Report

Study on Microwaveability of Aluminium Foil Packages
Phase II: Experimental Study

for:
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Content

1 Summary

Goal and Scope

After a first literature study on microwaveability of food packages containing aluminium foil and household foil, an experimental study on the subject was performed. The experimental study assesses feasibility, safety and performance of microwave heating foods in packages containing aluminium foil and household foil. Results of heating experiments will provide sound information on performance and proper use of these packages in microwave heating applications.

About 190 aluminium foil trays have been heated in four different kitchen microwave ovens. Test products have been tap water, egg batter, frozen lasagne, and minced meat. In addition, 10 plastic beakers and 10 trays with lids made from aluminium foil or aluminium laminate were tested. In these cases, the food products were a noodle soup and a children menu. Finally, microwave heating of food on a porcelain dish covered with household foil was tested. The test food in this case was a loaf of minced meat. Heating efficiency, heating uniformity, and possible hazardous conditions have been investigated.

Safety

Not a single case of hazardous condition has been observed in any of four microwave ovens during more than 200 heating procedures with packages containing aluminium foil at maximum microwave power setting. No damages or changes to ovens could be noticed. Severe abuse situations had to be constructed in order to provoke electric sparks with aluminium foil trays.

The abuse situations were:

+ empty aluminium foil tray inside oven, touching the oven wall at full microwave power;
+ two empty aluminium foil trays inside microwave oven, touching each other.

Both abuse situations are clear violations of heating instructions and should not occur in normal household use of microwave ovens. Therefore they seem not to be of practical relevance.

Twelve tests with household foil wrapped over dishes were also performed. Only one single electric spark without any relevance to safety occurred during these twelve tests. The spark formed for a fraction of a second at a large fold of the foil and burnt a hole of about 1 cm diameter into the foil. The incident had no consequence to safety or aesthetic of oven and did not alter quality of heated food.

Heating Time and Heating Efficiency

Heating efficiency is in general lower with aluminium foil trays. Heating times to achieve the same heating effect are longer than in plastic trays and the consumed electric energy is higher by the same proportion.

The extension of heating time for aluminium foil trays over heating time for plastic trays varied between 20% and 70%, depending on food and tray geometry. Also a large influence of oven design on heating performance of food in aluminium foil trays was observed with a preference for ovens with a horizontal magnetron antenna in the microwave feeding window.

Generally, the heating efficiency was smaller for small trays with a lower ratio of open surface dimensions to microwave wavelength. Also the ratio of open surface area to food volume may play a role. The dependence of the efficiency from food properties is not as clear. Efficiency was at the low end for tap water and at the high end for egg batter. Frozen lasagne and meat ball mass were in between.

For plastic containers with foil lid as tested with a children meal in a plastic tray and a noodle soup in a plastic beaker, the effect of the lid on heating efficiency is very small. The needed heating time extension to achieve the same heating effect as without lid was estimated to about 10%.

Heating Patterns and Heating Uniformity

Food heating patterns are quite different in aluminium foil trays and in plastic trays. In plastic trays, the microwave energy heats preferably the edges and corners of the food filling. The centre usually heats slower. In aluminium foil trays, microwave energy heats preferably the upper layers of the centre region of the filling. Corners and in particular the bottom edges are heated least. In trays of both materials, very uneven heating can be observed. It depends on the tray geometry and the food material, how uniform the heating will be.

In experiments with egg batter, the heating patterns were different between aluminium foil trays and plastic trays but similar with respect to amount of non-uniformity or to maximum temperature difference. The experiments did not indicate a clear advantage nor a disadvantage for aluminium foil trays with respect to heating patterns. In experiments with microwave heating of frozen lasagne portions and meat ball mass, rather satisfying and appealing heating patterns have been achieved in aluminium foil trays. Also heating seemed to be more uniform.

Visual appearance of lasagne and meat ball mass heated in foil trays was better because a nice brown crust was formed on the surface.

Conclusion

No hazardous situation or oven damages have been observed during heating more than 200 food portions in packages containing aluminium foil and household foil in four different microwave ovens at full microwave power.

Microwave heating patterns in aluminium foil trays are different from patterns in plastic trays and similarly uneven. In same cases, uniformity is better in aluminium foil trays. Satisfying heating results can be achieved in both tray forms.

Heating efficiency is lower in aluminium foil trays than in equivalent plastic trays. The actual difference in heating efficiency depends on food properties, tray geometry, and oven design.

Microwave heating of food packed in aluminium foil trays or in plastic containers with aluminium foil or aluminium laminate lids is perfectly viable. Use of aluminium household foil to cover foods during microwave heating is considered safe but may lead to sparking and should not be promoted.

2 Introduction

According to consumer perception and also to many operating guidelines for microwave ovens, the use of metal in microwave ovens is prohibited. This restriction affects in particular food packages containing aluminium foil like

- aluminium foil trays
- plastic trays with aluminium foil lids
- dishes or bowels covered with aluminium household foil.

From a physical standpoint however and confirmed by experimental work of different groups in the past, a controlled use of metal in microwave ovens is perfectly feasible. This has been confirmed by a literature study which preceded this experimental study (PFEIFFER 2004). Public perception and guidelines may therefore wrongfully neglect aluminium foil in applications for microwaveable food packages.

Goal of the experimental study is therefore to re-assess feasibility, safety and performance of microwave heating foods in packages containing aluminium foil. Results of the heating experiments will provide information on conditions and proper use of aluminium foil in microwave heating applications.

3 Objectives

Objectives of the experimental study on microwaveability of aluminium foil packages are:

- Identification of non-critical and safe as well as critical microwave heating situations with aluminium foil packages, including unintended abuse or violation of heating guidelines.

- Identification of absence or existence of possible additional critical situations and threats to consumer and oven in microwave heating of food in aluminium foil packages compared to plastic or microwave transparent packages.

- Comparison of heating quality/uniformity and efficiency of microwave heating of foods in aluminium foil packagers compared to plastic or microwave transparent packages.

4 Experimental Program

The experimental work program is based on the findings of a previous literature study for EAFA (PFEIFFER 2004) and a discussion with members of EAFA in February 2005. Methods applied in the tests follow in large parts European norm EN 60705, a norm with measurement procedures for the characterisation of usability of household microwave ovens (NORM 1999).

To cover a typical selection of microwave oven constructions found in households, four different oven models were used in the test. The actual selection of models was dependent on the availability of oven constructions on the market. The ovens were characterised with respect to output power, efficiency, and heating uniformity according to EN 60705.

The study looked into three different packaging situations with aluminium foil for food intended for thawing or reheating in household microwave ovens:
+ aluminium foil trays,
+ plastic containers with lids made from lacquered aluminium foil or foil laminate,
+ dishes or bowls covered with aluminium household foil.
Heating performance of these aluminium foil containing packages was compared to performance of similar packages without foil or made from plastic.

The investigated packaging situations together with used model foods are enumerated in detail below:

a) Single compartment rectangular aluminium foil tray with wrinkled wall

The literature survey and physical considerations indicate that an aluminium foil tray with wrinkled wall, un-lacquered, represents a “worst case” tray for microwave heating with respect to occurrence of sparks. With such a tray in standard size and with “frozen lasagne”, a food load that also is assumed to be critical because of its low microwave absorption, a critical or “worst case” situation was constructed. With this experimental setting the possible occurrence of sparks and arcs during microwave heating and its conditions was investigated.

b) Single compartment rectangular aluminium foil tray with smooth wall

The container is a standard container already in use for microwaveable foods. It was tested with two different high absorption model foods, “batter” and “meat ball mass”. In addition, the low absorption food “frozen lasagne” was tested to include a thawing procedure. Possible critical situations, uniformity and efficiency of heating were measured.

c) Dual compartment aluminium foil tray with smooth wall

Similarly shaped containers, made from plastic material, are already in use for microwaveable ready meals. Two different model foods, “batter” and “meat ball mass”, were used in the experiments. After own observation this package geometry in plastic is mainly used for ambient or chilled shelf ready meals, thawing of frozen food was not tested. Possible critical situations, uniformity and efficiency of heating were measured with aluminium as well as with plastic tray.

All heating experiments with aluminium foil trays a) to c) were repeated with similar shaped plastic trays and the same model foods. Results were compared with respect to heating uniformity and efficiency.

d) Plastic trays with laminated aluminium foil lid

Many of the ready meals in plastic trays have a lid with aluminium laminate. The influence of such a lid on microwave heating performance is also of interest to aluminium foil manufacturers. An appropriate test product in such a package (infant ready meal) was chosen on the market. Microwave experiments focused on possible sparks at the cut edge of the lid.

e) Plastic beakers with lacquered aluminium foil lid

A further package for convenience food is a plastic beaker with lacquered aluminium foil lid. Such packages are used for dry soup base portions on which boiling water is poured. The ready soup is then eaten directly from the beaker. Microwave performance of the beaker with the aluminium lid on was investigated. An appropriate product was chosen on the market (300 ml soup beaker). Microwave experiments focused on possible sparks at the cut edge of the lid.

f) Porcelain dishes covered with aluminium household foil

Household foil is a much used product in the home kitchen to cover food on dishes and bowls for short time storage. The use of foil is even recommended by microwave oven manufacturers to shield protruding parts on large food portions (like legs on chicken) from receiving too much energy during microwave cooking. For microwave experiments, a loaf of meat ball mass on porcelain plates was covered with aluminium household foil and microwave heated. Heating experiments focused on possible sparks at the tear-off edge of the foil and at wrinkles.

Tables 4.1 to 4.3 give an overview of the experimental program and the number of single experiments.

