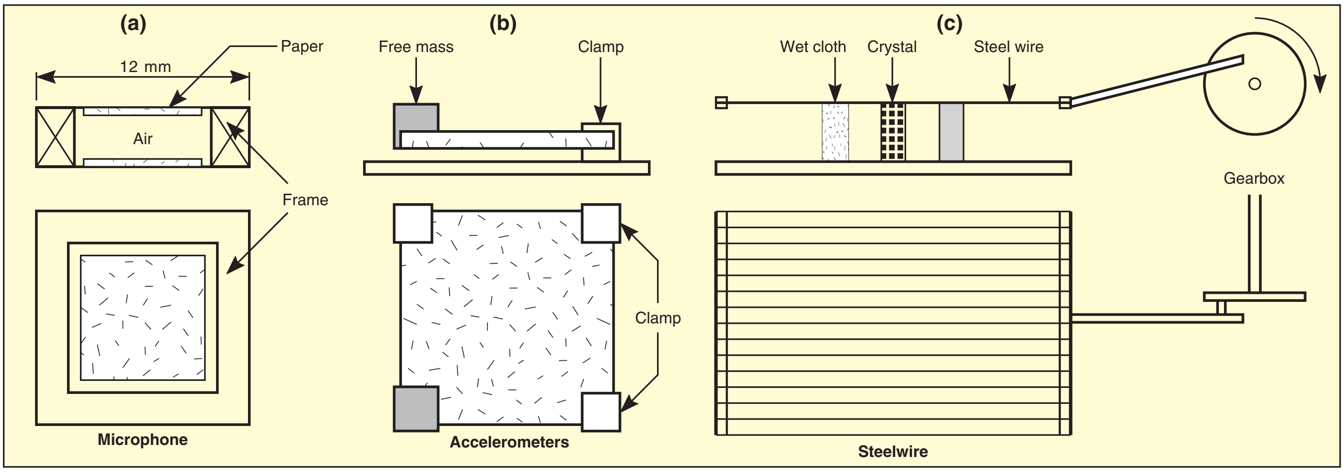


Figure 2. a) Microphone sensor with two Rochelle salt crystal plates and an air volume in a frame. b) accelerometer sensor clamped at three corners and free mass mounted at the fourth corner. c) F. Larris' idea to cut Rochelle salt crystals with wet wires to save its crystalline structure.

dustries, one would have expected them to have a greater interest in acoustics. But up to 1945, much more progress was made in Denmark. Sweden simply lacked a leader such as P. O. Pedersen in Denmark.

In the Technical Building Institute at KTH (Swedish Royal Institute of Technology), Professor Kryger had a small department run by Heimburger, who had been in the U.S. for some years and had brought back some know-how on reverberation time and sound insulation measurements. Also the Radiotjänsts (radio service) technical department was interested in studio acoustics and microphones.

L. M. Ericsson aided Professor Fant financially for a speech laboratory at KTH. Stellan Dalstedt at SF (Swedish Film) did some work on room acoustics. Glasuld in Billesholm and Skövde sold glasswool and rockwool acoustic absorption materials respectively. Glasuld were pioneers in developing very fine glasswool used for personal hearing protection devices (earplugs). There was almost no consulting in acoustics. But after 1950, many individual consultants and companies emerged that dealt with sound, sound insulation and room acoustics. Sweden has always been keenly interested in hearing damage risk. Their interest in acoustics problems resumed during and after the war. The laboratory at Chalmers started in 1943 and evolved to become a leading source of building technology in Europe. Professor Tor Kihlman of this laboratory had a significant influence on noise control legislation. From 1944 to 1947, the Acoustic Laboratory carried out a number of routine measurements of noise, vibration and sound insulation of ceilings and walls between apartments.

Rochelle Salt Sensors

During the war and some years later, acoustical laboratories were running short of good microphones and vibration pick-ups. We decided to develop transducers using Rochelle salt similar to the expensive ones made by Brush Electronics in Cleveland, Ohio before the war. We therefore cultivated crystals of Rochelle salt, cut them and made small sound cells for microphones and slices for accelerometers. The "sound cells" consisted of two thin crystal slices suspended on a very thin piece of paper and a frame that enclosed an air volume as shown in Figure 2a. This produced a sound pressure-sensitive element. As shown in Figure 2b, the accelerometer element was a single crystal slice that was fixed at three corners. A mass was mounted at the fourth corner to bend the slice when the whole transducer was subjected to acceleration.

We cut the slices using a band saw, which unfortunately partly damaged the surfaces. F. Larris found a way to cut the slices using a wet wire so that the dissolved salt settled again in the correct crystalline structure (see Figure 2c). This way, we could almost double the output of the process and cut many slices simultane-

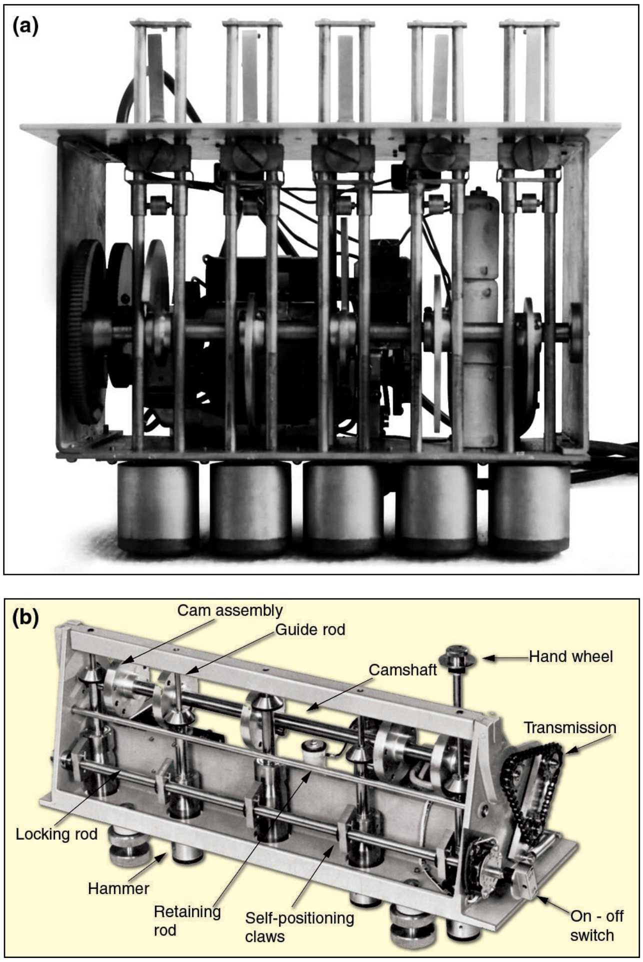


Figure 3. (a) tapping machine made at Chalmers with five hammers close to each other; it was later standardized by IEC in Geneva with more space between hammers. (b) Newer Danish model lifts hammer with circular movement.

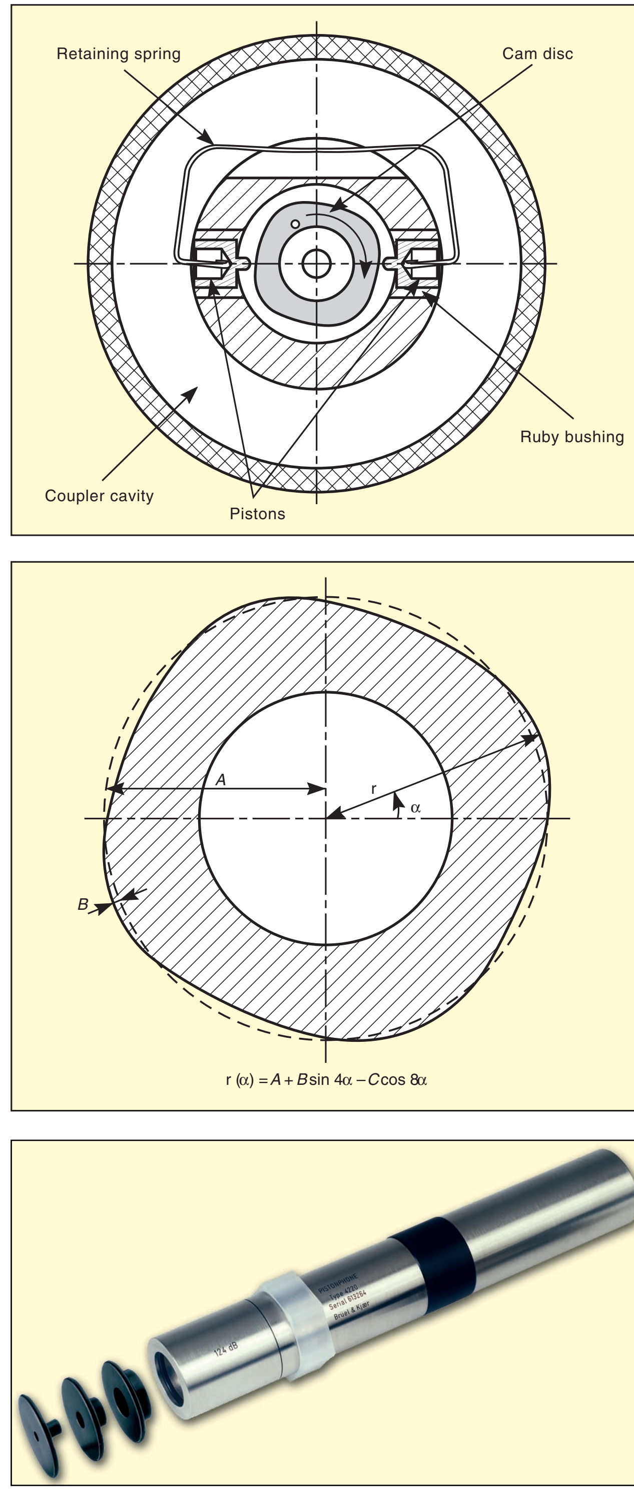


Figure 4. Operating principle of the B&K 4220 Pistonphone. Two pistons are symmetrically driven by a means of a cam disc mounted on the shaft of a miniature electric motor. They are seated in ruby bushings and made of Teflon, presenting a low-friction coefficient with the steel cam. The tension of the retaining spring is adjusted to maintain contact with the piston tips on the steel cam, which is polished to high accuracy. Rotating cam will give pistons a sinusoidal movement at a frequency equal to four times the speed of rotation. Consequently cavity volume is varied sinusoidally.

ously. However, the process was time consuming since it took several hours to advance one centimeter. When the war was over, we changed over to condenser microphones and accelerometers with ceramic piezoelectric discs, which react to pressure and shear forces. These products were made in Denmark.

Tapping Machine

Because of the intense work carried out by the Acoustic Laboratory at Chalmers on noise problems in wooden houses, we had to make many measurements of floor impact noise isolation. We had heard of some German experiments where the floor/ceiling between two flats was repeatedly impacted with a 500 gram hammer, and the noise level underneath was measured and corrected for the absorption in the receiving room. We wanted to use such a hammer, so we constructed an apparatus with five 500-gram hammers mounted close to each other (see Figure 3). Each hammer fell twice per second. We used this apparatus a lot. We also made one specimen for Norway, two for Finland and two for ourselves in Sweden. Soon after the war, the IEC (International Electrotechnical Commission) in Geneva wanted to standardize such an instrument. A working group was established, and as far as I remember, Dr. W. Furrer was appointed to convene the group. I heard about this, so I sent drawings and descriptions of our instrument to the IEC in Switzerland shortly before the Working Group meeting and said that I would be attending that meeting. I turned up in Bern with the instrument under my arm. I told the few that were present that five specimens had been made in Gothenburg and had been tried out in the Nordic countries. The production would take place in Denmark. All the technical details were fully acceptable, except that the group wanted a larger distance between the hammers. I had no objection to that.

Then came the laborious and frustrating formalities: 1) Which country did I represent? 2) Had the local IEC department in the country I represented agreed that I should be the appointee on behalf of that country? I suggested that the attendees could decide that for themselves. I was a postgraduate in Denmark with a Danish doctorate, was now an associate professor at Chalmers, but I lived in Sweden. The group decided that I represented Denmark, because the production would take place there. Everything was okay in Bern, where a report was sent from the meeting to the Danish Standards Organization, whose chairman (Holmblad) was

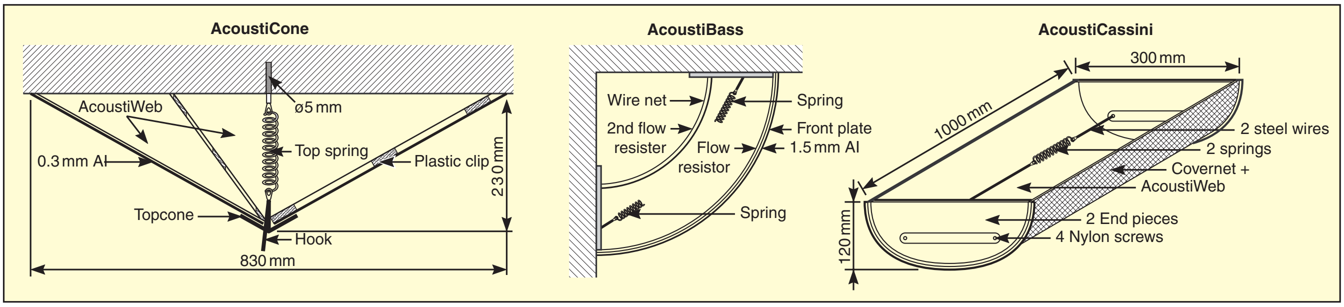


Figure 5. Prototype absorber units made of aluminum and polypropylene sheet as a flow resistor.

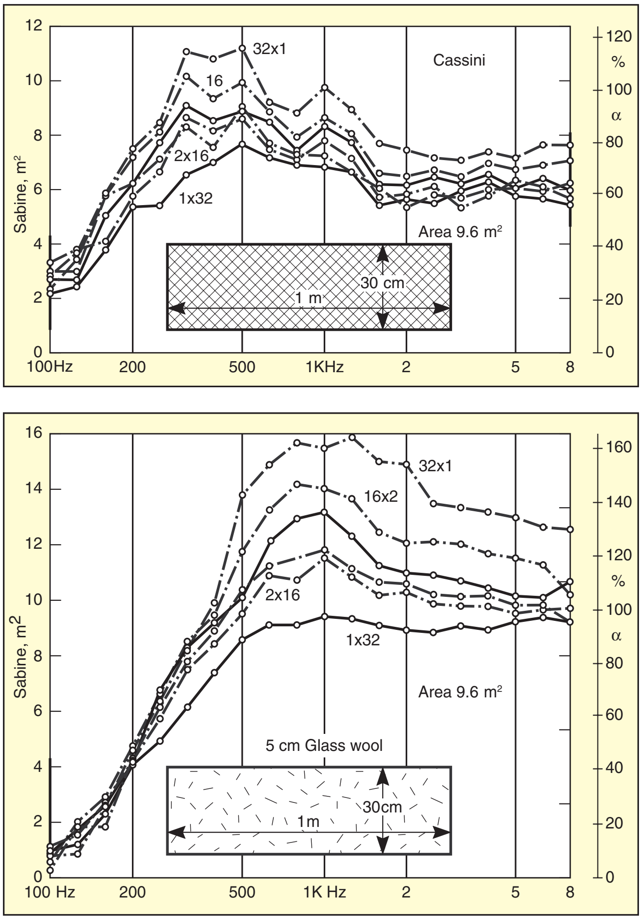


Figure 6. Measurements show how sound absorber units can be more effective by spreading them out. 1x32 is an adjoining unbroken area 9.6 m². 32x1 is 32 simple absorber units spread out over a total area of 24 m². More than 100% absorption is obtained simply by adjusting the flow resistance of the absorptive material to slightly below 400 Rayl, Some of the sound energy falls on the reflecting part of the ceiling. At the same time, the reflection from the total surface is a rather diffuse field.

completely surprised to hear that the Danish representative's proposal would now end up at the headquarters in Geneva for further discussions. This was not by the book, so I was in for a serious reprimand. However, the chairman was a very sensible man, who let bygones be bygones, and appointed this unruly Brüel to be the official representative for Denmark. I would then not have to pose as a Danish official in the future without being one.

