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TNO report

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Determining the effectiveness of ultrasound cleaning baths: Applicability of various physical measurement techniques

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Summary

This report presents the findings of the project "Determining the effectiveness of ultrasonic cleaning baths", which was financed by the Ministry of Economic Affairs, with KW2 and Branson Nederland as co-financers. The project was started in September 1999 and the final stages were completed in June 2001. The aim of the project was to examine whether a reproducible method of measuring with practical applications could be developed, to characterise larger ultrasonic cleaners unambiguously. The emphasis in this project was placed on research into the ultrasonic field in the cleaning bath and in the cleaning processes that take place in the cleaning bath. For this project, Branson placed a cleaning bath at the disposal of TNO.

To get an idea of the normal practical use of the cleaning baths, a study was carried out by KW2 in the form of a questionnaire given to 15 hospital users of cleaning baths. The conclusion from this was that a bath was expected to clean instruments well, as part of the whole cleaning procedure before sterilisation. Checks on the extent of the cleaning were however only done by visual inspection.

Standard soiled test objects were developed by TNO Industry (Section Cleaning Technology) to establish the cleaning effect of the bath expressed as the time necessary to remove 90% of the soiling. At first it seemed not possible to produce reproducibly soiled and representative test objects. Because possible measuring methods first had to be developed, the emphasis was laid on reproducibility. The final measurements were carried out on ceramic tiles with Edding marker ink as the standard soil. The cleaning time for a standard soiled test object in the bath is reproducible to within 16% (standard deviation from the results). This was observed for two different settings of the power. In view of the processes used in the cleaning bath, this is a reasonable result.

TNO-PG carried out ultrasound measurements in the bath to find one or more parameters, which could be related to the cleaning effect. The basic frequency of the bath was about 40 kHz. It soon appeared that the subharmonic frequency component (20 kHz) and the frequency components, averaged over 0,5 to about 20 MHz, were the two best candidates. However, when measured with a hydrophone, directly in the bath, the reproducibility of both parameters was rather too poor to be able to be used for an unambiguous comparison with the cleaning effect.

The use of a shielded hydrophone gave noticeably better reproducible results because instabilities were not detected from the entire cleaning bath. Low frequencies (up to a few hundred kHz) were indeed transmitted, with the result that in the measurement volume of the hydrophone (14 cm^3), normal cavitation could occur. Higher frequencies (> 1 MHz) were not or were hardly at all transmitted through the protective material, with the result that the hydrophone could measure only the cavitation activity in the smaller volume, in as far as high frequency components were concerned. This method is therefore really only useful for the average high frequency signal.

The average appears only to a small extent to be dependent on the position in the bath. This points to a fairly homogenous sound field, as the manufacturer wanted.

Other methods of detecting cavitation activity, such as detection of changes in density in water, heat detection, sonoluminescence and erosion were also investigated. However none of these gave sufficient starting points for further development as a practically applicable and reproducible method for establishing the effectiveness of cleaning baths.

Conclusions

It seems possible in the future to produce satisfactorily reproducibly soiled objects for establishing the effectiveness of the cleaning process. The subharmonic frequency component and in particular the average high-frequency signal level, as measured by a shielded hydrophone, are the two most promising parameters to relate to the cleaning effect. Some effort will however be required to make this method more routinely applicable. Reproducibility of standard soiled test objects could also still be improved.

Contents

1 Introduction

Ultrasonic cleaning baths are used in hospitals or other medical institutions to clean surgical instruments. In hospitals in particular this technique is applied as part of the sterilisation process. In extra-mural healthcare stand-alone equipment is mainly used. Practical experience, supported by the literature, indicates that the effectiveness of ultrasound cleaning can vary greatly. Although the technique has been in existence for a long time - the first literature dates back to 1920 -, little is known about the actual cleaning processes in these baths and methods for quantifying these processes [1]. Now that the technique is applied on a greater scale in the whole sterilisation process, users within the healthcare system and industrial suppliers need to have an objective and reproducible method of establishing the effectiveness of ultrasonic cleaning baths. The research carried out in this project is directed in particular at the practicability of methods for measuring ultrasound parameters, at the applicability of other physical measurement techniques and at the development of 'standard' test objects.

Before this project a preliminary study was undertaken into the feasibility of an effectiveness study [2]. In addition, contact was made with the National Physical Laboratory (NPL) in the UK, who have studied the possibilities of measurement techniques for observing cavitation [3] and have assessed the need for the standardisation of measurement methods of high power ultrasound fields [4].

Two very accessible introductions to the principle of ultrasonic cleaning and the use of cleaning baths are to be found on the internet [5,6].

In chapter 2 the results are presented of the survey carried out by KW2 in a number of hospitals concerning the use of cleaning baths. Chapter 3 deals with the development of standard test objects and the corresponding measurement of the cleaning effect, carried out by TNO Industry. In chapter 4 a report is given of the measurement of ultrasound parameters in the bath, under varying conditions, carried out by TNO Prevention and Health. The research into the possibilities of other physical methods of measurement is described in chapter 5. The comparison between the results of the cleaning measurements (Ch.3) and the ultrasound measurements (Ch.4) is drawn in chapter 6. Chapter 7 contains the most important conclusions of the whole project.

Chapter 8 is the signature page of this report. Chapter 9 contains the literature references.

2 Survey of the use of ultrasound cleaning baths in hospitals

Research into the effectiveness of ultrasonic cleaning baths is primarily targeted at their suitability for use in hospitals. It is essential therefore to have an overall view of the way in which these cleaning baths are employed and of what the expectations are for a cleaning bath as regards the quality of cleaning. For these reasons KW2 carried out a survey over 20 institutes, all of them regional hospitals. Among these 15 used cleaning baths. Six of them are in the West Netherlands, 5 in the central region, 2 in the north and 2 in the south. The questionnaire and a table of the answers given are appended to this report as Appendix A.

2.1 Results

In all cases the questionnaire was completed by someone from the department who was responsible for sterilisation, in most cases by the head of department. The results are as follows:

- The average water content is 46 litres.
- Usually tap water or demineralised water is used.
- Almost all baths have a closed compartment.
- In most cases a fixed replacement interval is maintained, of on average 5 hours, but never more than a day (8 hours).
- In all cases detergents are added. It is worthy of note that the concentrations recommended by the manufacturers differ from 0,1% to 15%. The recommended concentration is in nearly all cases adhered to in practice.
- In all cases but one organic soiling is involved and in some cases, oxidation.
- In almost all cases a preliminary treatment is applied, in most cases rinsing. In one case it is soaked in Biotex and in another case it is cleaned with domestic materials.
- The temperature in most cases is between 35 and 40°C, sometimes 30°C and in one case 50°C.
- The frequency is mostly 35 to 40 kHz; in one case it is 47 kHz.
- Average cleaning time is mostly 3 to 5 minutes, sometimes 2 and in one case 6.
- It is generally expected that the bath establishes pre-cleaning of the instruments, that the result is visually clean, or that specific or difficult places are cleaned. It is generally indicated also (with one exception) that these expectations are fulfilled.
- By "clean" is understood that the load is visually clean after the ultrasonic cleaning (12 cases). In each case a swap test is done or pH and conductivity measurements are carried out.

2.2 Conclusions

There is general satisfaction with the use of the cleaning bath and the result. There is a measurable criterion present in only a few cases for ascertaining whether an instrument is satisfactorily cleaned by the ultrasonic bath. This is because ultrasonic cleaning is only one step in the whole cleaning process, which is expected to deliver good preliminary treatment. Mostly only a visual check is done. There is possibly more quantitative control after the complete pre-cleaning process (up to sterilisation), but that falls outside the limits of this study.

3 Development of standard soiled test objects

TNO Industry, the department of Cleaning Technology and Textiles, the section Cleaning Technology have been working on a method for making standard soiled material (test objects). Next they considered whether it was possible to judge the effectiveness of an ultrasonic bath in removing applied soiling.
To test the working of cleaning baths in practice, an attempt must be made to apply representative soiling (biological) to the surface (surgical instruments). In order to be able to compare different experiments with each other, the soiling must be reproducible, both according to constitution and quality, as well as its adhesion to the surface.

3.1 Application of soiling

The application of the test soil to the surface of the tile is a critical step. The uniformity (thickness of the layer, composition) of the layer of soil applied and the strength of the adhesion determines largely how easily removable the soil is. The surface is a tile made of glass, metal or ceramics. Glass and metal were chosen because they are clinically representative materials. Ceramic was used because a better adhesion is expected.
Two types of soil were chosen: Browne soil (organic) and Edding ink (master pen). Special attention was paid to the preliminary cleaning of the samples. In fact a(n) (ultra) clear surface provides a good and possibly reproducible measurement. This surface was a glass plate, a metal plate (RVS 316) or a ceramic tile 4x5 cm², taken from a large tile which was sawn into small test tiles.
As a preliminary treatment the tiles were cleaned with one or more of the following cleaning techniques:

- Brushing with a soap solution.
- Rinsing with distilled water.
- Rinsing with ethanol and/or acetone.
- Cleaning in a dishwasher.
- Cleaning with UV or ozone.

The cleanliness of the tile is checked by a contact angle measurement with demineralised water. If the material is clean, it has an increased surface energy, by which the water is drawn to the surface. The angle thus formed between the material and the drop of water, the angle of contact, is consequently smaller the cleaner the surface is. When the angle of contact is less than 10%, the plate is considered clean and then the soil is applied.

Browne soil
Browne soil is an industrially produced, organic test soil. It contains animal/organic products (industry proteins) and was developed as a test reagent for checking cleaning apparatus.
After being mixed with water, the soil is applied to the test object with the brush supplied, after which it had to dry for a certain time (minimum 1 hour).

Edding marking ink
The permanent marking is an ink which can be supplied separately or can be applied with the well-known Edding marker pens. The ink is applied to the clean plate, according to a fixed pattern in one or more strokes. Then the plate is dried at 35°C during 1 to 7 hours or 15 to 24 hours, dependent on the treatment chosen, see also

section 3.2. The results of the final measurements are all taken after a drying period of 15 to 24 hours.

3.2 Measurement set-up and measurement method

Measurements were carried out in a Branson 8500 cleaning bath to measure the rate with which the soiled plates could be cleaned, see fig. 1. The plates were in all cases pre-treated with acetone and ozone. The bath was 55 cm long, 35 cm broad and 30 cm deep. Demineralised water was used with various detergents. The generator for the Branson bath was set at the desired power, which could be read off from the LED display of the generator. The frequency sweep was always set at high. For each experiment the water was degassed for an hour at 75 to 80% power.

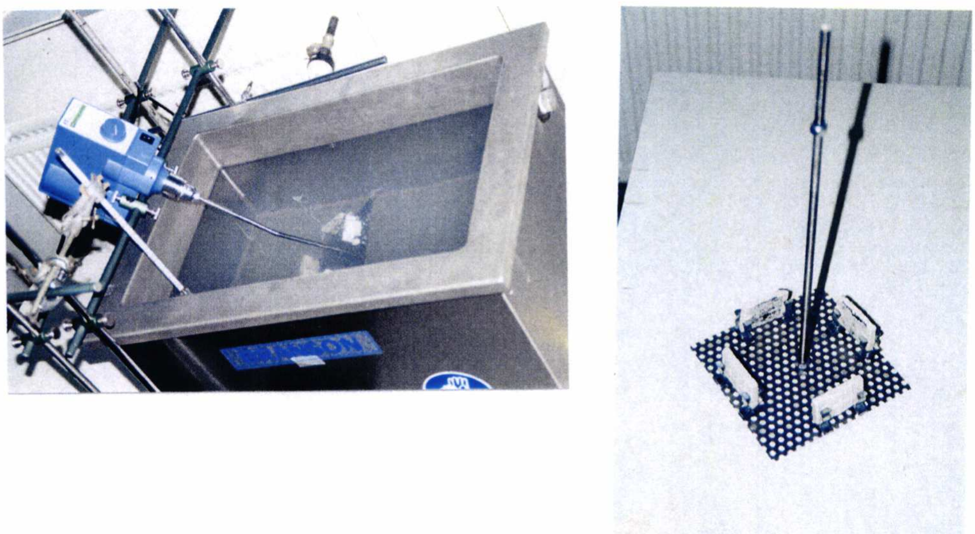


Figure 1: Photos of the set-up for measuring cleaning rate. On the left is the cleaning bath with the set-up for the motor with the sample holder, positioned roughly in the middle. On the right is the sample holder consisting of a perforated stainless steel plate, to which the tiles are stuck. The plate is held in place by a rod which rotates on its axis at around 30 rpm.

The measurements were carried out in two groups. The settings in the second group are the same as those for the ultrasound measurements (see chapter 4), so that a good comparison can be made between the results.

First set of measurements
The Edding ink was applied in several strokes to the ceramic tile. The bath was always filled to a depth of 23,0 ± 0,1 cm. As a detergent in the water 0,3% Teepol was used. The temperature of the water was 35°C, a temperature which was maintained at an ambient temperature of 20°C, when the bath was switched on without active heating. Experiments were carried out at 35% and 75% of the maximum power.

Second set of measurements
The Edding ink was here applied in just one stroke. The expectation was that by so doing its removal would be quicker and easier to reproduce than in the first group of

measurements. As a detergent in the water 0,6% of Neodisher LM2 was used. The water temperature was 40°C. Experiments were carried out at 40% and 80% of the maximum power.