Table 4.1: Experiments to characterise microwave ovens

01 Oven Characteristic with 1 l Tap Water in Glass Container

Samples	Ovens	Substrate	Evaluation
4	4	tap water	ΔT, Pth, Pel, thermal efficiency, electric efficiency
total	16		

02 Oven Characteristic with 5 x 100 ml Tap Water in Plastic Beakers

Samples	Ovens	Substrate	Evaluation
4	4	tap water	ΔT1..5, ΔTm, uniformity, Pth, thermal efficiency
total	16		

Table 4.2: Heating experiments with different food in aluminium foil and plastic trays

A **Wrinkled Wall Alu Foil Tray**

	Samples	Ovens	Substrate	Evaluation
Alu	10		preparation and abuse	critical situations
	2	4	tap water	ΔT, thermal efficiency, electric efficiency, t_alu/t_plastic
	4	4	frozen lasagna	Tmin, Tmax, thawed/frozen
	total	34		
Plastic	2	4	tap water	ΔT, thermal efficiency, electric efficiency, t_alu/t_plastic
	3	4	frozen lasagna	Tmin, Tmax, thawed/frozen
	total	20		

B **Smooth Wall Alu Foil Tray, Single Compartment**

	Repetitions	Ovens	Substrate	Evaluation
Alu	10		preparation and abuse	critical situations
	2	4	tap water	ΔT, thermal efficiency, electric efficiency, t_alu/t_plastic
	4	4	frozen lasagna	Tmin, Tmax, Txy, uniformity, efficiency, thawed/frozen
	4	4	batter	Tmin, Tmax, uniformity, efficiency, solid/liquid
	4	4	meat	Tmin, Tmax, Txy, uniformity, efficiency
	total	66		
Plastic	2	4	tap water	ΔT, thermal efficiency, electric efficiency, t_alu/t_plastic
	3	4	frozen lasagna	Tmin, Tmax, Txy, uniformity, efficiency, frozen/thawed
	3	4	batter	Tmin, Tmax, uniformity, efficiency, solid/liquid
	3	4	meat	Tmin, Tmax, Txy, uniformity, efficiency
	total	44		

C **Smooth Wall Alu Foil Tray, Dual-Compartment**

	Repetitions	Ovens	Substrate	Evaluation
Alu	10		preparation and abuse	critical situations
	2	4	tap water	ΔT, thermal efficiency, electric efficiency, t_alu/t_plastic
	4	4	batter	Tmin, Tmax, uniformity, efficiency, solid/liquid
	4	4	meat	Tmin, Tmax, Txy, uniformity, efficiency
	total	50		
Plastic	2	4	tap water	ΔT, thermal efficiency, electric efficiency, t_alu/t_plastic
	3	4	batter	Tmin, Tmax, uniformity, efficiency, solid/liquid
	3	4	meat	Tmin, Tmax, Txy, uniformity, efficiency
	total	32		

Table 4.3: Heating experiments with aluminium foil lids and aluminium household foil

D Plastic Tray with Aluminium Foil Laminate Lid

Repetitions	Ovens	Substrate	Evaluation
4	4	baby food	critical situations, Tmin, Tmax, t_w_lid/t_wo_lid
total	16		

E Plastic Beaker with Lacquered Aluminium Foil Lid

Repetitions	Ovens	Substrate	Evaluation
4	4	soup	critical situations, Tmin, Tmax, t_w_lid/t_wo_lid
total	16		

F Food Dishes Covered with Tear-off Household Aluminium Foil

Repetitions	Ovens	Substrate	Evaluation
4	4	meat	critical situations, Tmin, Tmax, t_w_wrap/t_wo_wrap
total	16		

5 Materials and Methods, General

5.1 Microwave Ovens Used in the Heating Experiments

During expeditions through stores in the Munich area with electric appliances, the observation was made that all offered microwave ovens launch microwave energy through a window at the right side wall of the cooking chamber. This design seems to rule today's home microwave oven market. However, the mounting of the magnetron and the polarisation of the microwave field entering the cooking chamber can be different. Ovens with vertical arrangement of the magnetron antenna and ovens with horizontal arrangement of antenna were found. Four ovens were chosen for the heating experiments. Their main characteristics as stated in the data sheets are summarised in table 5.1.

Table 5.1: Microwave ovens used throughout the heating experiments.

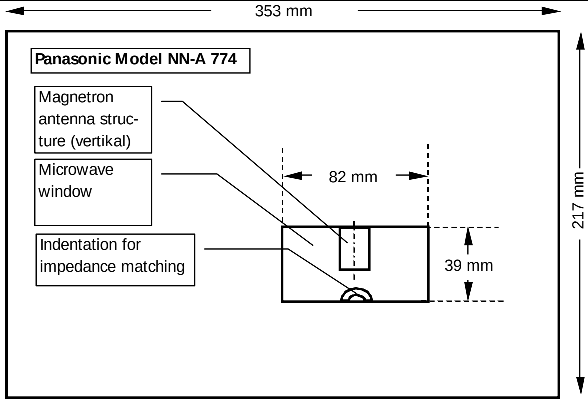
Manufacturer	**Panasonic**	**Sharp**	**Sharp**	**Medion**
Model	NN-A764 (Inverter oven)	R-734	R-208	Micromaxx MM 41580
Cooking chamber size (W/H/D) in mm	359/217/353	342/207/368	322/187/336	288/205/287
Volume of cooking chamber in l	27	26	20	17
Diameter of turntable in mm	340	325	272	245
Microwave power in W (data sheet)	1000	900	800	700
Power consumption in W (data sheet) without additional heating modes	1250	1370	1180	1150
Short name in report	Panasonic	Sharp 1	Sharp 2	Micromaxx

Specific characteristics, in particular microwave window design are, shown in the following photos and drawings of figures 5.1 to 5.4.

Front view of microwave oven

Cooking chamber with microwave window at the right side wall

View of microwave window with vertical antenna structure and indentation for electric impedance matching (mica window cover is removed)



Drawing of right side wall of cooking chamber with microwave window

Rated microwave power	1000 W
Volume of cooking chamber	27 l
Magnetron antenna orientation	vertical

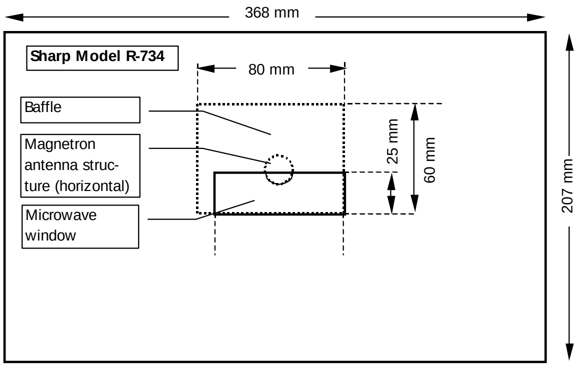
Figure 5.1: Panasonic Microwave Oven Model NN-A764 - Inverter oven (Panasonic)

The Panasonic NN-A764 (figure 5.1) is the oven with the highest power rating and the largest cooking chamber. The magnetron antenna is oriented vertical in the microwave window structure. A characteristic specific to the Panasonic oven is the power control. While in most ovens, microwave power control is via an on-off duty-cycle with adjustable on times, the Panasonic has a continuous electronic power control, termed “Inverter control” by the manufacturer.
The microwave window is situated rather low at the right side wall of the cooking chamber, magnetron antenna is mounted vertical which gives the microwave energy radiating from the window a primarily vertical polarisation (vector of electric field is oriented vertically).

Front view of microwave oven

Cooking chamber with microwave window at the right side wall

View of microwave window with horizontal antenna and aperture baffle for electric impedance matching (mica window cover is removed)



Drawing of right side wall of cooking chamber with microwave window

Rated microwave power	900 W
Volume of cooking chamber	26 l
Magnetron antenna orientation	horizontal

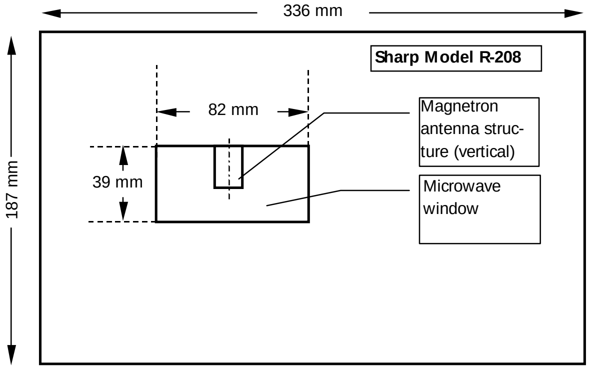
Figure 5.2: Sharp Microwave Oven Model R-734 (Sharp 1)

Next smaller in size among the four ovens is the Sharp Model R-734 with 900 W rated microwave power (figure 5.2). The microwave window is situated rather high at the right side wall of the cooking chamber. The magnetron antenna is mounted horizontally and separated from the cooking chamber by a reflecting baffle. The predominant polarisation of the radiated microwave energy is hard to predict without field calculation. It is however much less polarised vertically compared to the Panasonic oven.

Front view of microwave oven

Cooking chamber with microwave window at the right side wall

View of microwave window with vertical antenna structure
(mica window cover is removed)



Drawing of right side wall of cooking chamber with microwave window

Rated microwave power	800 W
Volume of cooking chamber	20 l
Magnetron antenna orientation	vertical

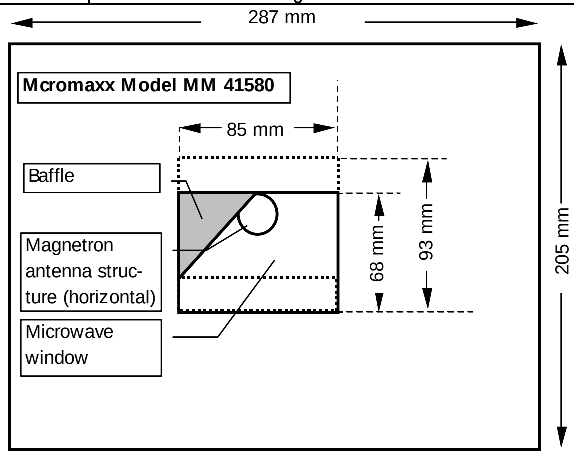
Figure 5.3: Sharp Microwave Oven Model R-208 (Sharp 2)

The third oven is the Sharp Model R-208 with 800 W rated microwave power (figure 5.3). The microwave window is situated rather high at the right side wall of the cooking chamber. The magnetron antenna is mounted vertically and the predominant polarisation of the radiated microwave energy is again vertical as in the Panasonic oven.

Front view of microwave oven

Cooking chamber with microwave window at the right side wall

View of microwave window with horizontal antenna struc-ture and aperture baffle for electric impedance matching (mica window cover is removed)



Drawing of right side wall of cooking chamber with microwave window

Rated microwave power	700 W
Volume of cooking chamber	17 l
Magnetron antenna orientation	horizontal

Figure 5.4: Medion Microwave Oven Model MM 41580 (Micromaxx)

The last oven is the Micromaxx MM-41580 with a rated microwave power of 700 W (figure 5.4). The microwave window is situated centred at the right side wall of the cooking chamber. The magnetron antenna is mounted horizontally and separated from the cooking chamber by a reflecting baffle. The predominant polarisation of the radiated microwave energy is hard to predict as in the case of the Sharp R-734, but is much less polarised vertically as in the Panasonic oven.