Barometric Pressure and Temperature Corrections

When we made noise measurements on Volvo cars in Gothenburg, we had difficulties with accuracy. When we repeated a measurement on Monday, the results did not always agree with those we made on the previous Friday. For development work on cars, household appliances, and machine tools, one is often interested in measuring very small changes. The noise we were interested in measuring was generated by vibration of large surfaces such as car bodies, side panels of washing machines, etc. These vibrating panels emit noise proportional to the density of air, or proportional to the static air pressure and inversely proportional to the absolute air temperature. So we suggested that all the noise measurements should be corrected for the standard atmospheric static pressure of 1013.2 hPa, temperature of 15° C, and relative humidity of 65%.

A pistonphone with one or two pistons would be ideal, as the sound generated would be proportional to the density of the air. We developed several different designs at Chalmers that did not turn out to be satisfactory. Around 1950 we came up with the ideal solution that had two pistons guided by a polished cam disc as shown in Figure 4. The design for guiding the pistons using a polished cam disc came from Gunnar Rasmussen. This mechanical construction is extremely stable and the sound pressure doesn't change even after many years of use. One Brüel & Kjær 4220 Pistonphone manufactured in 1960 with normal usage during 43 years had not changed within a measurement uncertainty of ±0.03 dB. The precision sound source is calibrated to generate a known sound pressure level in a standard atmosphere.

Using this small transportable sound source and a Class 2 sound level meter, we measure the same sound level of a sound source on top of a mountain or sea level at a standard atmosphere. We do not need any correction factors for our standard sound source or for the measured source. As we have a very stable calibration source, we can measure sound with an uncertainty that is five times lower than when we use a class 1 IEC standardized sound level meter.

Flow Resistor Absorber

During our job with the Radiohuset, we were experimenting to reduce the amount of material in absorbents by only having glass wool or rockwool at positions where the particle velocity was significant; that is, no absorbing material close to the wall as shown in Figure 1. Theoretically it should be possible to achieve 100% absorption using a thin 'braking' layer at the position of maximum particle velocity and where the acoustic impedance is around 400 Rayls (see Figure 5).

At Chalmers, the paper factory Lilla Edet (north of Gothenburg) got interested in making acoustic absorbents from paper and cardboard. The speciality of the paper factory was making soft, fine napkins and could therefore make 'braking' layers for every given resistance to the particle velocity. The factory could also produce excellent hard glossy cardboard that could be perforated with small holes. We made some very good acoustic absorbent specimens. We also found a hard glue that was applied at specific positions on the absorbents where they could be fixed to the ceiling. So we could use an ultrasonic gun and mount the absorbents by heating the gluing point for just a fraction of a second. Despite the amount of flammable material being minimal (not more than a newspaper lying on a table), we could not get permission to use them from the fire department. We tried to replace cardboard with masonite, but even that could not be approved. So the project had to be abandoned.

We learned two important lessons – effective sound absorbers can be made using very little material. By dividing the absorbents into small units and changing the flow resistance slightly, one could achieve a high degree of effective absorption. We participated in construction projects that provided 120-150% absorption coefficients over broad frequency ranges (see Figure 6). Another very important and often overlooked fact is to have a mixture of absorbing and reflecting surfaces that deflect the sound in several directions to generate highly desirable diffusion. This effect is most predominant at the lower frequencies. By designing curved specimens one can achieve diffusion at high frequencies.

Swedish Acoustical Society – SAS

In 1944, the Swedish Acoustical Society (SAS) was founded – 10 years earlier than the Danish Acoustical Society (DAS). DAS received and used the same organizational structure that we put together in Stockholm, In Sweden, there were four active individuals, namely Stellan Dalstedt (SF), Mattson (radio service), Heimburger (KTH) and myself (Chalmers). The founding of the society took place at Norra Tårnet on Kungsgatan. At almost the same time, the Scandinavian Airlines System (SAS) was also founded on the north side of Kungsgatan, but further down the road toward Birger Jarlsgatan. If we had known, we would have adopted another name or at least another acronym. The acoustical SAS has had a steady evolution. The society organized many good meetings and publishes a magazine that has consolidated the membership. The 50-year anniversary of SAS was celebrated modestly with a meeting in Stockholm where Tor Kihlman briefly reviewed its historical development. Much had happened during 50 years.

Level Recorder

J. Oskar Nielsen's very fast recorder for RT (reverberation decay time) measurements has already been mentioned and also the Neumann recorder, of which LTT received two specimens. Oskar Nielsen's recorder never went into production, and Siemens stopped production of the Neumann recorder when the war broke out in September of 1939. In 1942-43, there was a shortage of level recorders for the measurement of RT. Finland in particular needed them and put pressure on the Chalmers Acoustical Laboratory to develop a good instrument.

The cheapest and quickest solution would have been to make a modified version of Oskar Nielsen's recorder. The ingenious water potentiometer deterred us, since it had to be perfectly horizontal and we would also try to avoid the photographic recording method. The Finns (Arni) fervently urged us to make a direct copy of the Neumann recorder. The operating principle is shown in Figure 7. I was against that, because we had found the following disadvantages:

- The cradle that moved back and forth was very heavy, the system would overshoot and took time to settle down.
- If there was incorrect tension on the input potentiometer, the contact discs would rub against the cradle with full force and cause heavy wear.

So we had to invent a completely new construction. This resulted in a number of very often imaginative experiments:

- A logarithmic voltmeter with a copper oxide rectifier.
- An electrostatic stylus that burned a trace into the moving recording paper.
- A hydraulic model that squirted oil over the whole laboratory.

Finally we decided to make use of an electrodynamic system to drive the recording mechanism. We received some very good help from Danish academics assigned to us. Among them was engineer Freimut Larris, who was extremely well acquainted with German technical literature. So Larris and I put together an electromagnetic system with a coil, recording arm and a stylus. One of the difficulties was supporting the coil within the magnetic system. Larris found a solution using tensioned wires as shown in Figure 8. I also had Uno Ingård as an assistant for eight months before he left for the U.S. and became famous. Ingård, who was an electronic engineer, made the DC amplifier shown in Figure 9. When we were ready to put the components together, I expected the production to take place in our company facility, where we had good technicians.

But it was not so easy, since Viggo Kjær was convinced that we could not sell more than about 50 units. Kjær and I had an agreement that we would not produce anything that could not support a production run of at least 75 units. I felt I could sell 150 units, so I had to produce the first recorders in Sweden. Later Brüel & Kjær started to manufacture them. The total number of level recorders produced was 25,000 over 30 years. I have wondered why I predicted that only 150 units could be sold, but there was apparently a much bigger demand than we had anticipated. The level recorder with one stroke opened up the instrumentation market for Brüel & Kjær in the U.S., Japan, and the communist countries.

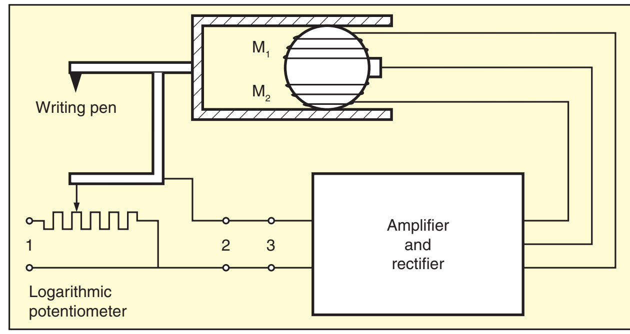


Figure 7. Operating principle of Neumann level recorder designed by v. Braunmühl in 1933. It was produced by Siemens in 1938.

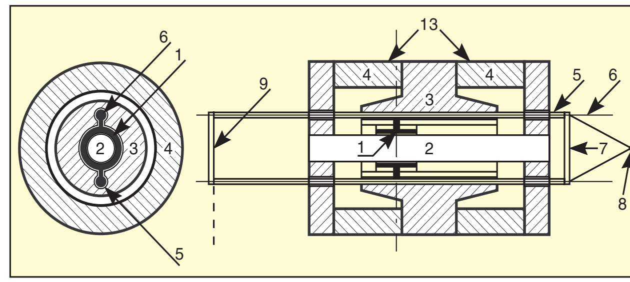


Figure 8. Magnet system of the B&K level recorder. The simple wire suspension was Freimut Larris' idea.

Since the market turned out to be so large, strong competition was expected. But we did not get any. I have seen an exact copy of our level recorder in the technical museum in Shanghai. I saw that one afternoon together with then foreign minister Uffe Elleman Jensen during an official visit to China. As far as I know, that level recorder never worked. The coil was very sluggish and there were no signs of any wear. I wanted to see it in more detail, so the next morning I took a taxi to the museum, where I was cordially received. I asked to see the displayed recorder more closely. The Chinese replied that they did not have any level recorders. In such circumstances one needs to smile and apologize for making a mistake.

I heard in Poland that the Russians had made a copy of our recorder, but I have never seen it myself. We had a request from the Russian side to help them develop a level recorder. We talked about it, but we convinced them that we sold it so cheap that Russian production could never compete. So I got an order for 100 units from them. There has not been any serious attempt from anyone in the west to make a similar level recorder. This is probably because our policy has been to never go after more than the market can bear, to produce as sensibly as possible and fix the price to give a reasonable profit. This turned out to be a very good policy.

The first two series of level recorders were equipped with a very large capacitor in parallel with the driving coil to damp the system. Without this damping, the drive coil shot past the null balance point at high velocity. This made the whole system relatively sluggish. Viggo Kjær was in the U.S. for half a year and visited Professor Campbell at MIT. There he learned how negative feedback could operate on systems consisting of both electrical and mechanical components. Kjær got the idea to use an extra coil next to the driving coil. The extra coil sensed when the balance point was approached, and the current in the main coil was fully reversed. We could dispense with the large damping capacitor, so we now had a very fast and precise recorder that was superior in all respects to the Neumann recorder.

One might wonder how a small, unknown company can break into two big inaccessible markets like the U.S. and Japan. Normally a lot of capital is required to penetrate these markets, and our company had none to spare. The reason for the marketing success was credited to a small half-page article published in the *Journal*

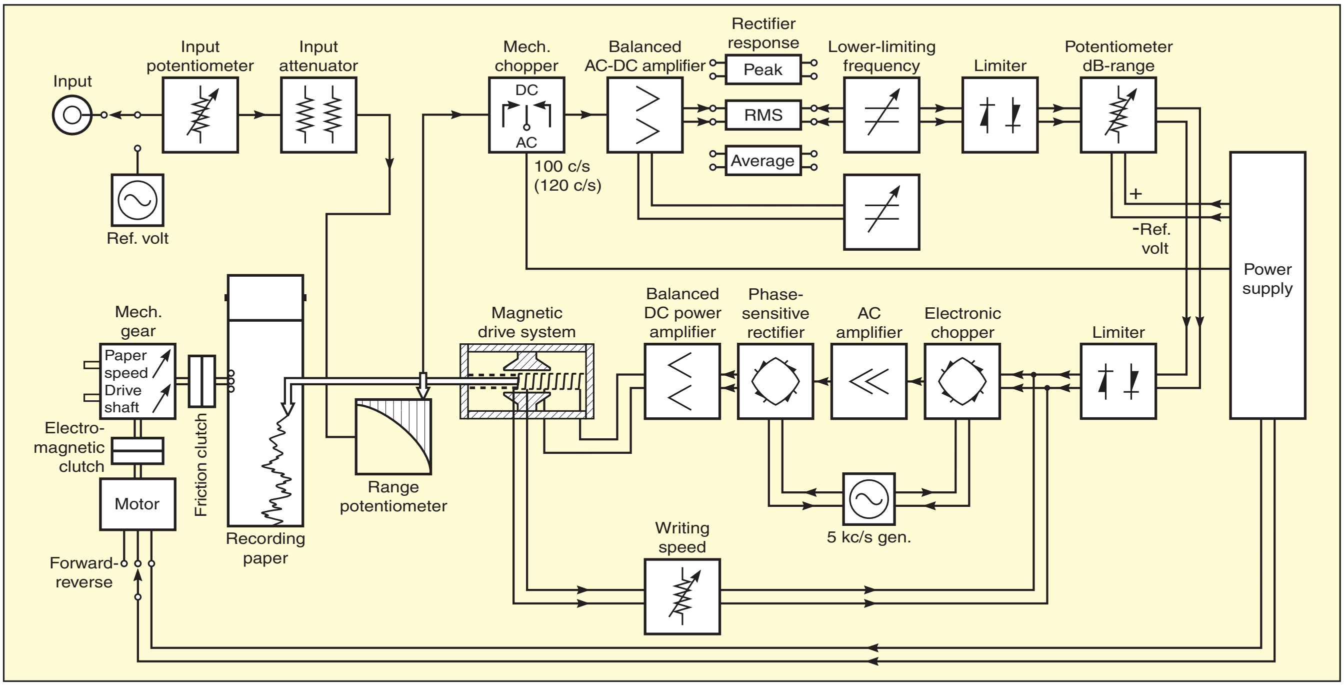


Figure 9. Schematic diagram of the B&K Level Recorder. The chart drive system could be mechanically coupled to oscillators and analyzers to completely automate a measurement procedure.

of the Acoustical Society of America (JASA). I believe the success was due to the following:

- There was a worldwide need for recording reverberation time in rooms.
- The equipment available elsewhere had severe technical faults (wear and high inertia).
- We had a simple solution that did not have the faults of the predecessors (electro-dynamic operating principle and feedback coil)
- Possibly the most important – the company managers knew the product applications and could discuss it with the customers.

Eventually the managers got to know all the leading institutions and researchers in this field (universities and development laboratories). Nevertheless, it is surprising that market analysis indicated a market for 150 units and we sold 25,000.

Apart from being a good business, there is no doubt that the level recorder was also to a large extent responsible in establishing Denmark's position as the country where there was knowledge of acoustics. Some years later we were successful in developing another product that had the same effect.

Condenser Microphones

Toward the end of the 1930s, it was known that Rochelle salt was not suitable for use in precision measurement microphones, since their sensitivity fluctuated with humidity. As a consequence, the need arose in the U.S. for a microphone that had a stable sensitivity over a long period of time. A decision was made to standardize three microphones for use in laboratories.

Two of the microphones were 1-inch and 1/2-inch piezoelectric cylinders placed on an iron block. They were completely useless as microphones; in fact they were more like bad accelerometers. These microphones were never used nor ever produced in quantity. They were developed by Frank Massa in Cleveland, Ohio. Massa was a hilarious individual full of good humor and crazy ideas. He had a terrific "gift of the gab," and convinced the standards committee of the ASA (Acoustical Society of America) to accept his microphones as a high quality product. But no one had ever tested their design. As soon as the standard was published, there was a deafening silence about the performance of these microphones.

The third laboratory standard was a condenser microphone developed at Western Electric under the type number W.E. 640AA. It was called a "1-inch microphone." A cutaway view of the microphone is shown Figure 10a. The 1-inch housing diameter of this microphone was not 25.4 mm but 23.77 mm. The technicians at Western Electric for some reason machined the diameter to 23.77 mm.

