An Explanation of Ultrasonic Cleaning

Ultrasonic cleaning is a result of sound waves introduced into a cleaning liquid by means of a series of "transducers" mounted to the cleaning tank. The sound travels throughout the tank and creates waves of compression and expansion in the liquid. In the compression wave, the molecules of the cleaning liquid are compressed together tightly. Conversely, in the expansion wave, the molecules are pulled apart rapidly. The expansion is so dramatic, that the molecules are ripped apart creating microscopic bubbles. The bubbles are not seen by the naked eye since they are so small and exist for only a split second of time. The bubbles contain a partial vacuum while they exist. As the pressure around the bubbles become great, the fluid around the bubble rushes in, collapsing the bubble very rapidly. When this occurs, a jet of liquid is created that may travel at this very high rate. They rise in temperature to as high as 5000 degrees C, which is roughly the temperature of the surface of the sun. This extreme temperature, combined with the liquid jet velocity provides a very intense cleaning action in a minute area. Because of the very short duration of the bubble expansion and collapse cycle, the liquid surrounding the bubble quickly absorbs the heat and the area cools quickly. As a result, the tank and liquid becomes only warm and does not heat up due to the introduction of parts during the cleaning process.

The Application of Ultrasonic Cleaning

Many articles exist describing "how ultrasonic cleaning works". The goal of this article is to help develop an understanding of the various components that ensure good ultrasonic cleaning.

First, establish a cleaning need, along with a determinantion as to how to measure the level of cleanliness. A few examples of measuring cleanliness include various levels of particle count, miscroscopic inspection, and a variety of adhesion tests, including the clear tape test that has the ability to remove additional contamination. These are just a few examples of cleanliness measurement.

There are seven major concerns related to successful ultrasonic cleaning:

1. **Time**
2. **Temperature**
3. **Chemistry**
4. **Proximity to the transducer/part fixture design**
5. **Ultrasonic output frequency**
6.

Watts per gallon

7

Loading - the volume (configuration) of the part being cleaned

TIME:

Typical cleaning times may vary tremendously - how dirty is the part and how clean is clean.
As a place to start, a normal trial period is two to ten minutes, since very few parts are sufficiently clean within a few seconds. Ultrasonic cleaning is not just a quick dip and zap, it's clean. Pre-cleaning may be required to remove gross contamination or to chemically prepare the parts for a final clean. Some applications require more than one ultrasonic cleaning stage to complete the required cleaning. Ultrasonic agitated rinsing is required in some cases to more thoroughly remove the wash chemicals.

TEMPERATURE/CHEMISTRY:

Temperature and chemistry are closely related. Generally, ultrasonic cleaning in an aqueous solution is optimum at 140 degree F. Some high pH solutions will require the temperature to be higher to enhance the synergistic effect of the chemistry. The chemical pH is a good place to start; however, chemistry is not the subject of this article.

The following should be considered the main components of aqeous ultrasonic cleaning chemistry:

A. Water - hard, soft, DI or distilled
B. pH
C.
    Surfactants
    Wetting agents
    Dispersants
    Emulsifiers
    Saponifiers
D.
    Optional ingredients
    Sequestrants
    Inhibitors
    Buffering agents
    Defoamers

The chemical formulation must consider all of the above characteristics.

Some chemicals that are designed for spray cleaning, or that include rust inhibitors, are not suitable for ultrasonic cleaning.

PROXIMITY TO THE TRANSDUCER:

The procedure for ultrasonic cleaning is generally as follows: Put parts in basket and place basket through three or four process steps; ultrasonic wash, spray rinse (optional), immersion rinse, dry. Some parts loaded in baskets can mask or shadow from the radiated surface of the ultrasonic transducers. Most ultrasonic cleaning systems are designed for specific applications. Bottom-mounted transducers or side-mounted transducers are decided upon during the process design stage. Automated systems must specifically address the location of the transducers to insure uniformity of the cleaning. Some parts require individual fixturing to separate the part for cleaning or subsequent processes. Some parts require slow rotating or vertical motion during the cleaning to insure critical cleanliness.

ULTRASONIC OUTPUT FREQUENCY:

Many technical articles claim that high frequencies penetrate more and lower frequencies are more aggressive. The majority of the ultrasonic cleaning that is done in industrial applications today uses 40 kHz as the base frequency. Lower frequencies, such as 20 - 25 kHz, are used for large masses of metal where ultrasonic erosion is of little consequence. The large mass dampens or absorbs a great amount of the ultrasonic cleaning power.

WATTS PER GALLON:

In general, smaller parts, requiring more critical cleaning, require higher watts per gallon to achieve the desired level of cleanliness. Most industrial ultrasonic cleaning systems use watt density from 50 - 100 watts per gallon. However, there is what is known as "the large tank phenomenon", which indicates that tanks over 50 gallons usually requie only about 20 watts per gallon. The only explanation available is a point of diminishing returns with regard to ultrasonic power.

LOADING:

Loading of the part(s) to be cleaned must be considered, with regard to the shape and density. A large dense mass will not allow internal surfaces to be thoroughly cleaned (i.e., metal castings). A rule of thumb for loading is that the load by weight should be less than the weight of half the water volume, i.e., in 5 gallons, approximately 40 lbs. of water, the maximum workload should be less than 20 pounds. In some cases, it is better to ultrasonically clean two smaller loads, rather than one larger load.

The above information is not meant to give all the details to utilize ultrasonic cleaning techniques. This information is to help the process designer gain some insight into the variables of industrial ultrasonic cleaning.

Ultrasonic FAQ

What is "cavitation"? top

"Cavitation" is the rapid formation and collapse of millions of tiny bubbles (or cavities) in a liquid. Cavitation is produced by the alternating high and low pressure waves generated by high frequency (ultrasonic) sound. During the low pressure phase, these bubbles grow from microscopic size until, during the high pressure phase, they are compressed and implode.

What is "degassing", and why should it be done? top

"Degassing" is the initial removal of gases present in the solution. Useful cavitation occurs after gasses have been removed from the cleaning solution, leaving a vacuum in the formed bubble. When the high pressure wave hits the bubble wall, the bubble collapses; it is the energy released by this collapse that will assist a detergent in breaking the bonds between parts and their soils.

How do I get the best ultrasonic cleaning? top

There are many considerations important to ultrasonic cleaning. Optimizing these variables will produce the best cleaning. The most important decisions to be made are choosing the proper cleaning solution, cleaning at the right temperature for the correct amount of time, and choosing the right size and type of ultrasonic cleaner.

Can ultrasonic cleaning damage my parts? top

With certain cautions, ultrasonic cleaning is considered safe for most parts. While the effects of thousands of implosions per second is very powerful, the cleaning process is safe since the energy is localized at the microscopic level. The most important cautionary consideration is the choice of cleaning solution. Potentially adverse effects of the detergent on the material being cleaned will be enhanced by the ultrasonics. Ultrasonic cleaning is *not* recommended for the following gemstones: opal, pearl, emerald, tanzanite, malachite, turquoise, lapis and coral.

What is "direct" and "indirect" cleaning? top
Direct cleaning occurs when the parts are cleaned in a cleaning solution which fills the cleaner, usually inside a perforated tray or mesh basket. The limitation of direct cleaning is that a solution must be chosen that will not damage the ultrasonic cleaner. Indirect cleaning involves placing the parts to be cleaned in an inner non-perforated tray or beaker that often contains a solution that the user may not want directly filling the ultrasonic tank. When choosing indirect cleaning, make sure that the water level inside the tank itself is maintained to the fill line (about 1" from the tank top) at all times.

Why is a special solution required for cleaning? top
Soils adhere to the parts... if they didn't, the soil would just fall off the parts! The purpose of the solution is to break the bonds between parts and their soils. Water alone has no cleaning properties. The primary purpose of the ultrasonic activity (cavitation) is to assist the solution in doing its job. An ultrasonic cleaning solution contains various ingredients designed to optimize the ultrasonic cleaning process. For example, increased cavitation levels result from reduced fluid surface tension. An ultrasonic solution will contain a good wetting agent or surfactant.