5.2 Heating and Measurement Procedure

For heating experiments, all ovens were equipped with glass turntables. Metal cook ware or browning dishes that were part of some of the oven accessories, were not used. Trays and other food containers were placed in centre of turn table. Microwave power was always set to maximum position in all heating experiments.

Tray filling with sample material was always controlled on a balance, in some cases also mass of filled trays were weighed after heating in order to determine evaporation loss. Start temperature of food before heating was controlled by cooling in a refrigerator and measured immediately before start of microwave heating.

After heating, liquid samples (water, soup) were stirred to get a mixing temperature. In solid samples, locations of maximum and minimum temperatures were determined and the temperatures measured. In many cases additional temperatures were measured manually with a fast-response thermo couple in a rectangular grid of measurement points.

In the case of egg batter, that partially solidified during heating, solid and liquid fraction were separated after heating and weighed separately. From the quantity of the solid fraction it was possible to conclude on efficiency of heating.

Also visual examination of heated samples was carried out. Crusts and dried out spots as well as burnt spots on food material were registered. All aluminium foil trays were also examined for signs of sparks.

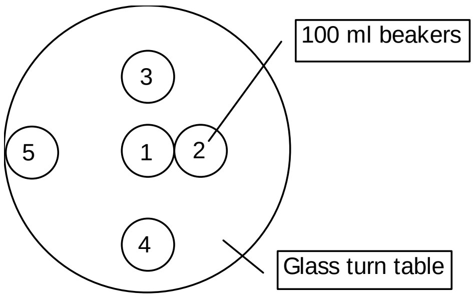
5.3 Measurement of Oven Performance

The actual microwave heating power of ovens can be measured according to norm EN 60705, section 8, with a water load (NORM 1999). 1 l tap water of 10°C was filled into a container, e.g. a large boro-silicate glass beaker (figure 5.5). The oven was set to maximum power and switched on until the water temperature reached about 20°C. Heating time and average temperature increase were measured.

From temperature increase, heating time, heat capacity of water and fractional heat capacity of glass container, the thermal power of the oven can be calculated. In this set-up, the microwave power is nearly completely converted into thermal power in the water; the experiment was therefore used to measure microwave power of the oven.

Figure 5.5: Arrangement of 1 l water in container for measurement of actual oven power

To characterise the electric efficiency of the ovens, i.e. the efficiency in converting electric into microwave power, the electric power consumption of the ovens during heating was measured with an electronic watt-meter (Energy Monitor 3000, Voltcraft GmbH, Hirschau, Germany).



Beaker	Position on glass turn table
1	centre
2	touching beaker 1
3	between centre and rim
4	near rim
5	at rim

Figure 5.6: Measurement of heating power at different locations in cooking chamber.

A second experiment according to norm EN 60705, section 10.2, was concerned with heating power at different load positions in the cooking chamber. Five small beakers were filled with 100 ml tap water of 20°C each and positioned on the oven turn table according to a specific scheme (figure 5.6). The oven was switched on at maximum power setting for a time equivalent of 50 kWs microwave energy generation. After heating, temperature was measured in each beaker. The measurements were evaluated for average temperature increase and maximum relative temperature difference between two beakers.

5.3 Used Food Trays

Three different aluminium foil trays were provided by EAFA members:
- a medium size tray with wrinkled wall
- a small tray with smooth wall
- a dual compartment tray with smooth wall

Also plastic trays of similar size and shape were provided. Detailed dimensions are given in table 5.2, photographs of the aluminium foil trays can be seen in figure 5.7.

Table 5.2: Aluminium foil trays used in microwave heating experiments together with similar plastic trays for comparison.

Tray	Format	Weight in g	Exterior Size in mm	Interior Size in mm	Volume in ml
1	Alu foil, wrinkled wall	8.6	185 x 134 x 35	177 x 123 x 28	470
2	PP, white or transparent	14	189 x 139 x 39	170 x 120 x 33	550
3	Alu foil, smooth wall	10.1	161 x 111 x 31	143 x 100 x 24	280
4	PET, beige	17.3	172 x 122 x 36	151 x 112 x 30	390
5	Alu foil, smooth wall, dual compartment	20.1	222 x 173 x 36	114 x 160 x 30; 89 x 160 x 30	375 + 265
6	PET, black, dual compartment	27.1	222 x 173 x 36	114 x 160 x 30; 89 x 160 x 30	375 + 265

 Aluminium foil tray, smooth wall	 Aluminium foil tray, wrinkled wall
	Aluminium foil tray, dual compartment, smooth wall

Figure 5.7: Photographs of trays used in microwave heating experiments

5.4 Model Foods

The heating experiments were performed with different model foods and media, which were taken in parts from European Norm for house hold microwave ovens EN 60705 (NORM 1999).

I) The most simple medium was tap water which in the institute has an electric conductivity at room temperature of 0.7 mS/cm. The liquid state makes it possible to stir and to measure a true mixing temperature after heating instead of a temperature distribution. Therefore the medium is helpful to measure absorbed microwave power.
Water was used to measure microwave oven output power and to characterise aluminium and plastic trays with respect to heating efficiency.

II) A semi-liquid medium used with trays was an egg batter according to EN 60705, Appendix A. The recipe is:

200 g	wheat flour
70 g	whole egg
20 g	sugar
4 g	salt
165 g	water

The liquid batter solidifies during heating. If heating is stopped after a partial solidification, heating patterns can be made visible by separation of liquid from solidified parts.

Egg batter was used to measure heating efficiency and heating patterns in smooth wall single compartment and dual compartment trays and to compare to similar plastic trays.

III) The third model food was frozen lasagne with sauce Bolognese and sauce Béchamel. This model food stands for a growing number of frozen prepared meals offered by the food industry in trays for rapid microwave thawing and reheating at full oven power. Since frozen food usually has a low microwave absorption, full power setting means very high electric field strength in the oven chamber and high electric stress for door seals, turn table, and magnetron.

Ready made 400 g portions of frozen lasagne in carton trays were purchased in a super market ("Smartprice" Lasagne Bolognese, frozen, 400 g portion, Wal-Mart Deutschland GmbH).
The portions were thawed until they got soft, transferred into the aluminium and plastic trays, pressed into the trays until the lasagne filled the trays from wall to wall, and then frozen again.

Lasagne portions were used in wrinkled wall aluminium foil tray and in single compartment smooth wall foil trays as well as in similar shaped plastic trays.

IV) A further solid model food was a meat ball mass according to EN 60705, section 12.3.3. The recipe for the mass is

800 g	ground beef
115 g	whole egg
2 g	salt

The mass was filled into trays and flattened with a spoon. The meat ball mass was used in experiments with smooth wall single compartment and dual compartment aluminium foil trays and similar plastic trays. In addition, meat ball mass was used for experiments with dishes covered with tear off aluminium foil.

V) For a series of tests with plastic trays covered with an aluminium foil laminate, a ready product was used.
A child meal of 250 g in a dual compartment tray with pasta in sauce and small meat balls in sauce (HiPP GmbH) was purchased in the supermarket.

VI) For a series of tests with plastic beakers covered with aluminium foil lid, also a ready product was used. A beaker with dry base of a spaghetti soup was ("5 Minuten Terrine" from Maggi) was purchased.

6 Experimental Results

6.1 Characterisation of used Microwave Ovens

Oven heating power

The measurements of microwave heating power with 1 l water load (tap water) according to norm EN 60705 (NORM 1999) provided the results tabulated in table 6.1. The norm allows for a rounding up of measured power to the next 50 W step. The ovens therefore completely (Panasonic, Micromaxx) or approximately (Sharp 1, Sharp 2) fulfil the requirements of norm EN 60705 for rated microwave power.

The electric efficiency of the ovens is obtained by measurement of electric power input with an electronic watt meter. The resulting efficiencies reflect the conversion efficiency of the oven magnetrons. They are in the range from 54% to 56% which is quite usual for household microwave ovens

Table 6.1: Measured heating power and efficiencies of used microwave ovens with 1 l water. Averaged results from 4 repetitions.

Oven	Panasonic	Sharp 1	Sharp 2	Micromaxx
Rated microwave power P_N in W	1000	900	800	700
Measured heating power P_{th} in W	982	844	734	654
Heating power according to EN 60705 in W	1000	850	750	700
Measured electric input power P_{el} in W	1760	1528	1327	1215
Thermal efficiency P_{th}/P_N	98%	94%	92%	93%
Electric efficiency P_{th}/P_{el}	56%	56%	55%	54%

It is worth noting, that heating power depends on the nature of the load and on the operating condition of the oven. Small and poorly absorbing loads would lead to a lower heating power, since part of the microwave energy is absorbed in the oven walls or reflected back to the magnetron. It was also observed, that a hot oven, i.e. an oven after several minutes full power operation delivers less microwave power compared to a cold oven. In particular the microwave power of the Panasonic decreased by more than 20% after a few minutes full power. The power decrease was not so significant with the other ovens.

Heating power at different locations in oven chamber

The measurement of microwave heating at different oven locations with 5 x 100 ml tap water in small beakers provided the results presented in table 6.2.
The total heating power is smaller than in the previous experiment because of the smaller amount of absorbing mass (500 ml vs. 1000 ml). Maximum difference in temperature increase between two beakers is between 21% and 30%, with Sharp1 oven at the upper end. It is interesting to note, that beakers with maximum temperature increase are found at different positions in different ovens. While in the Panasonic, the beaker with maximum temperature increase is located in the centre of the turn table (position 1), in the Sharp2 and Micromaxx ovens, it is found at the periphery of the turn table (position 5). The Sharp1 oven has an intermediate pattern. The results are a first indication, that the heating patterns of the ovens differ from each other. However a simple correlation with the magnetron and microwave window arrangement is not possible.