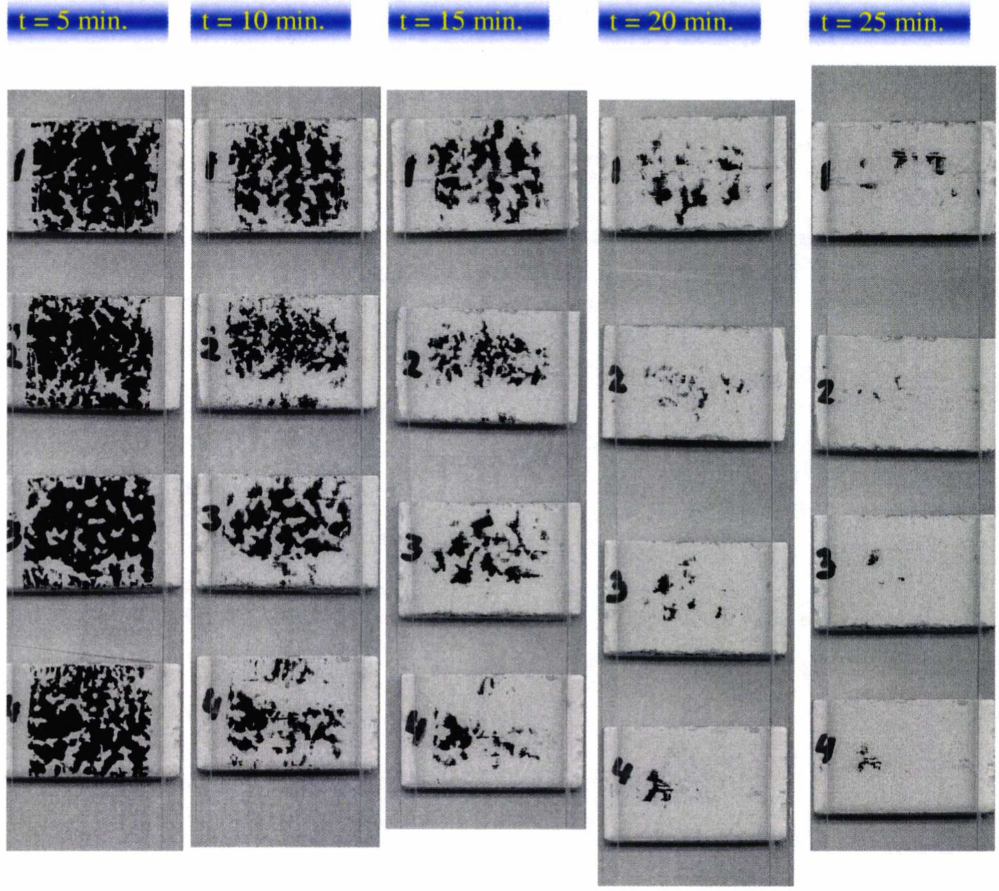


Figure 2: Photos of the ceramic tiles at various stages of cleaning. From top to bottom are the four tiles which are always cleaned together. On the left: after cleaning for five minutes and then by steps of five minutes to the right (25 minutes cleaning). The soil was generally removed from the edge of the tiles somewhat sooner than from the middle.

Four identical soiled plates were placed in the ultrasonic cleaning bath, mounted on the four sides of a square sample holder (a stainless steel perforated plate), which was mounted on the axle of a rotor. During cleaning the sample holder rotated in its plane around this axle at a speed of 30±10 rpm. The axle was precisely in the middle of the width of the container. The front of the sample holder was 35,5 cm from the outer edge of the bath (lengthwise) and the back 23,0 cm. the upper side was 12,0 cm under the rim of the bath, the underside 19,0 cm. Tolerance for all directions was estimated to be 0,3 cm.
The tiles were cleaned during a time period which varied from 5 to 60 minutes. Afterwards the tiles were dried and the colour was measured with a scanner. The scanner measured the greyness with always the same lighting conditions. The resulting photos (see Fig. 2) were analysed using an image processing programme. The percentage of cleaning is then calculated from the greyness of the clean sample (ceramic plates: almost white) and the greyness before and after cleaning, thus:

$$\text{Cleaning\%} = \frac{\text{greyness before - greyness after}}{\text{greyness before - greyness clean}} \cdot 100\%$$

Because measurements of cleaning were carried out under identical circumstances for various time periods, the cleaning percentage can be rendered as a function of time. From the graph (see Fig. 3 and Fig. 4) the time can be calculated, which is needed to remove 90% of the soil (cleaning percentage of 90%). This time is then the measure that is used to render the effectiveness of the cleaning. The variation in cleaning times between the four plates and the variation between experiments with similar set-ups provides information on the reproducibility of the method.

3.3 Results

Suitability of the surface and the type of soil

- The ceramic tiles are suitable as a surface, because soil adheres well and the surface is white, which is optimal for the use of a greyness scan.
- When ink strokes are applied to glass, it appears that the way the ink is applied determines to a great extent the resulting adhesion. If liquid ink is applied with a pipette and is smeared out, it seems that the ink adheres poorly or with difficulty, but if the ink is applied with a pen, it does adhere well. No research had been done into the causes of these differences, because this variation is sufficient reason not to work with glass plates. Moreover, the colour is less suitable for use with a scanning procedure for judging the soil removal.
- Stainless steel plates have the important disadvantage that soil removal cannot be judged using a scan because of the reflections that occur. The results would among other things then be too dependent on the precise angle used for the inspection.
- The Browne soil is too easy to remove to be suitable as a test soil for an ultrasonic cleaning test. The soil appears to have been almost completely removed from the sample plate (ceramic or metal) in as little as 10 - 20 seconds.

Preliminary treatment

- Preliminary treatment of the samples is very important for minimising the spread in cleaning rate.
- Rubbing with acetone followed by an UV/ozone treatment leads to an angle of contact smaller than 10° (wetting). For the time being this method seems to achieve a sufficiently good preliminary cleaning of the sample surface.

The actual cleaning process

- The Edding stain seemed to be removed very much only from a restricted area. In the photo of the experiment C5-8 (see Fig. 2) a pattern of stains is clearly visible on the sample surface. Broadly speaking, the ink is removed from the edges somewhat more quickly than from the centre. Round several 'soil removal areas' which appeared (places where the surface became visible), there was a further expansion of the removal area.
- From experiments with a lower ultrasound power (normally 35%) it seems that the removal of the soil takes place in two stages: a beginning phase where the soil layer becomes thinner but is not yet removed down to the surface, and an end phase where the soil is completely removed from the surface. This can be seen on the soil

removal curve from the fact that the low removal rate is followed by much faster soil removal (see Fig. 3 and 4).

- If ink is applied in several strokes with the marker, it is difficult to apply a 100% uniform layer. In those very areas where the marker strokes overlap and therefore a thicker layer is formed, the removal seems to take place less quickly. For this reason a broad marker pen is used in the second group, so that the ink could be applied in one stroke.

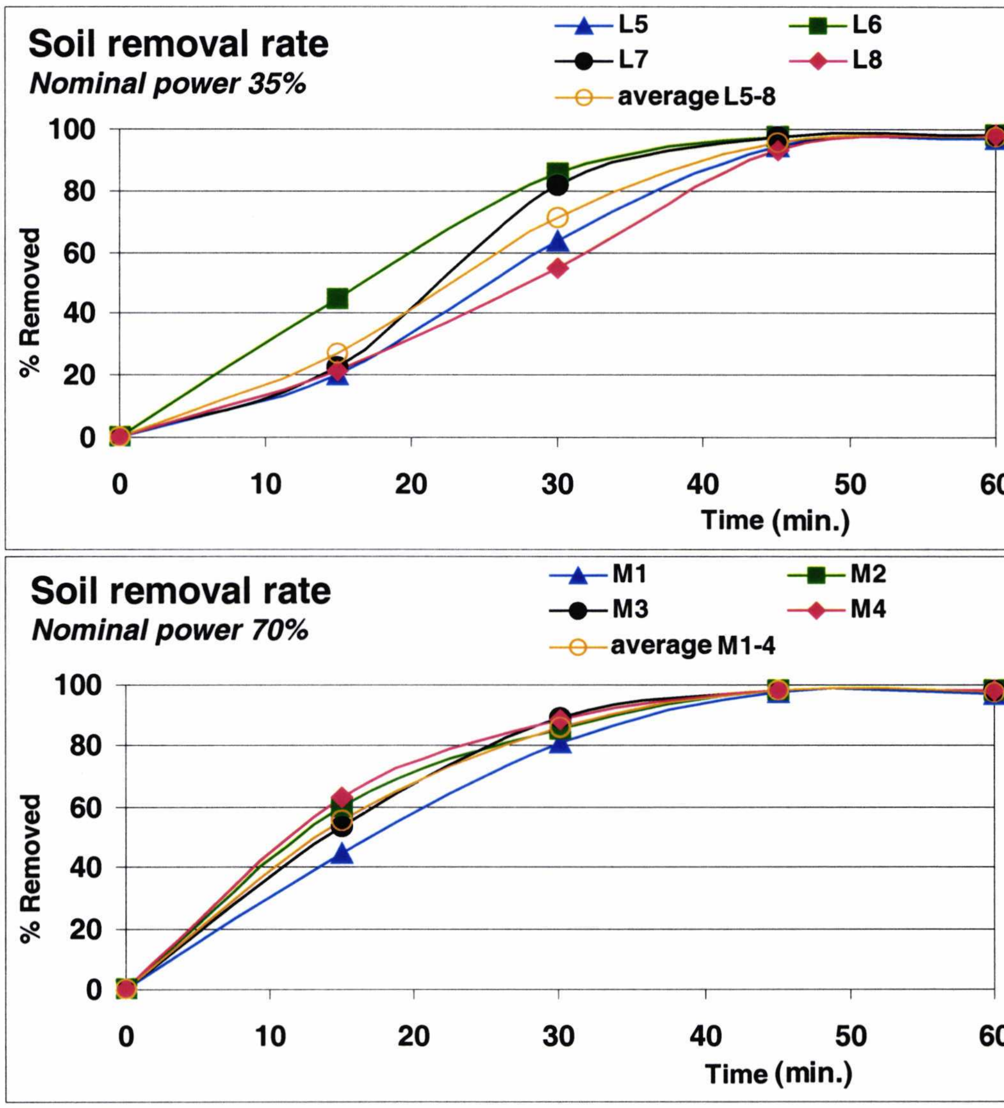


Fig. 3: Percentage of soil removal as a function of the cleaning period in two comparable cases in the first group of measurements. The only difference is the nominal power of the bath; 35% (above) and 70% (below). At a lower power it clearly takes longer before the layer of the soil is completely removed, which is in particular expressed by the "rather slow start" of the curves.

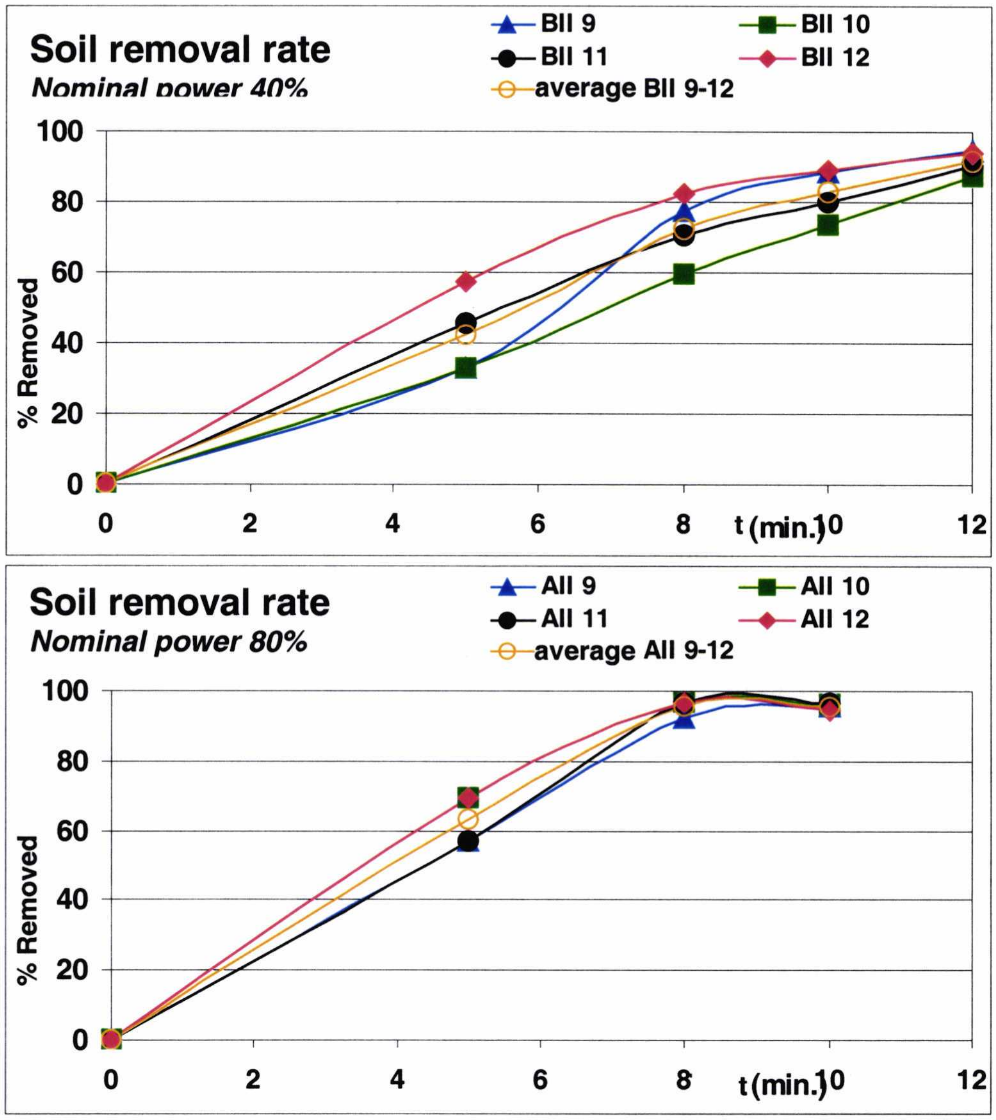


Fig. 4: Percentage of soil removal as a function of the cleaning period in two comparable cases in the second group of measurements. The only difference is the nominal power of the bath: 40% (above) and 80% (below). A higher power clearly speeds up the cleaning process. The rate of cleaning is significantly higher than in the first group of measurements.