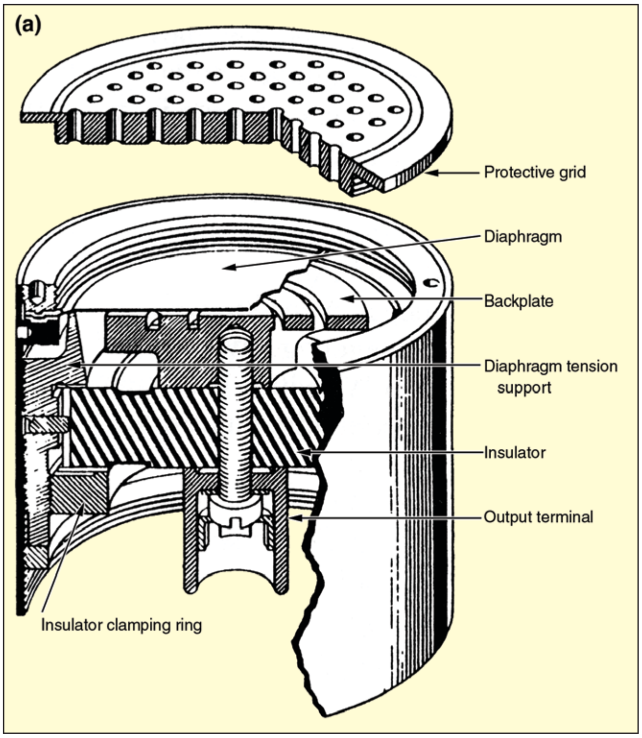
When the microphone was completed, it was calibrated extensively in Bell Laboratories' anechoic chamber. The frequency response, directional characteristics, reflections and sensitivities in different directions were all measured at different temperatures and humidities. ASA accepted this microphone, which was excellent in many ways, and made it a laboratory standard 1-inch microphone. The American standard was recognized all over the world; that is why a 1-inch microphone today is 23.77 mm in diameter. For many years, this was the microphone that was used as a laboratory standard. Brüel & Kjær used it a great deal, but changed to a larger, 36-mm microphone produced by Ortofon. It was developed by Dr. Schlegel and had a flat front surface. For this reason, the Ortofon microphone was, in fact, just as good as the W.E. 640AA. Developments continued and there was a need for a sound level meter with even greater demands on the stability and size of the microphones.

The W.E. 640AA had some disadvantages apart from the fact that the diaphragm was recessed into the housing. The microphone was designed to be mounted on a Western Electric preamplifier, which had a rather large thread. This required that the thickness of the microphone housing had to be small. If the housing was accidentally deformed, one had difficulty screwing the microphone onto the preamp. Even worse was the fact that the microphone became more sensitive with age. The sensitivity change was not constant, but between 0.5-1.5 dB per year. Other microphones were also investigated (Schraub and Ortofon), and they also became more sensitive with age.

If the diaphragm clamping ring and the housing had different temperature coefficients, no number of fasteners could prevent slippage between the ring and the housing and possibly allow the diaphragm to shift slightly. Consequently, the microphone became more sensitive with age. For the microphone to be stable it was necessary for the diaphragm to have a molecular bonding to the housing either through welding, hard soldering or electroplating. As the clamping ring became superfluous, Brüel & Kjær could make a stable microphone in all sizes, even down to 3 mm in diameter.

The time had now come for Brüel & Kjær to make a stable, small microphone. Fortunately, as there were no standards we were obliged to fulfill, we could freely optimize our design wishes:

- A microphone that was exactly a half inch in diameter. We chose 12.5 mm.



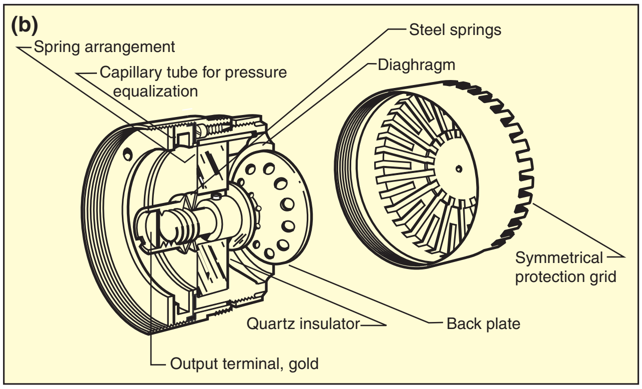


Figure 10. (a) Western Electric 640AA 1 inch microphone. The diaphragm is clamped within the housing with a series of small screws. (b) B&K 1/2 inch microphone. The diaphragm is welded to the housing and the microphone has no front cavity.

- A diaphragm as large as possible relative to the housing.
- Direct bonding of the diaphragm to the housing either through welding, hard soldering or electroplating.
- A back plate and housing of the same material to ensure a constant gap between the back plate and diaphragm independent of temperature.
- The diaphragm material should be very strong and have uniform molecular structure so that it can stretch without tearing and be reasonably corrosion resistant.
- The housing should not deform after a drop to the floor.
- The self-noise of the microphone should be minimized.

For 25 years, Brüel & Kjær has had the privilege of being a leading manufacturer of quality microphones. This single product has been responsible for an export of 30 to 50 million Danish Kroner per year. Only in recent years have competitors from Japan, China and the U.S. entered the market. All of them appear to be copies of Brüel & Kjær's original design (see Figure 10b). Even the design of the protective grids appears to be the same. It is thought provoking that a combination of rather simple technological changes and a straightforward design can create such a powerful monopoly that could last for more than 25 years.

The technological breakthrough was in attaching the diaphragm to the housing through welding or soldering instead of clamping. This technique was so obvious that it could not be patented. The characteristic design is primarily a product of stringent exploitation of known physical laws. The design was awarded a prize and was, in fact, so successful that our American subsidiary, B&K Instruments, Inc. once replaced their logo with a drawing of the prize-winning microphone grid.

Artificial Ears

Forty years ago, there was a major dispute on how an artificial ear should be designed. There were many different types, but none was based on measurements of the human ear. When Brüel and Kjær successfully developed some 3 mm microphones, it was possible to make some important measurements. Primarily we wanted to measure the impedance of the ear as a function of frequency approximately 15 mm into the ear canal, which is typically the termination of a hearing aid earmold. The measurement method is quite simple. Two small condenser microphones are inserted into the ear canal in parallel so that they are completely isolated from the outside except for the pressure equalization channel. One microphone operates as an emitter and generates a frequency-independent volume velocity. The other microphone measures the sound pressure, which is directly proportional to the impedance, as the volume velocity is constant.

To our astonishment we found that the impedance increased in two steps (see Figure 11a). As the measurements are difficult and time consuming, impedances of only Gunnar Rasmussen's and my right and left ears were measured. We obtained four impedance curves that were close to each other. On the basis of these results, an artificial ear could be constructed with the same impedance as we had measured. Figure 11g shows a drawing of the final result. IEC standardized this artificial ear; all the other types that were in use were withdrawn. My and Gunnar Rasmussens' ears now have the honor of being the foundation for the measurement of all present-day telephones, hearing aids and mobile phones the world over!

Békésy – Nobel Prize Winner

Many strange things occurred toward the end of the Second World War. One of them was that Georg Békésy worked part time at KTH in Stockholm with Professor Fant. Békésy was a Hungarian biophysicist who was awarded the 1961 Nobel Prize in Physiology or Medicine for his research on the function of the cochlea in the mammalian hearing organ. I had my lectureship in Gothenburg but was in Stockholm every Monday. I talked several times with Békésy, since I was especially interested in his audiometer, where the client under test controls the instrument. We had found in Gothenburg that if we interrupted the signal tone twice per second, one could still hear the tone all the way down to 10 or 15 dB below the noise level. This meant that it was unnecessary to have a noise isolated test chamber for taking an audiogram. Our aim was for companies to be able to do an audiogram of each employee yearly at a reasonable price and quickly. We also toyed with the thought of finding a relationship between one's intelligence and perception capability from an audiogram. Békésy did not think that was possible. We also found that out. We also discussed the time constant of the human ear. Békésy had measured that to be 300-350 msec. This did not agree with the values of others; e.g., Zwicker, 150 msec; Reichart (Niese), 15 msec; IEC and Fastl, 125 msec. Békésy did not think that the human ear perceived noise proportional to energy (10 dB/decade) but in a very strange relation between energy and time, approximately 4.5 dB/decade.

Békésy seemed to be rather quiet and modest but, in reality, he was difficult and complained about many things. His aides, for example, both engineers and especially his technicians, were not clever enough. Therefore he was not happy living in Stockholm. I asked him if he would like to try Copenhagen for a while. I tried different possibilities where Brüel & Kjær could manage the expenses for a period of time. At least we had clever technicians. Békésy was apparently interested at one point, but then the Americans snatched him. He was given some rooms in the cellar at Harvard facing MIT. I visited him twice, but he was still dissatisfied. Some time later he went to teach at the University of Hawaii, where he died in 1972. I never did see him again. As an afterthought, it was probably a good thing that he did not come to Denmark, as it

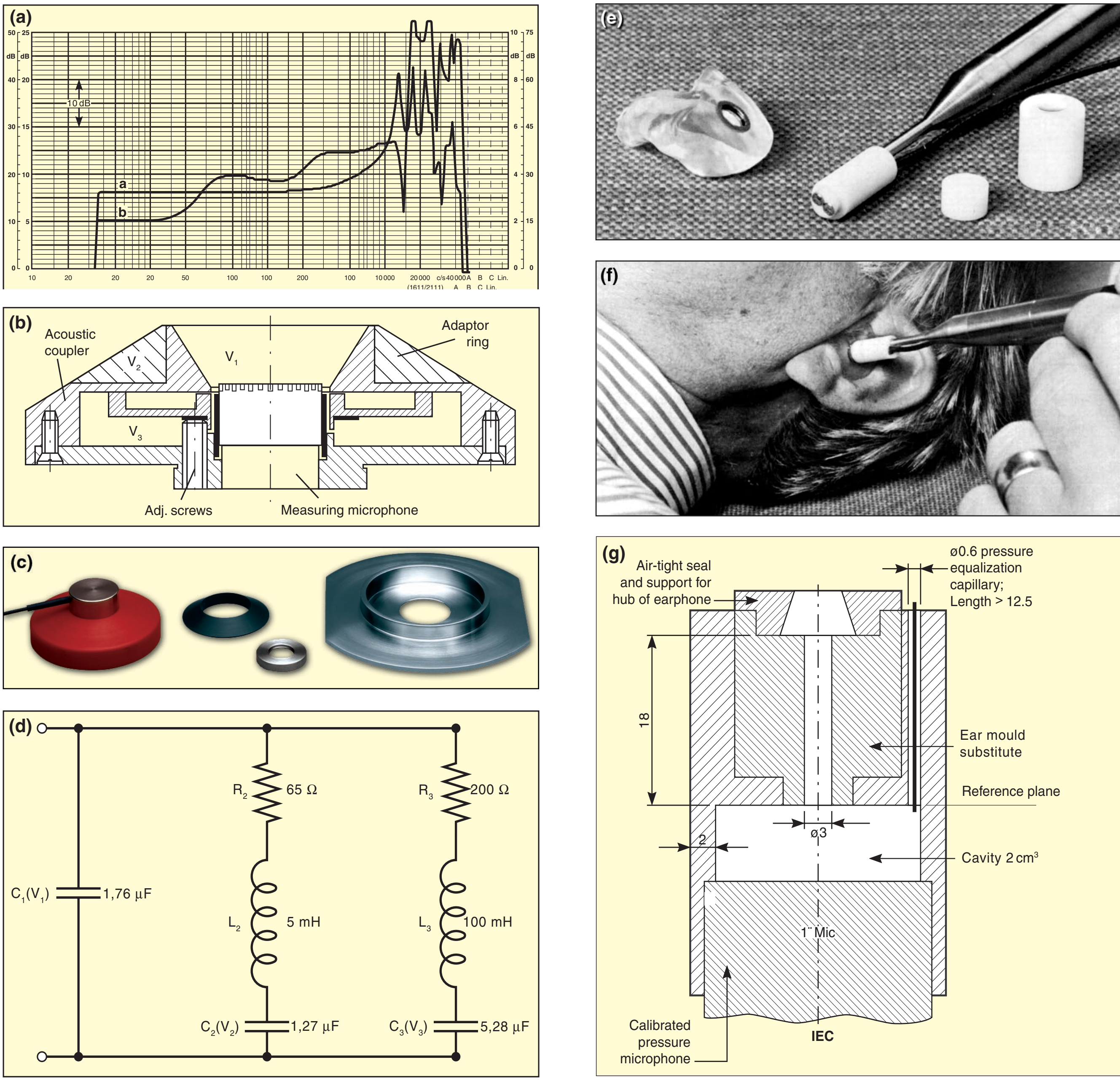


Figure 11. (a) Measured impedance of four ears (PVB and GR). (b) Cross-section of a NBS 9A coupler for testing over-the-ear headphones. (c) Parts of the above artificial ear. (d) Electrical analog of the above coupler. (e) Plug with two 3-mm microphones placed in a holder shaped like the earmold of a hearing aid for measuring impedance presented to the earphone. The receiver microphone had a low-stressed diaphragm, while the transmitter had a normal high-stressed diaphragm. (f) Earmold inserted in test client's ear (g) Standardized 2 cm^3 coupler for testing hearing aid earpieces.

probably would have ended in a fiasco.

In Békésy audiometry, it is the client that controls the sound pressure level. This is ingenious. Earlier, it was the audiometric technician that turned the knobs and asked what the client could hear. Using a Békésy model, the client can easily go through the whole process in a few minutes. In all industries where noise is of concern, the employees should be screened twice a year. With a Békésy audiometer, this could be an inexpensive procedure.

Soviet Union Microphones and Chinese Copies

Toward the end of the 1970s, the Soviet Ambassador came to Nærum and informed us that a delegation of three from the Academy of Science in Moscow was on their way to Nærum to learn how we made microphones. To them it was rather important that the Soviet Nation had the knowledge to manufacture microphones on their own soil. The ambassador referred to a letter he had received from President Brezhnev. The President was convinced that it would be a great honor for us to teach the Soviet delegation how we manufactured these excellent microphones, which was so important to his countrymen. The President referred to the huge business that the Soviet Union had with Brüel & Kjær and to the several visits I had made there to give lectures on theoretical topics. Nor should I forget all the friends I had in the Soviet Union. That concerned me a bit, about these friends. This was quite irrelevant to the matter, since I really did not have that many friends there. And those that I had were not interested in microphones. The person I talked most with was Dr. Viktor Akulitjev, but his specialty was ultrasound and cosmic radiation. Good advice was expensive. We had invested a lot in the Soviet market and did not wish to lose any part of it.

Our first attempt to make microphones with long-term stability was to electroplate the diaphragm membrane directly onto the microphone housing. This was achieved by filling the housing with wax, covering it with a conducting layer, and plating it with nickel. The process sounds simple, but in reality it is quite difficult. For example, the membrane has to be stretched so it yields slightly in order to be completely flat. This requires finely grained nickel. A concentration of plating current near the edges of the diaphragm caused discontinuities. But the biggest problem was the cost, since the process was very time consuming. The resulting microphones would be quite good, but we had to abandon this method and go to another that we utilized for the next 40 years.

Fortunately, Gunnar Rasmussen had kept many of the more or less unsuccessful specimens from our electroplating experiments. We could therefore show the Soviet delegation, how one made the world's best microphones. Since all the mechanical components such as the microphone housing, back plate insulator, electrodes with holes, tightening rings, decorative rings, gold electrical contacts and protective grids could be measured by anyone from an original sample, we might as well show them how we made these components and on which machines. We took a full day to go through every detail; even the electroplating baths for producing finely grained nickel diaphragms and the suspension tools were shown. The Russians painstakingly noted everything and were given a few samples to take back. We did not refrain from telling them about all the difficulties we had experienced, and how meticulous one had to be with every detail. Toward the end, they were rather tired and confused, and we believed that they were convinced that it was not so simple to make microphones.