Table 6.2: *Measured of heating power at 5 different locations in microwave ovens with 5   100 ml beakers. Averaged results from 4 repetitions.*

Oven	**Panasonic**	**Sharp 1**	**Sharp 2**	**Micromaxx**
Rated microwave power P_N in W	1000	900	800	700
Heating time in s	50	55	62	71
Measured heating power P_{th} in W	895	740	666	585
Maximum difference in temperature increase between two beakers	22%	30%	24%	21%
Beaker positions with maximum temperatures	1 centre	2 near centre	5 outward	5 outward
Beaker positions with minimum temperatures	5 outward	3 intermediate	1 centre	1 centre

6.2 Heating Tap Water in Trays

Heating Efficiency

The microwave access to food in aluminium foil trays is only from the metal free top side. In plastic trays, the access is from all sides. It may therefore be expected, that the intensity or efficiency of microwave coupling into the food is influenced by the tray material. This is also confirmed by earlier experiments reported in the literature [AHVENAINEN 1992, RISMAN 1992, ALUSUISSE 1987, DECAREAU 1978].
To measure the relation between aluminium foil trays and plastic trays with respect to heating efficiency and heating speed, microwave heating experiments with tap water were carried out. The ovens were operated at full power, heating times were varied from 30 s to 86 s to compensate for the different nominal

oven powers and the different water quantities in the three tray formats. Water temperature at heating start was near 10°C. After the end of heating, the water in the trays was stirred to achieve a true mixing temperature and to average out the complex microwave heating patterns. Taking into account the heat capacity of the water and the temperature increase during heating, the heating power can be calculated. The heating power provides a simple and straight forward measure for comparison of heating efficiency with different tray materials and geometries.

Heating or thermal power results and relations between aluminium foil and plastic trays are presented in table 6.3 for small single compartment trays, in table 6.4 for larger single compartment trays, and in table 6.5 for dual compartment trays.

Results of thermal power measurements show, that heating efficiency is reduced by 25% to 40% in aluminium trays compared to similar plastic trays. The reduction is more significant for smaller tray sizes. With large aluminium trays, in particular with the dual compartment tray, the surface area open for microwave access is large compared to the water volume and therefore the decrease in heating efficiency is less pronounced.

While heating efficiency of different ovens is very similar for the same plastic tray, there is a significant influence of oven design on heating efficiency with aluminium trays. It turns out the Panasonic oven shows the lowest heating efficiency for all used aluminium tray shapes. Sharp 1 and Micromaxx ovens in comparison show higher efficiencies. Both, Sharp 1 and Micromaxx ovens happen to be equipped with a horizontally oriented antenna in their microwave window to the cooking chamber while Panasonic and Sharp 2 ovens have vertically oriented microwave antennas. It seems that the difference in electric field orientation resulting from the different antenna orientation is responsible for the deviations in heating efficiency with aluminium foil trays.

Table 6.3: Heating power measured with smooth wall aluminium tray filled with tap water in comparison to similar plastic tray

Heating power P_{th} **Oven**	Heating time in s	$P_{th\ alu}$ in W	$P_{th\ plastic}$ in W	$P_{th\ alu}$ / $P_{th\ plastic}$
Panasonic	30	387	766	51%
Sharp 1	33	448	719	62%
Sharp 2	37	360	648	56%
Micromaxx	43	409	549	74%
Average of four ovens				**61%**
Heating conditions	trays filled with 300 g tap water of 10 °C, oven operated at full nominal power for adjusted heating time			

Table 6.4: Heating power measured with wrinkled wall aluminium tray filled with tap water in comparison to similar plastic tray

Heating power P_{th} **Oven**	Heating time in s	$P_{th\ alu}$ in W	$P_{th\ plastic}$ in W	$P_{th\ alu}$ / $P_{th\ plastic}$
Panasonic	45	556	852	65%
Sharp 1	50	609	753	81%
Sharp 2	56	473	668	71%
Micromaxx	64	426	565	75%
Average of four ovens				**73%**
Heating conditions	trays filled with 450 g tap water of 10 °C, oven operated at full nominal power for adjusted heating time			

Table 6.5: Heating power measured with dual compartment aluminium tray filled with tap water in comparison to similar plastic tray

Heating power P_{th} **Oven**	Heating time in s	$P_{th\ alu}$ in W	$P_{th\ plastic}$ in W	$P_{th\ alu}$ / $P_{th\ plastic}$
Panasonic	60	569	902	63%
Sharp 1	67	582	797	73%
Sharp 2	75	539	715	75%
Micromaxx	86	521	586	89%
Average of four ovens				**75%**
Heating conditions	trays filled with 600 g tap water of 10 °C, oven operated at full nominal power for adjusted heating time			

Heating power relations between aluminium and plastic trays for each tray geometry as obtained from the measurements were averaged over the four ovens and inverted to obtain a heating time extension factor. The heating time extension factor gives an indication how much longer food has to be heated in an aluminium tray compared to a plastic tray of same geometry in order to obtain similar heating result. Table 6.6 shows the time extension factors for the three used tray formats.

Table 6.6: Extension factor for heating time in aluminium tray compared to a comparable plastic tray for similar heating results.

Tray format	t_{alu} / $t_{plastic}$
Smooth wall aluminium foil tray, small	1.7
Wrinkled wall aluminium foil tray, large	1.38
Dual compartment aluminium foil tray	1.33

The measured heating efficiencies and the calculated time extension factors were used to adjust heating times for aluminium trays in comparison to plastic trays in the later experiments with egg batter, frozen lasagne and meat ball mass.

The electric power input to the ovens is independent of the tray material used in the heating experiment. The heating time extension factors therefore translate directly into relations of the energy that is needed to achieve the same heating effect.

Heating Safety

In all 30 heating trials with aluminium foil trays filled with water, no spark or other exceptional performance was observed. As long as single trays are placed on the glass or ceramic turn table and do not touch the wall of the oven chamber, microwave heating of water in aluminium foil trays is perfectly viable.

6.3 Heating Egg Batter in Trays

Heating experiments with egg batter are suggested in norm EN 60705, Appendix A (NORM 1999). The liquid batter starts to solidify, if heated above a temperature of 70°C to 80°C. By observing patterns of solidified batter information on temperature distribution patterns created by non-uniform microwave heating can be obtained.

Smooth wall single compartment and double compartment aluminium foil trays as well as similar plastic trays were filled with batter to a height of about 25 mm. The starting temperature of the batter was about 10°C. In all heating trials, ovens were operated at full power. Heating times were adjusted in initial trials to achieve approximately a 50% solidification of the batter. Derived from the initial trials, for each oven, tray format, and for both aluminium foil and plastic trays, heating times were calculated. In the time calculation the different nominal powers of the ovens and the heating time extension factors between plastic and aluminium trays (table 6.6) were taken into account. An overview on experiment conditions is given in table 6.7.

Table 6.7: Conditions for heating experiments with egg batter. Ranges for full power heating times result from different nominal oven powers.

Tray format	Oven	Batter filling in g	Heating times alu trays in s	Heating times plastic trays in s
Small single compartment tray	Panas. (1000 W)	250	118	69
	Sharp 1 (900 W)		124	73
	Sharp 2 (800 W)		138	81
	Microm. (700 W)		161	94
Dual compartment tray	Panas. (1000 W)	640	190	141
	Sharp 1 (900 W)		215	160
	Sharp 2 (800 W)		241	179
	Microm. (700 W)		293	218

Directly after end of heating, minimum and maximum temperatures were measured, maximum temperature difference calculated, solid/liquid patterns were judged, solid and liquid fractions were separated and weighed and percentage of solid fraction was calculated. In some experiments, the amount of water evaporated during heating was determined by weighing.

Heating Patterns

The results in table 6.8 for small trays of type smooth wall aluminium foil and plastic and in table 6.9 for dual compartment trays made from foil and plastic show, that the relation of solidified fraction to total batter is near 50% in most cases. Though results for aluminium foil trays were achieved with longer heating times (see table 6.7). Heating patterns in aluminium and in plastic trays are however completely different.

Table 6.8: Microwave heating patterns of egg batter in smooth wall aluminium foil and plastic trays. Measurement of solidified batter fraction and of temperature difference between maximum and minimum temperature.

	Aluminium (average over 4 experiments)		Plastic (average over 3 experiments)		Alu/plastic
Oven	ΔT in °C	Solid fraction in %	ΔT in °C	Solid fraction in %	Relation of solid fraction in %
Panasonic	53	47	47	58	81
Sharp 1	51	64	50	49	131
Sharp2	54	52	52	47	111
Micromaxx	48	72	50	58	124

Table 6.9: Microwave heating patterns of egg batter in dual compartment aluminium foil and plastic trays. Measurement of solidified batter fraction and of temperature difference between maximum and minimum temperature.

	Aluminium (average over 4 experiments)		Plastic (average over 3 experiments)		Alu/plastic
Oven	ΔT in °C	Solid fraction in %	ΔT in °C	Solid fraction in %	Relation of solid fraction in %
Panasonic	41	46	51	53	87
Sharp 1	34	54	53	47	115
Sharp2	39	54	60	46	117
Micromaxx	43	56	62	45	124

In the case of aluminium trays, microwave power input to food load takes place primarily from surface of the tray. So the batter starts to solidify at the surface. Edges and corners are shielded by the rim of the metal container and heat very slow. The same is true for the batter near the bottom. With the used heating times, batter was still liquid at corners and at the bottom (see figures 6.1 left). In all cases, a microwave resonance pattern forms inside the foil tray with an energy minimum directly at the centre, where in some cases the batter stays liquid even at the surface. For a better visualisation of the solidification pattern, the liquid batter fraction has been scraped away in figure 6.1 bottom/left. Minimum temperatures are measured at the bottom in tray corners, maximum temperatures are always near surface on both sides between centre and short edge.

The shape of heating patterns in plastic trays seems to be complementary. Solidification of batters starts at edges and corners of fillings (see figure 6.1 right). In some cases, solidification is observed at the centre bottom. Most of the centre area including the surface stays liquid with the chosen heating times. The liquid batter fraction has been scraped away in figure 6.1 bottom/right for better visualisation of the pattern of solidified batter. Maximum temperatures are measured at corners, minimum temperatures are measured left and right of centre.

The difference ΔT between measured maximum and minimum temperature is in both cases, aluminium and plastic, near 50°C. Neither from solidification patterns nor from temperature difference measurement, a clear advantage for a tray material can be seen with respect to heating uniformity. The evaporation of water is a little bit higher in aluminium foil trays (5 g vs. 3 g), the solidified surface of the batter in aluminium trays looks already a little bit dried out or crusted at the chosen heating times.

Heating patterns in the dual compartment trays follow a similar scheme (see figure 6.2). In the case of aluminium foil trays, solidification starts at the surface near centre. Corners, edges, and bottom areas are still liquid at the end of the chosen heating times. Maximum temperatures are measured at surface near centre, minimum temperatures at bottom near corners of compartments.