Rate of soil removal

Table 1 gives the 90% soil removal times for both groups of measurements. The results are averaged over experiments with the same settings and the variation is given both within an experiment and between similar experiments. Variations are quantified in the form of standard deviations of the removal times. Within an experiment the variation in question is between four ceramic tiles; the standard deviations are afterwards averaged over similar experiments. The standard deviation between similar experiments is based on the average removal times per experiment.

Table 1: Time needed to remove 90% of the soil (2nd column) for two measurement groups, for both power settings per group. The average SD within an experiment is given (3rd column). The SD between the average removal times per experiment are in the 4th column. Because only one experiment was carried out for the first group at 70% power, no variation is known between the experiments for this situation. Finally in column 5 the SD is given for all removal times at the relevant settings

	90%-removal time average	**st.dev. within experiment (average)**	**st.dev between average of experiments**	**st.dev. of all individual results**
1st group, P=35%	43 min.	13%	15%	16%
1st group, P=70%	33 min.	8%	not known	not known
2nd group, P=40%	10,3 min.	14%	9%	16%
2nd group, P=80%	7,7 min.	8%	10%	11%

At the higher power cleaning takes place more quickly, as could be expected. The relation between the cleaning times in group 1 is approx. the same as for that in group 2 (1,30 to 1,35). The fact that the two groups can be compared on this point, is because the difference between 35 and 40% power and between 70 and 80% power, is not great, as can be derived from the results in chapter 4.

Within the first group of tests the variation is fairly great, both within an experiment and between independent experiments. The possible reasons for this spread are a non-reproducible ultrasound field, no optimal preliminary treatment and non-reproducible soil application. With the aim of increasing the reproducibility, the soiling was applied in a way which is more easily reproducible and then the measurements in group 2 were carried out.

Within the second group of tests the soil removal occurs remarkably more quickly, as expected, because there was only one stroke of soiling applied. In fig. 4 a number of soil removal curves for group 2 are given. However, the variation within an experiment, and thus between the four tiles, remains more or less the same, which points to the fact that:

- the soil application in the second group was not more reproducible than in the first group, or
- the method of application does not greatly determine the variation in cleaning rate.

The variation between the experiments is certainly smaller in group 2 (40% power) than in group 1 (35% power). Given the similar variation within an experiment, it is not safe to assume that the cause of this lies in a more reproducible soil application. The element of chance can play a great role here, because the first group consists of only 2 series of 4 tiles and the second group of 3 series. Besides this, the number of degrees of freedom (1 and 2 resp.) involved is very small and thus influences the SD strongly: the factors are $\sqrt{(2/1)} = 1{,}41$ for the first group and $\sqrt{(3/2)} = 1{,}22$ for the second group.
When the SD of all the individual results is calculated, the number of degrees of freedom for the first group is $2 \cdot 4 - 1 = 7$ and for the second group $3 \cdot 4 - 1 = 11$. The difference between the corresponding factors is now smaller: $\sqrt{(8/7)} = 1{,}07$ for the first group and $\sqrt{(12/11)} = 1{,}04$ for the second group. It would seem that this is partly the cause of the fact that the difference between the SDs between experiments in a group does not recur in the total SDs for both groups.

3.4 Conclusions

- The aim is to measure the cleaning rate, for which the 90% cleaning time is a measure. A representative soiling on a representative surface is for the time being difficult to achieve, because of problems with the reproducibility and because organic soil leaves the surface too easily and quickly. A time measurement cannot be accurately enough carried out using organic soil.
- A reproducibility of 16% was achieved and can be acceptable, given the difficulty in applying the soil reproducibly and given the variations in the parameters measured for the ultrasound field in the bath (see sections 4.4 to 4.7).

4 Research into the ultrasound field in a specific cleaning bath

Much research has been done into the characteristics of ultrasound in the Branson 8500 cleaning bath in terms of pressure and frequency spectrum. Settings such as temperature, power and frequency modulation, and the variation in the acoustic field in the bath (position-dependency) form important factors. Parameters to be taken into account in describing the effectiveness of the cleaning must in any case be reproducible.

Cleaning by means of ultrasound is based on inertial cavitation, the process whereby gas, vapour or vacuum bubbles oscillate in water under the influence of sound and then implode. At the point of such an implosion, a water jet is often formed, a powerful spurt of water at microlevel. The soil is "shot loose" from the surface by the great forces, in combination with the working of the added detergents. More information about cavitation is given in [7] en [8], including the processes which occur at the level of the individual bubble.

The occurrence of cavitation can be observed in the ultrasound frequency spectrum via the presence of the frequency component at half of the fundamental frequency (the subharmonic). The 12 transducers of the Branson cleaning bath have a fundamental frequency of around 40 kHz. The frequency spectrum of the ultrasonic field is measured in frequency regions up to 200 kHz and up to 20 MHz. Measurement in the low region gives individual frequency peaks at ½ and 1½ times the fundamental frequency (subharmonic and ultraharmonic). Measuring in the high region, the presence of high frequency components is studied, because they too can give an indication of cavitation.

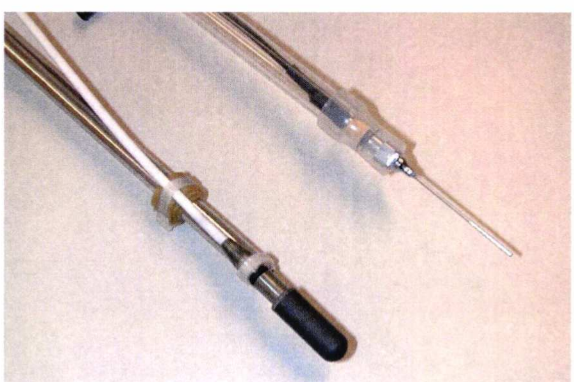


Fig. 5: The two hydrophones, used to characterise the ultrasound field in the cleaning bath. Above: Dapco hydrophone; below: Brüel and Kjær hydrophone.

Measurements of the ultrasonic field are carried out using two hydrophones (see fig. 5): a Dapco hydrophone (type NP10) with preamplifier, suitable for frequencies of 0,5 to 20 MHz and a Brüel and Kjær hydrophone (type 8103) for frequencies up to about 250 kHz. Nevertheless, measurements with the B&K were later carried out up to 20 MHz, because in that frequency region a signal could still be observed, which was related to the ultrasonic field. At an even later stage use was made of a shield around the hydrophones, in order to be able to measure the spectrum in a smaller area (see section 4.6.).

4.1 Schematic set-up for ultrasound measurements

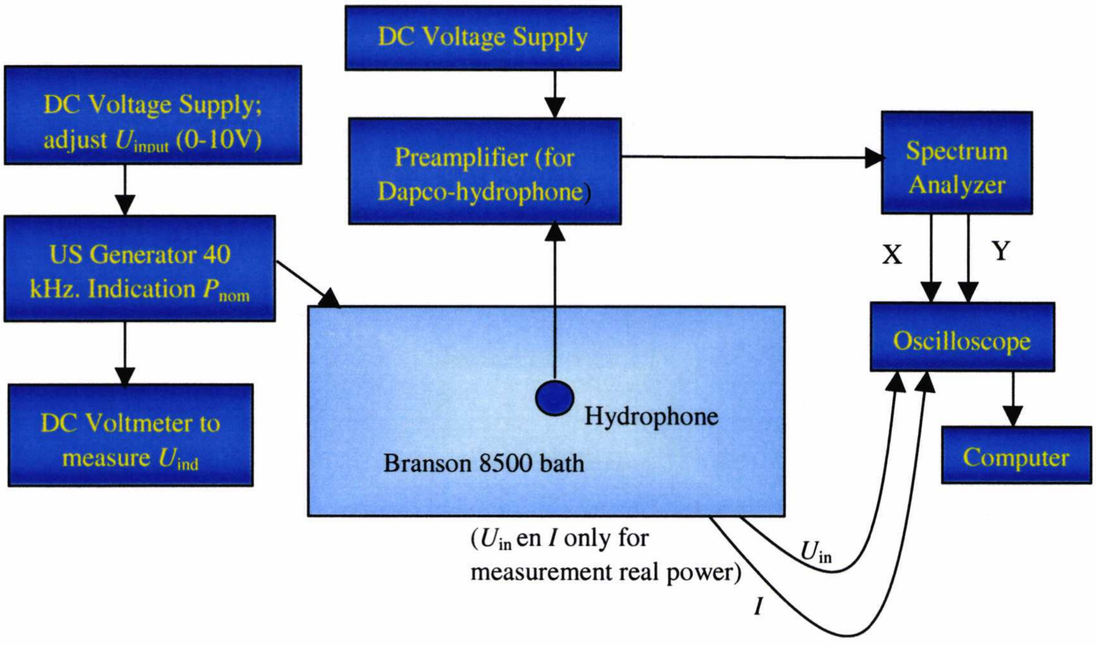


Fig. 6: Schematic set-up for measurements in the Branson 8500 cleaning bath.

In Fig. 6 the set-up is given schematically. The generator is driven by another DC power source. A voltmeter measures the "indication voltage" U_{ind} between two of the 25 pins on the cable from the generator, which is an indicator of the power. The actual electrical power (via U_{in} and I) to the transducers is measured once; afterwards these connections are not made again. Spectra are always shown on the spectrum analyser and sent to the oscilloscope to be stored so that further processing can be done on the computer. The hydrophone is secured to the system by a few rods, with markings to show the precise positioning. In this way the x, y and z-co-ordinates are reproduced within around 0,3 cm in new measurements series.

4.2 Relation between nominal and actual electric power

The actual power P_{meas} is measured through the input voltage U_{in} over the transducers connected in parallel under the bath and the current I to the transducers. The measurement is carried out with an oscilloscope, with 500 kHz sampling frequency. The product U_{in} times I is numerically integrated over time (20 ms) to get an average power P_{meas}. This measurement is carried out without frequency modulation ('sweep'), but it is established that the power is not or hardly influenced by the modulation.

Fig. 7 gives the relation between the indication voltage and both the nominal and the measured power. The nominal power is plotted against the indication voltage, which is set at the same value for all further experiments (within 2%).

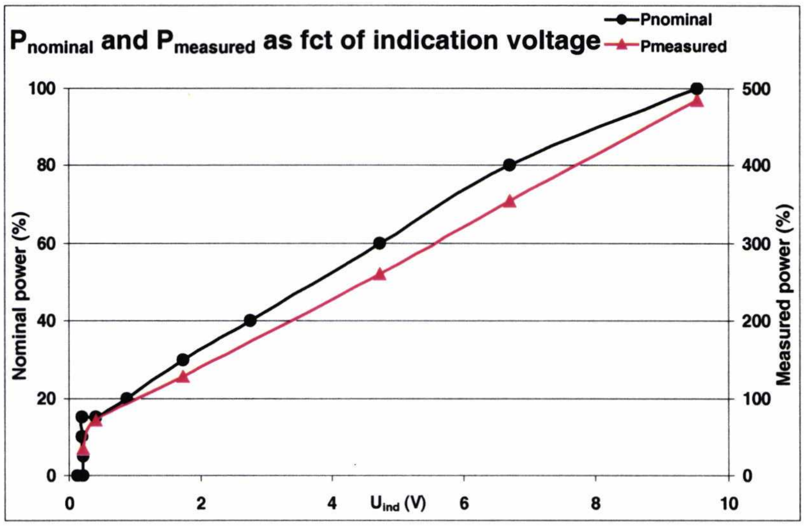


Fig. 7: Nominal and measured power as a function of indication voltage. The relation in both cases is practically linear above U_{ind} *= 1 V, but raising the driving voltage in the beginning raises the power, but not the indication voltage.*

Because the relationship between power and indication voltage is almost linear above U_{ind} = 1 V, the indication voltage can be easily used to calculate the actual power. Linear regression starting at U_{ind} = 1 V yields a maximal difference in power between the measured point and the regression line of 4% (P_{nom}) and 2% (P_{meas}).
If a scaling factor is applied to P_{nom} to find P_{meas} (almost 500W/100%), the maximum difference between the points of P_{nom} and P_{meas} in the graph is 7%, in the region above U_{ind} = 1 V. At U_{ind} = 2 V and P_{nom} = 5 W, the difference is 30%.
All later measurements are carried out reading P_{nom} and U_{ind}. All measurement values are related to these. For this reason the results henceforth are not given in terms of P_{meas}, but of P_{nom}.

4.3 Time dependence

From the moment of switching on the bath, the ultrasound pressure and two frequency components of the ultrasound field are measured with a hydrophone at a depth of about 7 cm under the surface of the water. These are the 20 and 60 kHz components, resp. ½ and 1½ times the fundamental frequency of 40 kHz. These two components were chosen because they can indicate the amount of the cavitation in the bath.
As appears from Fig. 8, the ultrasound field is not yet stable after the bath has been switched on. This can be seen from the slow change in the ultrasound pressure and the frequency components. This phenomenon is observed both with degassed demineralised water and non-degassed tap water. In the first case the values measured decrease by 15 to 20% down to the equilibrium value; in the latter instance there is in the beginning scarcely any measurable field which in time increases to the equilibrium value. In both situations it takes about an hour to reach equilibrium. Therefore further measurements are always carried out after the bath has been turned on at P_{nom} = 80%.

Conclusion of this part
The bath must have been running for minimally an hour at a nominal power of 80% before measurements can be made.