The three-man Soviet delegation went home with a wealth of details. We did not hear from them about their microphone developments, but they subsequently bought many more Brüel & Kjær microphones. Five years later during a conference in Moscow, one of the three men approached me and asked me with a half smile if I had really told them everything about microphone production, because they had to give up. During the last 10 years, the Chinese have been successful in making exact copies of Brüel & Kjær microphones which are now sold on the world market at rather low prices.

Precision Sound Level Meters

The International Electrotechnical Committee's (IEC) first standard for a sound level meter (RE 123) permitted high tolerances for various specifications. One of the biggest problems was that the instrument should merely accommodate a crest factor of 5 dB; i.e., the dynamic range was too low. When one considers continuous noise in a car, driving at a constant speed of 90 km/hr, the ratio of peak to RMS value is often 15 dB and sometimes even 18 dB. Even simple noise sources could not be measured accurately with an IEC sound level meter (SLM). IEC established a working group (WG) to draft a standard for a precision SLM. M. Charvasse, the chief engineer for the French P&T, convened the group. He was a small hot-tempered gentleman who could not speak English but, on the other hand, he spoke French twice as fast as anyone else.

The specifications for the sound level meter were directly adopted from the first standard, and therefore the objective of the Working Group was simply to tighten the tolerances. Charvasse's viewpoint was quite simple – that all the tolerances should be as small as possible and that it should be possible to fulfill them. Charvasse did not want the less important characteristics to have higher tolerances than those that were more important. The meetings took place in Paris and, like all his contributions, were in French, an accepted IEC language. So there was no point in wasting time on translations. When Charvasse had spoken, he would look around at the audience and, as everyone would sit paralyzed after his barrage of words, there would be no reaction for the first few seconds. Then he would quickly burst out: d'accord, approuvé! (agreed, approved!). Occasionally, some bold members would manage to get in a request: "English translation please." To his great irritation, a quick English translation would have to follow. I was in Paris as an official Danish representative for IEC standardization of the tapping machine for measurement of floor impact noise isolation.

Our laboratory manager's younger brother, Møller Petersen in Nærum, worked on a precision sound level meter with Gunnar Rasmussen, who gave good advice and took care of measurements. It was Rasmussen's idea that a sound level meter should look like a bottle of gin. Such a design minimized reflections of sound waves back to the microphone. Depending on frequency, the reflected sound arrived in or out of phase with the sound one wished to measure. Therefore, the reflected sound reduced the measurement accuracy. Rasmussen was a specialist in this important field.

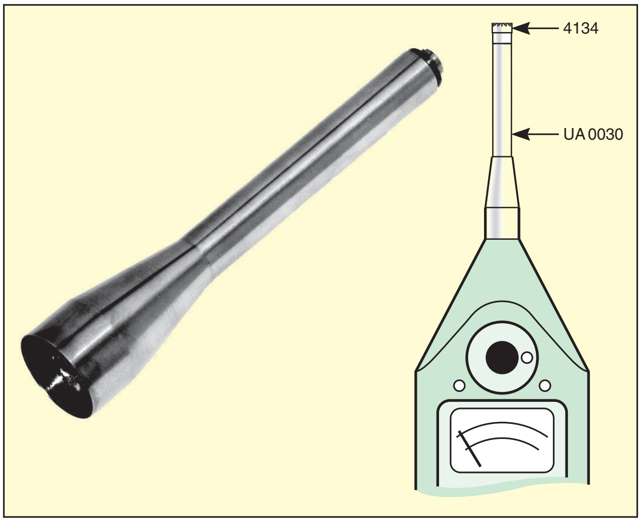


Figure 12. Microphone extension used with the 2203 Sound Level Meter to improve the accuracy of free-field measurements around 4 kHz.

My role in Paris was to ensure that we could fulfill the standard's specifications and simultaneously push the tolerances as low as possible to make it more difficult for competitors. Of course, it was an unfair thing to do. But in love and war, one is blind. For a whole week in Paris, we went through all the characteristics step by step. Since Brüel & Kjær was the only company that was involved in developing a precision SLM, we were also the only one who could give a proposal for the tolerances. Charvasse looked at me and expected a response on the tolerances. In reality I could not give a reply without consulting with Nærum. I therefore called home and requested that Rasmussen provide me with a sensible value. He had to use the prototype for these measurements, so I could only give a reply the next day. That was satisfactory for all parties. Rasmussen's measurements were meticulous and cleverly carried out, yet errors occurred for a rather small insignificant point. It was the tolerance for the directional characteristics at 4 kHz for an incidence angle of 30º that was given too tight a tolerance; this was impossible to fulfill with the microphone in its correct position. Later the finished SLM would have had to be approved by PTB (Physicalische-Teknische Bundesantalt) Braunschweig. We could get an approval only if we could place the microphone on a 40-cm-long rod sticking out in front of the instrument. It looked terrible; it was impractical and completely unnecessary. But Dr. Diestel was a German, so there was no way around it.

The instrument could not be approved without the microphone extension. Personally, I suspected that Dr. Diestel felt that he had "put one over" on Brüel & Kjær. He knew how the negotiations had gone in Paris and our efforts to make life difficult for our competitors. Since others also had problems with the directional characteristics, the matter ended with getting PTB to use narrow band warble tones for the tolerance tests instead of pure tones. This solved the problem, and we could have further tightened the tolerances.

Since the tolerance at 4 kHz was for all practical purposes completely irrelevant, one could ignore the microphone extension rod. A shorter extension rod shown in Figure 12 was available for those who felt they needed it. After that, Brüel & Kjær had the privilege for five years to be the only company in the world that could produce and deliver a precision sound level meter that could fulfill the IEC specifications. That was really a best seller in those years, because we dominated the market. Later, many competitors more or less copied the Brüel & Kjær model.

It is interesting to look back and reflect on the number of times Brüel & Kjær has been the first to market a product and been the sole provider for a number of years, after which several competitors produced very similar products. Just to name a few: the level recorder, automatically-tunable spectrum analyzer, tapping machine (IEC standard), 1-inch and 1/2-inch condenser microphones (now IEC standards), pistonphone, artificial ears (IEC standards used all over the world).

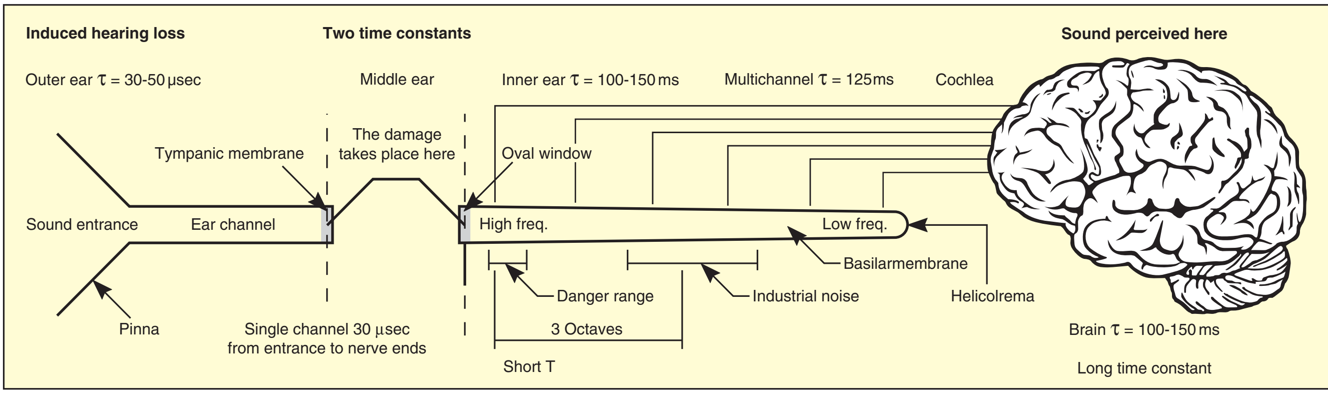


Figure 13. Schematic diagram of the human ear. Up to the basilar membrane, it is a single system that has a very short time constant necessary for perceiving frequency components up to 20 kHz. Contact points between the nerves and basilar membrane are part of a multichannel system that can transfer higher frequencies with a much lower time constant. In a human ear, the time constant is approximately 125 msec.

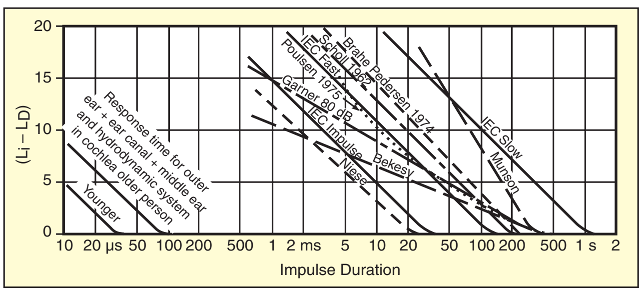


Figure 14. Slanted lines indicate how many dB must be added to the amplitude of a sound impulse to get the same impression as a tone of longer duration. We can cross the point between the lines and the baseline, or time constant. Tones longer than the time constant are perceived with the same amplitude, while shorter tones are perceived proportional to energy. You can see a great difference of opinion between researchers. Today we agree that Zwicker (IEC Fastl), with a time constant of 125 msec is correct. Békésy, Reichart, and Niese are wrong. Consequently the IEC impulse time weighting is wrong. IEC should never have chosen 35 msec for impulse time weighting. "Fast" or 125 msec is the correct value.

Noise Induced Hearing Loss

Noise induced hearing damage is a very important yet quite difficult a problem, but we have yet to find a good solution. A further complication is the wide disagreement between researchers in this field. Let us first look at our hearing system. Someone without a sensorineural hearing loss can hear frequencies from 20 Hz up to 15-20 kHz. The time constant for our hearing system is 125 msec. Note here that both Professors Békésy and Reichart disagree. However, I am convinced that 125 msec is correct. E. Zwicker and a number of other researchers support this. We assume that the time constant of our hearing system is 125 msec. This is also built into our sound level meters when set to the 'Fast' time constant. A telecommunications engineer would immediately notice that something was wrong here. One cannot transmit 20 kHz over a single channel that has such a long time constant. Therefore the ear must be divided into several channels. If there was only a single channel, all the way from ear canal, middle ear and cochlea and into the hearing nerves, a 20 kHz sound could not be transmitted.

Figure 13 shows a schematic diagram of the ear's function. According to this diagram, a very short impulse from a hammer blow, for example, will affect the hearing nerves with full strength. However, the perception in the brain would be 30-40 dB lower. Our sound level meters are also built similarly so that they measure what we perceive. The sound level meters do not reveal the loading on the hearing nerves that could be 30-40 dB higher than what we both hear and measure. According to the diagram, we have two time constants in our hearing system – a short one of 30-50 µsec, from the outer ear to the hearing nerves, and a long one of 100-150 msec. This is a difference factor of 3000. I gave a lecture in 1974 at the Imperial College of Science and technology on this topic, and half a year later I was awarded the Lord Rayleigh Gold Medal for this research.

This ear functionality model explains the paradox, which we have known for more than 100 years – that hearing damage begins to occur at high frequencies, although the noise level around 200-2000 Hz is 20 dB higher. Explanation – noises such as hammer blows are very short in duration with high amplitudes. They cannot be measured or heard with correct loudness. But the nerves are exposed to their full strength and are damaged.

A number of medical specialists with interest in hearing damage have been critical about the theory of two time constants of the human hearing mechanism. Meanwhile, no other explanation has been offered for this paradox. Some specialists have encouraged me to develop a sound level meter to measure hearing damage risk. Both German- and American-army laboratories have suggested cooperation with this task.

Figure 14 shows that the human auditory system perceives the loudness of sounds proportional to the amplitude of the sound that is sustained for at least 125 ms, where as shorter sounds (pistol shots, hammer blows) are judged proportional to the impulse; i.e., time × amplitude squared. For example, we see that an impulse lasting 1 msec is perceived to be 22 dB lower than if it had lasted 125 msec. A typical hammer blow of 100 µsec duration sounds 32 dB lower than its peak amplitude.

In Sweden, they are very interested in noise-induced hearing loss in metal forming industries, in shipyards, among forest and mine workers, hunters, building workers and heavy construction machinery operators. One seems to run into the same paradox everywhere. The damage occurs on nerves that are sensitive in the frequency range of 4-7 kHz, but the noises the individuals have been exposed to have maxima in the frequency region two to three octaves lower. No one has come up with a plausible explanation.

Impulse Noise Sources

To get an idea why we can expect high-level impulses with high-frequency content when collisions occur between metallic surfaces, we carried out some experiments as shown in Figure 15. On the left is the contact time for a steel ball falling on a block of aluminium, cast iron and hard steel. The ball is in contact during the deformation period, but loses contact when the surface of the block returns to its original position. Since the surface at this instant has the highest velocity, it will continue outward, though with a lower amplitude. Figure 15c shows a hammer striking a large metal block. The drawing is highly exaggerated. It can be seen that the area that emits sound is rather large. For example: A steel hammer strikes an iron block from a fall of 16 cm. (black dots). The contact time is 80 µsec; i.e., a full wavelength is 160 µsec corresponding to a frequency of approximately 6 kHz. One can expect that the loudest sound that arrives from the hammer blow is an impulse with first a negative and then a positive pressure with a time period of 160 µsec.

Further amplification is caused by the pinna of the ear. This increase of sound pressure at the entrance to the ear, can be 15-20 dB. If one measures the noise in a workshop with a sound level meter, the RMS and L_{eq} levels would be found to be rather constant. If instead one measures the peak values using a small microphone, there would be considerable variation. At some locations in a metal workshop, one might measure peak values 45-50 dB over

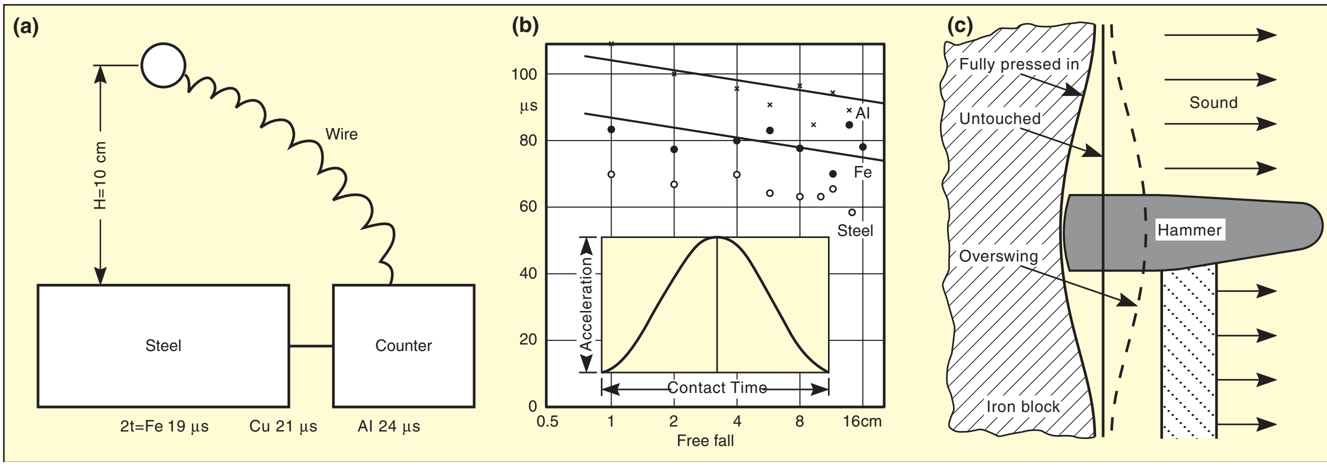


Figure 15. (a) Technique for measuring contact time between two materials impacted together. (b) Contact times for hard steel against another metal. You get an unexpectedly shorter contact time for a harder stroke. Maximum frequency of sound pulse can be estimated from contact time. (c) Surface motion during hammer blow; whole wavelength corresponds to one-half contact time.