In the case of plastic trays, solidification starts at edges and corners of compartments. The centre region is still liquid at end of heating time. Maximum temperatures are measured near corners, minimum temperatures are measured at centre.

Temperature difference between maximum and minimum temperature is slightly smaller in the case of aluminium foil trays (see table 6.9).

Smooth wall aluminium foil tray	Small plastic tray
 Egg batter after heating	 Egg batter after heating
 Egg batter; liquid fraction at tray bottom	 Egg batter; solidified fraction
 Egg batter; solidified fraction	

Figure 6.1: Heating patterns with egg batter in smooth wall aluminium foil trays (left) and in similar plastic trays (right).

Aluminium Foil dual compartment tray	Plastic dual compartment tray
 Egg batter after heating	 Eg batter after heating
 Egg batter; liquid raction at bottom of tray	 Egg batter; solidified fraction

Figure 6.2: Heating patterns with egg batter in dual compartment trays. Aluminium: left, plastic: right. Above: batter at end of heating; below: solid fraction turned up or liquid fraction scraped away.

Heating Efficiency

In both tray formats, the fraction of solidified batter is slightly higher than 50% in the case of aluminium foil trays, while in the case of plastic trays it is less than or about 50%. The chosen heating time extensions for the aluminium foil trays, that are based on heating experiments with water, seem to overcompensate a little bit the shielding effects of aluminium foil trays. If the solidified batter fractions in aluminium foil trays and plastic trays are used to correct the heating time extension factors for egg batter, the effective factors of table 6.10 are obtained

Table 6.10: Effective extension factors for heating time in aluminium foil trays filled with egg batter vs. similar plastic trays.

Tray format	Heating time extension factors for tap water	Heating time extension factors for egg batter
Smooth wall aluminium foil tray (small)	1.7	1.5
Dual compartment aluminium foil tray	1.3	1.2

Also visible, in particular with small trays (tables 6.8) is a significant influence of oven construction on heating efficiency. As in heating experiments with tap water, ovens Sharp 1 and Micromaxx have a better heating performance with aluminium foil trays while the Panasonic oven performs least.

In the hitherto reported heating experiments with egg batter in aluminium foil as well as in plastic trays , the batter did not completely solidify. This results from the chosen heating times that aimed at a 50% solidification in order to visualise heating patterns. By choosing longer heating times, the batter could be solidified completely in both, aluminium foil and plastic trays as shown in table 6.11.

Table 6.11: Microwave heating experiments in Panasonic oven with egg batter in trays. Heating until batter is completely solidified.

	Batter filling in g	Heating time in s	Solid fraction in %
Smooth wall aluminium foil tray (small)	250	240	100
Plastic tray (small)	250	140	100

It should be emphasized again, that all heating experiments were performed with maximum power setting of ovens. No attempts have been made, to optimise heating patterns by adjusting heating power to different levels. Heating with lower power settings would need longer heating times but would also result in different heating patterns, since heat conduction and convection would contribute to a larger extent to the overall temperature distribution.

Safety

In about 60 heating trials in four different microwave ovens with batter in aluminium foil trays at full power setting, no indication of sparks or other malfunction was found. The use of aluminium trays with egg batter in microwave ovens is therefore safe and adequate, provided the trays are placed on the glass or ceramic turn table and do not touch the wall of the oven chamber.

6.4 Heating Frozen Lasagne in Trays

Frozen foods usually have a low absorption for microwave fields. The electric field strength inside the cooking chamber of an oven will be therefore higher with frozen food inside than with a high absorption material. Heating of frozen food will create more stress to the components of the oven like door seals and magnetron and it will also make the formation of electric sparks more easy.

As a high stress situation, microwave heating of frozen lasagne in aluminium foil trays was chosen. In addition, one of the used tray formats was made with wrinkled foil, a material that is expected to be more prone to sparking.

The rapid heating of frozen food at full power to serving temperature in microwave ovens is of high relevance, since more and more frozen ready meals appear on the market which are recommended for this form of heating. Unlike traditional microwave thawing, which is performed on a low power setting, the rapid heating from frozen state to serving temperature is performed at maximum power setting.

The food material used in the heating experiments was a frozen lasagne Bolognese portion from a super market. In initial heating experiments, it turned out that the trays had to be filled with lasagne from wall to wall in order to get reproducible results. Remaining gaps between frozen lasagne block and aluminium tray wall created very irregular heating patterns with much energy going into the edge of the frozen block parallel to the gap. To avoid the gaps, the frozen lasagne block was thawed, an appropriate amount cut off and pressed into the trays used for heating experiments (figure 6.3 and 6.4 top). The uniformly filled trays were then frozen again.

Prior to microwave heating, starting temperatures of the frozen lasagne portions were measured. Start temperatures were between –16°C and –12°C. The trays with frozen lasagne were placed on centre of the oven turn table. In initial trials in one microwave oven heating times were adjusted in order to achieve a serving temperature of 40 to °C at the coldest spot of the heated portion. From these trials, for each oven, each tray format, and for both aluminium foil and plastic trays, heating times were calculated. In the heating time calculation, the different nominal powers of the ovens and the heating time extension factors between plastic and aluminium trays (table 6.6) were taken into account. An overview on experiment conditions is given in table 6.12. However, not in all cases was the desired serving temperature achieved with the selected heating times. In some cases, a change of heating times was performed in the course of the experiment in order to avoid excessive browning.

Table 6.12: Conditions for heating experiments with egg batter. Ranges for full power heating times result from different nominal oven powers.

Tray format	Oven	Lasagne filling	Heating times foil trays in s	Heating times plastic trays in s
Small single compartment tray	Panas. (1000 W)	290 g	422	247
	Sharp 1 (900 W)		470	275
	Sharp 2 (800 W)		529	309
	Microm. (700 W)		605	354
Large single compartment tray (wrinkled wall foil)	Panas. (1000 W)	420 g	432	360
	Sharp 1 (900 W)		480	400
	Sharp 2 (800 W)		540	450
	Microm. (700 W)		617	514

The evaluation of heated samples included search for location of minimum and maximum temperatures including their measurement, additional temperature measurements on a rectangular grid of measurement points, visual judgement of quality, measurement of evaporation loss, and calculation of average end temperature from temperature measurements at about 20 points in the tray.

Heating patterns

Heating in aluminium trays is most intensive at the surface between centre and small edges. There also the maximum temperatures are measured. The minimum temperatures are measured near corners at bottom and in some cases at the bottom at centre of the tray. At the surface, in most cases a dry and crispy crust forms. In a few cases, the crust gets very dark and almost burnt (figure 6.3 and 6.4 bottom). The evaporation of water during heating amounts to 13 to 37 g.

In the case of the plastic trays, the thawing and heating starts at the edges of the tray filling. In all heating trials with plastic trays, the lasagne cooked at the edges and corners towards end off heating. Maximum temperatures were measured at the tray corners, minimum temperatures are found at the surface of the filling between centre and short edges of tray. A crust does not form. The evaporation of water during heating amounts to 18 to 22 g.

If the temperature measurements of experiments with small trays are analysed (table 6.13), it appears that the minimum temperatures in aluminium foil trays are equal or better than in plastic trays. The only exception is the Panasonic oven, which showed already poor performance with aluminium trays in previous experiments. Since the average temperature is lower in aluminium foil trays compared to plastic trays, the temperature differences are smaller. The heating of frozen lasagne is therefore more uniform in the small aluminium foil trays than in plastic trays.

Table 6.13: Heating experiments with frozen lasagne in smooth wall aluminium foil trays and small plastic trays. Temperature measurements after heating.

	Aluminium (average over 4 experiments)		Plastic (average over 3 experiments)	
Oven	Minimum end temperature in °C	Average end temperature in °C	Minimum end temperature in °C	Average end temperature in °C
Panasonic	11	50	40	79
Sharp 1	29	65	29	77
Sharp 2	41	61	28	73
Micromaxx	57	75	30	80

Smooth wall aluminium foil tray	Small plastic tray
 Lasagne frozen	 Lasagne frozen
 Lasagne after heating	 Lasagne after heating
 Lasagne with dark crust	

Figure 6.3: Frozen lasagne in smooth wall aluminium foil trays and in small plastic trays before and after microwave heating.

Similar heating patterns can be observed in the larger trays. Figure 6.4 shows pictures of the trays filled with lasagne before and after heating. Table 6.14 presents results of temperature measurements. In the case of the aluminium trays, both minimum temperature and average temperature are too low. Obviously, the heating time was not sufficient to achieve a high enough temperature level. Still, in a number of heating runs a strong crust formed at the surface of the aluminium tray filling (figure 6.4 bottom). No crust was observed with plastic trays. Again, temperature differences seem to be smaller in aluminium foil trays than in plastic trays, indicating a more uniform heating. The evaporation was between 23 g and 24 g in the aluminium trays and 22 g to 36 g in plastic trays.

Table 6.14: Heating experiments with frozen lasagne in wrinkled wall aluminium foil trays and large plastic trays. Temperature measurements after heating.

	Aluminium (average over 4 experiments)		Plastic (average over 3 experiments)	
Oven	Minimum end temperature in °C	Average end temperature in °C	Minimum end temperature in °C	Average end temperature in °C
Panasonic	23	58	44	84
Sharp 1	21	64	24	76
Sharp2	20	59	29	77
Micromaxx	25	65	31	81

Heating efficiency

As in previous experiments with water and batter, significant difference between ovens is observed with respect to heating in aluminium trays. Sharp 1 an Micromaxx produce higher average temperatures and Micromaxx also higher minimum temperatures. In some cases, lasagne in the Micromaxx oven was heated with a shorter heating time for less crust forming. It is therefore hard to give a common rule for all four ovens, that takes into account only the difference in nominal power.

Still, if results of all four ovens are averaged, the estimated time extension factors in table 6.15 result, which indicate how much longer lasagne in aluminium trays has to be heated compared to plastic trays in order to get similar heating results. Unlike the extension factors for egg batter, the factors are equal or even longer than extension factors for tap water in similar trays.

Wrinkled wall aluminium foil tray	Large plastic tray
 Lasagne frozen	 Lasagne frozen
 Lasagne after heating	 Lasagne after heating
 Lasagne with dark crust	

Figure 6.4: Frozen lasagne in wrinkled wall aluminium foil trays and in large plastic trays before and after microwave heating.