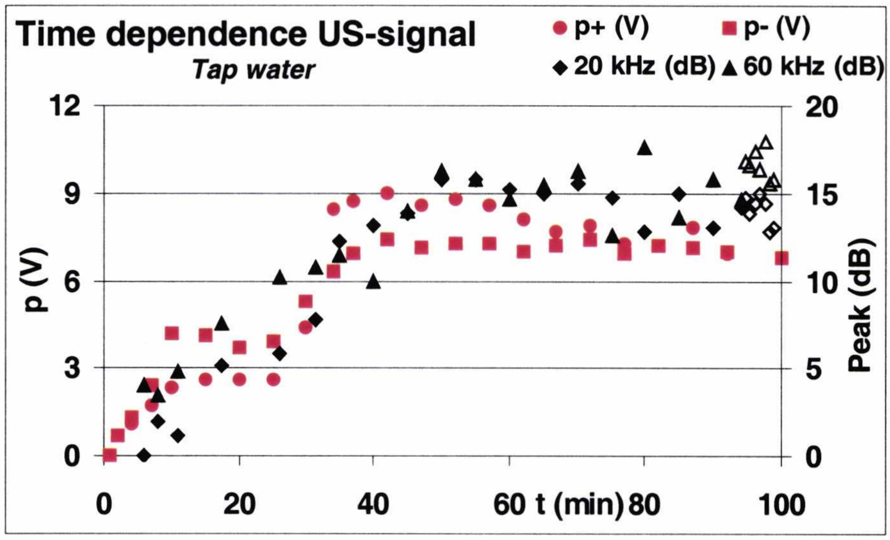


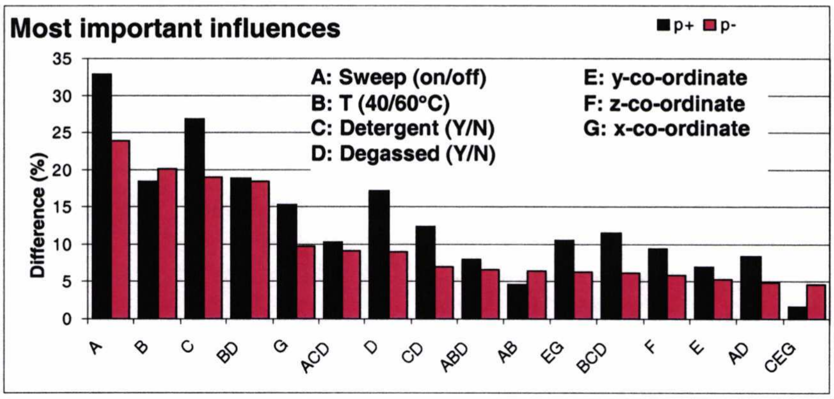
Fig. 8: Slow change in the ultrasound field. The ultrasound pressure and the frequency componnts at ½ and 1½ times the fundamental frequency of 40 kHz were measured. Above: in degassed water there is directly a well-developed ultrasound field, which decreases during the first hour after the bath is switched on. Below: in non-degassed tap water hardly any field can be measured. After about an hour, the ultrasound field has stabilised

4.4 Influence of various settings on the sound pressure and sub- and ultraharmonic

The positive and negative amplitudes of the ultrasound pressure and the peak height in the spectrum at the subharmonic and the ultraharmonic were measured (4 parameters in all). A factorial analysis was carried out on the results of all the measurements to determine which input parameters influence the 4 parameters measured. The input parameters with their values are:

- Frequency sweep of the generator "high" (on/off)
- Degassing of the water (yes/no)
- Temperature of the water (40/60°C)
- Detergent concentration (Neodisher LM2) in the water (0/0,6%)
- x co-ordinate hydrophone: lengthwise (10/34 cm from the inner wall); randomly chosen.
- y co-ordinate hydrophone: widthwise (5/21 cm from the inner wall); randomly chosen.
- z co-ordinate hydrophone: height (5/16 cm from the surface of the water); randomly chosen.

All combinations (2^7 = 128 measurements) were made, at which pressures and spectra were measured. The nominal power was always set at 80% (read off from the LED indicator on the generator). Fig. 9 (above) gives the most important influences of the parameter on the ultrasound pressure measured (split into p+ and p-), and Fig. 9 (below) gives the most important influences of the parameters on the sub- and ultraharmonic frequency component measured in the ultrasound spectrum. All measurements are carried out with the Dapco hydrophone, unshielded.



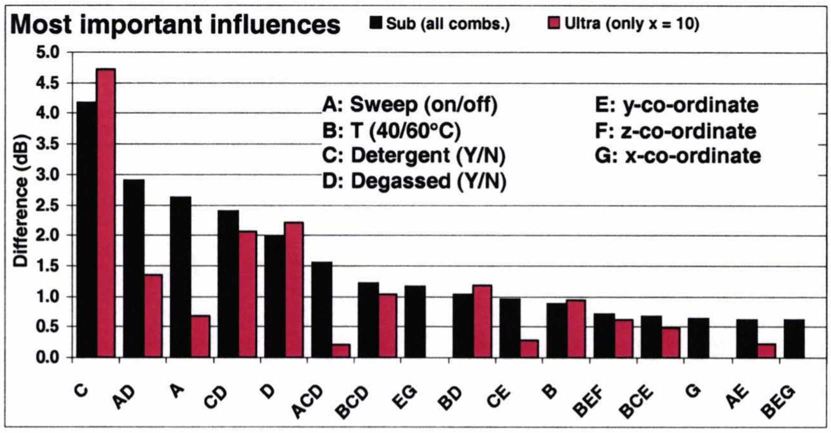


Fig. 9: The most important influences of settings to the ultrasound pressure measured (above, sorted by p-), and the spectral components (below, sorted by subharmonic). The set parameters (horizontal axis) can always have 2 values. Because the value of a parameter can influence the influence of other parameters, combinations of several parameters are also considered an influencing factor. The vertical axis gives the difference in pressures (above, in %) or heights of the peaks (below, in dB) as measured at the two values of the set parameters

The results are, in brief:

- After the cleaning bath is switched on, the amplitudes of the pressure variations and the heights of the spectral components (in particular the sub- and ultraharmonic) go slowly to an equilibrium value. When the bath is used with degassed water, the values are first high and gradually become a little lower. With non-degassed water the values begin at 0 and then rise to their equilibrium. In both cases the stabilisation process lasts for about an hour.
- The addition of detergent (0,6% Neodisher LM2) has a great influence on the ultrasound pressure and the sub- and ultraharmonic components in the spectrum: pressure becomes 20 to 25% higher (in Pa) and spectral components 30 to 35% (in dB).
- Position dependence is fairly weak: the variation is smaller than 10 to 15% for pressure and smaller than 10% for spectrum.
- Using the sweep setting (high) produces a 25 to 30% higher pressure and 19% higher subharmonic. The ultraharmonic hardly alters.
- Raising the temperature from 40 to 60°C raises the pressure by 19%, but the spectral components by only around 6%.
- There is an interaction between temperature and degassing in the influence on the pressure: the two situations (high temperature + non-degassed water) and (low

temperature + degassed water) produce a 19% higher pressure than the other two combinations.

- There is also an interaction between sweep and degassing in influencing the subharmonic: the situation (sweep on + non-degassed) and (sweep off + degassed) produce a 21% higher subharmonic than the other two combinations.
- There is also an interaction between detergent and degassing: (detergent + non-degassed) and (no detergent + degassed) produce 16% higher sub- en ultraharmonic components. In short this indicates that for a higher subharmonic spectral component (seen as an indicator of cavitation) and higher sound pressure, detergent should be added, frequency modulation should be applied (sweep) and if possible, the temperature should be high (weaker influence).

Influence of the type of detergent

The type of detergent which is added to the water, has as expected an influence on the ultrasound field. Therefore experiments are carried out using two sorts of detergents: Teepol and Neodisher LM2, which is provided with the cleaning bath. The concentrations are chosen according to the manufacturer's instructions. With 0,63% of Neodisher in water, the amount with which most of the ultrasound measurements are carried out, the surface tension is 46 mN/m (at 40°C, measured by TNO Industry). This can be compared with the value of water, 73mN/m. Although the concentrations of Neodisher (0,63%) and Teepol (0,32%) are different, a comparison is made between the effects of both solutions. The effect of the kind of detergent on the subharmonic frequency component (measured by the Brüel & Kjær) and on the average signal between 0,5 and 20 MHz (measured with the Dapco) was investigated. For the usefulness of the average signal: see section 4.5. The results of the measurements are given in Fig. 10.

It seems that 0,32% Teepol as a detergent for use at nominal powers up to 50% generally leads to a somewhat higher average signal level than 0,63% of Neodisher LM2. Above 50% the difference is only minor. The same is true to a lesser extent for the subharmonic frequency component. The effect of the detergent is position-dependent, for at x = 10 cm the influence is smaller than at x = 34 cm.
With these observations comes the comment that the average signal under 50% power can be rather difficult to reproduce, see Fig. 13. Therefore these results for the two detergents should only be taken as an indicator.

Conclusions from this section

To increase cavitation activity, detergent must be added and frequency modulation (sweep) applied. A higher temperature in general also increases cavitation activity.

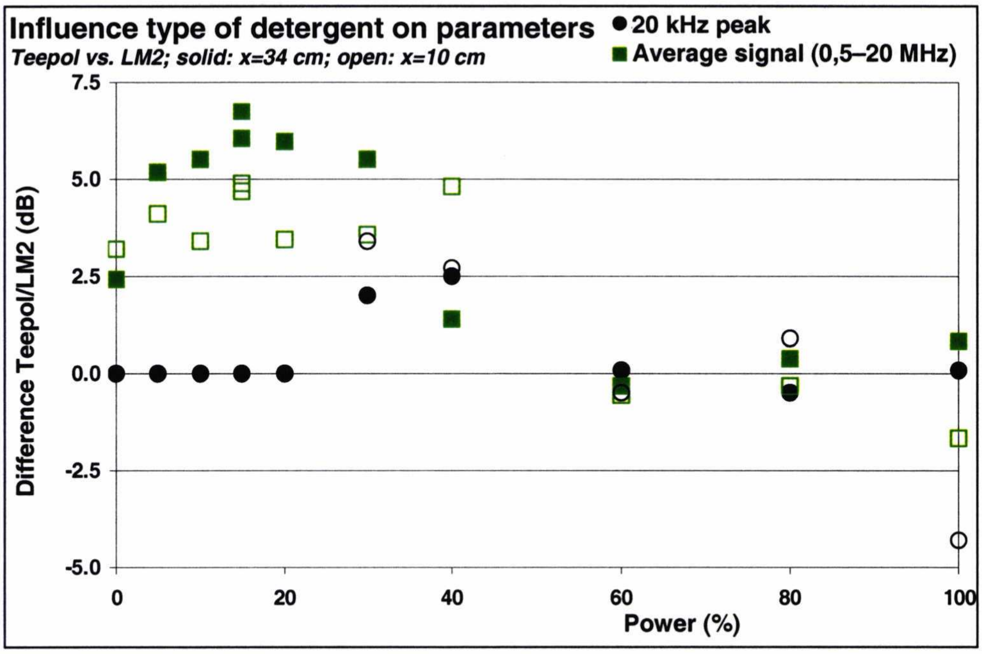
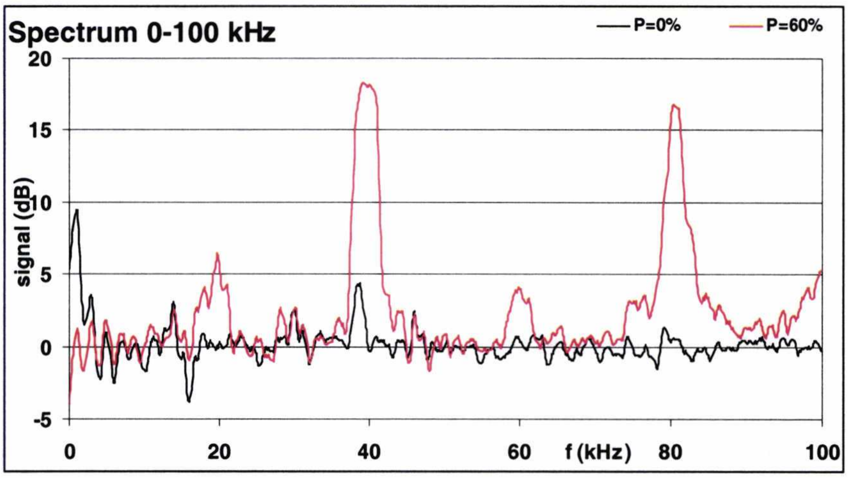


Fig. 10: Influence of the kind of detergent on the subharmonic and on the average signal level between 0,5 and 20 MHz.

4.5 Influence of the power on the frequency spectrum

It is expected that the subharmonic and ultraharmonic peaks in the frequency spectrum will be higher, as the input power increases. The same is true for the average signal level between 0,5 and 20 MHz. In fact it was observed earlier that the level of signals up to at least 20 MHz is increased if there was strong cavitation (a substantial subharmonic peak). From this the conclusion was drawn that cavitation is possibly responsible for very high frequency components in the spectrum. To quantify this, the average signal level was defined: the integral of the signal (in dB) of 0,5 MHz to about 20 MHz, divided by the width of the spectrum (about 19,5 MHz).

The three parameters, subharmonic, ultraharmonic, and average signal level, were measured several times for a varying power. In this way the reproducibility of the measurements can be established, which is possibly a measure of the stability (over a longer time period) of the ultrasound field in the bath.