What cleaning solution should I use? top
Modern ultrasonic cleaning solutions are compounded from a variety of detergents, wetting agents and other reactive components. A large variety of excellent formulations are available, designed for specific applications. Proper selection is crucial for acceptable cleaning activity and to preclude undesirable reactivity with the part being cleaned. Crystal Electronics can help you to identify either the optimal 'stock' cleaning formula, or likely candidates to test and evaluate.

What cleaning solution shouldn't I use? top
Flammables or solutions with low flash points should never be used. The energy released by cavitation is converted to heat and kinetic energy, generating high temperature gradients in the solution, and can create hazardous conditions with flammable liquids. Acids, bleach and bleach by-products should generally be avoided, but may be used with indirect cleaning in a proper indirect cleaning container, such as a glass beaker, and appropriate care. Acid and bleach will damage stainless steel tanks, and/or create hazardous conditions.

When should solutions be changed? top
Cleaning solutions should be replenished when a noticeable decrease in cleaning action occurs, or when the solution is visibly dirty or spent. A fresh batch of solution at each cleaning session is usually not required.

Why must I keep solution at the tank's level indicator? top
The solution level should always be maintained at the level indicator in the tank, with trays or beakers installed. The ultrasonic cleaning system is a 'tuned' system. Improper solution levels will change the characteristics of the environment, can affect the system frequency, decrease effectiveness, and potentially damage the cleaner. Maintaining the proper solution level provides optimum circulation of solution around parts, and protects heaters and transducers from overheating or stress.

What is the length of cleaning time? top
Cleaning time will vary, depending on such things as soil, solution, temperature and the degree of cleanliness desired. Highly visible removal of soils should start almost immediately after the ultrasonic cleaning action begins. Cleaning time adjustment is the easiest (and most often misapplied) factor used to compensate for process variables. Although new

application cycle duration can be approximated by an experienced operator, it usually must be validated by actual use with the chosen solution and the actual soiled parts.

What is the purpose of the unit heater? top
The primary purpose of the unit heater is to maintain a solution temperature between cleaning cycles. The tremendous energy released by cavitation will generate the heat for cleaning.

How do I know if the unit is cavitating properly? top
Most poor cleaning usually results from improper control of one or more process variable(s); such as choosing the wrong detergent solution, insufficient heat, or not allowing enough time for the particular soil to be removed. If you suspect that your ultrasonic cleaner is not cavitating properly, there are two simple tests you can perform: the "glass slide" test and the "foil" test.

How do I perform the "glass slide" test? top
Wet the frosted portion of a glass slide with tap water and draw an "X" with a No. 2 pencil from corner to corner of the frosted area. Making sure that the tank is filled to the fill line, immerse the frosted end of the slide into fresh cleaning solution. Turn on the ultrasonics. The lead "X" will begin to be removed almost immediately, and all lead should be removed within ten seconds.

How do I perform the "foil" test? top
Cut three small pieces of aluminum foil about 4" x 8" each. Fold each piece over a rod that you will use to suspend the foil in the tank. A clothes hanger works well. Your cleaner should be filled with an ultrasonic cleaning solution, degassed, and brought up to normal operating temperature. Suspend the first "square" in the center of the tank and the other two a couple of inches from each end of the tank. Make sure that the tank is filled to the fill line, and turn on the ultrasonics for about ten minutes. Remove the foil and inspect: All three pieces of aluminum foil should be perforated and wrinkled to about the same degree.

Why must trays or beakers be used? top
Items being cleaned should never be placed directly on the tank bottom. Transducers (which produce the ultrasound) are bonded to the bottom of the tank. Items resting directly on the tank bottom can damage the transducers and/or reduce cavitation. Additionally, a tray or beaker will position the item within the optimal cleaning zone of the tank. The tray or beaker will also hold the load together and allow for easy, no-touch removal, draining and transport of the items to the next step in the cleaning process.

What is the optimum cleaning temperature? top
Heat usually enhances and speeds up the cleaning process, and most detergent solutions are designed to work best at an elevated temperature. The best way to find the optimum temperature, which will give you the fastest, cleanest and safest results, is to run tests. Usually, the best results are within the 50¡C to 65¡C range.

Is rinsing required after cleaning cycles? top
Rinsing is recommended to remove any chemical residue, which could be harmful to the part. Parts can be rinsed right in your ultrasonic cleaner, using a clean water bath, or in a separate tub containing tap, distilled or deionized water.

Why shouldn't I leave my cleaner on constantly? top
Low solution levels can seriously damage your cleaner. Running your unit continuously runs

the strong risk of lowered levels as the solution evaporates, especially when heated. Getting into the habit of shutting off the ultrasonics when not in use, and monitoring the solution level when in use, will yield many years of trouble free service from your ultrasonic cleaner.

Maximizing Overall Cleaning Effect

Cleaning Chemical selection is extremely important to the overall success of the ultrasonic cleaning process. The selected chemical must be compatible with the base metal being cleaned and have the capability to remove the soils which are present. It must also cavitate well. Most cleaning chemicals can be used satisfactorily with ultrasonics. Some are formulated especially for use with ultrasonics. However, avoid the non-foaming formulations normally used in spray washing applications. Highly wetted formulations are preferred. Many of the new petroleum cleaners, as well as petroleum and terpene based semi-aqueous cleaners, are compatible with ultrasonics. Use of these formulations may require some special equipment considerations, including increased ultrasonic power, to be effective.

Temperature was mentioned earlier as being important to achieving maximum cavitation. The effectiveness of the cleaning chemical is also related to temperature. Although the cavitation effect is maximized in pure water at a temperature of approximately 160°F, optimum cleaning is often seen at higher or lower temperatures because of the effect that temperature has on the cleaning chemical. As a general rule, each chemical will perform best at its recommended process temperature regardless of the temperature effect on the ultrasonics. For example, although the maximum ultrasonic effect is achieved at 160°F, most highly caustic cleaners are used at a temperatures of 180°F to 190°F because the chemical effect is greatly enhanced by the added temperature. Other cleaners may be found to break down and lose their effectiveness if used at temperatures in excess of as low as 140°F. The best practice is to use a chemical at its maximum recommended temperature not exceeding 190°F

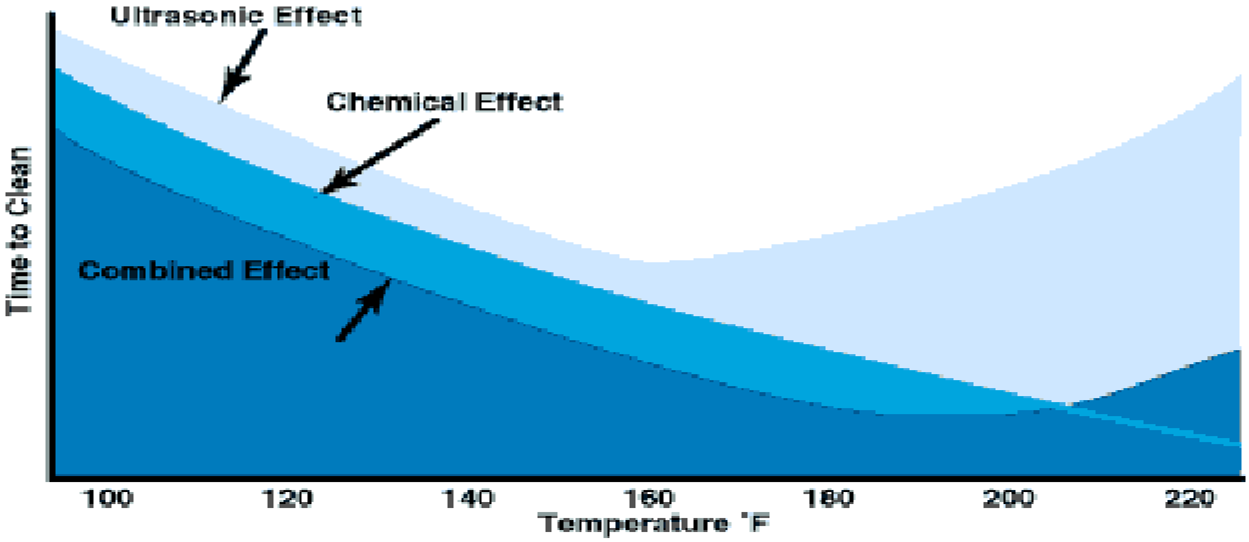
Degassing of cleaning solutions is extremely important in achieving satisfactory cleaning results. Fresh solutions or solutions which have cooled must be degassed before proceeding with cleaning. Degassing is done after the chemical is added and is accomplished by operating the ultrasonic energy and raising the solution temperature. The time required for degassing varies considerably, based on tank capacity and solution temperature, and may range from several minutes for a small tank to an hour or more for a large tank. An unheated tank may require several hours to degas. Degassing is complete when small bubbles of gas cannot be seen rising to the surface of the liquid and a pattern of ripples can be seen.

