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Bad food and good physics: the development of domestic microwave cookery

Kerry Parker[1] **and Michael Vollmer**[2]

[1] Sheffield, UK
[2] Physikalische Technik, Fachhochschule Brandenburg, Magdeburger Straße 50,
14770 Brandenburg, Germany

Abstract

This article forms the second of two papers on the subject of microwave cookers. In the first paper Michael Vollmer describes the physics behind the production of microwaves in the magnetron of the oven, the waveguide and the interaction between the microwaves and the food. This article looks at the physics of cooking, and how the appliance and the food industries have developed products which are now part of many of our students' lifestyles. We include many interesting demonstrations that illustrate this history and which could be used to teach many principles of physics.

Introduction

It sells, at a local supermarket, for a mere £35. An estimated 95% of Americans own one and 75% of them use it every day [1]. In the first half of 2003 its sales outstripped those of both DVD players and refrigerators, and sales are rising. People are intrigued by its operation, which for many users is a mystery verging on magic, yet in these days of video-transmitting cell phones its physics is relatively simple. The microwave cooker is a forgotten tool in the physics lab, or to put it another way, with virtually every student having access to a microwave oven, you could be giving them some great kitchen-based investigations!

The discovery of microwave cooking

The story of the discovery of microwave cooking is the stuff of legends. In 1945 Percy L Spencer (figure 1) was a man renowned for his insatiable curiosity about everything [2] and already a Second World War hero for his development of the proximity fuse [3] and his work in radar. One day, working with a high intensity magnetron microwave generator, he noticed a strange feeling as he walked past a magnetron and he noticed that a chocolate bar in his pocket had melted. Sending the message boy out for some popcorn, he did a few quick experiments and soon demonstrated the cooking effect of the microwaves. According to one account [4], the next day Spencer decided to put the magnetron tube near an egg. He and a colleague "watched as the egg began to tremor and quake. Evidently the curious colleague moved in for a closer look just as the egg exploded and splattered hot yolk all over his amazed face."

The development of the microwave cooker

The Raytheon company, Spencer's employers, took only a year to develop the discovery into a demonstration model: the Raytheon RadaRange. The first commercial models were housed in refrigerator-sized cabinets, and cost between $2000 and $3000.

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Figure 1. Percy Spencer, the inventor of the microwave oven. (Photograph courtesy Spencer Family Archives.)

The first microwave ovens to arrive in the UK were described in the language of the time: ‘as tall as a woman and took four men to move’ [5]. These early models (figure 2) required installation to a water supply for cooling the magnetron.

At those prices and cooking tasteless, soggy food, the early microwave ovens were not an instant hit! It wasn’t until 1967 that a real contender for the domestic market emerged: a 100-volt microwave oven, which cost just under \$500 and was smaller, safer and more reliable than previous models. The magnetron was, by now, air-cooled. Sales gradually grew during the 1970s as the price came down and cooks gradually began to learn what microwaves were good for. Of course, as demand and production increased, the cost of cookers plummeted and sales increased and spiralled upwards. In 1975, 4% of US homes used microwave cookers. By 1976 the figure was 60%. In 2003, 95% of US homes have a microwave cooker. Since the mid-1970s there has been little change to the basic design of the cooker (discussed in the first paper)—electronic timers and extras such as the inclusion of infrared grills to brown food and the like, but the basic machine is the same (but much cheaper!).