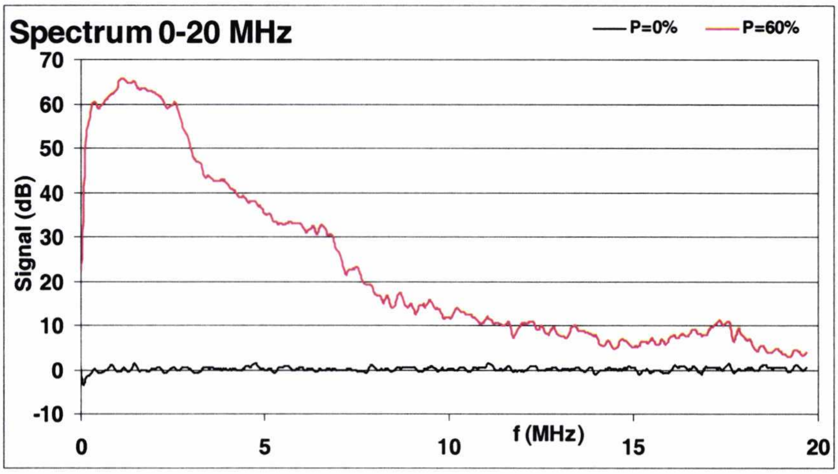


Fig. 11: Spectrum 0-100 kHz (with B&K hydrophone) and 0-20 MHz (with Dapco hydrophone), for a 0% nominal power (black) and for 60% nominal power (red). The signal levels are different as a result of the unequal frequency-dependent sensitivities of the two hydrophones.

In Fig. 11 the spectra from 0 to 100 kHz and from 0 to 20 MHz are given, both for P_{nom}= 0% (the bath completely turned off) and P_{nom}= 60% (by means of the drive voltage, the indication voltage is set at 4,70 ± 0,04 V). The first spectrum was measured with the B&K hydrophone; the second with the Dapco hydrophone. Because the two hydrophones have different frequency dependent sensitivities, the two spectra are not directly comparable. The spectra were corrected for the situation at P = 0% by withdrawing a P = 0% spectrum which was measured at the start of the same measurement session. The spectra given in Fig. 11 at P = 0% therefore give an indication of the random variation (partly as a result of noise) in the measurements. Not only are the 40 and 80 kHz peaks clearly visible, but also the sub- and ultraharmonic frequency components at 20 and 60 kHz respectively are clearly present. In the spectrum to 20 MHz the signal is raised with regard to the zero level.

To study the influence of the nominal power (0-100%), the three earlier mentioned parameters were measured for 10 power settings with the use of LM2 as the detergent. The nominal power was set using the indication voltage and in this way is easy to reproduce (resolution of the power is 5%).

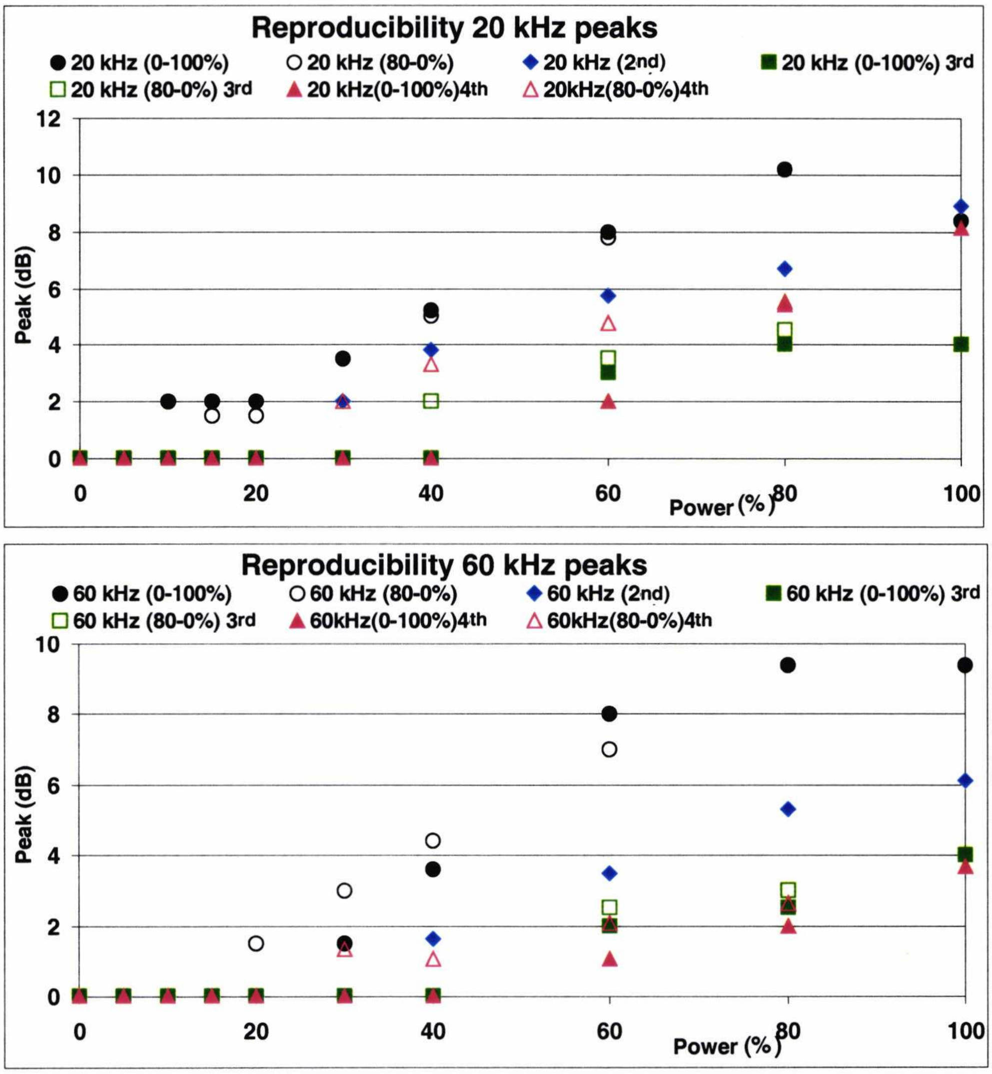


Fig. 12: Power dependence and reproducibility of the subharmonic (above) and ultraharmonic (below) peak. Four different measurement series were carried out on different days. The various forms of the markers indicate the different measurement series. In series 1, 3 and 4 hysteresis is also investigated: the peak for decreasing power is also investigated there

For P_{nom} = 15% measurements were done at two indication voltages: U_{ind} = 0,19 V and U_{ind} = 0,39 ± 0,01 V. Both settings give a nominal power of 15%, but at the low U_{ind} there is significantly less ultrasound than at the high U_{ind}. Also at P_{nom} = 0% two measurements were carried out: one with the bath switched off and one at a setting where a sound is just audible, but where P_{nom} = 5% has not yet been reached.

In Fig. 12 power dependence and reproducibility of the sub- and ultraharmonic peaks are indicated, always for the same position: (x, y, z) = (34, 21, 7) cm. In Fig. 13 this is done for the average signal level.

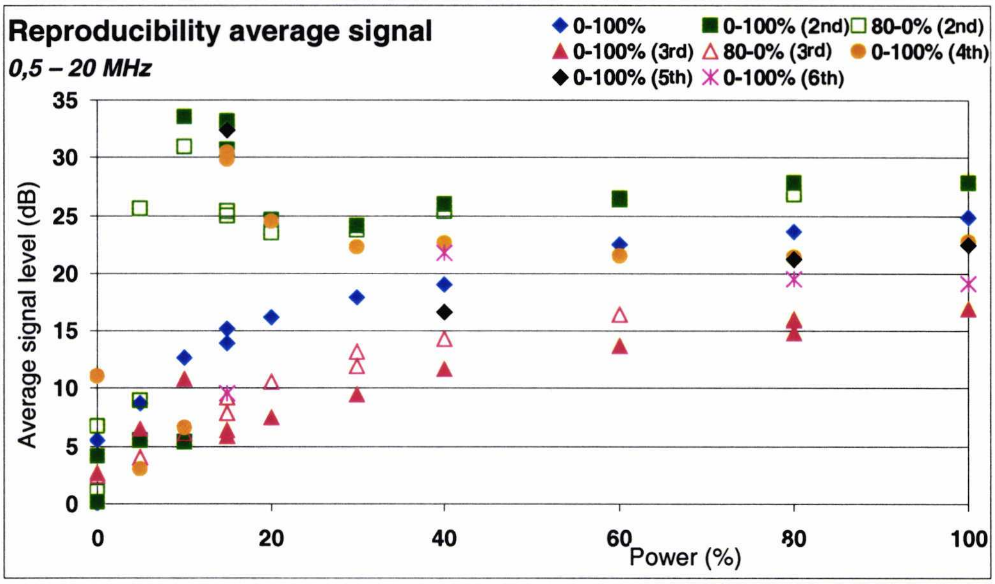


Fig. 13: Power dependence and reproducibility of the average signal level between 0,5 and 20,0 MHz. Six different measurement series were carried out on different days. The different forms of the markers identify the different measurement series. Measurement series done on the same day as in Fig. 12 have also the same colour and form combination. For series 2 and 3 hysteresis was also investigated.

In the graphs the following can be seen:

- The 20 kHz peak only increases when the power passes a boundary value, in this case 20%. Only the first of the four measurement series increases as early as at 10% power. This agrees with the idea that cavitation is a phenomenon with a threshold value.
- It is estimated that above 70% power the subharmonic does not increase any further.
- The 60 kHz peak behaves as the 20 kHz peak, but is lower. That is expected, because this can be seen as the combination of the subharmonic and the ground frequency. Therefore research is subsequently only done for 20 kHz.
- The average signal level increases directly from P_{nom} = 0% onwards. This effect levels off above P_{nom} = 40%. The fact that the level directly increases is an indication that it is not (solely) a measure of non-inertial cavitation. Inertial cavitation is possibly also visible in this signal.

Despite the (as far as possible) equal settings and positions used for the measurements, the difference between the highest and the lowest measured peak is 5 to 6 dB for 20 kHz (above 40% of the nominal power) and 6 to 7 dB for the 60 kHz (above 60% of the nominal power). The first measurement series in Fig. 12 produces significantly higher peaks than the other three series. The difference between the extremes is about the same as the average height of the peak. The reproducibility of these measurements is therefore as yet unsatisfactory for carrying out a good unambiguous characterisation of the cleaning bath. As a check, the bath was switched on a few times for a period of less than a minute and then switched off again and at the last time the hydrophone was taken out and then repositioned in the bath. The total variation with this procedure in the 20 kHz component was less than 1,5 dB; the repositioning of the hydrophone had no observable influence on the variation. These results indicate that variation in results does occur not solely because the ultrasound field in the bath is built up again (and possibly differently) after having been switched off.

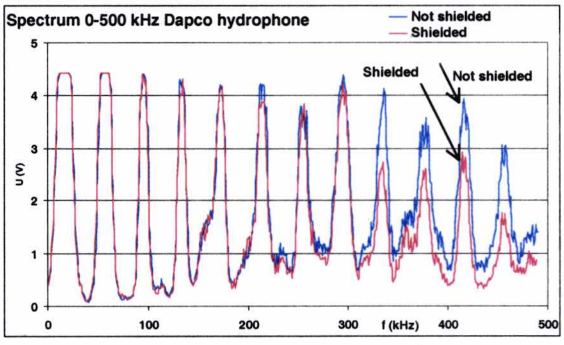
The variation in Fig. 13 per measurement series is not parallel to those in Fig. 12. In three of the six measurement series a leap from a low to a high signal level is observed between 5 and 15% power, where it seems as if the bath is "starting up". It is not known why this happens sometimes and not other times. Apart from that, the average signal level of above 30% power varies by 10 to 15 dB, at an average of about 20 dB. Turning the bath on and off as was done also for the 20 kHz component, provides a variation of not more than 1 dB. The building up again of the field does not therefore determine the variation.

Conclusion of this section
Reproducibility remains a problem for the measurements. As far as the average signal level is concerned, a decreased sensitivity to events in the whole bath could possibly effect improvement in this. The hydrophone is therefore shielded, see section 4.6.

4.6 Reproducibility when the shielded hydrophone is used

A small container (around 20x20x35 mm³) was made from "Wallgone", a strong ultrasound absorbing material (above 1 MHz) and placed around the hydrophone.
The purpose of this is to transmit only relatively low frequencies (< 1 MHz) in order that in the high frequency area the hydrophone can observe only cavitation within the closed-off area. Because we assume that the (low) fundamental frequency (40 kHz) in particular causes cavitation, the "cavitation intensity" will not be too greatly affected. The idea came from the NPL (National Physical Laboratory), UK. They have good experience with a detector which was protected on four sides from the environment. The NPL detector is described in [9] and is patented (UK Patent Priority Application No. 9921982.6).

Measurements confirm that Wallgone transmits frequencies up to around 300 kHz almost unattenuated. Above that, absorption quickly increases and above 3 MHz hardly any signal is transmitted by Wallgone. These transmission measurements were carried out at a fairly low power, to be certain that there was hardly any cavitation in the container itself. Fig. 14 shows the results.



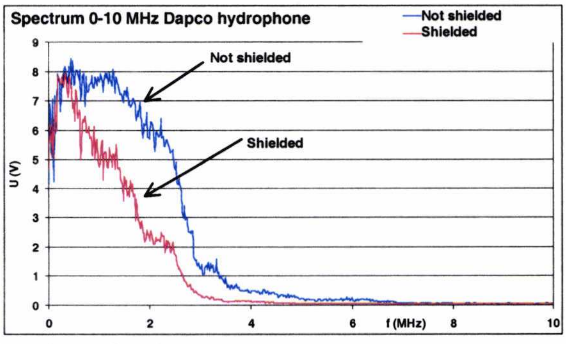


Fig. 14: Spectrum in the low (left) and high (right) frequency area. Measurements were carried out with and without shielding around the Dapco hydrophone. Between 0,3 and 3 MHz the effect of the shielding increases from almost zero to almost complete.

Measurements with the Dapco hydrophone

The average signal level (0,5 to around 20 MHz) was measured four times with the shielded Dapco hydrophone at the same position as in Fig. 13, on three different days (series 1 and 2 on the same day) and under identical circumstances. The result is given in Fig. 15. The 10%, 30% and 60% power settings were only used in series 1. The reproducibility is remarkably better than without shielding.