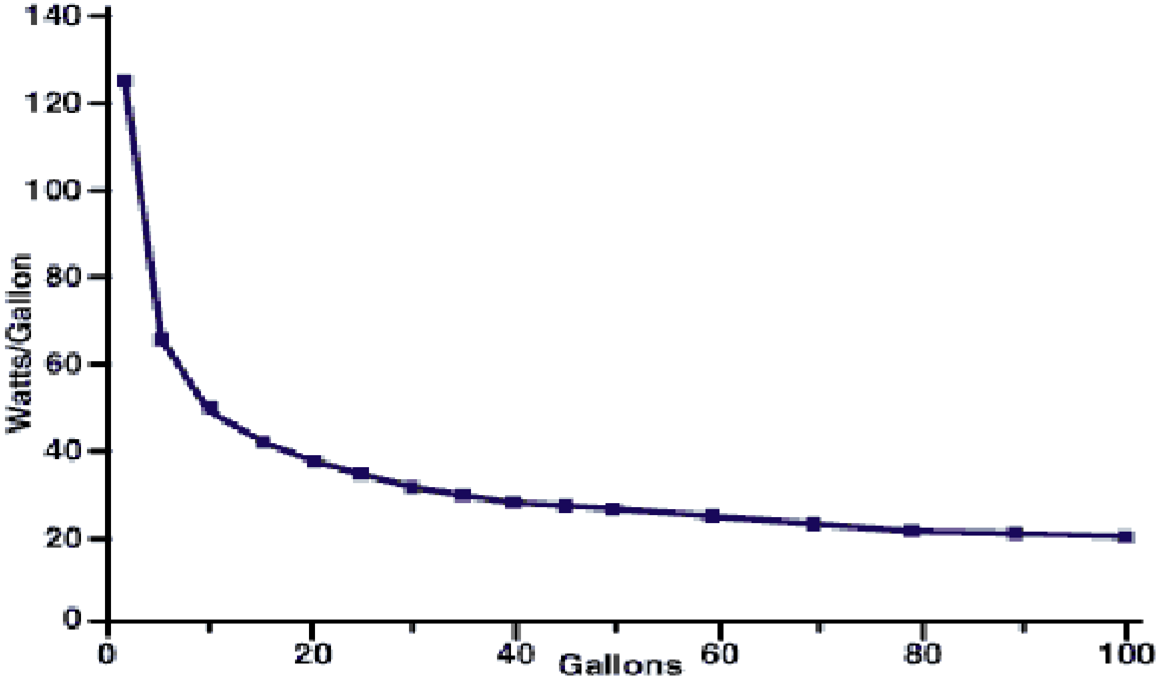
The Ultrasonic Power delivered to the cleaning tank must be adequate to cavitate the entire volume of liquid with the workload in place. Watts per gallon is a unit of measure often used to measure the level of ultrasonic power in a cleaning tank. As tank volume is increased, the number of watts per gallon required to achieve the required performance is reduced. Cleaning parts that are very massive or that have a high ratio of surface to mass may require additional ultrasonic power. Excessive power may cause cavitation erosion or "burning" on soft metal parts.

If a wide variety of parts is to be cleaned in a single cleaning system, an ultrasonic power control is recommended to allow the power to be adjusted as required for various cleaning needs. Part Exposure to both the cleaning chemical and ultrasonic energy is important for effective cleaning. Care must be taken to ensure that all areas of the parts being cleaned are flooded with the cleaning liquid. Parts baskets and fixtures must be designed to allow penetration of ultrasonic energy and to position the parts to assure that they are exposed to the ultrasonic energy. It is often necessary to individually rack parts in a specific orientation or rotate them during the cleaning process to thoroughly clean internal passages and blind holes.

Conclusion

Properly utilized, ultrasonic energy can contribute significantly to the speed and effectiveness of many immersion cleaning and rinsing processes. It is especially beneficial in increasing the effectiveness of today's preferred aqueous cleaning chemistries and, in fact, is necessary in many applications to achieve the desired level of cleanliness. With ultrasonics, aqueous chemistries can often give results surpassing those previously achieved using solvents. Ultrasonics is not a technology of the future -- it is very much a technology of today.





Custom Ultrasonic System

September 15, 2003 — L&R Manufacturing Company was awarded the bid for a custom manufactured Ultrasonic Cleaning System. The “Grand Sweep 4015” measures 50’” x 50” and stands 65” high and was recently shipped to a major automotive manufacturer. The stainless steel constructed tank holds 415 gallons and will be used to clean a millhead cutter unit used in automobile production.

This made-to-order tank is powered by two immersible racks and four 4002 CPO ultrasonic generator units generating 6000 watts of ultrasonic power, 3.75 watts per square inch and 14.4 watts per gallon. The operating ultrasonic frequency is 43kHz. For over 70 years, L&R has been serving a variety of industries around the world for virtually any cleaning application.

For more information about custom ultrasonic cleaning tanks or other ultrasonic cleaning systems, accessories and solutions formulated for industrial and manufacturing cleaning, contact L&R at www.LRultrasonics.com.

Resume:

3.75 W/sq-inch = 0.58125 W/cm2 (this is OK)
14.4 W/Gallon = 3.804077 W/lit (this is too low)

MPI standards:
0.5 to 2 W/cm2
10 to 30 W/lit

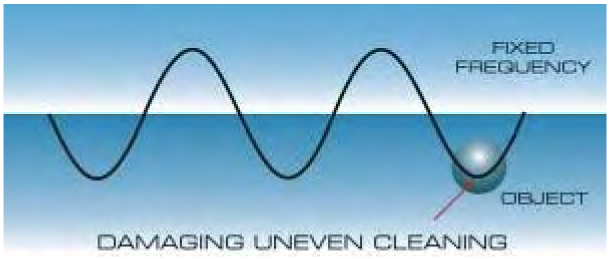
Pulse Swept Power®

Ultrasonics is now considered “world’s best practice” when it comes to cleaning of delicate instruments such as those used for “Key Hole Surgery”. Soniclean's patented *Pulse Swept Power®* sets exciting new standards for ultrasonic cleaning by improving the effectiveness and efficiency of the cleaning process. Pulse Swept Power® technology is now recognised by many leading institutions as the safest and most cost efficient method of cleaning surgical instruments.

Soniclean pioneered Pulse Swept Power® in the early 1990's and since then have made further advances and improvements to this innovative approach to the cleaning surgical instruments.

How does Pulse Swept Power® in Ultrasonics work?

Unlike conventional ultrasonic machines, Pulse Swept Power® prevents standing waves from developing in the cleaning tank and instead distributes the ultrasonic energy more evenly throughout the tank. This greatly increases the power efficiency of the machine and results in a more even clean.



Conventional fixed-frequency ultrasonic cleaning.

Soniclean's Pulse Swept Power® cleans evenly and efficiently.

Pulse Swept Power® has been designed to meet and exceed the highest ISO Clean Room Standards and is CE and TGA compliant.

Frequently Asked Questions (FAQ)

1. **What is ultrasonics and how does it work?**
2. **Why do I need to degas the fluid prior to the cleaning process?**
3. **What detergents should I use for surgical and dental instruments?**
4. **How long do I need to clean the surgical instruments?**
5. **How often do I need to change water?**
6. **Can I put my hands into the water when my ultrasonic cleaner is activated?**
7. **Do I have to operate my ultrasonic cleaner with lid closed?**
8. **How do I test the ultrasonic efficiency of my ultrasonic cleaner?**
9. **Why I should use a basket/tray?**
10. **How do I clean my ultrasonic cleaner?**
11. **What is the warranty?**

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1. What is ultrasonics and how does it work?