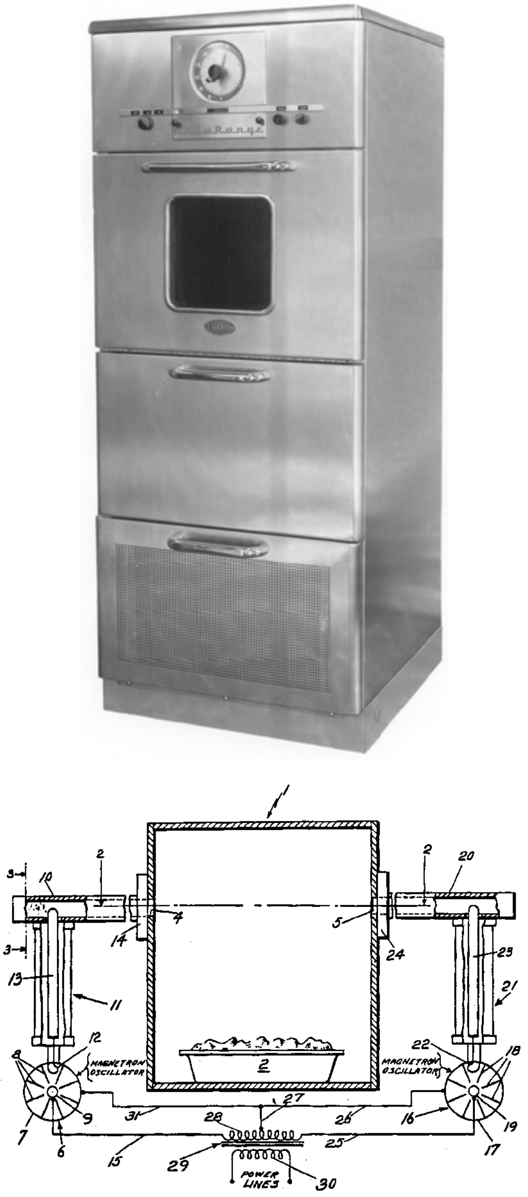

Figure 2. Top: the first microwave oven, the RadaRange. Bottom: part of Spencer’s original patent—the basic design is very similar to ovens we use today. (Images courtesy Spencer Family Archives.)

The development of microwave cookery

Until 1947 all food was cooked ‘conventionally’: food got hot by conduction, convection and radiation. The insides of solids could only be heated by conduction, the heating of the outside surface being accomplished either by radiation (grilling/toasting) or by direct contact with air (roasting/baking), water (boiling), steam (steaming) or hot oil (frying). Each heating method has a characteristic effect on the food and cooks had come to understand these methods by experience handed down over centuries.

The initial mistake made by microwave[1] manufacturers was to suggest that microwave cooking could rival these well-tried conventional techniques and to suppose that cooks who had trained to use conventional techniques could use microwaves equally proficiently.

Browning and crusts

Consider bread:

Cold, old bread can be dull, and most cooks know that the bread rolls and loaves can be rejuvenated before eating by heating them in an oven for a few minutes. Slices of bread can be toasted, fried in oil or even warmed with sugar and spice in milk.

In 1975 one of us (KP) was working in a small kitchen in a pub, and can even now vividly remember the state of the crusty bread rolls after they had been warmed in the new microwave oven. The once crisp brown crusts were broken, swollen and soggy. The rolls were tough and dry and they were certainly inedible because, she was informed, 'microwaves cook from the inside out'.

Bread does not absorb microwaves strongly (the absorption depending principally on the water content), so the penetration depth for typical 'toasting' bread (the depth at which approximately 63% (i.e. $1-1/e$) of the energy has been absorbed) is about 3.5 cm [6].

As the bread absorbs microwaves its surface is cooled by the air in the oven (which is close to room temperature), whilst further inside where the bread is surrounded by warming bread, the temperature rises. In the case of the pub's crusty rolls this meant that the bread well under the crust got to 100 °C first and blew steam out through the cooler crust, making the crust damp and soggy. In conventional cookery the outside is always the hottest part of the food, so this can't occur.

A nice demonstration of this is to put some rolls or piles of sliced bread in a microwave oven and to remove them at 1 minute intervals. The precise results will depend on your oven, but the final effect (once you have passed the damp soggy stage) is to produce a very stiff, dried-out roll which has blackened in the middle (see figure 3).

Figure 3. A section through a stack of sliced white bread before and after five minutes on full power in a microwave oven. The cooked bread is extremely hard and is noticeably smaller. The slices on the right show how the bread has blackened most inside a stack.

Conventional toast

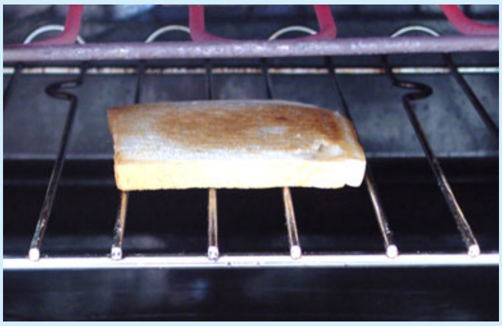

Figure 4. Toasting bread under a conventional grill.