Table 6.15: Effective extension factors for heating time in aluminium foil trays filled with frozen lasagne vs. heating time of similar plastic trays.

	Water filling	Lasagne filling
Smooth wall aluminium foil tray	1.7	1.7
Wrinkled wall aluminium foil tray	1.38	1.5

Safety

Despite the initially expected critical conditions with low absorption frozen food and wrinkled aluminium foil trays, no sparks or other exceptional conditions have been observed in 70 single heating trials with frozen lasagne aluminium foil trays. The use of aluminium foil trays with frozen food in microwave ovens can therefore be considered as safe and adequate.

6.5 Heating Meat Ball Mass in Trays

Heating experiments with meat ball mass show the effect of heating fat material since the minced meat contains about 20% fat. Also of importance is the complete cooking of the meat filling. To achieve this, the coldest part of the meat filling ("cold spot") has to surpass a temperature of about 75°C.

The meat ball mass was prepared according to recipe (in section 5.4) and cooled down to a starting temperature of 5°C. Than suitable amounts of the mass were filled into smooth wall aluminium foil trays, into dual compartment aluminium foil trays and into equivalent plastic trays. The filling surface was flattened by a spoon.

Trays were put open into the microwave ovens on centre of turn table and the oven turned on with maximum power setting. With initial heating trials in two ovens, the appropriate heating times were tested in order to get a complete cooking of the meat mass. The heating parameters finally used are shown in table 6.16. Heating times were varied according to nominal power of ovens. Also the necessary heating time extension for aluminium foil trays were accounted for. In the case of the small smooth wall aluminium foil tray, the heating time had to be extended beyond 200% of heating times in plastic trays to achieve complete cooking. Also for some ovens, heating times were retuned during experiments. However, not in all cases complete cooking of the meat ball mass was achieved.

Table 6.16: Conditions for heating experiments with meat ball mass. Ranges for full power heating times result from different nominal oven powers.

Tray format	Oven	Meat ball mass filling	Heating times foil trays in s	Heating times plastic trays in s
Small single compartment tray	Panas. (1000 W)	280 g	380	190
	Sharp 1 (900 W)		375	215
	Sharp 2 (800 W)		420	210
	Microm. (700 W)		540	240
Dual compartment tray	Panas. (1000 W)	600 g	490	405
	Sharp 1 (900 W)		540	450
	Sharp 2 (800 W)		610	505
	Microm. (700 W)		695	580

The evaluation of heated trays consisted of search for minimum and maximum temperature location, measurement of minimum and maximum temperatures, additional temperature measurement on a grid of 12 measurement points, calculation of average temperature, measurement of evaporation, test of visual appearance, and test of complete cooking.

Heating Patterns

Results of heating experiments with meat ball mass filled into smooth wall aluminium foil containers and small plastic containers are shown in table 6.17. Pictures of the fresh and cooked meat filling are shown in figure 6.5.

In aluminium foil trays, first the surface of the filling was heated most. After some heating time, the meat mass contracted and formed gaps to the tray walls. Then most cooking started at edge of the solidified mass and there maximum temperatures are measured after end of heating. In nearly all cases, the maximum temperatures were at 100°C. Minimum temperatures were measured at bottom of tray. In plastic trays, maximum temperatures were measured at edges of filling. During the late phase of heating, a liquid fat water mixture surrounded the solid meat mass (figure 6.5 bottom) and cooked heavily. The minimum temperature was measured at surface of meat filling between centre and short edge of tray.

Smooth wall aluminium foil tray	Small Plastic tray
 Meat ball mass fresh	 Meat ball mass fresh
 Meat ball mass after heating	 Meat ball mass after heating
 Sliced meat ball mass after heating	

Figure 6.5: Heating patterns with meat ball mass in smooth wall aluminium foil tray and small plastic tray.

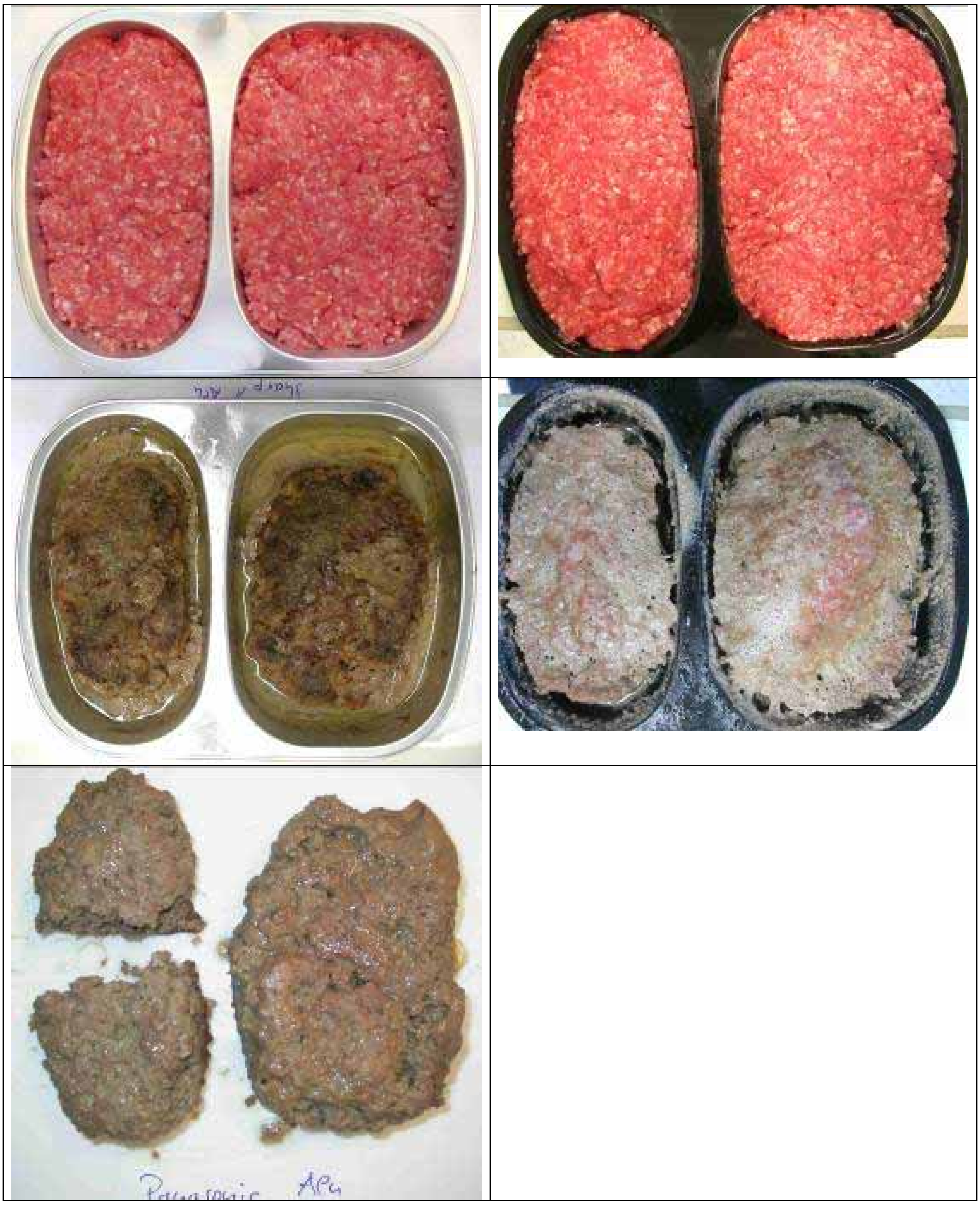


Figure 6.6: Heating patterns with meat ball mass in dual compartment aluminium foil trays and equivalent plastic trays.

Table 6.17: Heating experiments with meat ball mass in smooth wall aluminium foil trays and small plastic trays. Temperature measurements after heating.

	Aluminium (average over 4 experiments)		Plastic (average over 3 experiments)	
Oven	Minimum end temperature in °C	Average end temperature in °C	Minimum end temperature in °C	Average end temperature in °C
Panasonic	77	89	74	90
Sharp 1	79	91	63	85
Sharp2	78	89	66	87
Micromaxx	92	98	64	85

The minimum temperatures and the average temperatures were significantly higher in the aluminium foil trays. In several experiments with plastic trays, minimum temperatures were too low with the chosen heating times to achieve complete cooking. Over all, heating uniformity seems to be better in aluminium foil trays. A further advantage of the foil trays is surface browning of the meat mass. In many trials, a nice browned crust was achieved without using the additional grill function provided by some microwave ovens. In plastic trays, no browning was observed.

Heating patterns in the dual compartment trays were not different from patterns in the single compartment trays. Temperature measurements are shown in table 6.18, pictures of filled trays before and after heating are shown in figure 6.6. I

n aluminium foil trays, minimum temperatures were measured at bottom near centre of the larger compartments, maximum temperatures were measured at edge of the solidified mass as a consequence of gap forming. In most cases, a nice browning was achieved at surface of the filling.
In plastic trays, minimum temperatures were at the surface of filling near centre, maximum temperatures were measured at edges of the solidified meat mass. No browning was observed.

Minimum temperatures are higher in aluminium foil trays than in plastic trays, the average temperatures are very similar. Again, heating seems to be more uniform in aluminium foil trays. Also the visual impression is much better.

Table 6.18: Heating experiments with meat ball mass in dual compartment aluminium foil and plastic trays. Temperature measurements after heating.

	Aluminium (average over 4 experiments)		Plastic (average over 3 experiments)	
Oven	Minimum end temperature in °C	Average end temperature in °C	Minimum end temperature in °C	Average end temperature in °C
Panasonic	69	83	69	90
Sharp 1	81	88	70	85
Sharp2	80	90	70	88
Micromaxx	82	89	70	88

Heating Efficiency

From averaging about 12 single temperature measurements, an average temperature of the meat mass after heating was calculated. Comparing average temperatures from aluminium foil trays and plastic trays and taking into account the longer heating times used for aluminium trays, effective heating time extension factors for meat ball mass in aluminium foil trays were estimated. These are tabulated in table 6.19. The estimated extension factors are very similar to those obtained from heating experiments with tap water.

For the small aluminium foil trays, significant longer heating times and energy amounts are needed to achieve the same heating result. For the larger dual compartment trays, the difference is only about 20%.

Table 6.19: Effective extension factors for heating time of aluminium foil trays filled with meat ball mass vs. heating time of similar plastic trays.