Ultrasound is energy in the form of a wave motion which is above the maximum level of audible sound. This energy is transmitted to the cleaning solution via a bank of transducers underneath the machine. The result of this process is termed cavitations, tiny bubbles of vaporized liquid which explode when they reach a high pressure. Cleaning takes place as shock waves dislodge soil from the surface of the contaminated articles placed in the water bath.

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2. Why do I need to degas the fluid prior to the cleaning process?

After filling the tank with water (not temperature critical) and adding a measured amount of recommended detergent, then switch on your machine for a few minutes in order to expel dissolved air bubbles as these bubbles will affect the cleaning effectiveness. You will notice a change in sound and hear a high pitch "hissing" sound when degassing process is completed. When loading each time, place the basket/tray inside the tank gently to avoid re-introducing air into the fluid. Degassing time will vary depending on type of chemical used (e.g. aqueous or solvent), temperature, viscosity etc.

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3. What detergents should I use for surgical & dental instruments?

Use only a neutral or low alkaline detergent. It must be low foaming as there is a risk that foam may settle on the instruments when being removed from the machine. Do not use detergents containing chlorides or any corrosive chemicals that will corrode the tank. Be aware that excess amounts of certain chemical additives will not support ultrasonic cavitations. Check with your manufacturer or supplier if in doubt.

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4. How long do I need to clean the surgical instruments?

It should take 3-5 minutes. Extended times are likely to re-deposit the soil removed back onto the instruments. Generally, it is difficult to establish guidelines due to the several factors need to be considered as follows:

- Wide variety of sizes, weights etc.
- Using appropriate cleaning solution.
- Overload the machine with unnecessary mass.

It is therefore wiser to start with a few parts so that they can be cleaned quickly and thoroughly. You can add additional parts and check to ensure the same cleaning results.

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5. How often do I need to change water?

When the water is heavily contaminated, it should be immediately replaced. Replacement of the cleaning solution is necessary at least daily (where the machine is used daily) or more frequently, depending on how many what types of parts are being cleaned in your ultrasonic cleaner. If the solution is excessively contaminated, it will cause a loss of ultrasonic cleaning power and possible damage to your machine.

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6. Can I put my hands into the water when my ultrasonic cleaner is activated?

As part of the occupational health and safety, no part of the operator's body should be submerged into the water during operation as the ultrasonic energy is enough to cause damage to joint tissues and result in long-term arthritic conditions.

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7. Do I have to operate my ultrasonic cleaner with lid closed?

Your machine should be operated with lid closed in order to prevent excess emission of noise and aerosols.

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8. How do I test the ultrasonic efficiency of my ultrasonic cleaner?

We recommend the aluminium foil test. After the fluid is degassed, the aluminium foil test can be carried out as follows:

1. Suspend a strip of thin aluminium foil approximately the width of the tank and double the depth.
2. Lower the foil into the operating tank vertically until almost touching the bottom and hold for 10 seconds.
3. Remove the foil from the tank and observe the even distribution of perforations and small pin prick holes.
4. The indentations should be fine and evenly distributed.

For more information on the above foil test procedures, please visit our foil test web page at http://www.soniclean.com.au/ulc/foiltest.html.

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9. Why I should use a basket/tray?

Dropping in heavy/sharp/hard parts into the tank can damage your ultrasonic cleaner.You should use a basket/tray in order to prevent damage to the transducers and also protect the tank from scratching. Do not use baskets, trays, racks etc. fabricated from heavy and dense material (including soft material e.g. rubber, wood and fabric) as they will absorb ultrasonic energy and affect the cleaning effectiveness.

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10. How do I clean my ultrasonic cleaner?

Use an appropriate suitable stainless steel cleaning powder if the tank is stained with marks. If the outer sealing compound is marked, wipe over with general purpose cleaner. If a scratch has occurred in the tank, use the finest available sandpaper and carefully polish out the scratch. Clean the tank regularly. After use, rinse out the tank and wipe dry.

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11. What is the warranty?

Our Soniclean ultrasonic cleaner is guaranteed for a period of one (1) year from date of purchase. Extended warranty period up to two (2) years also available. Conditions apply.

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Continuing Developments in Ultrasonic Technology, F. John Fuchs, September 2004

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Ultrasonics, the sound you cannot hear, has emerged as a valuable tool in achieving the cleanliness required by todayís ever-advancing technology. Disc drives, silicon wafers and chips, medical implants, and all sorts of critical hardware require ultrasonic cleaning to function properlyóor at all. Traditional ultrasonic equipment operating in the 20 to 40kHz range served well for most of 50 years. Prior to the 1980s, ultrasonic technology was essentially ìmatureî with periods of excitement provided only by the occasional advancement in transducer and/or generator technology initiated by the availability of new fabrication materials for transducers and electronic devices; this improved the efficiency and reliability of generators. This period also saw the advancement of the increasingly affordable ultrasonic technology into more and more ìindustrialî applications including plating, surface finishing and metal fabrication.

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Starting in the 1980s, however, a new ìwaveî of ultrasonic technology development was initiated as ultrasonic manufacturers began to expand the envelope of available ultrasonic parameters. One cannot be sure if the technology preceded the need or if the technology was prompted by need, but in any event, things started happening. Ultrasonic technology began to move forward and with this motion came a flurry of ìposition jockeyingî by the handful of primary ultrasonic suppliers.

Ultrasonic Generator Technology Sweep Frequency

The first major generator development was sweep frequency. Ultrasonic cleaning had long been troubled by the formation of standing waves which, under the right conditions, could produce parts with ìzebra stripes.î These stripes were created as the reflecting sound wave fell back on itself and reinforced its intensity in horizontal zones located approximately one half wavelength apart. At best, one saw these bands as areas of cleaning vs. non-cleaning on the surface of the part. At worst, parts, especially those fabricated from softer metals including aluminum, brass and copper, were actually etched by high ultrasonic intensity in the areas of reinforcement. A simple solution to this problem was to move parts vertically through the ultrasonic field to spread out the high intensity effect by scanning the part.

It was discovered that varying or ìsweepingî the ultrasonic generator frequency over time effectively broke up the standing waves and reduced the tendency for zebra striping to occur. It was assumed that since the spacing of the stripes was based on frequency, formation of damaging standing waves relied on a fixed ultrasonic frequency. Varying the ultrasonic frequency slightly up and down would cause movement of the bands of high intensity. The effectiveness of sweeping frequency in reducing zebra strips was demonstrated repeatedly when the rate of sweeping and the bandwidth of sweep frequencies were designed to prevent resonance of the liquid column.

Another effect of sweeping went almost unnoticed. Ultrasonic transducers of the time were all relatively ìHigh Qî devices. In simple terms, like a tuning fork, they operated well at their resonant frequency, but as the driving frequency was changed, performance deteriorated rapidly. Sweeping the ultrasonic frequency attempted to drive the transducer at a frequency somewhat off its resonant frequency during most of the sweep cycle. This effort effectively reduced the output power of the transducer without an apparent reduction in the power delivered from the ultrasonic generator. Interestingly, a reduction in ultrasonic output power was also shown to reduce the zebra striping effect.

In defense of sweep frequency, most ultrasonic transducers consist of an array of individual driving elements (also sometimes individually called transducers). Despite the considerable effort given in manufacturing to assure that these individual elements all operate at the same frequency, there is always a slight variance in frequency of the elements in any transducer array even if they are individually chosen and matched prior to bonding to the tank. When a transducer array is operated at a single, fixed frequency, the individual elements (which are wired in parallel), are forced to divide up the available power. Elements with resonant frequencies closest to the frequency provided by the ultrasonic generator will draw the largest portion of power and therefore provide the highest ultrasonic intensity. Meanwhile, elements operating off their resonant frequency will have reduced output. The effect is non-uniformity of the ultrasonic field.