Toasting is an excellent example of heat transfer by radiation—conduction through air is very poor and with a grill arrangement as illustrated (figure 4), any convected air will rise away from the food.

It is also an excellent example of runaway heating. As the toast browns it absorbs a larger percentage of the incident radiation, so it gets hotter quicker. The heating makes the surface darker and darker, until the surface is black. Black toast reflects very little of the incident radiation, so it gets very hot and can catch fire.

Cooking quicker

The main selling feature of microwave ovens has always been the speed at which they can warm

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[1] This is the first of many places in which the authors use the term 'microwave' as a short-hand for microwave oven, in its common usage outside of physics!

and cook food. By conventional cookery the only way to warm a solid object is by conduction. The only way to increase the rate of conduction, without tampering with the food, is to increase the temperature of the surface. Many readers will have experience of trying to cook something quickly, possibly on a barbecue, and blackening the outside while the inside is still virtually raw. The physics of conduction means that you can't increase the rate of heating this way and still get something edible!

Consider potatoes:

Potatoes are conventionally cooked by boiling, baking or frying. Each method produces a distinct texture and flavour. Frying is quickest, whereby the potato is surrounded by hot fat at about 170 °C, but you have to cut the potato up into thin pieces to allow the heat the penetrate to the middle before the chip is overly browned. It is the browning of many foods, of course, that gives them a distinctive flavour. The Maillard reactions are very complicated [7] and their discussion will not form part of this article, except to mention that without these browning reactions many people find foods dull and tasteless, and they only occur at temperatures above about 140 °C. Boiled potatoes don't have this distinctive taste, but baked and roast potatoes both get some degree of browning as they cook in an oven.

Microwave cookery books [8] have tended to go overboard in emphasizing how everything can be prepared in a microwave. Boiling potatoes, however, is little different from boiling potatoes in a pan on a hot-plate. The water surrounding the potatoes absorbs most of the microwaves, and the potatoes cook very similarly, with a very slightly reduced cooking time compared with ordinary boiling. French fries could be pre-cooked in a microwave to reduce frying time. In researching this article we have not met anyone who cooked anything other than baked potatoes in a microwave—and even then many people prefer to finish them off in a conventional oven. The cooking time of over one hour is reduced to just over ten minutes (for up to two potatoes).

Hot spots

Designing recipes and food products for microwave ovens is beset with difficulties in comparison with conventional cookery.

Microwave recipe for baked potatoes

Choose two potatoes, approximately 175 g each. Prick with a fork (or else they could explode) and place in the microwave on full power for five minutes. Turn the potatoes over, and cook for another five minutes. Allow to stand for four minutes.

(The turning is to avoid overcooking in hot spots, and the standing is to allow time for conduction from hot spots.)

A conventional baked product will take ingredients from room temperature in an oven of known temperature (say 180 °C ± 10 °C) and be able to achieve a reproducible result within a typical time-span of 10–100 minutes. Over- or undercooking by five minutes is unlikely to be critical. And any overcooking is usually betrayed by an overly browned outside.

When it comes to cooking with microwaves, achieving reproducible, edible results is much more challenging.

'Hot spots' occur in a microwave oven during cooking because of the various modes of resonance that occur as the microwaves build up standing waves in the oven cavity. This causes the food to cook unevenly (see the blackened bread, and the recipe for baked potatoes). It would be wonderful if ovens could be designed to produce an even intensity of microwaves throughout the oven, but unfortunately this is very difficult. As soon as food (a strong absorber) is introduced into the chamber the variation in intensity of the microwaves changes (see figure 5). The type and quantity of the food will affect the distribution of hot spots and, because the absorption of microwaves is affected by temperature [9], their distribution will change even during cooking. There seems to be no way round it: the food needs to be either stirred, turned or given a standing time for conduction from the hot spots to even up the temperature inside the food. A turntable, as mentioned by Vollmer [9], reduces the effect of hot spots but cannot eliminate them entirely.