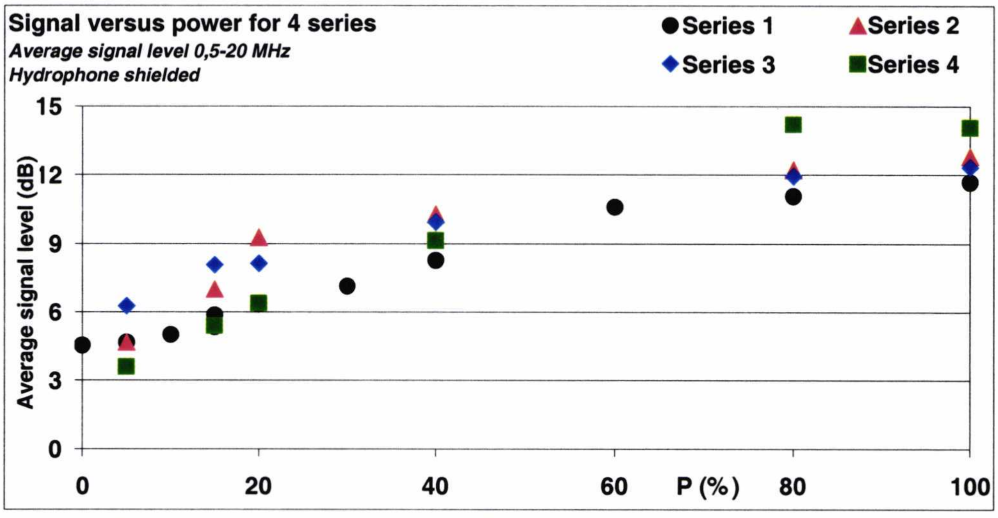


Fig. 15: Four measurement series of the average signal level with shielded Dapco hydrophone. The difference with Fig. 13 is only the shielding. Variations are considerably decreased.

Variation is reduced to 2 to 3 dB (average is 12 dB at high power), while without shielding it was 10 to 15 dB (average is 20 dB). The leaps in the average signal level at 5 to 15% power are absent when the hydrophone is shielded.

Measurements with the Brüel & Kjær-hydrophone

No (low frequency) measurements of the subharmonic frequency component were carried out with the shielded B&K hydrophone, because shielding has hardly any effect on it. High-frequency measurements were however done, because the B&K hydrophone is indeed sensitive in that area, although less than for frequencies up to 200 kHz. Fig. 16 shows the frequency spectrum measured for low power (P_{nom} = 15%).

Between 12,5 and 18,5 MHz there is a broad "plateau", which already appears at low powers. The cause may lie in the specific sensitivities of the hydrophone at these frequencies. This could probably be an indication of cavitation, because the signal increases with increasing power starting at as little as 0% power, just as the average signal level of the Dapco hydrophone.

The average signal level for the region between 0,5 and 20,0 MHz was calculated in the same way and at the same positions as for the Dapco hydrophone. Here it concerned an indicative measurement; therefore only two measurement series were carried out. The result is given in Fig. 17.

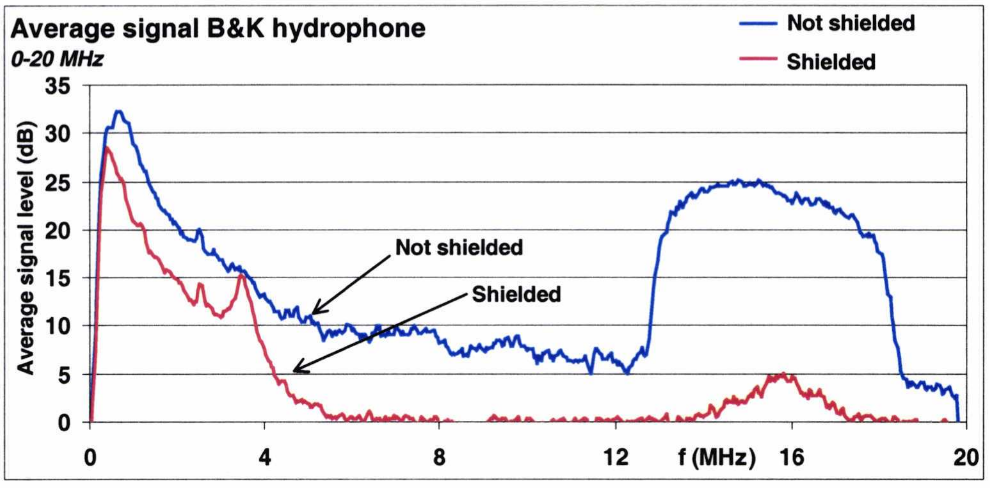


Fig. 16: Frequency spectrum of the B&K hydrophone at low power (15%) and the influence of shielding.

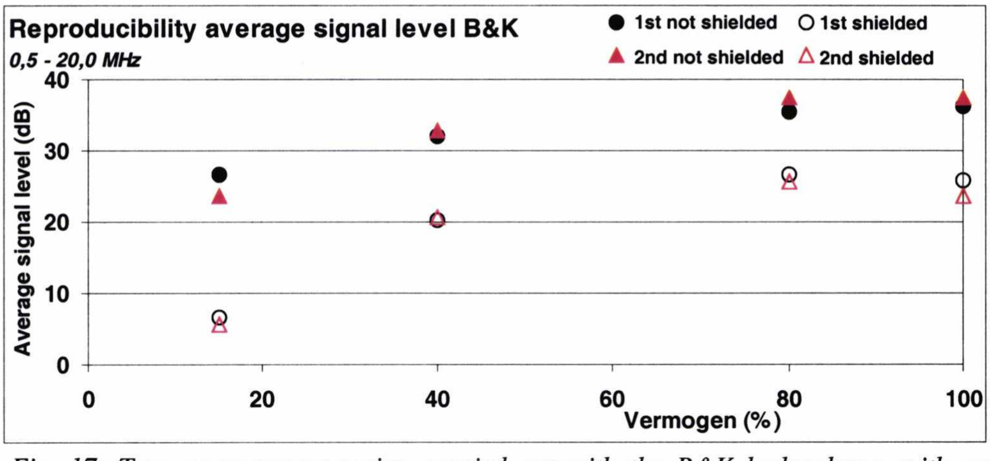


Fig. 17: Two measurement series, carried out with the B&K hydrophone, with and without shielding. The variation of the average signal level is about the same with shielding as without, and is always small.

From 40% nominal power onwards the signal level varies less than 2 dB for the 35 dB signal (not shielded) and 2,5 dB for the 25 dB signal (shielded). These variations are acceptable.

A remaining question is to what extent shielding influences the cavitation in situ. The low frequencies are indeed present and unchanged, but also high frequencies can possibly influence cavitation intensity. In other words: cavitation can possibly reinforce itself. The reduced presence of high frequencies means that the "snowball effect" could be less. No further research has been done to date on this point.

Conclusions of this section

Shielding of the hydrophone offers the advantage that cavitation effects can be studied locally, without the signal being strongly disrupted by instabilities from the cleaning bath. The reproducibility of the measurements of the average signal level up to about 20 MHz is strongly improved by the use of a shielded detector. This applies particularly to the Dapco hydrophone; for the B&K hydrophone insufficient measurement series have been carried out to make a good statement. The variations with this hydrophone seem however to be small enough to allow further research.

4.7 Position dependence of the frequency spectrum for different detectors

The frequency spectrum varies with the position in the cleaning bath. The spectrum is measured at four positions in order to establish the influence of the position on the spectrum. This dependence is in turn influenced by whether or not a shielded hydrophone is used (to measure more locally) and by whether or not frequency modulation, the "sweep", is used (to make the distribution of ultrasound in the bath more homogenous). The results are given here only for the shielded hydrophone, because it seems that shielding improves the reproducibility of measurements significantly, see section 4.6.

The subharmonic frequency peak is not measured again. In section 4.4 it had already been found that switching on the sweep strongly increases the subharmonic, but also that the position dependence (determined there for 8 positions) is small. Shielding has, as was found in section 4.6, little influence on the subharmonic, so new measurements would not contribute much.

The average signal level between 0,5 and 20 MHz was measured with both shielded hydrophones, at four different positions (x,y,z) (see section 4.4 for position definition) and at two sweep settings (switched on and off). The aim was to determine the position dependence of the signal level, to obtain in this way a measure for the homogeneity of the ultrasound field in the bath and to investigate the influence of the sweep, which is expected to make the field in the bath more homogenous.

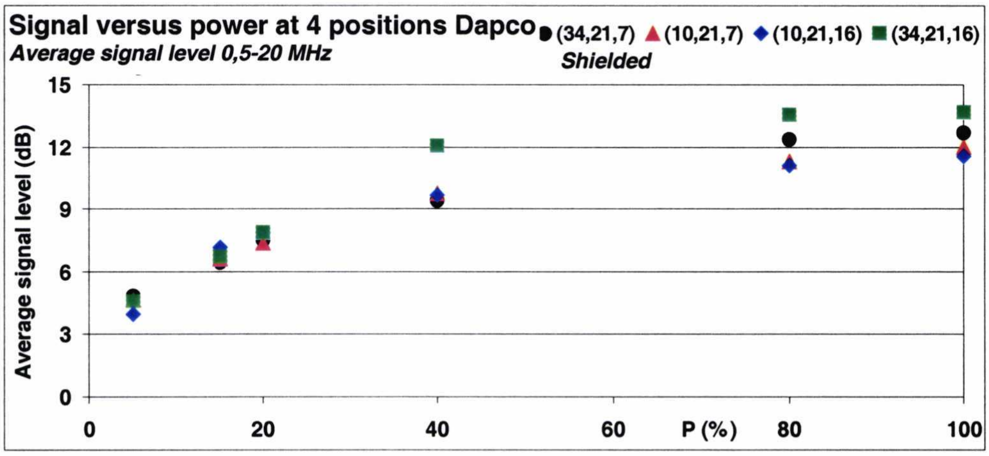


Fig. 18: Power and position dependence of the average signal level as measured using the Dapco hydrophone. Sweep was switched on.

Fig. 18 presents the measurement results with the Dapco hydrophone at 5% to 100% nominal power at four different positions with sweep switched on. Position dependence is only small, as would be expected with the sweep.

Because the power dependence in this stage has already been satisfactorily studied, only the measurement results with 80% nominal power are given from now on for convenience.

In Fig. 19, Fig. 20 and Fig. 21, position dependence of the average signal level is given. Fig. 21 gives the increased signal level of the B&K hydrophone between 12,5 and 18,5 MHz (see also the spectrum in Fig. 16).

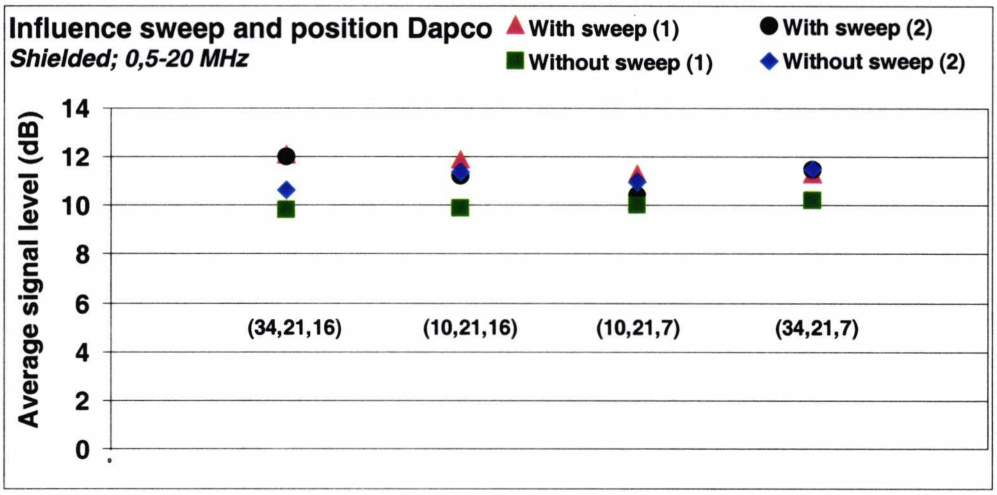


Fig. 19: Influence of the sweep and the position in the bath on the average signal level of 0,5 to 20 MHz for the Dapco hydrophone at 80% power. Two identical measurement series were carried out. The influence of position is not significant (95% confidence) for both sweep settings.

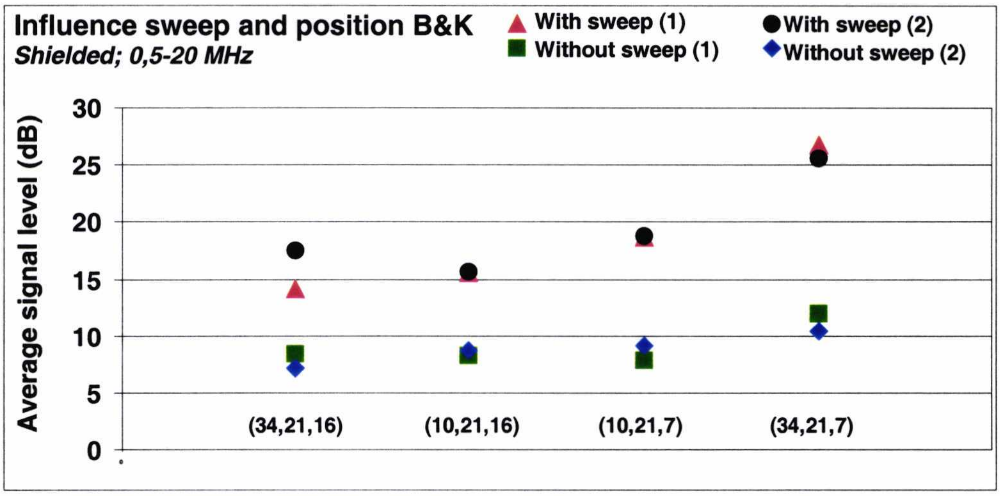


Fig. 20: The influence of sweep and the position in the bath on the average signal level of 0,5 to 20 MHz for the B&K hydrophone at 80% power. Two identical measurement series were carried out. The influence of position is only significant (95% confidence) if the sweep switched on.