With sweep frequency, each transducer element sees its preferred driving frequency twice during each sweep cycle (provided it is within range of the sweep). The result is that a much more uniform ultrasonic field is produced in the cleaning tank. In addition, the use of sweeping frequency provides more useful cavitation per watt of ultrasonic excitation as a larger bubble population is resonated as the frequency varies. These are undeniable benefits of sweep frequency ultrasonics.

Extensions of sweeping frequency technology include varying the bandwidth and frequency of the frequency sweep itself. In some cases the sweep is randomized to eliminate the potential for damaging resonance effects that may be created as a result of the sweep frequency itself. These enhancements have found value in applications where both delicate and seemingly robust components are prone to fatigue failure when excited at their resonant frequency.

Pulse

Within the same time frame as the development of sweep frequency, ìpulseî was identified as an important parameter in ultrasonic cleaning. In simple terms, pulse means turning the ultrasonic energy on and off. Variables are duty cycle (percentage of ON time), frequency of the repeating on-off cycle, and pulse amplitude. Although it would at first seem counter-intuitive to better cleaning to turn off the ultrasonic power for a portion of time, this action does result in better cleaning results. The reason is that there is a burst of high energy ultrasonic power generated each time the ultrasonic power is turned on, which occurs before the cavitation bubble field reaches saturation. During this time, sound passes quite freely through the liquid without being attenuated by the saturated cloud of bubbles which are released by the sound field after the ultrasonic energy is initiated. This effect is familiar to those who have witnessed ultrasonic energy in some very low surface tension solvents. Droplets of solvent are often driven several inches high during the initiation of cavitation in a solvent.

The impact of the recognition of this effect was somewhat softened when it was realized that most ultrasonic cleaning systems at that time already had some inherent degree of pulse at twice the power line frequency as a result of a one half wave rectified power supply. Many manufacturers, in fact, adjusted the duty cycle of this inherent pulse as a means of providing a form of ìpower control.î Pulse, by the way, should not be confused with ìdegas.î The degassing cycle uses considerably longer time periods to allow gas bubbles, formed as the result of cavitation, to float to the surface of a liquid prior to re-applying ultrasonic energy. Pulse usually means 50 to 150 on-off cycles per second while degas uses a cycle time up to several seconds between pulses. The effect of pulse is most pronounced in solvents but can also be seen in aqueous solutions.

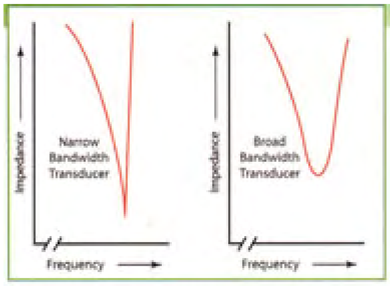

Figure 1. Narrow bandwidth vs. broad bandwidth.

Waveform Flexibility

In its simplest form, an ultrasonic generator is nothing more than a frequency converter. Just as a rectifier changes alternating current to direct current, an ultrasonic generator changes electrical energy at the power line frequency to electrical energy at the frequency required to drive the ultrasonic transducer.

Ever-advancing electronic technology has given designers of ultrasonic generators the tools to allow them to customize generator characteristics not limited to sweep and pulse. Today, nearly any imaginable wave characteristic can be customized (using techniques much like those used in musical synthesizers). Ultrasonic frequency and amplitude can be modulated instant by instant. Waveform patterns can be programmed or randomized depending on each individual application. Research continues to explore and define the proper use of all of these waveform parameters.

Transducer Technology

Many of the developments in ultrasonic generator technology were driven at least in part by developments in ultrasonic transducers. Transducer technology has advanced notably over the past several years.

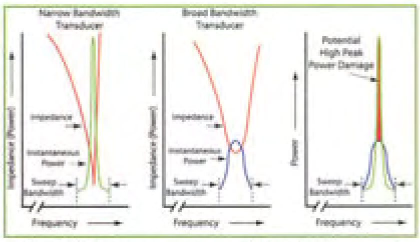

Figure 2. The two graphs on the left show power curves resulting from narrow and broad band transducers. The area under the power curve represents total delivered power. Although the area under the curve is the same in both examples, the narrow band transducer may produce high peak power as shown at the right, which may potentially cause damage to delicate substrates.

Transducer Bandwidth

Ultrasonic transducers are typically designed to resonate at their operating frequency. Much like bells and tuning forks, however, they are less efficient when driven at a frequency even slightly different than the one at which they were intended to operate. The impedance vs. frequency characteristic of a resonant device expresses its sensitivity to frequency. The deeper and sharper the resonance, the more selective the device is to frequency. Figure 1 shows the impedance vs. frequency curves for a transducer with a narrow bandwidth and a transducer with a broad bandwidth.

Classical transducer technology would favor sharper and deeper resonance, as shown in the graph on the left in Figure 1, for a transducer designed to operate at a single, fixed frequency. Ultrasonic transducers, providing sharp resonance, provide high efficiency output and the feedback required to allow feedback loops that control and automatically adjust generator frequency in real time in response to the characteristics of changing loads.

The development of frequency sweep technology, therefore, presented a bit of a technical conundrum. Sharply resonant transducers suffer a significant reduction in power output when driven by an ultrasonic generator providing sweep frequency. In fact, maximum efficiency is only achieved at the instant the driving signal equals the resonant frequency of the transducer (twice every sweep cycle). Maximizing the effectiveness of sweeping frequency prompted the redesign of ultrasonic transducers to provide a wider frequency acceptance. Figure 2 shows one benefit of a wider bandwidth transducer.

Higher Frequencies

Prior to the early 1990s there was a notable gap in the utilized ultrasonic spectrum. This gap was bordered by the highest ultrasonic frequency (something just short of 100kHz) and the frequencies near 1mHz used for megasonic cleaning. It is generally agreed that megasonic cleaning is based on the phenomenon of acoustic streaming, which is a somewhat different mechanism than that of cavitation, which is associated with ultrasonic cleaning. Acoustic streaming does not necessarily involve the formation and violent collapse of cavitation bubbles. Megasonic technology is also a more ìline of sightî phenomenon than cleaning using cavitation.

This frequency gap started closing when the removal of micron and sub-micron sized particles became important. Increasing frequency has two effects that are beneficial to the removal of small particles. Higher frequencies produce smaller cavitation bubbles that are able to produce a force normal to the substrate of sufficient magnitude to dislodge and remove very small particles. In addition, the thickness of the ìboundary layerî present at the interface between a liquid and a substrate is reduced at higher frequency. Within the boundary layer, it is difficult or impossible to produce the relative shearing forces required to remove particles. Reducing the thickness of the boundary layer provides access to smaller and smaller particles for removal.

The operating frequency of a transducer is determined by its geometry. In general, a shorter transducer (just like a shorter tuning fork) will operate at a higher frequency. However, by utilizing harmonics, transducers of varying size can be designed to operate at a frequency other than that established by length alone. In any event, transducers became available that would operate at frequencies above 100kHz. These transducers quickly found favor in systems where the removal of very small particles was of primary importance. This area of cleaning was quickly dubbed ìprecision cleaning.î The frequency spectrum continues to grow, now having reached 300kHz. The benefit of higher frequency in the removal of small particles is well established. The down-side of higher frequency is that larger particles are often too well attached to be removed by the more gentle force provided by the implosion of smaller cavitation bubbles produced at higher frequencies.

Multiple Frequencies

The effectiveness of higher ultrasonic frequency for removing small particles has been demonstrated. Higher frequencies, however, may not provide cavitation implosions with sufficient energy to dislodge and remove larger particles. In fact, a given frequency will most effectively remove particles falling within a given size range.

The removal of a wider range of particle sizes can be achieved in one of two ways. Increased ultrasonic power at a single frequency may provide sufficient energy to remove particles in a broader size range. The risk of this approach is damage to the substrate as a result of extremely high power.

The other approach is to use multiple ultrasonic frequencies each of which removes particles in a targeted size range. A series of cleaning tanks operating at a discrete frequency can do this.

›ontinuing ultrasonic transducer development now offers ultrasonic transducers that resonate at more than one frequency. These multi-frequency transducers, used in conjunction with a digitally controlled multi-frequency generator provide the ability to remove particles with a wide range of sizes in a single process tank.