	Water filling	Meat ball mass filling
Smooth wall aluminium foil tray	1.7	1.7
Dual compartment aluminium foil tray	1.38	1.2

Safety

No sparks or other exceptional conditions have been observed in 40 single heating trials with meat ball mass in aluminium foil trays. The use of aluminium foil trays with this kind of fat food in microwave ovens can therefore be considered as safe and adequate.

6.6 Plastic Trays and Beakers with Aluminium Foil Lid

Further application of aluminium foil or aluminium foil laminate in food packaging is as lid material on plastic containers like trays and beakers. To also test these packaging applications in the microwave oven, a meal for children in a dual compartment plastic tray with foil laminate lid (figure 6.7 a to d) and a noodle soup in plastic beaker with aluminium foil lid (figure 6.7 e to g) were chosen.

Microwave Heating Tests with Child Meal

The child meal consists of 165 pasta in sauce and 85 g meat balls in sauce in a dual compartment plastic tray with laminated aluminium foil lid. Reheating instructions suggest hot water bath and microwave oven. Instructions for microwave heating request complete removal of laminated aluminium foil lid and a heating of 1 min at a medium power setting of the microwave oven.

In contradiction to the heating instructions, heating in the microwave oven was performed without removing lid. Only small holes were pierced into the lid with a needle in order to allow overpressure to escape during heating without blasting the package. In addition, heating was performed at full microwave power and shorter heating times. For comparison reasons, heating tests were also performed with removed lid.

At start of heating tests, the filling was at room temperature of about 22°C which is the standard situation, since the sterile product can be stored without cooling. Microwave heating times have been chosen in order to achieve a serving temperature of 50°C at end of heating. Chosen heating times varied between 30 s and 57 s depending on nominal power of oven.

After end of heating, the lid was removed and the compartments were stirred with a spoon to achieve uniform mixing temperatures. The mixing temperatures were measured. Table 6.20 shows the end temperatures that result from heating with and without laminated foil lid. Temperatures seem to differ between compartment a little bit less with foil lid on, but the effect is not significant. Calculation of effective heating power show, that about 10% longer heating times are needed to achieve the desired heating effect with the foil lid on, i.e. the heating time extension factor with lid on is about 1.1.

Table 6.20: Temperature measurements in a dual compartment child-meal tray. Tray covered with aluminium laminate, and tray covered with plastic wrap film for comparison.

	Aluminium laminate lid (average over 2 experiments)		Plastic film cover (average over 2 experiments)	
Oven	Average end temperature compatment 1 in °C	Average end temperature compatment 2 in °C	Average end temperature compatment 1 in °C	Average end temperature compatment 2 in °C
Panasonic	53	51	51	53
Sharp 1	45	52	49	54
Sharp2	51	51	51	53
Micromaxx	52	60	48	59

Microwave Heating Tests with Soup Beaker

The prepared noodle soup in plastic beaker with foil lid consists of 62 g dry soup base. The preparation instruction requests to remove lid, pour boiling water into the beaker with the soup base, to let soak for 5 min, and to stir.

In contradiction to the instruction, the lid was opened a little bit and 195 ml cold water were poured into the beaker which resulted in a complete filling height of 80 mm. The mixture was stirred. After closing the lid again, the beaker was put into the microwave oven on the centre of the turning table and heated with full power. Heating times were chosen in order to bring the mixture to boiling. Comparison experiments were carried out with foil lid off and beakers covered with a plastic wrap film.

The used heating times ranged from 120 s to 170 s depending on nominal oven power. For beakers with foil lid removed, heating time was about 10% shorter. The heating time extension factor was therefore 1.1 with foil lid on.

a) child meal with aluminium laminate lid
b) child meal (bottom view)
c) child meal with opened lid after MW heating
d) child meal after MW-heating without aluminium laminate
e) soup beaker, side view
f) soup beaker with foil lid after addition of water to soup base
g) soup beaker without foil lid after MW-heating

Figure 6.7: Plastic tray and plastic beaker with lids made from aluminium laminate or aluminium foil

After heating, the hot soup was stirred to achieve a uniform mixing temperature. Table 6.21 presents the measured heating temperatures for heating tests with foil lid on and with foil lid off. In all cases, the filling came to boiling. No significant difference between foil lid on and foil lid off were observed in the tests with respect to heating uniformity or quality.

Table 6.21: Temperature measurements in plastic beakers with soup mixture after microwave heating. Beakers in microwave with aluminium foil lid on and with lid off for comparison.

Oven	Aluminium laminate lid (average over 2 experiments) average temperature in °C	Plastic film cover (average over 2 experiments) average temperature in °C
Panasonic	83	87
Sharp 1	93	83
Sharp2	82	87
Micromaxx	90	88

Heating safety

No sparks or other exceptional conditions have been observed in the 20 heating trials with foil lidded trays and beakers. The sharp edges of the lids, where high field strength can occur, did not provoke any unusual performance. Microwave heating of food in plastic containers with aluminium foil or foil laminate lids can therefore be considered as safe and adequate.

6.7 Dishes Wrapped with Aluminium Household Foil

A widespread use of aluminium foil in households is the wrapping of solid food items or the wrapping of open containers, bowls, and dishes with foil. The use of household foil is even suggested by microwave oven manufacturers to wrap exposed portions of food in the oven (like the legs and wings of a chicken during microwave heating) in order to avoid excessive heating of these exposed food parts.

To test the performance of household foil in microwave ovens, an arrangement was chosen were a porcelain dish with a loaf of meat ball mass of 200 g was wrapped with foil (figure 6.8 a to d). To allow microwave heating, most of the bottom part of the dish was kept free from foil (figure 6.8 c). The wrapped dish was put into the microwave oven on centre of turn table and heated at full power setting. Starting temperature of the meat loaf was about 15°C.

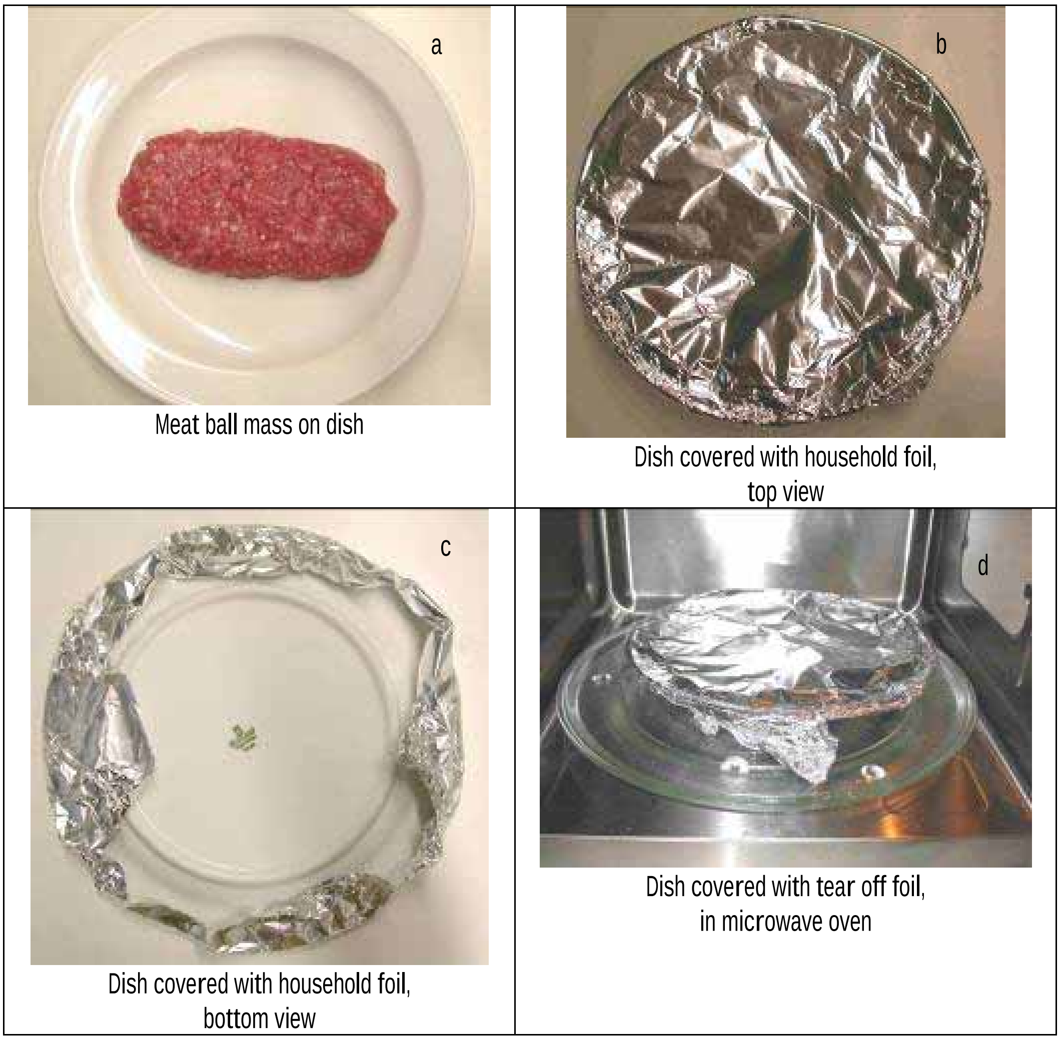


Figure 6.8: Porcelain dish with meat ball mass, covered with aluminium household foil

Comparison trials were made with meat loaf on dish without foil wrapping. Heating times were chosen in order to get a complete cooking of the meat loaf. The used heating times were 120 s to 170 s without foil and 170 s to 240 s with foil, depending on nominal oven power.

Initial trials have also been made with 200 ml tap water in the dish with and without foil wrapping. From these initial trials, a heating time extension factor of about 1.2 was expected for heating with foil wrapping. Compared to the extension factor of 1.7 for tap water in the small aluminium foil tray, 1.2 is surprisingly low. It seems, that the microwave couples very effectively through the open region at the bottom of the dish. The experiments with meat ball mass however required a longer heating time extension of 1.4. After heating, minimum and maximum temperatures in the meat loaf were measured and the loaf was inspected for complete cooking.

Figure 6.9 shows pictures of the meat loaf after microwave heating, table 6.22 shows temperature measurements after microwave heating. The maximum temperature is always 100°C since parts of the meat loaf cook during heating. The difference is in the minimum temperature. If minimum temperature is below 65°C, the cooking of the meat loaf is not complete. The cold spot is always found centred on top of loaf. This applies to loaf with and without foil wrapping. Maximum temperatures or cooking mostly occurs at ends of the loaf.