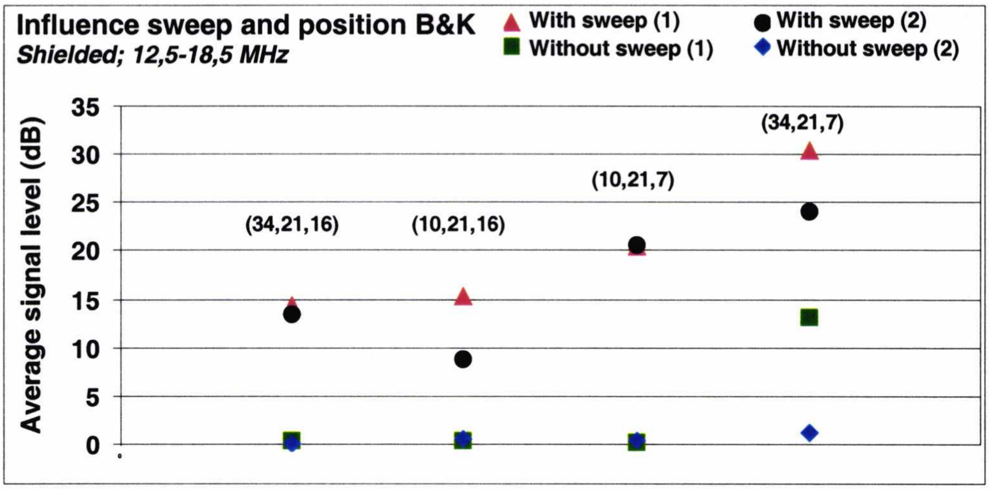


Fig. 21: Influence of the sweep and the position in the bath on the average signal level of 12,5 to 18,5 MHz for the B&K hydrophone. Two identical measurements were carried out. The influence of position is not significant (p = 5%) for both sweep settings.

The following observations were made:

- With the Dapco hydrophone no distinct position dependence was observed. The variation is not more than 1 dB for both sweep settings.
- With the B&K hydrophone a distinct position dependence was observed for the whole spectrum: a variation of 10 dB for sweep "on" and 3 dB for sweep "off".
- With the B&K hydrophone a distinct position dependence was observed with sweep "on" (variation is 15 dB) for the spectrum between 12,5 and 18,5 MHz. For sweep "off" virtually no signal was observed, except for one measurement at position (34, 21, 7) cm. The cause of this was not known.
- At position (34, 21, 7) cm, the signal level is higher than at the other three positions, for measurements with the B&K hydrophone. With the Dapco hydrophone there is no distinct difference.

The position dependence seems in all cases to be stronger with sweep than without, although with the Dapco hydrophone the difference is small. This is not what had been expected beforehand, because it was assumed that the sweep would make the ultrasound field in the bath more homogenous. For a reliable statement to be made, the measurements would have had to be carried out in several positions with several repeat measurements. Within the present project these variations were not applied.

Conclusions from this section

Contrary to expectation, it would appear that use of frequency modulation leads to a less homogenous ultrasound field, mainly with the B&K hydrophone. Because only two measurement series were carried out, further research is necessary to confirm this observation.

5 Research into other detection methods

5.1 Detection of local density changes in the water

Due to the pressure variation in the water caused by ultrasound, the density of the water is position dependent. This is visualised using a Schlieren set-up, by which the refraction of light can be rendered visible. In the initial situation the image is black, but with local changes of density, and with them the refraction index, lighter places emerge in the image. This set-up includes a cuvette, consisting of Schlieren-free glass, water in which ultrasound is transmitted from the bottom using a transducer originally belonging to a cleaning bath. The pattern of standing waves between the transducer and the surface of the water is photographed using the Schlieren set-up, see Fig. 22.

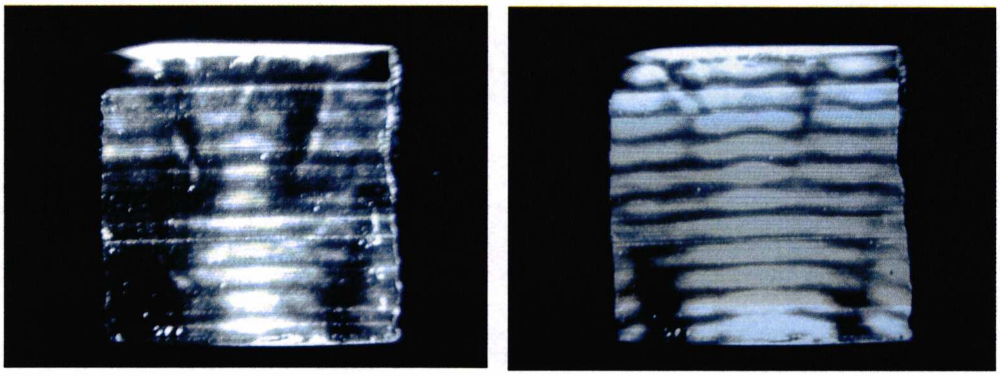


Fig. 22: Example of an ultrasound Schlieren image in a cuvette with water. The transducer in the bottom has a frequency of 54 kHz. On the left: maximal ultrasound pressure p_+=47 kPa. On the right: maximal ultrasound pressure p_+=147 kPa.

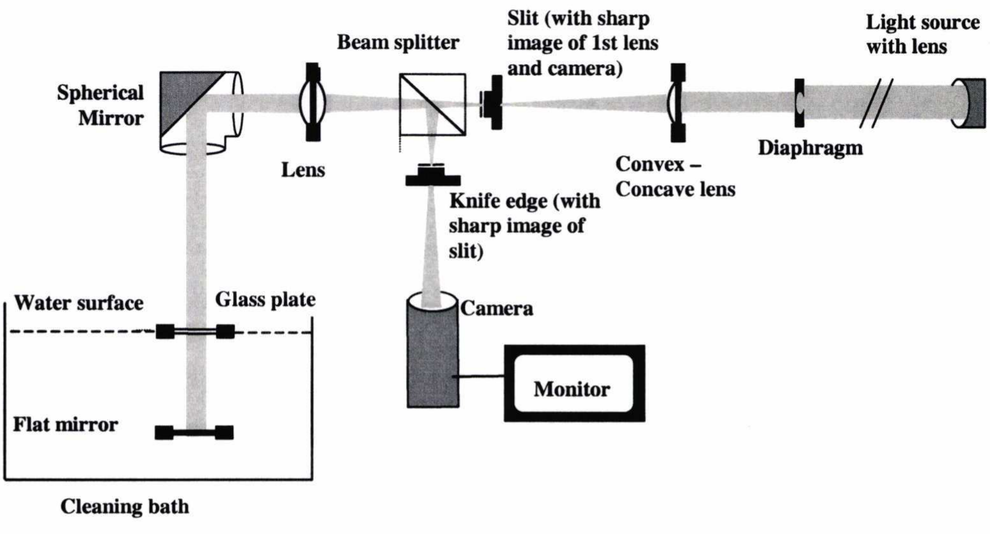


Fig. 23: Schematic view of the Schlieren set-up. The beam of light reaches the cleaning bath via a system of lenses and a beam splitter. From there the light is reflected and reaches the knife edge via the semitranslucent mirror. If there are no local variations in pressure in the bath, the light does not reach the camera, because it falls on the knife material. With small local variations in pressure in the bath, the beam is deflected somewhat and reaches the camera via the knife edge. These deflections in the bath are therefore visible as light areas on the mirror.

However a cleaning bath does not have glass sides, with the result that any possible angle of vision into the bath must be achieved from above and the light beam has to change direction several times. Moreover the introduction of equipment will influence the working of the bath. Despite this the Schlieren set-up was constructed for use in the Branson cleaning bath (see fig. 23).

It did not prove possible to make qualitative measurements of the density variations in water, for the following reasons:

- The surface of the water of the cleaning bath is very unstable. For this reason much light will reflect in an undefined way. A possible way to avoid this is to use a thick sunken glass plate on the surface of the water. This must clearly be mounted independently of the cleaning bath.
- The water in the cleaning bath behaves in a very unstable way. Because of the accompanying forces the water vibrates violently. The image is therefore seriously disrupted. An attempt has also been made to visualise the density variations in a vertical instead of a horizontal direction, by using two mirrors at the bottom of the bath, each at an angle of 45° to the horizontal. In this situation also it proved impossible to make an image on account of the disruption of the water surface and the violent movements in the bath.
- Due to the large dimension of the light beam and the lenses available, the set-up showed rather little sensitivity to small variations in density. To improve this the set-up was reconstructed in different ways, but without satisfactory result.

Conclusion of this section

Because of the problems mentioned above the optical method seems not to be a simple to use alternative for visualising or quantifying the processes in the cleaning bath. Given the experience gained so far, it is not certain whether a large investment in optical equipment would indeed promote any useful result. Against this background the decision has now been made not to proceed any further with the detection of local density changes in the water.

5.2 Heat detection

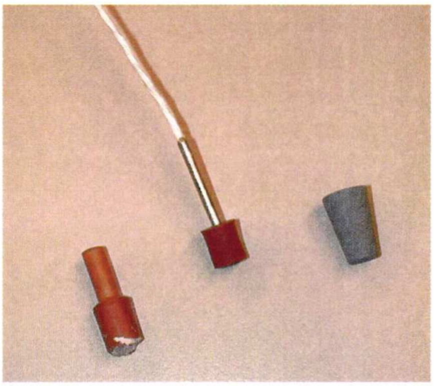


Fig. 24: PTC-probe PT100 sheathed in a rubber sleeve for measuring the temperature to get a measure for the local energy density. Three materials are reproduced: a bottle top (right), Wallgone (centre, with probe) and a third sort of rubber (left) that is eventually not used for measurements, and therefore is not represented in Table 2.

By covering a PTC thermoprobe with a small piece of rubber (of various types, see fig. 24), the field can be characterised locally in the cleaning bath via the equilibrium temperature of the rubber on the position of the thermoprobe. The rubber is expected to warm up by absorbing ultrasound. The outside is in contact with water and thus maintains ambient temperature. The inside is in contact with the thermocouple and will become warmer, because the rubber is a poor heat conductor. To supplement the measurements with the thermoprobe, measurements were also carried out with the infrared camera on the outside of the rubber. The results were obtained in a short measurements series like that given in Table 2.

Table 2: Temperatures and rises in temperature in the cleaning bath as measured with the PTC thermoprobe and with the infrared camera.

Meas no.	Set-up	T_{start}(°C) (probe)	T_{end}(°C) (probe)	ΔT (°C) (probe)	$T_{end,IR}$(°C) and ΔT_{IR}	Remarks
1	Tip of thermoprobe covered by a plastic and kneadable sealant	20,0	21,4	1,4	20,1; 1,4	Tip about 1 cm under water surface; P_{nom}=100%
2	See 1	20,2	25,8	5,6	26,5; 6,3	Tip about 6 cm uinder water surface; P_{nom}=100%
3	Whole thermoprobe covered by a plastic and kneadable sealant	20,4	26,8	6,4	23,5; 4,2	The same
4	See 3	20,8	26,9	6,1	24,1; 4,3	The same
5	Tip of thermoprobe covered by Wallgone	21,2	24,2	3,0	24,2; 4,2	The same
6	See 2	21,5	26,5	5,0	23,8; 3,2	The same; T is position dependent: 26,5-31,1°C; (ΔT = 5,0 to 9,6°C; not searched for extremes). P_{nom}=100%
7	Tip of thermoprobe covered by rubber	22,4	60	38	Not high (too late measured)	T is position dependent: 55-88°C; (ΔT = 33-53°C; not searched for extremes). P_{nom}=100%
8	See 7		55 inst. of 88	≈22 inst. of 65	Not measured	Position at max. ΔT. Rest the same. P_{nom}=5%. Compare with 7.

From measurements in different positions it seems that warming is clearly dependent on the position of the probe (compare also measurements 1 and 2 from Table 2). Also the kind of material used has a great influence; the rate of absorption and heat conductivity of the different rubbers can vary greatly. The high temperature rise which is measured at only 5% power, is striking, because certainly not many high-frequency components are present. This is an indication that the low-frequency 40 kHz wave is absorbed in the rubber. Heat detection is therefore not specific enough to detect the presence of high-frequency components and therefore also cavitation.

Conclusion of this section

Because heat detection is not specific enough to detect cavitation, no further research was carried out on this method.

5.3 Sonoluminescence

The vapour or vacuum bubbles in the cleaning bath implode after a certain period of pulsation. In this process much energy is released, which leads to very high local temperatures. At these temperatures the molecules in the bubbles can reach a higher energy state, as a result of which upon relaxation radiation is emitted as visible light (sonoluminescence, SL). The light can be measured using a photomultiplier. Contact was made with a member of the group working on Fluid Dynamics and Heat Transfer (Faculty of Applied Physics) of the Technical University of Twente (UT), the Netherlands, where much research is being done into SL. The following information regarding SL in a cleaning bath was obtained from him:

- The yield of light is very low also for multibubble SL, such as can occur in cleaning baths. To take a measurement, there must in any case be a sufficient period of integration.
- An SL measurement is local. For a bath a grid must therefore be measured.
- It is possible to measure in depth, for water is transparent to light. However bubbles influence the path of the light, with the result that if there are too many bubbles, it can be difficult to measure at any depth.
- There is a strong interaction between bubbles and the ultrasound field. The many bubbles absorb and diffuse the sound. Interaction of bubbles with each other leads to non-sperical bubbles.
- The amplitude of the pressure variations with degassed water must be minimally 100 to 150 kPa for SL to occur. With non-degassed water about the same is applicable.
- Costs are not very high: the photomultiplier costs € 2500 to € 5000.