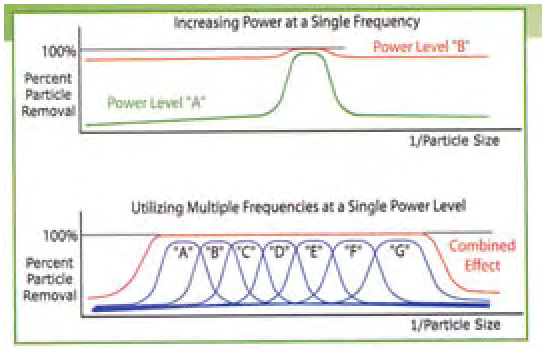

Figure 3. The upper illustration shows the effect of increasing power to increase the range of particle sizes removed from a substrate. This may require power levels sufficient to cause damage to the substrate. The lower illustration shows the use of several frequencies, A, B, C, etc., each at lower power to provide removal of a wide range of particle sizes without risk of damaging the substrate.

Application

The options for ultrasonic technology have advanced from a few, set frequencies to a veritable ìorchestraî of inaudible sound. Some of the advancements described above were developed in response to clearly defined needs such as improving the uniformity of cleaning or eliminating part damage due to induced resonance. Others are natural extensions of developing technology and, although available, do not yet have a clearly defined use.

Although cleaning has always been a primary target application for high power ultrasonic technology, new uses are being developed for growing ultrasonic technology as this article is written. De-agglomeration and particle size refinement of CMP slurries, micro-finishing of surfaces to change or enhance surface characteristics, applications in liquid particle counting, enhancement of plating and other deposition processes, and a multitude of other new developments are either at or nearing production stage.

F. John Fuchs is Technology Specialist at Blackstone~NEY Ultrasonics, Inc., P.O. Box 220 - 9 North Main St., Jamestown, NY 14701. He can be reached at 800-766-6606 or; Email,

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Ultrasonic Cavitations and Precision Cleaning

BY SAMI AWAD, PH.D.,
VICE PRESIDENT
CREST ULTRASONICS CORP.

> As the quest for higher cleanliness levels becomes more intense, the combination of chemistry and process chosen is more crucial to the success of the cleaning.

CREST
ULTRASONICS

Precision or critical cleaning is currently in great demand and is expected to increase in the future. The rapid advancements in various current technologies and the constant trend in miniaturizing of components have created a need for higher cleanliness levels.

Contamination in the level of monolayers can drastically alter surface properties such as wettability, adhesion, optical or electrical characteristics. Particles in the range of few microns down to submicron levels, trace contaminants such as nonvolatile residues (NVR) in the range of micrograms/cm^2 and pictogram/cm^2, ionics in the same range or traces of corrosion have become part of the daily concerns of the manufacturing engineers in major industries such as semiconductors, automotive, disk drive, optics, ophthalmic, glass, medical, aerospace, pharmaceuticals and tool coatings, among others.

The specifications on trace contaminants and particle sizes are being tightened periodically to reflect the new technology trends. Every industry has its own set of cleanliness specifications and the focus differs.

For example, while NVR has not been an automotive industry issue until now, it has been crucial for the semiconductor and the disk drive industries for years. Trace contaminants are not acceptable in the carbide, optics and ophthalmic industries, as they may cause adhesion failures in a multi-coating process that follows cleaning.

For obvious reasons, absolutely clean surfaces are an extremely critical requirement in cleaning medical devices. Concern about particles has become a common denominator among all industries.

Precision Cleaning

Precision or critical cleaning of components or substrates is the complete removal of undesirable contaminants to a desired preset level. The preset level is normally the minimum level at which no adverse effects take place in a subsequent operation. To achieve this level, it is critical not to introduce new contaminant(s) into the cleaning process.

For example, if the cleaning of organic and ionic contaminants is achieved by an aqueous process, it is important to have high quality water and the proper parameters in the rinsing stages. Otherwise, residual detergent and/or ionics from the rinsing water will be the new contaminants. If drying is slow, deionized rinse water may react with some metallic surfaces at high temperatures and create undesirable stains or marks. Re-contamination of cleaned parts with outgassed residues produced from packaging or storing materials is another big concern.

To select an effective cleaning method, the three essential factors directly influencing cleaning results are the cleaning

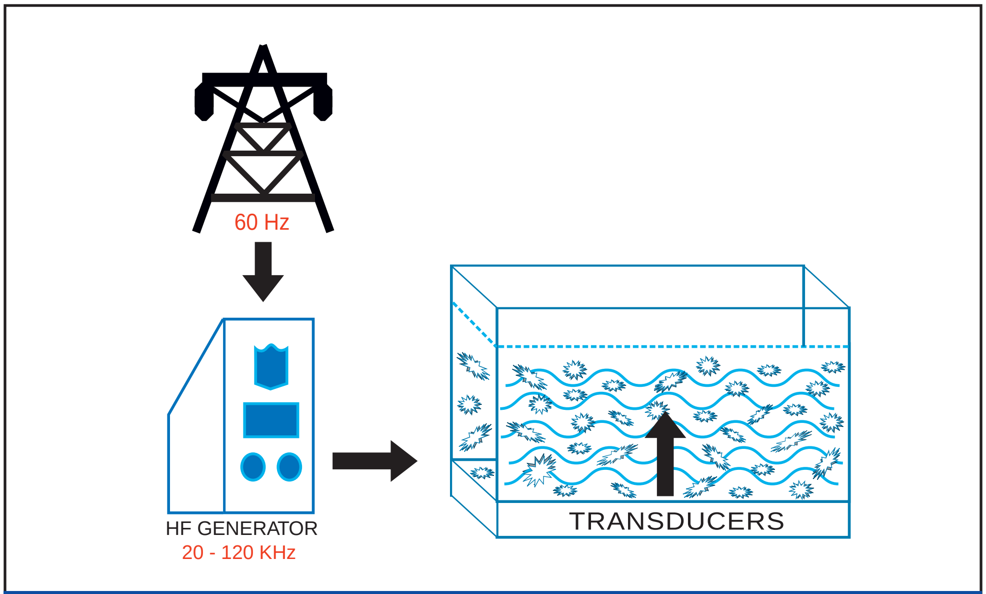

Figure 1 **Ultrasonic Cleaning System**

chemistry, the scrubbing method and the process parameters. The subject of examining various combinations of available cleaning methods and their effectiveness, or lack there-of, is massive and well-explained in the current literature.

The focus in this article will be on ultrasonic cavitations and the ultrasonic cleaning mechanism. Ultrasonic technology is proven to be a versatile method for cleaning various organic, inorganic and particle contaminants from various metallic and nonmetallic surfaces.

Ultrasonic Cavitations and Surface Cleaning

Cleaning with ultrasonics offers several advantages over other conventional methods. Ultrasonic waves generate and evenly distribute cavitation implosions in a liquid medium. The released energies reach and penetrate deep into crevices, blind holes and areas that are inaccessible to other cleaning methods. The removal of contaminants is consistent and uniform, regardless of the complexity and the geometry of the substrates.

Ultrasonic waves are mechanical pressure waves formed by actuating the ultrasonic transducers with high frequency, high voltage current generated by electronic oscillators (power generators) **(Figure 1)**. A typical industrial high power generator produces ultrasonic frequencies ranging from 20-120 kHz. Typical PZT transducers are normally mounted on the bottom and/or the sides of the cleaning tanks or immersed in the liquid. The generated ultrasonic waves propagate perpendicularly to the resonating surface. The waves interact with liquid media to generate cavitation implosions. High intensity ultrasonic waves create micro vapor/vacuum bubbles in the liquid medium, which grow to maximum sizes proportional to the applied ultrasonic frequency and then implode, releasing their energies. The higher the frequency, the smaller the cavitation size. The high intensity ultrasonics can also grow cavities to a maximum in the course of a single cycle. At 20 kHz the bubble size is roughly 170 microns in diameter (**Figure 2**). At a higher frequency of 68 kHz, the total time from nucleation to implosion is estimated to be about one third of that at 25 kHz. At different frequencies, the minimum amount of energy required to produce ultrasonic cavities must be above the cavitation threshold. In other words, the ultrasonic waves must have enough pressure amplitude to overcome the natural molecular bonding forces and the natural elasticity of the liquid medium in order to grow the cavities. For water, at ambient, the minimum amount of energy needed to be above the threshold was found to be about 0.3 and 0.5 watts/cm^2 per the transducer radiating surface for 20 kHz and 40 kHz, respectively.