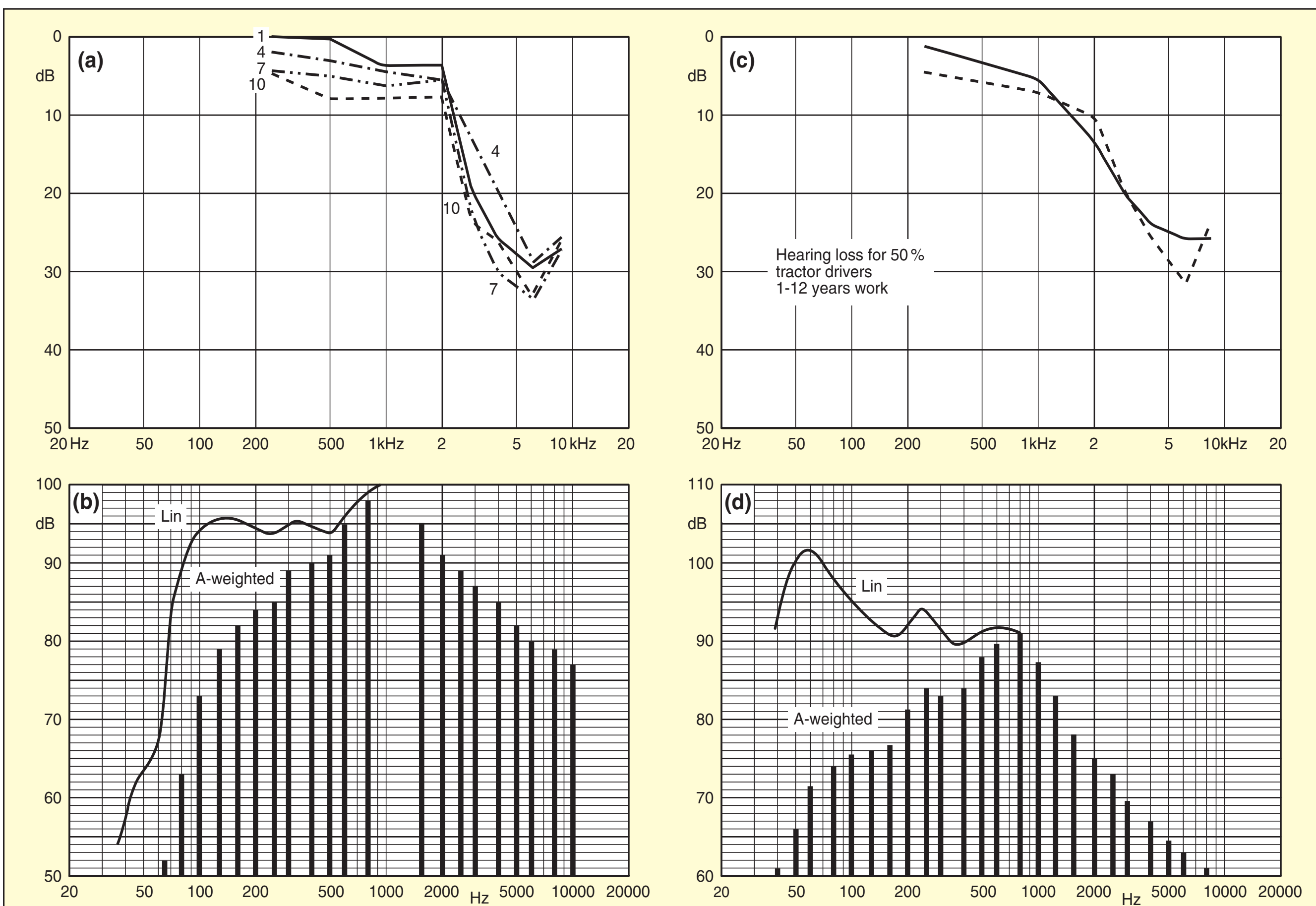


Figure 16. Typical noise induced hearing losses and exposure spectrums. (a) A woodsman who has worked 1, 4, 7 and 10 years. (b) Chain saw noise spectrum (curve) and A-weighted (bar graph). (c) Swedish tractor driver who has worked for 10 years. (d) Tractor noise spectrum. The frequency of the maximum noise is several octaves below the frequencies where the damage occurs. All measurements made about 1948.

L_{eq}. In carpentry workshops one rarely finds crest factors higher than 30-35 dB. When measurements are carried out using an A-weighting network, one under estimates, as shown earlier, by 8 dB for the critical frequency range 2.5-8 kHz. We can now estimate the maximum sound pressure at the ear of a worker in a metal workshop. Assume that the L_{eq} is 85 dBA. Then 85 dB plus crest factor of 45 dB + pinna amplification of 18 dB + (A – D) weighting differential of 8 dB = 156 dBD. These high levels persist for short time periods, but they occur often.

We have measured crest factors (30 µsec peak relative to 1 min L_{eq}) between 30 and 55 dB. A mean value would be 45 dB in industries with many hammer blows or other impact noise sources such as in metal forging and sheet metal industries.

Robust Ears

In 1946, I asked my friend C.A. Tegnér (now deceased) if he knew how many hearing aids he and his dealers sold to workers in various industries and what trade they performed. He replied that it was very difficult to estimate, but his feeling was that ship builders, forest workers and workers in metal industries constituted a large group. However, bricklayers and carpenters seldom required hearing aids. Willi Passchier Vermeer in 1968 carried out for TNO in Holland a large survey among industrial workers (more than 8,000 participants) on noise induced hearing loss related to the noise levels in industries. She found a difference of 12-15 dB between those who worked with wood and those who worked with metals. You might conclude that workers in wood

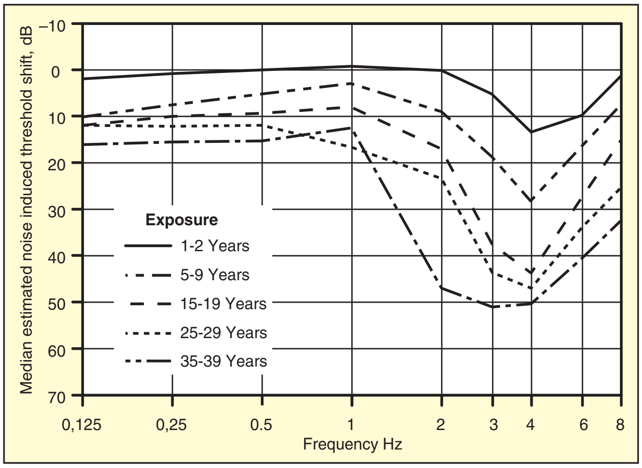


Figure 17. Typical audiograms of individuals with noise induced hearing loss as a function of years of exposure.

working industries had 12 dB more robust ears. Around 1975, a similar survey was done in Sweden and showed that metal workers had more noise-induced hearing loss for the same L_{eq} than wood workers (see Figure 16).

It has been shown that members of the Swedish symphony orchestra in Stockholm have approximately 6 dB more robust ears than ship builders. Some might explain this phenomenon with the fact that musicians have become acclimated to high noise levels over a long period of time. If this is true, we need a reason why shipbuilders have not done the same.

The correct explanation is that metal workers are exposed to short but intense sound impulses, which contribute very little to L_{eq}, while carpenters and musicians are exposed to high level sounds of longer duration, which contribute significantly to L_{eq} levels and also contain many low-frequency components. The short impulses to which metal workers are exposed contain mainly high frequencies (4-7 kHz), where both the pinna effect and A-weighting attenuation have greater effects on L_{eq} than at lower frequencies. Everything indicates that:

- Our ears function as shown in Figure 13 with two time constants.
- L_{eq} is a sensible indicator for sounds that we perceive and hear.
- L_{eq} is not suitable for establishing limits for damaging noise.
- A sound level meter is needed that can give a risk measurement of developing noise induced hearing loss.

Professor Henrik Møller at Ålborg University in Denmark has measured the influence of the pinna on the amplification and attenuation of sound impulses and found that, for certain directions in the octave band from 4-8 kHz, there would be an amplification of up to 18 dB from a free-field to the entrance of the ear canal. All L_{eq} measurements were carried out using A-weighting which, around 4 kHz and up, underestimates the sound level by 8 dB (see Figure 18b).

A 'Risk' Sound Level Meter

Purely by chance, I received some interesting measurements from a third party. They concerned 100 young men who were exposed to approximately 90 impulses of short duration over a period of three months. The sound pressure was measured with a 6-mm microphone at the entrance to the ear canal.

- At a sound pressure of 168 dBA peak: serious hearing damage occurs in 95% of the men.
- At a sound pressure of 164 dBA peak: hearing damage occurs in 50% of the men.
- At a sound pressure of 160 dBA peak: hearing damage occurs in 5% of the men.

If one dares to believe these values, a small number of impulses at 150 dBA peak should be free of danger. But one should remember to correct for the crest factor of 30-50 dB. There shouldn't be any corrections for the pinna or A-weighting, since they are accounted for in the measurements. I do not have any more details other than a 6-mm Brüel & Kjær microphone was used; it can measure up to 172 dB with distortion of less than 3%.

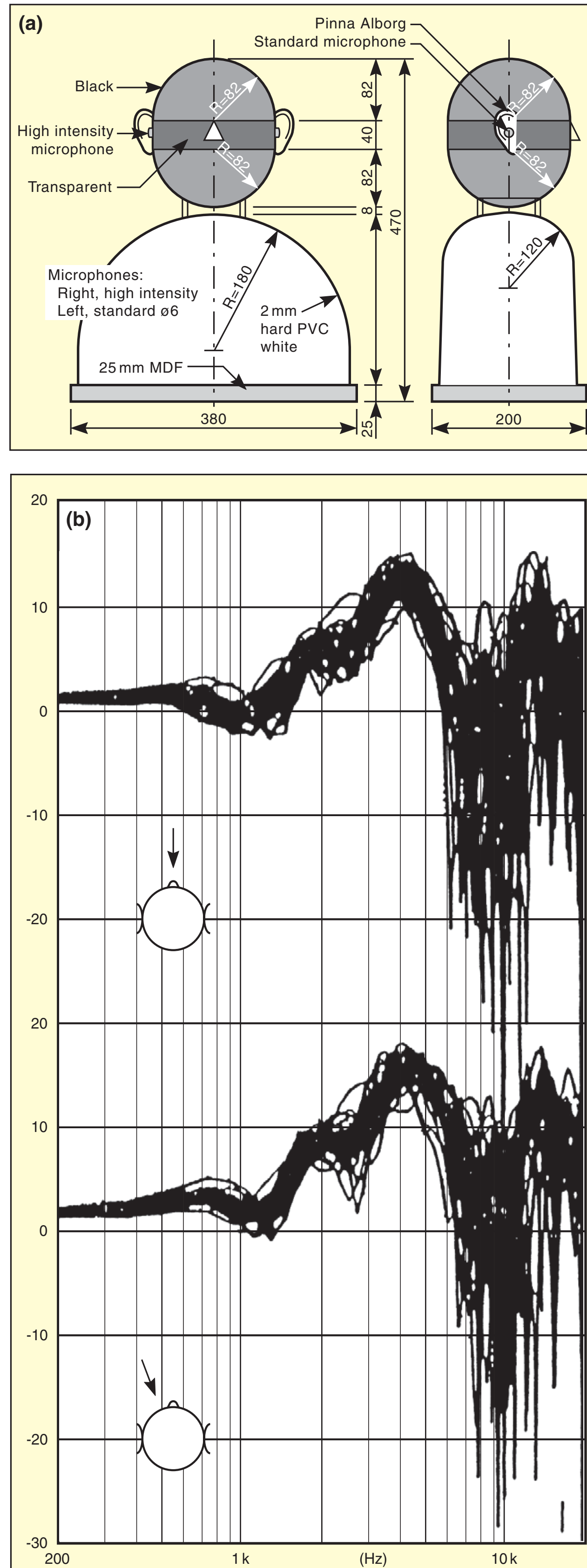


Figure 18. (a) Experimental model of a risk SLM. Looks like a human torso with an exact copy of an average person's pinnae. (b) Some of Prof. Henrik Møller's results of measuring sound pressure level variations at the entrance of the ear canal.

As shown in figure 18a, a risk sound level meter might consist of a simplified head and torso with a very accurate and well docu-

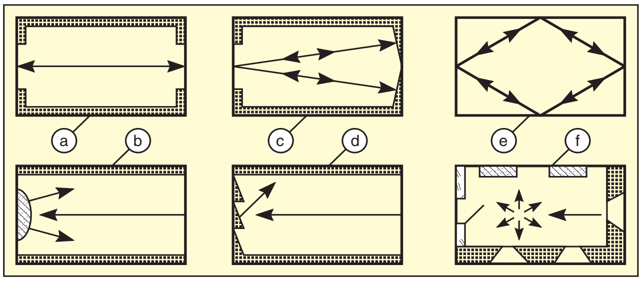


Figure 19. (a,b) Two forms of one-dimensional flutter echoes reflecting from two surfaces. (c,d) Two-dimensional flutter echoes traveling between surfaces. (e,f) How to avoid those echoes.

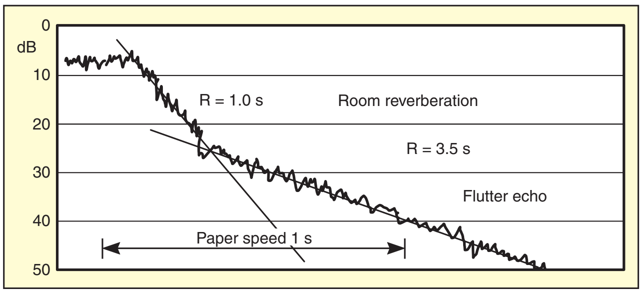


Figure 20. Typical RT curve for room with pronounced flutter echo. Note that both the exponential main group (three-dimensional modes) and decay of flutter group are very 'clean.' Flutter echo overrides the main group 20 dB down. But flutter is still disturbing, so the "acoustic well-being" is bad.

mented pinna. The idea behind this is that at high frequencies, the pinna contributes 90%, while the head and torso only 10% to the difference between the sound pressure in a free field and near the entrance of the ear canal. Two 6-mm condenser microphones are mounted close to the ear canal so that the sound field is not disturbed. A week's data of levels, sound peaks, duration, 1 min L_{eq}, A- and D-weighting and time of recording would be recorded.

We cannot compensate electronically for the amplification and damping caused by the pinna. It has to be done in a similar fashion like it does in nature; i.e., the sound level meter should be built from a head, torso and pinna. We have a prototype of both, developed by Professor Henrik Møller at the Acoustical Laboratory in Ålborg. The 6-mm microphones should be mounted in the ear canal so that the impedance as seen from outside is not affected.

To date we do not have enough know-how to develop a simple instrument, because we do not know what levels of peak amplitudes cause permanent damage to the hearing nerves in the inner ear. Neither do we know the relation between the number of impulses and amplitudes.

Diffusion, Flutter Echo and Acoustic 'Well-being'

V. Jordan mentioned in 1938 that Erwin Meyer had experimented in the 1930s with diffusion, which proved that reflection of sound waves occurred in all directions. This is exactly the opposite of flutter echo. The name suggests that flutter echo occurs when sound waves move forward and backward in fixed paths. We can conclude that good diffusion implies that there are no flutter echoes (see Figure 19). Meyer tried to quantify diffusivity on a scale of 0 to 100%, where we use the reverberation decay and clearly see if there is a flutter echo. When the flutter echo takes over after 20 dB or 0.3 sec as shown in Figure 20, the remainder of the reverberation curve is also exponential, and sound waves move along the same paths (no diffusion). If there is high diffusion and therefore no flutter echoes, the reverberation decay is a straight line on a log plot (purely exponential). We gave up quantifying it.