Concerning the feasibility of observing SL in a cleaning bath:

- The low yield is a serious problem, certainly in combination with the violent movements in the bath.
- Because multibubble SL is present, the bubbles are not symmetrical (spherical), with the result that the implosion does not occur regularly. This lowers the light yield.
- Because of the multibubble effect, the result of the SL measurement will show considerable variation, even if the bath were to provide a reproducible field.
- Characterising effects deeper in the bath is more difficult because of disturbances such as bubbles, or a turbulent water surface. The contact person from the UT felt strongly that characterising a UG cleaning bath as regards SL would not succeed, even if the bath were to provide a reproducible field.

The National Physical Laboratory (NPL, UK) was also consulted about the functionality and applicability of SL as a detection method. Work is underway to develop a standard cleaning bath, for which the reproducibility of the bath is the main object. This differs from the EZ-project reported here, which was concerned with achieving a practically applicable measurement method to determine the cleaning effect. At the NPL no cleaning experiments were carried out.
At the NPL SL-experiments were carried out, from which it appears that SL can give a quantitative indication of cavitation activity in the bath used: the SL light yield increases monotonically with the power. However, an advanced set-up is needed to observe SL, which is of little use for routine tests of cleaning baths of various sorts and sizes.

Conclusions of this section

- Low light yield can be a problem, although it appears that that can be solved with a more advanced set-up.
- The reproducibility is probably poor.

The set-up which is required to be able to observe SL well enough, is so advanced that the method is difficult to apply practically. For these reasons sonoluminiscence does not appear to be a viable alternative for characterising the processes in the cleaning bath. Against this background the decision was made not to study sonoluminiscence any further as a possible indicator of cavitation.

5.4 Erosion of thin foils

A possibility is to investigate to what extent thin foils are affected by cavitation. Aluminium foil is often used to show visually that cavitation is possibly present in the cleaning bath, because after a short time in the bath, holes appear. However the precise thickness of the foil is of great influence, reproducible positioning in the bath is difficult, and the standard IEC 60866 [1] sets out that the amount of erosion cannot always be related to the cleaning effect.

Conclusion of this section

Because attaining sufficient reproducibility would be difficult and the relation to the cleaning effect very uncertain, the possibility of applying this method quantitatively has not been studied.

6 Comparison between detection methods and the cleaning effect

A comparison was made between the experimental results from chapters 3 and 4. This concerned resp. the 90% soil removal time and the average signal level between 0,5 and 20 MHz in the bath as measured using the two hydrophones. The sub- and ultraharmonic frequency components were not used in the comparison, because they were not easy to reproduce; see Fig. 12 and 13. For this reason all measurements were taken with the shielded hydrophone. Regarding the cleaning measurements, only the second group of measurements was used in the comparison, because they were specifically carried out with the same settings as the ultrasound measurements.

The variation between similar cleaning experiments can be compared with the variation between the series of measurements, such as appears e.g. for the series in Fig. 15. The raw data to the figures in chapter 4 are used for this. Table 3 attempts to make a connection between the cleaning time and the average signal level.

Table 3: Soil removal time compared with the average signal between 0,5 and 20 MHz, as measured by the two hydrophones. The figures in brackets give the total standard deviation. The settings for both kinds of experiments are the same. Sweep was switched on. The results in the last column give are based on measurements at one position; the two central columns give spatial average signal levels. Because with the B&K hydrophone only two identical measurements were carried out which had a very small variation, no standard deviation is given with them.

	90% removal time (min.)	**Dapco signal (spatial avg) (dB)**	**B&K signal (spatial avg) (dB)**	**Dapco signal (one position) (dB)**
P = 40%	10,3 (1,6)	9,9 (1,6)	20,6	9,4 (2,0)
P = 80%	7,7 (0,9)	11,8 (2,0)	26,2	12,3 (3,1)
Factor	1,3	1,6	3,6	2,0

From Table 3 it appears that a higher signal (at higher power) leads to faster soil removal and that the relative decrease in the soil removal time largely corresponds to the relative increase in the signal. The variations spreads are substantial, especially in the acoustic measurements, but in the average result this relation is visible.

Conclusion for this comparison

This result indicates points of departure for carrying out further research into the possibility of relating the effectiveness of a cleaning bath - quantified by cleaning rate - to the acoustic measurement results.

7 Conclusions

7.1 Survey of the use of ultrasound cleaning baths in hospitals

- From the survey conducted over 15 hospitals, it appears that in practice checks on the extent of cleaning consist mostly of only a visual inspection of the objects cleaned. No measurable requirements have been set for the result of this step within the whole cleaning and sterilisation process.

7.2 Development of standard soiled test objects

- Ceramic tiles with Edding marker ink as the standard soiling seem to be a suitable test object which can fairly reproducibly be produced and, moreover, which provides a good adhesion of the soil to the surface. It seems nevertheless not possible for the time being to manufacture representative test objects, with organic soil, which have these characteristics in sufficient measure. In particular the adhesion is not strong enough.
- The 90% removal time for these test objects is 10,3 min. at 40% power and 7,7. min. at 80% power if the ink is applied in one stroke. The standard deviation of the measurements is around 10% over the measurement series and the total standard deviation, taking into account the variation between individual tiles, is about 16%. Given the process involved in the cleaning bath, this is a reasonable result. Possible causes for the variation: a non-reproducible ultrasound field and a suboptimal preliminary treatment. Non-reproducible soil application can also be a cause, although this seems to have no great influence on the total variation, see section 3.3.

7.3 Research into the ultrasound field in a specific cleaning bath

- The ultrasound field in the bath has sufficiently stabilised after an hour to carry out measurements of ultrasound pressure and frequency components.
- Turning on the sweep, adding detergents and to a lesser extent raising the temperature influences the sub- and ultraharmonic frequency components.
- The subharmonic frequency component (20 kHz) and the signal level averaged over a wide frequency range (0,5 to almost 20 MHz) are the two best candidates to relate to the cleaning effect.
- Measurements with a free hydrophone in the cleaning bath are greatly disturbed by instabilities in the bath. This is apparent from the great variations in the subharmonic (around 6 dB for both hydrophones) and the average signal level (10 to 15 dB) between measurements taken under similar circumstances.
- The use of the shielded hydrophone to measure the average signal level (high frequency), gives noticeably better reproducible results than the free hydrophone. The variation is cut back to 2 to 3 dB for both hydrophones.
- None of the other methods of detecting cavitation are promising enough for further development as a practically applicable and reproducible method for establishing the effectiveness of cleaning baths.

- With the B&K hydrophone a clear position dependency was observed for the average signal level; this was not the case for the Dapco hydrophone. From the measurements it does not seem that the field is more homogenous when the sweep is switched on.

7.4 Comparison between rate of cleaning and acoustic measurements

From the comparison between the results of the soil removal (chapter 3) and the acoustic measurements (chapter 4) it seems that the soil removal proceeds faster if the acoustic signal, averaged over 0,5 to 20 MHz, is higher. The relative decrease in the removal time largely fits in with the relative increase in the signal. In the acoustic measurements, the variations are larger than in the cleaning measurement.

This result provides sufficient starting points for carrying out further research into the possibility of relating the effectiveness of the cleaning bath - quantified by the rate of cleaning - to the acoustic measurement results.

7.5 Summary

It seems possible in the future to produce satisfactorily reproducible test objects for establishing the cleaning effect. The average high-frequency signal level as measured using a shielded hydrophone is the most promising parameter for relating to the cleaning effect. Much effort will be necessary to make the method more routinely applicable. Reproducibility of standard soiled test objects is now adequate, but can possibly be improved even more.

8 Signatures

Authors	Signatures
R.A. Bezemer M.Sc. MTD	
R.T. Hekkenberg Senior Research Manager	
Review	Signature
J.A.M. van Boxsel, PhD Head of Section	

9 References

1 International Electrotechnical Commission, *Investigations on test procedures for ultrasonic cleaners*, Technical Report IEC 60866, 1987.

2 R.A. Bezemer and R.T. Hekkenberg, *Literature study into use, efficiency and standardisation of ultrasonic cleaning baths*, TNO research report PG/TG/98.145, TNO Prevention and Health, November 1998.

3 M. Hodnett and B. Zeqiri, *A strategy for the development and standardisation of measurement methods for high power/cavitating ultrasonic fields: Review of High Power Field Measurement Techniques*, NPL Report CIRA(EXT)015, National Physical Laboratory, January 1997.

4 B. Zeqiri, M. Hodnett and T.G. Leighton, *A strategy for the development and standardisation of measurement methods for high power/cavitating ultrasonic fields: Final Project Report*, NPL Report CIRA(EXT)016, National Physical Laboratory, January 1997.

5 F.J. Fuchs, *Ultrasonic Cleaning: Fundamental Theory and Application*, URL: http://www.pmrsystems.com/contents.html.

6 H. Houke, *The Ins and Outs of Ultrasonic Cleaning*, 1990, URL: http://www.healthsonics.com/houke.htm.

7 L.A. Crum, *Comments on the evolving field of sonochemistry by a cavitation physicist*, Ultrasonics Sonochemistry **2**(2) (1995) S147-152.

8 T.G. Leighton, *Bubble population phenomena in acoustic cavitation*, Ultrasonics Sonochemistry **2**(2) (1995) S123-136.

9 B. Zeqiri, S.C. Davies, P.N. Gelat, M. Hodnett and U.I. Lula, *Novel sensors for monitoring acoustic cavitation*, Proceedings of the 2000 IEEE Ultrasonics Symposium, 417-410, 2000.

Appendix

Survey of the use of ultrasound baths

Applied ultrasound survey KW2 V&M

Customer's reference number:

Ultrasound bath

Brand of ultrasound bath:
Type of ultrasound bath:
Closed compartment: yes/no

Water

Tap water: yes/no
Demineralised water: yes/no
RO water: yes/no
Other:
Amount of water:
Frequency of water change:

Detergents

Are detergents added? yes/no
If yes:
- brand of detergent:
- type or sort:
- manufacturer's recommended dilution/concentration:
- concentration/dilution used by user:

Load

Sort of load:
Method of loading:
Is the load treated before US treatment? yes/no
If so, what is done?

Soil

Human body fluid: yes/no
Oxidation: yes/no
Other:

Bath settings

Temperature:
Frequency:
Duration of treatment:
Freely adjustable parameters: yes/no
If yes:

Customer definitions

What was within the institute expected of the US bath?
Was this expectation realised by the US bath? yes/no

What is used within the institute as a definition of clean?
Visually clean: yes/no
Bacterially clean: yes/no
Swap test clean: yes/no
Other:

Survey Results

Brand / Type		Sanamij ?	Branson 47KWH	Rovevi 95071101	Linden ?	Branson ?	Branson mtn-2618-40-18/s	Branson 7000 serie	Branson 8200	Ultrawave IND 5535	Ultrawave ?	Ultrawave u2800d	Branson ?	Branson B7040-12PZT	Branson 8510	Branson ?
Bath	*Closed*	x	x	x	x	x	x	x	x	x	x	x		x	x	x
	Open												x			
Water	*Tap*			x			x			x	x		x		x	
	Demi	x	x			x		x				x				x
	RO				x									x		
	Other								Deionised Tap							
	Amount	45	24	35	50	40	77	110	18	90	40	30	30	40	20	35
Frequency	*Fixed*		2	3	8	4	4	continuous	8	4	?	8	4	2	8	4
	None	x									?					
Detergents	*Used*	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Brand	instruzym	neodisher US	neodisher	neodisher medizym	neodisher US	Ruhof endozyme	henkel	biotex	neodisher	secumatic	biotex	neodisher US	neodisher US	neodisher	?
	Type	enzym	enzym	LM2	enzym	enzym	enzym	P3-coa CP92	green	LM2	FRE	?	enzym	enzym	LM2	
Concentration	*Prescription*	1	5-15	0,5-2	1,2	3	0,75	0,9	0,4	8	0,1	?	2-4	1-3	0,5-2	?
	Used	1	8	2	1,2	1	0,75	0,9	?	8	0,1	?	2,5	1-3	2	?
Load	*Pre-treatment*	Y	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y
	How	flush	Flush	flush	flush		Soak		flush	flush	flush	flush	flush	Cleaning by hanc	flush	flush
Soil	*Human fluid*	x	X	x	x	x	x		x	x	x	x	x	x	x	x
	Oxidation				x			x			x		x		x	
	Other							Y								
	How other							See remark								
Settings	*Temperature*	37,5	35	40	37,5	40	40	50	?	30	37,5	40	40	40	27,5	40
	Frequency	?	47	40	35	40	?	3	?	35	35	30	40	40	40	40
	Time (minutes)	6,5	5	2	5	Variable	3	5	5	5	3	5	1,5	3	4	5
	Freely adjustable	N	N	N	N	time	N	N	Time	N	N	time / temp	time	time	temp / time	temp / time
Expected result		pre-cleaning	pre-cleaning	pre-cleaning	Visually clean	Visually clean	pre-cleaning	pre-cleaning	pre-cleaning	pre-cleaning	pre-cleaning	pre-cleaning	pre-cleaning	Difficult places	Difficult places	Difficult places
Result realised?		Y	Y	nee	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	x	x
Definition Clean	*Visual*		x		x		x	x	x	x	x	x	x	x	x	x
	Bacterial	x		x	x	x										
	swap test				x											
	Other			x				x								
	How other			"domestically clean"				pH, conductivity and TOC								
Remarks								Burned proteins					If necessary more often; 15 min de-aerated			