The energy released from an implosion in close vicinity to the surface collides with and fragments or disintegrates the contaminants, allowing the detergent or the cleaning solvent to displace it at a very fast rate. The implosion also produces dynamic pressure waves which carry the fragments away from the surface. The implosion is also accompanied by high speed micro streaming currents of the liquid molecules.

The cumulative effect of millions of continuos tiny implosions in a liquid medium is what provides the necessary mechanical energy to break physically bonded contaminants, speed up the hydrolysis of chemically bonded ones and enhance the solubilization of ionic contaminants. The chemical composition of the medium is an important factor in speeding the removal rate of various contaminants.

Cavitation Generation and Abundance

The ultrasonic cleaning model (**Figure 3**) illustrates the generating cavitations through at least three steps: nucleation, growth and violent collapse or implosion.

The transient cavities (or vacuum bubbles or vapor voids), ranging 50-150 microns in diameter at 25 kHz, are produced during the sound waves' half cycles. During the rarefaction phase of the sound wave, the liquid molecules are extended outward against and beyond the liquid natural physical elasticity/bonding/attraction forces, generating a vacuum nuclei that continue to grow. A violent collapse occurs during the compression phase of the wave. It is believed that the latter phase is augmented by the enthalpy of the medium and the degree of mobility of the molecules, as well as the hydrostatic pressure of the medium.

Cavitations are generated in the order of microseconds. At the 20 kHz frequency, it is estimated that the pressure is about 35-70 K Pascal and the transient localized temperatures are about 5000°C, with the velocity of micro streaming around 400 Km/hr (**Figure 2**).

Several factors have great influence on the cavitation's intensity and abundance in a given medium. Among these factors are the ultrasonic wave form, its frequency and the power amplitude.

Other determining factors are the colligative properties of the liquid medium, including viscosity, surface tension, density and vapor pressure; the medium temperature and the liquid flow, whether static or dynamic or laminar; and dissolved gases.

In general, at low frequencies (20-30 kHz), a relatively smaller number of cavitations with larger sizes and more energy are generated. At higher frequencies, much denser cavitations with moderate or lower energies are formed. Low frequencies are more appropriate for cleaning heavy and large-size components, while high frequency (60-80 kHz) ultrasonics is recommended for cleaning delicate surfaces and for the rinsing step.

For example, at 68 kHz, the cavitation abundance is high enough and mild enough to remove detergent films and remove submicron particles in the rinsing steps without inflicting damage on surfaces. The 35-45 kHz frequency range was found to be appropriate for a wide range of industrial components and materials.

Estimates of cavitation abundance at various ultrasonic frequencies have shown that the number of cavitation sites is directly proportional to the ultrasonic frequency. For example, about 60 to 70 percent more cavitation sites per unit volume of liquid are generated at 68 kHz than at 40 kHz. The average size of cavities is inversely proportional to the ultrasonic frequency.

Therefore, one would expect that at the higher frequency, at a given energy level, the scrubbing intensity would be milder, particularly on soft and thin or delicate surfaces, and more penetration and surface coverage into the recessed areas and small blind holes would be expected.

Ultrasonic Frequency and Particle Removal

Recent investigations have confirmed that higher frequencies are more effective for the removal of certain contaminants. Reports on particle removal efficiency have shown that the removal efficiency of one micron and submicron particles in deionized water has increased with the higher frequency. At 65 kHz, the removal efficiency of a one micron particle is 95 percent, versus 88 percent at 40 kHz. A similar increase in efficiency results was reported for 0.7 and 0.5 micron particles. It was also reported that there was zero or little difference in the removal efficiency of particles at the ultrasonic frequency of 65 kHz and at the megasonic frequency of 862 kHz. Both frequencies showed 95 percent removal efficiency of one micron particles and 87/90, 84/84 for 0.7 and 0.5 micron particles, respectively.

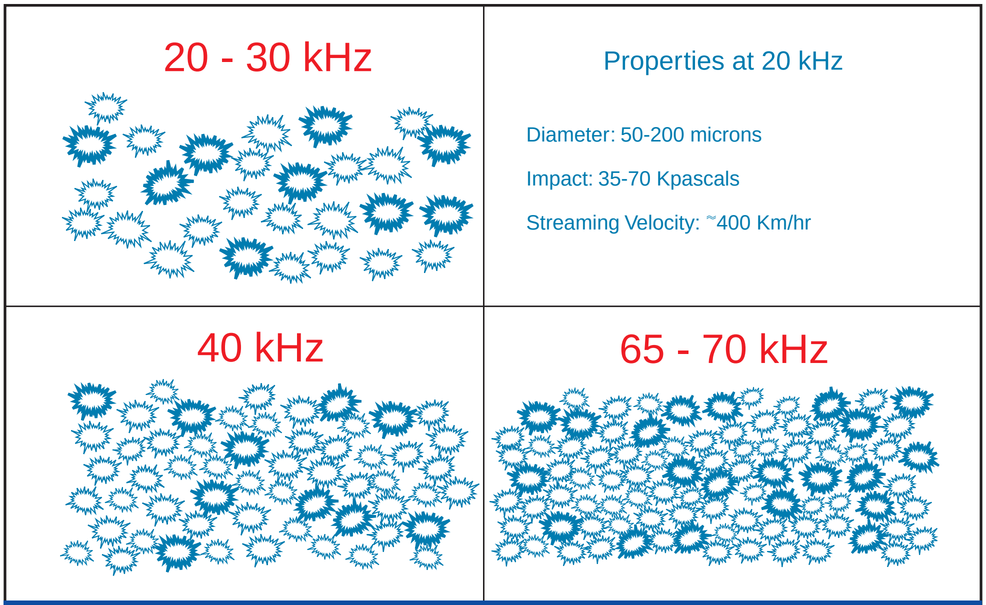

Figure 2 **Ultrasonic Frequency & Cavitation Abundance**

Aqueous and Semi-Aqueous Ultrasonic Cleaning

Cavitations generated in plane water can clean limited numbers of certain contaminants. However, cleaning is more complex in nature than just extracting the contaminants away from the surface. Consistency and reproducibility of results are the key, particularly in industrial production lines. Cleaning chemistry, as part of the overall cleaning process, is a crucial element in achieving the desired cleanliness. First, the selected chemistry must cavitate well with ultrasonics. Also, compatibility of the chemistry with the substrates, wettability, stability, soil loading, oil separation, effectiveness, dispersion of solid residues, free rinseability and chemistry disposal are all crucial issues that must be addressed when deciding on the proper chemistry. Chemistry is needed to do on or multiple tasks - to displace oils or solvents, to solubilize or emulsify organic contaminants, to encapsulate particles, to disperse and prevent redeposition of contaminants after cleaning. Special additives in cleaning chemistries can assist in the process of breaking chemical bonding, removal of oxides, preventing corrosion or enhancing the physical properties of the surfactants.