We experimented with two identical rooms. One was reference room (A), where we tried to optimize everything in it. Among other things, we had diffuser/absorbers in the ceiling. In the other room (B), we modified the ceiling to obtain different degrees of diffusion. The rooms had parquet flooring, which had high absorption at about 200 Hz (see Figure 21). The reference room had 27 sound absorbing and diffusing cones, shown in Figure 22, that were permanently installed. In Room B, the number of cones was

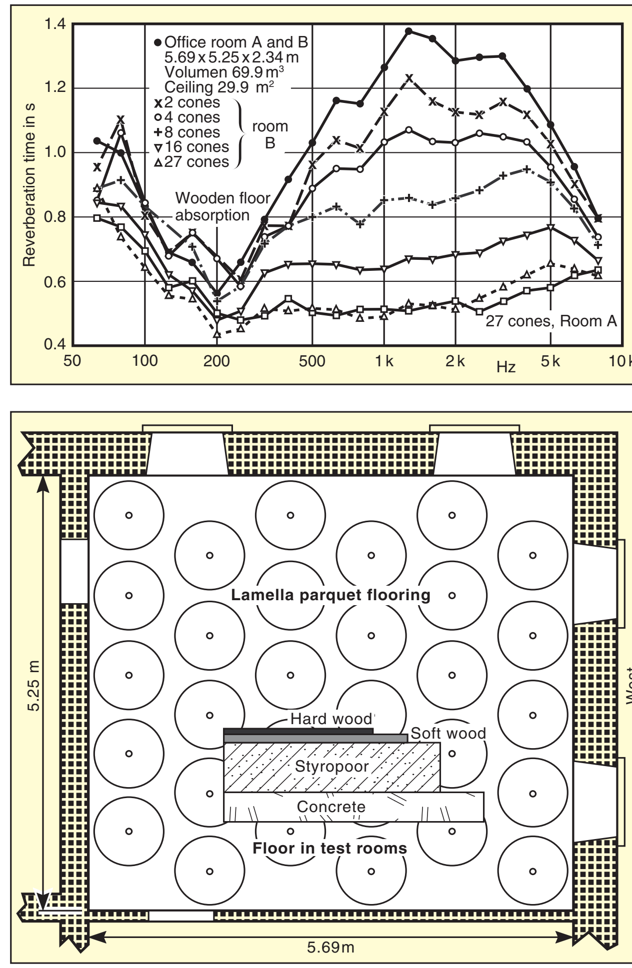


Figure 21. Reverberation time in Reference Room A with 27 cones (RT=0.5 sec). In Room B, different numbers of cones were installed. Room A was judged to have excellent acoustics (RT=0.5 sec) Room B was judged to have good acoustics with both 16 cones (RT=0.65) and with 27 cones (RT=0.5 sec).

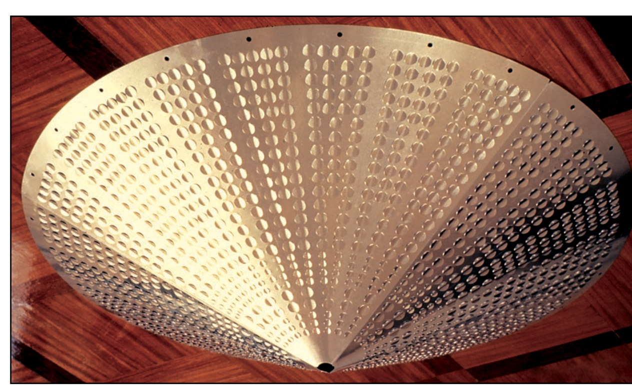


Figure 22. AcoustiCone sound absorber unit.

changed every 14 days. The rooms were used for office work, computer tasks and development of electronics. The experiment went on for four months. We did not have any objective criteria for the acoustic quality. We asked after two weeks work in the room, how it compared to the reference room.

We also got completely unexpected reactions. When they were in the reference room, strangers sometimes exclaimed spontaneously "how nice the acoustics were" and how pleasant it was to be there. We also requested that they comment on the pleasantness of being in the other room.

In these experiments, we only modified the shape of the ceiling in Room B, which naturally resulted in variation of the reverberation times. We were convinced that the shape of the room had the greatest influence, especially when the floor was flat and reflective; therefore, the opposite surface had to be made diffusive. All this

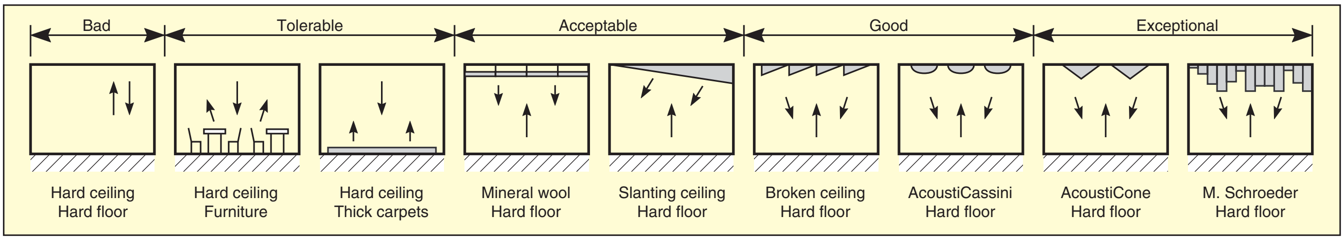


Figure 23. Rough scale of acoustic diffusion when combined with correct reverberation time is also a scale of "acoustic well-being."

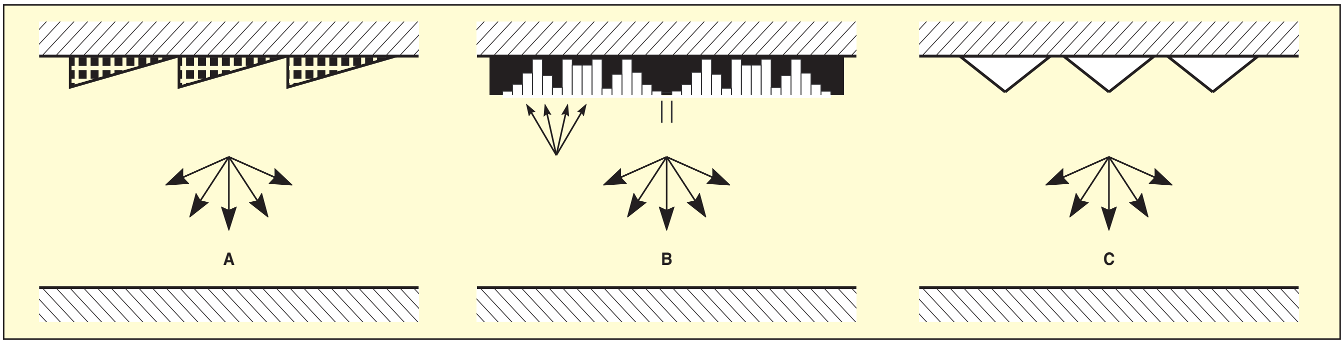


Figure 24. Three different ways to obtain a diffusing ceiling. (a) Broken slanting surfaces; (b) Prof. Schroeder's effective construction. (c) Cones covering about 40% of ceiling area.

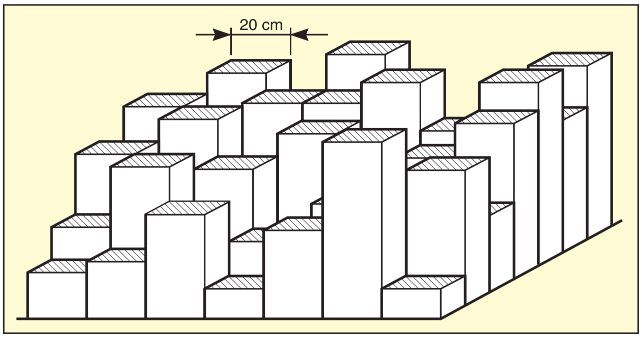


Figure 25. Part of a Schroeder ceiling shown upsidedown. Boxes with different length all have same square bottom and are often made of plywood. Today some are made of plastic.

was known already in 1938, so all the ceilings in the Radiohuset were made diffusive or without horizontal surfaces. In 1940, we did not have the imagination to link diffusion and flutter echo.

Today we know that one should avoid flutter echos, which are a group of resonances that have less damping than the rest of the resonances. Here one could wonder again about these resonances having a life of their own. There is no connection between individual resonances. One can apparently achieve negative absorption as predicted by the calculations made by Leo Beranek and Dah-You Maa. Furthermore a rectangular room, where the ceiling is completely absorbent, is also far from being ideal. It would feel unnatural to enter, for example, an empty room with a fully absorbent ceiling. Figure 23 shows a number of sketches that explain and illustrate typical "acoustic well being" conditions. Ways to obtain a diffusing ceiling are shown in Figure 24.

Another very successful acoustical solution is the so-called Schroeder ceiling developed by Professor Manfred Schröder (Göttingen) and shown in Figure 25. He is a disciple of and was assistant to Professor Meyer, from whom he learned that to achieve good acoustics, one must have diffusive ceilings. Schroeder, apart from being a clever physicist, was also an excellent mathematician. With the help of number theory, Schroeder developed a ceiling design that looks like a city of skyscrapers turned upside down. This design is used widely in small studios and some offices in the Los Angeles area. There are over 2000 such ceilings installed. Architects have conflicting opinions about these ceilings, but they are excellent for diffusing sound.

Physicists and Architects

Although we are aware today of the importance of both reverberation time and diffusion for acoustics, banks and classrooms are still built with bare, smooth walls and heavily absorbent flat ceilings. In 1935, Professor Meyer showed that the walls and ceilings should reflect the sound diffusely. Schroeder developed a ceiling construction that is accepted to be well suited for studios. In concert halls and radio studios, we could never dream of having flat ceilings. In recent years, we have appreciated what it means to have diffusive ceilings for "acoustic well being."

In 1947 at Chalmers, we developed some absorption units from fire-proof cardboard. We learned that spreading out the absorption material was highly effective and simultaneously resulted in diffusive reflections in the frequency range from 300 to 1500 Hz. Later in 1950, I developed with C.A. Tegnèr a construction with metal and rockwool that was patented. Neither cardboard nor rockwool was the right material, and we developed a flat cone made from thin aluminium sheet and polypropylene fiber as shown in Figure 22. By covering 33% of the ceiling, one can achieve 100% absorption coefficient in some frequency ranges and diffusive reflection for lower frequencies (after the Huygens principle). The higher frequencies are reflected diffusely from the curved surface of the cone. This is a cheap solution for improving classrooms, offices and workshops.

Classroom Noise

Two schools in the suburbs of Los Angeles had so much noise and unrest that educational performance did not meet standards. Teachers were often absent and looked for other employment because of unbearable noise. Using a concealed microphone, L_{eq} was measured for 30 minutes in the middle of each lesson over a two-week period. The classrooms with pupils had reverberation times of 1.1 sec. Both the ceilings and the upper parts of the walls were treated with sound absorption so that the RT was almost halved to 0.6 sec. The L_{eq} was again measured over a period of two weeks with the same equipment and microphone positions. The result was a noise reduction of 12 dB in one school and 15 dB in the other. How could the noise be reduced so much? Physical laws say that halving the RT should result in only a 3-dB noise reduction. The correct explanation of this apparent paradox would have great consequences for many of our kindergartens and schools.

I heard of these astonishing results from Dr. David Lubman, of Westminster, California, who arranged for the measurements at the two schools. Lubman is a good acquaintance of mine, and we have an amicable discussion as to who was the first to come up with a plausible explanation of this apparent paradox. The measurement results confirmed my explanations for Svend Prytz's observations. Prytz, chief physician at Bispebjerg, found that children from cer-

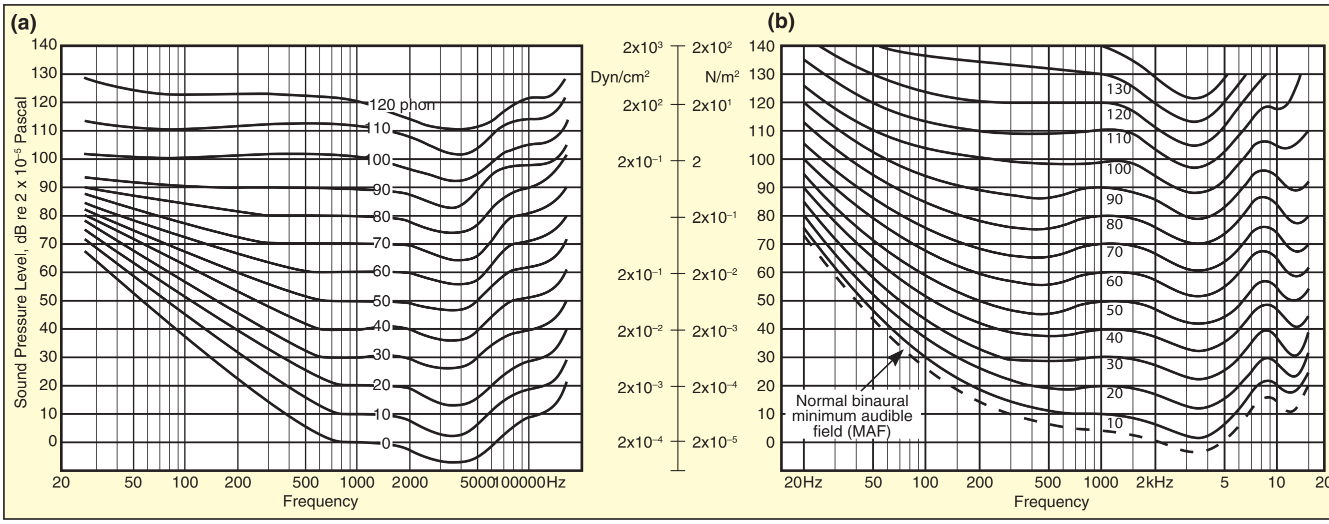


Figure 26. (a) Fletcher & Munson equal loudness curves for pure tones presented with headphones, 1929. (b) Dr. King's equal loudness curves for pure tones presented in a free field, Liverpool, 1931.

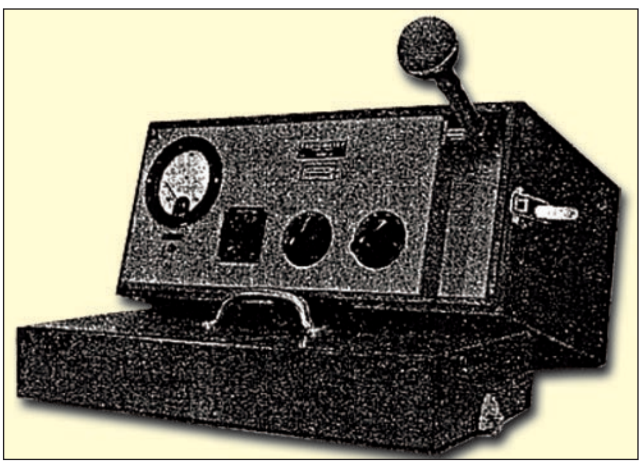


Figure 27. Radiometer sound level meter.

tain schools and kindergartens had overstrained vocal chords that caused medical problems. For some pupils, this situation caused irreversible damage. In other schools and kindergartens there were no such cases. Prytz asked me what could be the reason for such big differences? We quickly discovered that there were high noise levels in schools where there were many vocal cord injury cases and low noise levels in schools with no vocal cord injuries. We also found the reasons for the high noise levels in some schools and what we could do to remedy them. We are still working with these problems and are placing emphasis on some measurement results from Australia.