Predicting cooking times

With a conventional cooking time of over an hour, and a microwave time of 10 minutes, baked

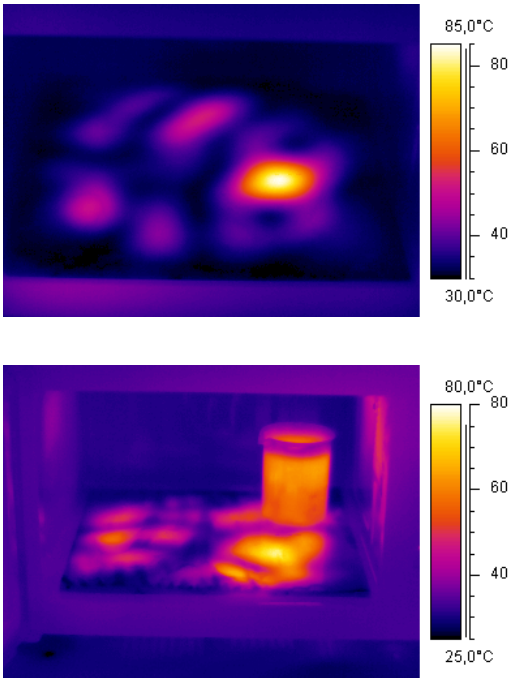

Figure 5. Thermal infrared images of the inside of a microwave oven, with (bottom) and without (top) a cup of water.

potatoes cooked in a microwave are relatively easy. You can overcook them for 30 seconds and they will be okay. It is easy enough to hold the potato in a glove and feel whether it is soft enough to eat (if not, put it back in for another minute). However, for other foods the timing is much more difficult.

The food in a microwave oven is radiated with a fixed power of microwaves, dependent on the magnetron. Generally, the smaller the volume of water in the food, the faster it will heat up. Heating up a litre of water takes a long time! (Racing a 2 kW electric kettle against a microwave oven may be a good way to win a bet with anyone who tells you that microwave cooking is always quicker!)

Cooking a baked potato works reasonably well if you use the same amount of potato each time. But suppose you only wanted one small (80 g) potato, or you happened to have a very large (300 g) potato. An experienced conventional cook would know that the larger potato would take longer to heat through (because the heat has to conduct further),

Whatever you do, be it boiling, baking or frying, the time taken depends on the size and not the overall amount of food being cooked. What

Measuring the speed of light

Many people are impressed by a simple ‘measurement’ of the speed of light by looking at the separation of hot spots in a microwave oven. Having observed standing waves on a string, students will appreciate that the distance between hot spots is approximately half the wavelength of the microwaves.

You can study them using damped thermal fax paper, or by melting or burning various foods. We have seen it done with marshmallows, melted cheese and (a students’ favourite) by melting Milky Way chocolate bars on a flour tortilla. (The tortilla, being relatively thin, absorbs little of the microwave energy, and makes a handy vehicle for getting the melted chocolate from the oven to an enthusiastic student’s mouth!)

Figure 6. A student measures the distance between hot spots in melted marshmallows.

The frequency of the microwaves is written on the back of the oven (2.45 GHz). Of course, the complex modes of vibration in three dimensions make it difficult to detect anything like a one-dimensional wave in a string, but there are often hot spots about 6 cm apart.

$$\begin{aligned} v &= f\lambda \\ &= 2.45 \times 10^{9} \times (2 \times 6) \times 10^{-2}\ \mathrm{m\,s^{-1}} \\ &= 3 \times 10^{8}\ \mathrm{m\,s^{-1}}. \end{aligned}$$

matters in a microwave is the mass of potato (because this indicates the mass of water), and for reliable results foods need to be weighed.

The window of success

Designing a microwave recipe, or designing a food product for microwave cooking, is very difficult because of the criticality of the timing. The window of success [6] is a set of conditions that produces a good food product. In a microwave, the time between producing an edible, a perfect and an inedible product is often less than one minute. In conventional cookery the window often extends from 5–30 minutes. A cook who is used to examining an underdone food and 'giving it another five minutes' will invariably overcook and spoil food in a microwave.

Convenience foods and microwaves ovens

When microwave ovens began to be commonplace in kitchens food manufacturers responded by adjusting heating instructions on existing products so that they could be prepared in a microwave oven, but there were still very few products designed to be prepared in a microwave. It proved incredibly difficult to design foods that could be successfully and reliably 'microwaved'. The dream of having a fridge filled with an exciting range of chilled food ready to microwave to perfection has still to be realized, as anyone who has eaten a series of airline dinners, or eaten from the buffet on a train, will appreciate!