Meat ball mass after heating | Meat ball mass after heating

Figure 6.9: Porcelain dish with meat ball mass, after microwave heating with aluminium household foil cover.

With aluminium foil wrap, the cold spot is particularly pronounced but small and is located where the foil touches the top of the loaf. It seems that the electric field is very weak near the foil. In addition, the foil insulates the spot of the meat loaf where it touches from access of steam that develops under the foil. Most of the loaf is cooked, however. The situation could be improved by slower heating that would give heat conduction more time to heat the cold spot or by providing an air gap between foil and filling. This can easily be achieved by using a bowl with higher rim.

The ovens differed significantly with respect to performance with oven Sharp 2 performing best.

Table 6.22: Temperature measurements in meat loaf on dish after microwave heating. Dish with and without aluminium household foil wrapping.

	Aluminium foil wrap (average over 2 experiments)		no wrap (average over 2 experiments)	
Oven	Minimum end temperature in °C	Maximum end temperature in °C	Minimum end temperature in °C	Maximum end temperature in °C
Panasonic	65	100	80	100
Sharp 1	44	100	67	100
Sharp2	74	100	67	100
Micromaxx	48	100	52	100

Safety

During the 12 microwave trials with dishes covered with household foil in one case a bright spark was observed that occurred at a fold-back of the foil and caused a 1 cm burnt away or rather evaporated hole in the foil (figure 6.10). Such an event does not pose any danger nor does it affect safety and operability of the oven. Not even the quality of the food was influenced. Because of the bright light however, a non-prepared user of the oven may be alarmed and concerned.

The heating of food on containers covered by household foil is perfectly possible as long as a large enough area of the container wall or bottom is uncovered for microwave access. Only slight extensions of heating time have to be accepted compared to uncovered heating, if touching of the foil to the food surface can be avoided.

However the nature of the wrap with folds will lead to occasional sparks which may alarm and trouble the user of the oven, though they pose no safety risk. The use of aluminium foil in this specific application should therefore not be promoted.

Fold of foil	Burnt hole after heating

Figure 6.10: Porcelain dish, covered with aluminium household foil. Burnt spot at fold of foil.

6.8 Abuse experiments

Several trials were carried out with large wrinkled wall and with small smooth wall aluminium foil trays.

The trays were put empty into the microwave ovens into different positions and the ovens were turned on to full power. Since no absorbing load is in the oven with empty trays, electric field strength in the oven is maximum and the chance to trigger sparks is high.

Even under these unfavourable operating conditions, which are strictly discouraged by all operating instructions, it was difficult to create sparks. In order to achieve sparking, it was necessary to bring the tray into direct contact with the walls of the oven chambers. Figure 6.11 shows the mark of a spark that burnt for a fraction of a second between tray rim and oven wall during direct contact. It was also possible to create sparks by putting two trays into the oven side by side with direct contact or a distance below 1 mm.

Figure 6.11: Aluminium foil tray after touch with cooking chamber wall during microwave exposition.

Table 6.23: Occurrence of sparks during abuse experiments with empty foil trays in microwave oven.

Position of tray	Panasonic	Sharp 1	Sharp 2	Micromaxx
at edge of turn table, no contact to oven wall	never	never	never	never
1-2 mm distance to oven wall	never	never	never	never
direct contact to wall	occationally	occationally	occationally	occationally
two trays side by side in direct contact	occationally	occationally	occationally	occationally
two trays side by side, 1 mm distance	occationally	occationally	occationally	occationally
two trays side by side, >2 mm distance	never	never	never	never

Table 6.23 gives an overview on the results from abuse experiments with the large wrinkled wall foil trays. The experience from the experiments is, that sparks occur only in extreme configurations and that direct contact between tray and oven wall or between two trays is needed in order to trigger a spark. The sparks also pose no real risk. They extinguish as soon as the turntable has moved the tray away from wall or as the spark has burnt away some foil and created a small gap again. The usual consequences are black spots on the oven wall and possibly small amounts of soot from burnt lacquer. In the absence of highly inflammable materials, it is extremely unlikely, that self-preserving flames occur and lead to a fire inside the oven chamber.

7 Guidelines

Microwave heating of food in packages containing aluminium foil like foil trays or plastic containers with foil lids is uncritical. Only very few additional rules have to be followed compared to packaging or containers without foil. More or less the guidelines issued many years ago by the American Aluminium Foil Container Manufacturers Association (AFCMA) still apply:

1) Remove metal lid or wrap from container

2) Make sure the container is not much bigger than the food it holds

3) Loosely cover the container with plastic wrap

4) Place foil container directly on plate or glass dish

5) Position the foil container in the centre of the microwave oven – at least 2.5 cm away from the side walls - and ensure that the container is not touching other metal or foil

6) Cook or heat food to desired temperature

Modern microwave ovens have turn tables made from glass or a ceramic material with a rim. These support positioning of food trays in order to avoid any touch to the wall (rule 4 and 5). The consumer has to be made aware, that a foil tray must not be put directly onto the metal floor of the cooking chamber, on a metal browning plate or a metal grill delivered with many microwave ovens. Also it is important to remind, that aluminium foil lids on foil trays or other foil wraps that prevent entrance of microwave energy to the food have to be removed prior to heating.

If these rules are followed, microwave heating of foods in packages with foil is perfectly safe and adequate.

Food manufacturers however have to consider some additional and more complicated questions. To answer these questions, microwave heating experts may be consulted.

With plastic containers with foil lids, not much difficulties will arise. Heating is safe and heating times to achieve a desired heating effect are only slightly longer with foil lid than without or with plastic film cover. Also heating patterns will not be significantly affected, if the gap between food surface and lid is large.

If the manufacturer intends to market food in foil trays intended for microwave heating, some technical questions have to be resolved. In particular the food composition and arrangement and the tray geometry have to be optimised in order to support efficient and uniform heating. The general rules concerning tray geometry are:

1) Filling height in the tray should not exceed 25 mm.

2) The food should fill the tray from wall to wall without air gaps at the walls, since these would promote intensive energy coupling into the food near the gap.

3) The corners and edges of the tray should be rounded to avoid spots with very low field intensity and poor heating.

4) Larger trays have better heating efficiency than small trays.

5) The manufacturer also has to keep in mind, that heating patterns in foil trays are completely different from heating patterns in plastic trays and may therefore lead to different sensory results. This is in particular of importance for solid foods that cannot be stirred to create a uniform mixing temperature.

An additional concern is the proper heating instruction for the consumer. Usually the heating times necessary to achieve a desired heating effect are longer for food in aluminium foil trays than for food in plastic trays. The actually needed increase in heating time depend on the food, the tray geometry, and the oven design. Extensive testing is needed during product development to achieve good heating results in most microwave ovens.

If these questions can be positively resolved, the resulting food product in packages with aluminium foil can be heated in a microwave oven rapidly, with good efficiency, and to a sensory quality that is not different from food in plastic trays.

8 Conclusions

Heating safety

Not a single case of hazardous condition has been observed in any of four microwave ovens during more than 200 heating procedures with packages containing aluminium foil at maximum microwave power setting. No damages or changes to ovens could be noticed. Severe abuse situations had to be constructed in order to provoke electric sparks with aluminium foil trays.

The abuse situations were:
+ empty aluminium foil tray inside oven, touching the oven wall at full microwave power;
+ two empty aluminium foil trays inside microwave oven, touching each other.

Both abuse situations are clear violations of heating instructions and should not occur in normal household use of microwave ovens. Therefore they seem not to be of practical relevance.

One spark without any relevance to safety occurred during 12 tests with household foil wrapped over dishes. The spark formed for a fraction of a second at a large fold of the foil and burnt a hole of about 1 cm diameter into the foil. The incident had no consequence to safety or aesthetic of oven and did not alter quality of heated food.

Microwave heating of food in foil trays or in plastic containers with foil lid is safe if a few guidelines are followed. The basic rule is, that contact from the foil of the package to oven walls oven floor or to other metal parts must be avoided. Even if such a situation occurs by error or incident, it is very unlikely, that a dangerous situation will develop. The occurrence of sparks can be spectacular and may alarm and worry the user but is not a dangerous situation and will not damage the oven.

Quality of heating

Heating patterns differ considerably between aluminium foil and plastic trays. In many cases they are complementary. In some applications (frozen lasagne, meat ball mass) the microwave heating seems to be more uniform in aluminium foil trays than in plastic trays. This is of no importance, if the food is liquid and can be stirred after heating to achieve a uniform mixing temperature.

In some cases also the visual appearance of heated food was better in aluminium foil trays by surface browning and crust forming than in plastic trays, where the surface remained wet and soft.

In practically all heating trials, it was possible to achieve satisfying heating results with aluminium foil trays and with plastic trays without optimising the heating regime. The trials always used maximum oven power and heating times that resulted from a schematic calculation. Further improvements of heating results in aluminium foil trays seem possible, if heating regime is optimised and adapted to the specific food.

Heating efficiency

Heating efficiency is in general lower with aluminium foil trays. Heating times to achieve the same heating effect are longer than in plastic trays and the consumed electric energy is higher by the same proportion.

The extension of heating time for aluminium foil trays over heating time for plastic trays varied between 20% and 70%, depending on food and tray geometry. Also a large influence of oven design on heating performance of food in aluminium foil trays was observed with a preference for ovens with a horizontal magnetron antenna in the microwave feeding window.

Generally, the heating efficiency was smaller for small trays with a lower ratio of open surface dimensions to microwave wavelength. Also the ratio of open surface area to food volume may play a role. The dependence of the efficiency from food properties is not as clear. Efficiency was at the low end for tap water and at the high end for egg batter. Frozen lasagne and meat ball mass were in between.

For plastic containers with foil lid as tested with a children meal in a plastic tray and a noodle soup in a plastic beaker, the effect of the lid on heating efficiency is very small. The needed heating time extension to achieve the same heating effect as without lid is estimated to about 10%.

With a porcelain dish wrapped by household foil, the heating efficiency was not much decreased by the foil, despite the fact that only a rather small area at the bottom of the dish was open for microwave entrance to the covered food. In a trial with water as a food load, the heating time extension compared to heating time without lid was estimated to 20%, with meat ball mass it was estimated to 40%.

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