Sound Level Meters and D-Weighting

In 1937, I saw my first a Barkhausen sound level meter, which was used for exercises at LTT (Laboratory for Telephony and Telegraphy). Later in 1938, LTT acquired a 'modern' sound level meter developed by Radiometer shown in Figure 27. It used a Brush Electronics crystal microphone, A, B, and C weighting networks and fast and slow time constants. There were many U.S. manufacturers of sound level meters. Their sound level weighting networks were based on the Fletcher & Munson equal loudness curves for pure tones (Figure 26a) measured using headphones in 1929. In 1931, Dr. King in Liverpool obtained similar curves from measurements made in a free field as shown in Figure 26b. On the basis of these curves, General Radio, Cambridge, Massachusetts, made a quality sound level meter in 1933. Arnold P. G. Petersen was the designated builder and had a good idea. The C-weighting network had a flat frequency response. By adding two resistors and two capacitors, one could obtain the A-network frequency response. Peterson asked his friend Leo Beranek, who like himself had just graduated from MIT, to give him some advice. These two young men discussed over a cup of coffee how to implement the small 'bump' of 9-10 dB on account of the resonance in the ear canal from 1 to 4 kHz. That was difficult to do, so they agreed not to incorporate the ear canal resonance in the frequency response.

The sound level meter was a success, and its characteristics were standardized by ASA and a few years later by IEC. Thereafter, the whole world had a standardized sound level meter that measured noise 9 dB too low in the frequency range of 2-6 kHz. We can rightly criticize both ASA and IEC for this serious error. The situation was further exacerbated, since IEC thought that we could dispense with the B-weighting network, which was to be used for the sound level range of 50-90 dB. We now measure all noise sources using the A-curve. In 1956, Robinson and Dadson developed a series of equal loudness curves for the free field (Figure 28b). These investigations generally confirmed Dr. King's results. Note especially the increased sensitivity due to the resonance in the ear canal.

Around 1958, the U.S. Federal Aviation Administration (FAA) discovered that the noise around airports was not being measured correctly with a standard sound level meter. The FAA asked Karl Kryter to find the reason for it and suggest something better. Kryter found that the B-weighting curve was good enough up to 1000 Hz, but over 1 kHz, it lacked the amplification that Petersen and Beranek had neglected. After some minor adjustments, Kryter suggested the D-weighting curve, which was hereafter adopted by IEC, but solely for the measurement of aircraft noise.

We are now in an uncertain situation where the following researchers have shown that the A-weighting curve is erroneous and also used incorrectly: 1) Fletcher and Munson in 1929; 2) King, *et al*. in 1931; 3) Karl Kryter in 1952; 4) Dadson and Robinson, 1956; 5) Zwicker, 1970; 6) Zwicker and Fastl. Not a single investigation has shown that the A-weighting curve as it is standardized today is correct. Shall we try and place responsibility? In 1933, Peterson and Beranek, although aware of the 'bump' did not incorporate it in General Radio's new sound level meter. They retained the A, B and C-weighting curves in a slightly improved version. The time constant 'fast' was not scientifically proven, but was shown later to be correct. ASA, which has often standardized certain designs instead of characteristics, concluded that it was best to standardize the General Radio meter. It was many years later that Karl Kryter came up with the correct D-weighting curve. Therefore, the main responsibility lies with IEC in Geneva, Switzerland which many years later copied the ASA standard. IEC was well aware of the curves from 1929, 1932, and 1956 as well as Kryter's curve, which was standardized as an alternative. Zwicker voiced a strong warning, but IEC would not listen. The A, B, and C curves are to be used depending on the sound levels. And then the IEC went crazy. First the D-weighting network was abolished (except for heavy aircraft). Then the next best B-weighting curve was dropped, and finally the A-weighting curve should be used also for high sound levels. Also, noises containing low-frequency components below 500 Hz

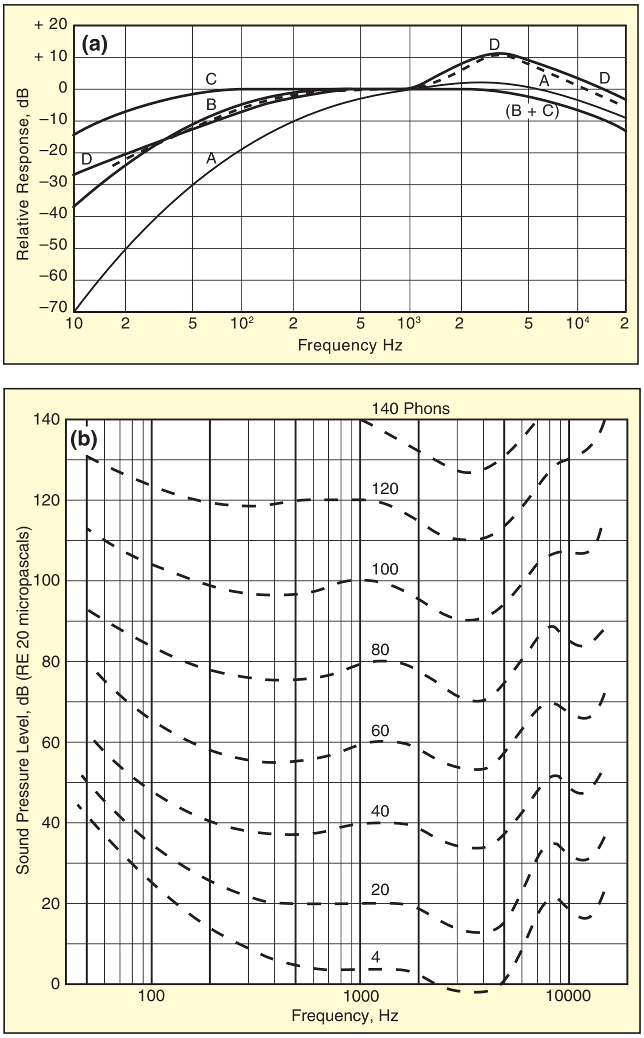


Figure 28. (a) Standardized frequency response curves for sound level weighting networks A and C. The B-curve and D-curve are superimposed. (b) Robinson-Dadson equal loudness curves for pure tones presented in a free field, 1956.

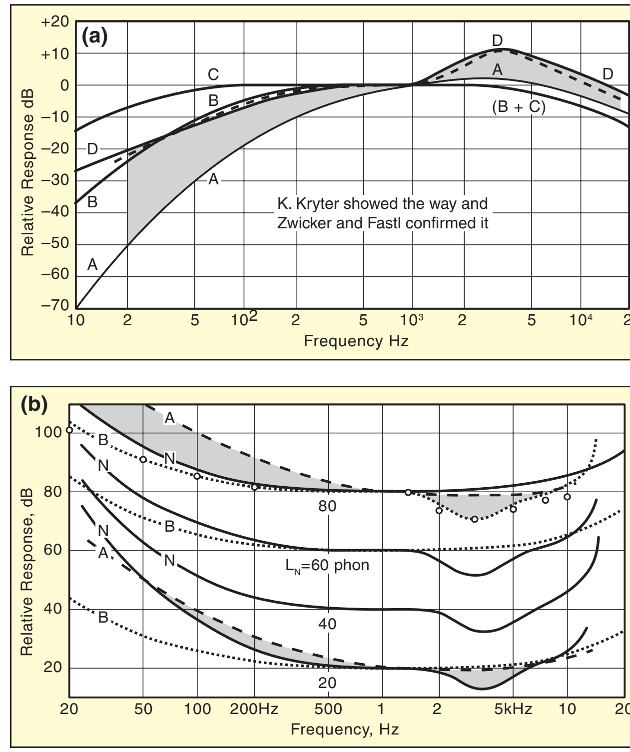


Figure 29. (a) Under estimate of noise measurements by using A-weighting as compared to D-weighting. (b) Fastl's measurements in Japan of noise from aircraft and railways compared with Zwicker phons and A-weighted sound level measurements. Note how close Zwicker phons follows D-weighting also in the 2-5 kHz band.

are underestimated (see Figure 29a).

Professor Zwicker was the one who knew the most about human perception of noise, and he protested vehemently the last 30 years of his life against the A-weighting curve. When he gave a presentation in Copenhagen in 1980, he had brought with him two different noise sources, A and B. The audience with great certainty claimed that noise source A was much louder than noise source B. A sound level meter with A-weighting indicated the opposite. Zwicker couldn't get very far with his criticism of A-weighting and developed a completely different system for loudness evaluation. His measuring system was complicated and was utilized for product noise evaluations.

Professor Fastl, after a long stay in Japan, headed an extensive investigation using subjects who judged the noise at Narita airport and noise from the bullet train between Tokyo and Osaka. The subjective impressions were compared to the A-weighted sound level measurements and the Zwicker loudness measurements. This was carried out over a wide range of levels and several repetitions. These investigations are probably the most accurate that have ever been carried out. The investigation was only carried out for two noises that had a broad spectrum and were continuous. The investigation showed a very high degree of agreement between the subjective impressions and the Zwicker method, while the A-weighted sound level fell significantly short. Fastl has shown that the Zwicker method is correct, and that the A-weighting method differs by 15 dB at the lower frequencies and up to 10 dB for frequencies between 3 and 4 kHz.

After I read Professor Fastl's report and had convinced myself that the A-weighted measurements were also carried out meticulously, I added the difference between the A-curve and the earlier standardized D-curve to the A-curve; i.e., A + (D–A) = D and could use Fastl's measurements to compare the D-weighted levels with both the Zwicker method and the subjective judgements. All three results agreed (see Figure 29b). It is probable that there is agreement between the D-weighted levels and Zwicker method as well as the D-weighted levels and the subjective reactions. These conclusions are limited to continuous sounds in the sound level range of 55-90 dBA, which are most important, since 95% of all noise measurements are taken in this sound level range. Using the D-weighting network we can get the same results as using the complicated Zwicker method.

It should be added that although B&K had by far the best condenser microphones, we had difficulties in adapting the high impedance of the microphones to the low impedance of the input circuits. The first sound level meter from 1964 was therefore equipped with a small battery-driven vacuum tube at the input stage. The introduction of the MOSFET (metal oxide semiconductor field effect transistor) enabled us to construct a fully transistorized SLM. From 1963 Brüel & Kjær was unquestionably the leader in the SLM market. Soon after, Brüel & Kjær was also the prime mover for the IEC standard for precision sound level meters.

The Cold War

Brüel & Kjær not only made the world's most stable microphones, but also some very highly sensitive hydrophones with flat frequency response. The Type 8103, shown in Figure 30, was used all over the world as a reference hydrophone because of its frequency response and stability. B&K sold microphones and hydrophones to research institutes in both U.S. and USSR. We did not know what many were used for, but several of the customers were universities, where some employees worked on projects for space research and underwater acoustics.

Quite naturally the Americans were very interested in knowing what we sold to the Russians and vice versa. We had to watch our step. Since both sides had ways of getting information about what the other party had bought, we decided not to classify what we sold and to which country, but we did not know what they were used for. When the East-West relations were most tense, Denmark

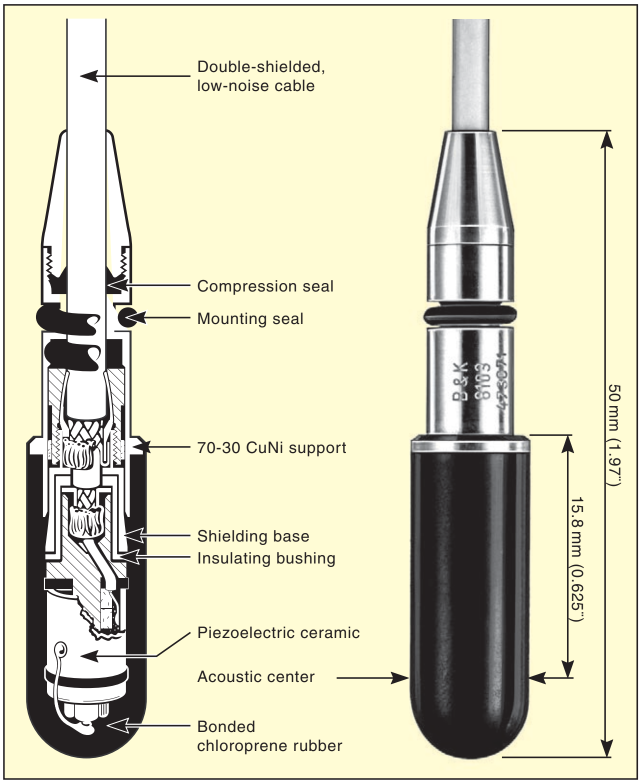


Figure 30. Construction and dimensions of Type 8103 Hydrophone.

introduced legislation forbidding export of certain goods without a special export license. Among them were some of our products. In practice, it meant that we had difficulties for sales only to the Eastern block. For a long period of time, we had good contact with a physicist who worked for an underwater laboratory in Washington, DC. He often visited us and inquired about our future plans and advised us as to what products we should restrict and what we could sell to the Eastern block. The few meetings we had were always planned several days ahead of time. But one day he called me from Copenhagen and requested a meeting in an hour.

I felt something brewing in the air, and rightly so. He had brought along with him a list of seven of our instruments, which apparently were in Murmansk, U.S.S.R. I insisted that these instruments were sold only to the West and with their permission. However, if he could get hold of the serial numbers of the instruments, we could inform him exactly whom we had sold them to. Our angry friend called Washington and obtained the serial numbers, which all agreed with our type numbers. Our records showed that we had sold them to a small company in Florida, and could reveal the address of the company as well as the dates for invoicing. When our friend was given photocopies of the papers, he excused himself but mentioned that he did not understand how this could have happened. I told him that I would like to know the full story behind this matter, so that we could avoid repetition of such situations in the future. After some pressure from me, we were informed that the Americans had got hold of the complete list of instruments that were at the base in Murmansk, and on that list were also the instruments that we had sold to the company in Florida. We no longer received any orders from that company. The last we heard was that one of our letters was returned after being intercepted.

We did not suspect in the least, because the company had informed us that the equipment (analyzers, microphones and hydrophone) were to be used at the launch pads at Cape Canaveral (Kennedy Space Center). This seemed plausible for a company in Florida. We never saw our friend from Washington DC again, nor do we know what became of that company in Florida.

Zwicker Sound Level Meter

It was noted previously that Professor E. Zwicker very convincingly proved to a full audience in Copenhagen that it was incorrect to use A-weighting for sound level measurements. On this same occasion, he had a big sound level meter he had developed that could correctly measure the noise levels from different sound sources relative to each other. This made us decide at Brüel & Kjær to develop a sound level meter after Zwicker's principles. I contacted Professor Zwicker who was apparently very glad to hear that we would make a Zwicker sound level meter. He would not have any royalties or anything else for his contribution. Zwicker was an idealist but, as we later learned, a very stubborn one at that. Zwicker's model was big, heavy (16 kg) and not very aesthetic.

I explained to Zwicker that we would not make a copy of his model but would make a smaller sound level meter. Zwicker thought that was a good idea and that we could just use smaller components. I told him that by simplifying a number of circuits, we would significantly reduce the number of components needed. Therefore, it was necessary to find test signals that could be used to establish design tolerances, just as PTB (Physikalisch Teknische Bundesanstalt) did when approving a standard IEC SLM. I had also imagined that by interchanging five or more frequency weighting curves automatically, we could avoid using Zwicker's inaccurate logarithmic unit.