Most 'microwavable' foods in supermarkets are precooked, and the microwave is used to simply reheat them prior to consumption. By packaging precise quantities of known food types and specifying the starting temperature ('cook from frozen' or 'keep refrigerated until use') it is possible to produce a reasonably consistent product. It is interesting to note that by reducing the fat and salt content of sauces (such as in macaroni cheese) the penetration depth is increased, allowing for more uniform heating *and* the food is healthier.

Specific heat capacity

The absorption of energy is not the only factor that decides how hot something becomes in a microwave cooker. Oils and fats absorb less strongly than water, but because of their much lower specific heat capacity and lower density they can heat up quickly, giving rise to the belief that fats heat more quickly than water in a microwave. A simple test shows this not to be the case.

(The website of the Explorit Center at Edgerton, Nebraska, has a very simple description of such an experiment [10], but it is not true that microwaves are not absorbed by oils.)

The lower density and lower specific heat capacity of oils favour a more rapid heating compared with water, but the difference in ε_2 far outweighs this (see figure 7). When cooking foods such as meats it is the water, not the oil, that heats

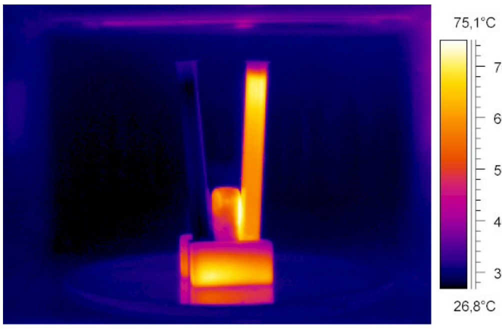

Figure 7. Thermal infrared images of oil (left) and water (right), before and after heating in a microwave oven.

From equation (8) in the preceding article

$$P = \omega\varepsilon_0\varepsilon_2 E_{\mathrm{eff}}^2 V$$

so

$$\Delta P = \varepsilon_2 V K$$

where $K = \omega\varepsilon_0 E_{\mathrm{eff}}^2$, which is constant. Thus

$$\text{Absorbed energy: } \Delta P\,\Delta t = \varepsilon_2 V K\,\Delta t$$

$$\text{Temperature increase: } \Delta Q = cm\,\Delta T.$$

Neglecting for the moment other loss mechanisms (conduction to support, convection by air, radiation):

$$\varepsilon_2 V K\,\Delta t = cm\,\Delta T$$

so

$$\frac{\Delta T}{\Delta t} = \frac{\varepsilon_2}{c\rho}K$$

where ρ is the density of the food.

up first. If you try cooking a piece of bread in a saucer of oil in a microwave, the bread still burns in the middle (as in figure 3) while the oil is only warm. ‘Microwavable’ hamburgers and other such foods rely heavily on the use of emulsifiers, gums, proteins and sugars to manage the water content of the bun and the meat, so that the bun does not burn before the meat is cooked.

High-sugar foods also present a problem because of their rapid heating. Schiffmann [6] warns that it is very difficult to make a single-step microwave caramel popcorn because the sugar/oil blend heats so quickly that the sugar can burn before the popcorn pops. Most microwave popcorn comes with caramel sauce that can be warmed separately and poured over the popcorn when it is cooked.

It’s in the box

Water management may provide for efficient heating, but this alone will not produce the intense heating of the outside of a food required to produce the browned crust required in foods such as pizzas and French fries. ‘Microchips’ and other such products are now available in supermarkets in most countries: in the UK McCain are the market leader. The sophisticated technology is in the box: a group of electronic engineers, working in stealth technology, who explained this were very enthusiastic.

Most ordinary cooks are very confused about the effect of metals in a microwave oven. The rule ‘don’t put anything metal in a microwave oven’ is well known, and badly understood. As explained in the preceding article, metals essentially reflect microwaves (see figure 8), but the process means that small pieces of metal can become hot and also spark and arc. (CDs and ‘Poptart’ wrappers make an impressive, if toxic, display in a microwave, best viewed on video (see Microwave weblinks in the Web Watch on page 102)).

The heating effect can be demonstrated very impressively by placing an ordinary tungsten filament bulb in the microwave (figure 9). A standard 60 W bulb in a 700 W oven will explode in about 30 s, so you should only switch on for a few seconds and you should put a glass of water in the microwave with the bulb to absorb some of the microwave energy. The bulb lights (with ‘no power supply’!) and it does so even if the filament is broken. The safety of this wonderful demonstration of the heating of metals in a microwave is still a little controversial—the only risk is from a bulb exploding if it gets too hot. Check your local rules before using this in class, and be very careful before you send your students to try it out at home!

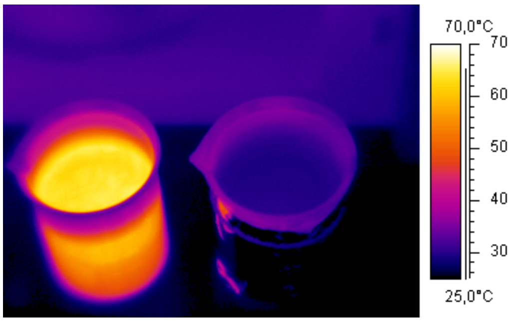

Figure 8. Thermal infrared image of two cups of water that started at the same temperature. The cup on the right has remained cool because it was surrounded in aluminium foil of 10 μm thickness (i.e. approximately ten times larger than the penetration depth). The cup on the left was heated normally.

Figure 9. A filament bulb in a microwave oven.

Unpack ‘microwavable’ pizza, French fries or popcorn and you will find in the packaging a metallized film of sprayed aluminium. This is designed to heat up in the microwave and heat the food more conventionally. You can try cooking the food in the microwave with and without the box—without the box the food is soggy and does not brown. The browning, even with the box, is limited, but for many customers the convenience of quick-cooking frozen foods outweighs the loss of quality. If you want to demonstrate this you don’t have to keep buying pizzas. You can re-use the aluminized boxes from ‘micro-pizzas’ to

COOKING INSTRUCTIONS:
Keep frozen until ready to use.
These are guidelines only.
NOTE: For a crisper crust, prepare in conventional oven.

CONVENTIONAL OVEN:
- Preheat oven to 375°F / 190°C / Gas Mark 5.
- Remove pizza from all packaging, discard the cardboard tray and place directly onto oven shelf. Bake for 20-22 minutes at the top of the oven.

Check product is hot throughout before serving and that the cheese is melted and lightly browned.

MICROWAVE:
Remove pizza from wrapper and place on the enclosed microwave tray.

Microwave:	750W or D	850W or E
Heat on Full for:	3½ mins	3 mins
Stand for:	1 min	1 min

NOTE: Please do not attempt to microwave more than one pizza at a time. Due to microwave oven variances, heating times may require adjustment. Ensure product is hot before serving.

Figure 10. The outer box of a ‘microwavable’ pizza shows how precise the cooking instructions have to be (top) and the cooking tray from such a pizza (bottom). The bread, with a little oil, has been cooked in a microwave to get its browned crust.

cook bread in a microwave, and compare the ‘toast’ with bread warmed without the box (see figure 10).

There is still a lot that is not understood about microwave cookery, even by professional food designers. Using some very cheap ‘microwavable’ sugar popcorn from a local supermarket it was intriguing to test whether Schiffmann was right about the sugar burning before the corn kernels popped. The fat and sugar mixed with the unpopped kernels are clear in figure 11. Most of the popcorn was edible, but the sugar that was close to the hot aluminium was badly burned by the time all the kernels had popped!

Figure 11. Top: popcorn after cooking and in its uncooked state. Bottom: the remains of the popcorn that burned on the bag—the square of aluminized film where the temperature was greatest is clearly visible.

Conclusion

Many students are proficient microwave oven users and are intrigued about their operation. They enjoy taking their physics home and using it to understand and improve their cooking skills. At the same time, using a microwave helps them understand many basic physics processes. Activities can be designed to suit students from primary school level and upwards. The success of ‘microchip’ type products shows how understanding relatively simple physics can lead to a very profitable product.

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Kerry Parker is Editor of *Physics Education*.

Michael Vollmer is a Professor of experimental physics at Fachhochschule Brandenburg. He has a Diploma, PhD and Habilitation from the University of Heidelberg. His current activities include applied research in infrared imaging, experiments for physics education and teacher training seminars.