But Zwicker wanted the instrument to be exactly like his model. We offered to send a couple of our employees to Munich, who under Zwicker's guidance, could find the necessary input and output signals. Even that wasn't acceptable. I also said that we needed to change over to digital techniques to avoid temperature drift. But no, either it was to be made as he had made it or not at all. Therefore no hand-held Zwicker SLM was made despite good intentions from both sides. It was a pity, as we could have developed a really nice small instrument. Today, many years after Fastl's measurements in Japan, just by using Karl Kryter's D-weighting, we can get an instrument that measures Zwicker phons in the sound level range of 50-100 dB. We could also have developed a couple of weighting curves for both higher and lower levels. Had Zwicker been just a bit less stubborn, we might be using Zwicker's SLM all over the world. Maybe we could have eliminated A-weighting and used D-weighting instead.

It is a mystery to me why Zwicker did not succeed in getting IEC to change from A-weighting to Zwicker weighting. One of the reasons could be that Zwicker never referred to Fletcher and Munson, King, Dadson, Robinson or Kryter. Through careful measurements, they not only showed that the A-weighting curve was wrong, but also how the weighting curves should be used for different levels. Why did Zwicker not use all this excellent material in his presentation? There is not a single experiment or any investigation that proves that A-weighting is correct. IEC should have considered this before specifying that A-weighting was not only correct but should be used for all levels. To ensure that everyone now measures as incorrectly as possible, IEC has removed the B-weighting curve from the sound level meter standard, which was correct for frequencies below 1000 Hz. It is laughable that IEC and ISO would not listen to the one person in the world who was most knowledgeable about the reaction of humans to noise. This was not the only time that the IEC repudiated Zwicker.

1966 IEC Meeting in Prague

At the 1966 IEC meeting in Prague, Czech Republic, the time constant for the sound level meter was discussed. The two young engineers, Arnold Petersen and Leo Beranek, together would make an especially good sound level meter. They discussed how fast the sound level meter should react to a sudden impulse. In 1933, no one had measured the time constant for the human perception of noise. The two young engineers were aware that the human perception was very fast, and therefore the sound level meter should be made to react as fast as was practically possible. The limiting element was the meter itself. They got Western Electric to make a moving-coil meter that had a big powerful magnet and a very light moving coil. The pointer was made from a thin walled aluminium tube for low moment of inertia. The display instrument had a time constant of 125 msec, which was called 'fast.' The pointer was quick to respond, and it was difficult to read the meter for short impulsive sounds. Electronically the response could be slowed down to 1/8th the velocity; i.e., a time constant of 1 sec was called 'slow.' Later there were many, among them Zwicker, who measured the time response of the human ear, which was between 100 and 150 msec. One could say that the two young engineers were fortunate that their instrument had a time constant of exactly 125 msec.

A few others, among them Professor Reichart in Dresden, had measured the time constant to be 15 msec, or about 10 times faster than Zwicker's and many others. Toward the end of the 1960s, electronics was so advanced that one could utilize a very short 'rise time' and capture the result electronically.

There were still many of the opinion that although one measured with 'fast,' the human ear was still faster. Therefore, an impulse sound level meter was put on IEC's agenda. A meeting was set up in Prague, where the impulse sound level meter was to be discussed. It was important that Professor Reichart, who had measured these very short time constants, was there together with Zwicker. Meanwhile, Reichart could not get permission to travel to the West because of the cold war, so the participants from the U.S. and Western Europe had to travel to Prague. At the meeting, we could not agree on what the time constant for the impulse sound level meter should be. Zwicker and Reichardt contended vigorously each for their own opinions. The difference was not insignificant, it was 1:10. The last day when all of us were to go home at 4 p.m., the two gentlemen were sent to lunch together and were told not to return until they could present a value of the time constant for the impulse sound level meter.

It was rather foolish, as one could surmise, that something was not right because of such a large discrepancy. It turned out later that Zwicker was right with 150 msec, almost the same as Peterson and Beranek had concluded in 1933. The two professors also returned, however, without reaching an agreement. Zwicker said that the participants should decide. He recommended that the idea of an impulse sound level meter should be dropped completely, it was superfluous, and that the normal sound level meter with a 'fast' time constant was the best available. Reichart would not insist on the 15 msec, but suggested that the delegation use 35 msec. Everyone was happy and could go home now, until someone in the first row asked: How can one manage to read the meter when it is so fast? Here was a problem no one had thought of. A bright guy suggested that the "rise time" could be τ = 35 msec and the "decay time" could be much slower, τ = 3 sec. No one had given any thought that one could not integrate 35 msec up and 3 sec down or use them to measure rapid hammer impulses. Zwicker shook his head in despair, and Dr. Robinson from England mumbled something about a kindergarten. Robinson also made sure that England never approved the IEC impulse sound level meter. Others should have done the same. Neither has the IEC standardized impulse sound level meter ever been used in practice. The acoustic world would have been served much better if the IEC committee had made use of the many frequency sensitivity measurements of the human ear carried out during the period from 1929 to 1935 and had listened to Kryter, Zwicker and Robinson.

It is more than 50 years ago that Zwicker proved that the A-weighting curve was wrong and that the standardized time weighting of 125 msec was correct. All reliable measurements indicate that Zwicker was right, and no one has proved that A-weighting is correct. Therefore, all sound level measurements in the world are based on incorrect weighting, which we cannot undo. This is a stupendous mistake in my opinion. And one is tempted to believe that Zwicker himself didn't have the ability to 'sell' his ideas. Personally I felt that Zwicker was polite and kind – but also stubborn.

Today I regret that we did not develop a Zwicker sound level meter with several weighting curves for different levels. I do not believe that Zwicker would have objected if we could have demonstrated that our model measured the same as his big model. As mentioned earlier, Professor Fastl from his measurements in Japan, has shown that Kryter's D-weighting curve agrees with Zwicker's in the range of 55-90 dB, precisely the range where 95% of all sound measurements are carried out.

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Measurement Microphone History

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I was employed by Brüel & Kjær in 1950. At that time there were only 30 employees and everything was produced in house – metal working, sheet-metal forming, electronic assembly and finishing. The product range was not focused on acoustical products, but included a wide variety of voltmeters, precision attenuators and radio transmission equipment. One of the products was a measurement microphone based on a Rochelle salt sensing element. The element was coated with wax but was still affected by humidity. The effects of other factors like temperature and barometric pressure were to a large degree unknown.

A 36-mm condenser microphone for sound pressure measurements was introduced in 1950. The microphone was designed and developed by Dr. Schlegel from the Danish company Ortofon with a brass housing and aluminium diaphragm. The microphone was manufactured by Ortofon. They would produce batches of ten units and the production was shared between B&K and another Danish company Radiometer. The new microphone was certainly an improvement over the Rochelle salt microphone as it could be calibrated with an electrostatic actuator. This method was also developed by Dr. Schlegel from Ortofon. The most common measurement microphones of the day are shown in Figure 1.

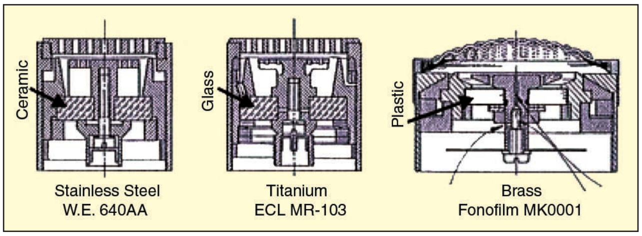

Figure 1. Measurement microphones available in 1954.

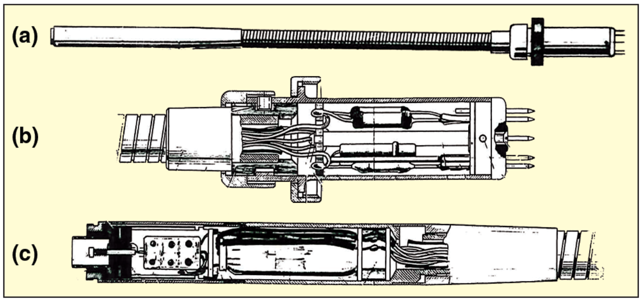

Figure 2. 1/2-inch microphone preamplifier based on a sub-miniature vacuum tube. (a) Gooseneck assembly. (b) Internal components of connector. (c) Internal components of preamplifier housing.

In 1955 I was sent to USA to implement service and sales at Brush Electronics in Cleveland, Ohio. This was my first introduction to real measurement microphones in the form of the Western Electric 640AA and the ANSI 224.4-1949 standard (see Figure 1). I knew of the W.E. 640AA from Beranek's *Acoustic Measurements* and from a doctoral thesis by A. Kjerbye Nielsen "Microphone Measurements." In 1947 he invented a practical reciprocity calibration technique. Later this method was further developed by Dr. P. Rubak for more precise calibration. This was the basis of the IEC 327 standard.

I had the opportunity to travel extensively in the US, meeting many acousticians, and to be exposed to many applications from rocket testing to listening for beetles moving inside oranges. On my return to Denmark, B&K was having problems with the quality of the 36-mm microphones. The aluminium diaphragms were easily corroded and tended to develop short-circuiting whiskers between the diaphragm and backplate. I was asked by Viggo Kjær to work on a 1-inch microphone compatible with the ASA 224.4 standard. I developed a new design, where the diaphragm could be screwed onto the front of the microphone body and allowed diaphragm tension to be adjusted from the front. The W.E. 640AA

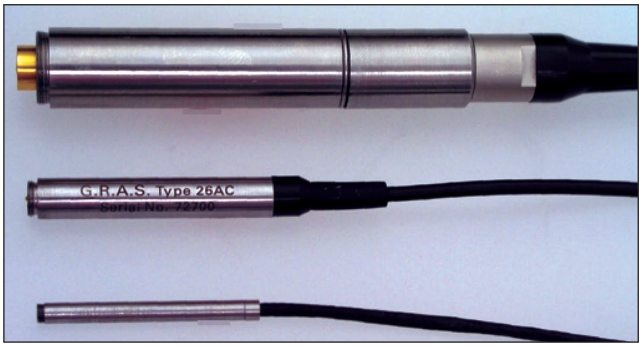

Figure 3. G.R.A.S. 1/2-inch, 1/4-inch and 1/8-inch microphone preamplifiers based on semiconductors and ceramic substrates.

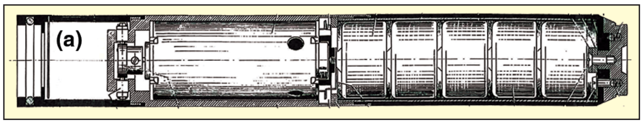

Figure 4. (a) Drawing of the first dual-piston pistonphone. (b) The G.R.A.S pistonphone has a built-in precision barometer and temperature correction for accurate measurement of sound pressure level at any altitude.

and the ECL MR-103 were adjusted by moving the internal assembly.

We produced nickel diaphragms by an electroplating process using uncut lacquer disks for phonograph recording as base material. The diaphragms of the W.E. 640AA, MR-103 and MK0001 were clamped, which caused problems with stability. I tried different methods. One was soldering which was unstable, because it peeled off the threaded diaphragm ring. Another was vacuum deposition of a thin film of metal, which worked, but the production equipment turned out to be too expensive for the company. I ended up using a crimping technique which has worked well for many years. With the addition of today's laser welding techniques, it is possible to choose the most relevant process for a specific microphone type, considering stability and long term corrosion effects.

Free-field calibration required an anechoic room of reasonable size to calibrate a 1-inch microphone at frequencies above 5 kHz. We did not have a suitable room available at B&K. After a lot of testing in different rooms I was finally allowed to get a room in the basement of the factory with outside dimensions of 2 × 2 m and anechoic space of 1.4 × 1.4 m. This was too small for a free-field reciprocity calibration of 1-inch microphones. It was therefore necessary to develop a 1/2-inch microphone to confirm the measurements on the 1-inch design and go even further with a 1/4-inch microphone in order to be able to scale down. The 1/4-inch microphone enabled me to test a new sound level meter configuration on a 1/4-inch scale model made of wood.

The small scale models of the microphones were not well received by the management. I got a salary cut as a reward and was not allowed to take out any patents. My early experiments were redeemed when the 1/2-inch design ended up being the most used and copied microphone for general acoustic measurements.

Condenser microphones are high impedance devices and require an impedance converter to drive the connecting cable and instrumentation. Semi-conductors of the 1950s were not suitable for preamplifiers. The W.E. 640AA used a fairly large vacuum tube preamplifier. It looked like a Coca-Cola bottle, where the microphone was the cap. To gain full advantage of a small microphone, a preamplifier of the same diameter as the microphone is desired for free-field measurements. I designed a 1-inch and 1/2-inch microphone preamplifier based on sub-miniature tubes as shown in Figure 2.

The original B&K 4111 microphone was 36-mm in diameter and used an EF40 tube that caused self-noise problems. The new preamplifiers were a considerable improvement (see Figure 3). Modern preamplifiers are free of microphonics due to the use of ceramic substrates and low noise FET input stages. They have a 20-40 GΩ input impedance enabling linear response to below 2 Hz. The old MK0001 microphones were calibrated to within ±1 dB using an electrostatic actuator. Careful calibrations improved the accuracy until we could show <0.1 dB variation between standards laboratories.

During microphone development work I needed a precise and fast method for determining small changes in microphone sensitivity in order to determine expected long term stability and thermal effects as well as effects of ageing. Reciprocity calibration is very time consuming and normally involves three microphones. So I had to use a more direct absolute calibration method. Traditional methods like comparison of a test microphone to a calibrated standard microphone could not be used because that is what I was trying to develop. Pistonphones available at that time were not very accurate. Optical measurements of piston displacement and motion between the piston actuator and optical read-out could not be implemented. A free floating, dual-piston mechanism actuated by a cam disc overcame these problems (see Figure 4a). Developed sound pressure could be based on a precise cam disc, precise piston diameters and microphone coupler volume. Barometer accuracy for atmospheric pressure correction has been the weak point for many years. Precision laboratory barometers using mercury are easily obtained for the laboratory but not very portable. The development of precision grade barometers has enabled us to develop the modern precision pistonphone. I developed the pistonphone calibrator shown in Figure 4b. The long-term uncertainty is less than 0.1 dB.

The protective grids of the new microphones were designed to allow them to remain on microphones in actual use. This was not the case for the W.E. 640AA, which was typically used without its protective grid. The new grid for the 1/2-inch microphone was designed to extend the high frequency range to 20 kHz.

Dr. Per V. Brüel actively supported my free-field calibration procedures and we published an article on the frequency response of microphones in the *B&K Technical Review*, 1959. With high quality microphones available it was possible to continue developing sound level meters, artificial ears and artificial mouths as well as numerous applications. Some of these were extremely interesting such as the surface mounted microphones for the Concorde, outdoor microphones with built-in actuator calibration, telephone test equipment, etc. During this time I also designed accelerometers, force transducers and whole-body hand-arm vibration transducers and I invented the Delta shear configuration for accelerometers. Carl Wahrman-Jensen, my colleague in vibration transducer development, made many valuable contributions to calibration techniques.

I left the transducer development department in 1973 and took over a separate department for the development of new measurement techniques and instrumentation. This lead to the production of phase-matched microphones, intensity probes with well defined spacers, hydrophones, railway monitoring systems, sound intensity applications, and sound power measurements. In cooperation with Ole Roth, we developed the first true real-time intensity analysis system including gating techniques.

I was laid off from Brüel & Kjær in 1993 after the take over by A.G.I.V. and started the company G.R.A.S. Sound & Vibration. The company produces a complete line of measurement microphones and accessories.

FAQs. Today's measurement microphones are stable and rugged, but still they are and should be treated as high precision delicate instruments. Just to give an example of the dimensions involved – for a standard 1/2-inch microphone measuring a sound pressure level of 40 dB (corresponding to the level in a quiet living room), the diaphragm will move approximately 10^{-11} m. In order to appreciate the magnitude of this tiny movement, imagine that the microphone diameter was the same as the diameter of the earth (12,700 km). The diaphragm would move only 10 mm. S/V

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