For example, we have found that ultrasonic cavitations enhanced the removal efficiency of hydrophobic solvent cleaning films by about 30 to 40 percent versus using a spray rinse technique, when

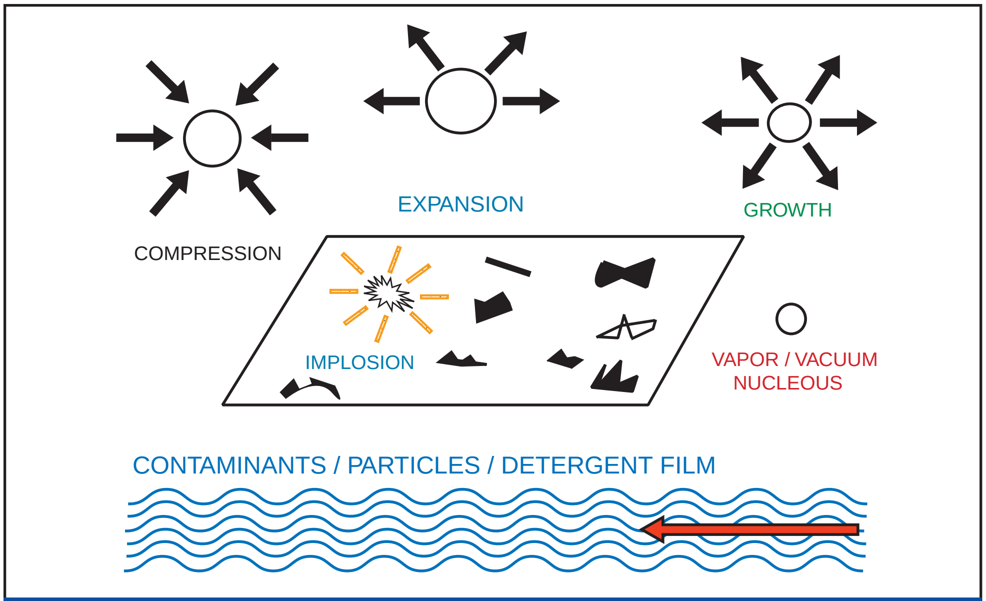

Figure 3 **Ultrasonic Cavitations & Cleaning**

coated metallic and non-metallic surfaces were treated with aqueous displacement solutions (ADS). The ADS material is chemically designed to be compatible with the substrate and to rapidly displace hydrophobes. All tested surfaces were rendered solvent-free and hydrophilic.

Particles, in general, are not spherical and have irregular shapes. Some of the adhesive forces that influence detachment of a particle are van der Waals, electrical double layer, capillary and electrostatic. One would expect that small particles are easier to remove. The fact is that the smaller the particles, the more difficult they are to remove. The weight of the particle is another factor greatly influencing a particle detachment. Kaiser has recently reported that although the force between a particle and an adjacent surface decreases with particle size, it becomes more difficult to remove a solid particle from a solid surface because of the value of the ratio, Fa/W, where Fa is the force of attraction and W is the weight of the particle. The value of Fa/W increases rapidly as the diameter of a particle decreases.

Ultrasonic Systems

Typical ultrasonic aqueous batch cleaning equipment consists of four steps: ultrasonic cleaning, two ultrasonic reverse cascade water rinses and heated recirculated filtered clean air for drying. The number and the size of the stations are determined based on the required process time. A semi-aqueous cleaning system includes an extra station for solvent displacement, connected to a phase separation/recovery system. Typical tank size ranges from 20 liters to 2,000 liters, based on the size of the parts, production throughput and the required drying time. The cleaning process can be automated to include computerized transport systems able to run different processes for various parts simultaneously. The whole machine can be enclosed to provide a clean room environment meeting class 10,000 down to class 10 clean room specifications. Process control and monitoring equipment consists of flow controls, chemical feed-pumps, in-line particle count, TOC measurement, pH, turbidity, conductivity, refractive index, etc. The tanks are typically made of corrosion resistant stainless steel. However, other materials are also used – such as quartz, PCV, polypropylene or titanium – to construct tanks for special applications. Titanium nitride coating is used to extend the lifetime of the radiating surface in tanks or immersible transducers.

Automation of a batch cleaning system is an integral part of the system. Advantages of automation are numerous. Consistency, achieving throughputs, full control on process parameters, data acquisition and maintenance of process control records are just a few.

Mechanism of Cleaning

Two main steps take place in surface cleaning. The first step is contaminant removal and the second is keeping those contaminants from re-adhering to the surface. The removal of various contaminants involves different mechanisms, based on the nature and/or the class of the contaminant.

Three general classes of common contaminants are organic, inorganic and particulate matter. Particles do not necessarily belong to a certain class and can be

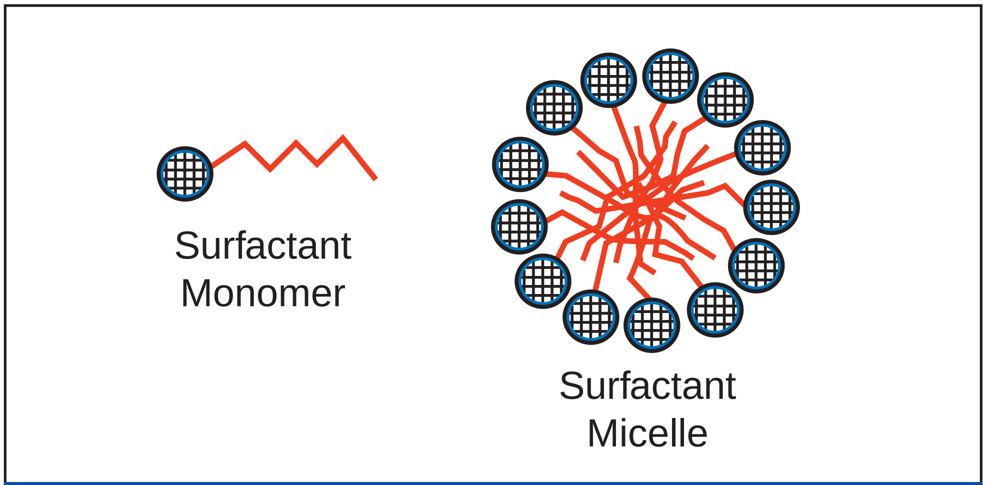

Figure 4 **Monomer/Micelle Aggregate**

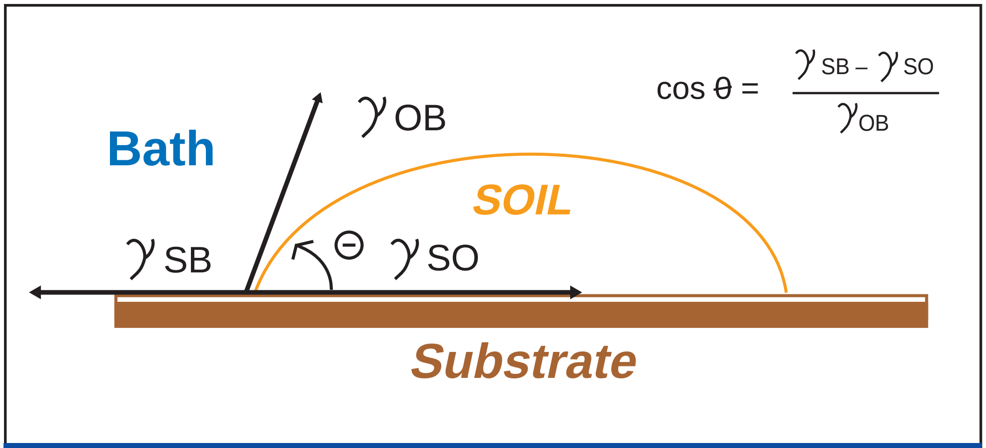

Figure 5 **Liquid Soil Removal**

from either class or a mixture. Contaminants of any class could be water soluble or water insoluble. Organic contaminants in most cases will be hydrophobic in nature, such as oils, greases, waxes, polymers, paints, print, adhesives or coatings.

Most inorganic materials are insoluble in solvents that are water-immiscible. Water is the best universal solvent for ionic materials, organics or inorganics. However, water insoluble inorganics, such as polishing compounds made of oxides of aluminum, cerium or zirconium, require a more complex cleaning system.

Organic contaminants can be classified into three general classes - long chain, medium chain and short chain molecules. The physical and chemical characteristics are related to their structure and geometry. Organic contaminants are removed by two main mechanisms. The first is by solubilization in an organic solvent. Degree of solubilization in various solvents is directly related to their molecular structure. The second mechanism is by displacement with a surfactant film followed by encapsulation and dispersion.

In aqueous cleaning, the detergent contains surfactants as essential ingredients. Surfactants are long chain organic molecules with polar and non-polar sections in their chains. Surfactants can be ionic or non-ionic in nature, based on the type of functional groups attached to or part of their chains. When diluted with water, surfactants form aggregates called micelles (**Figure 4**) at a level above their critical micelle concentration (CMC).

The mechanism of removal of organic contaminants by detergent involves wetting of the contaminant as well as the substrate. According to Young's equation, this will result in increasing the contact angle between the contaminant and the surface, thus decreasing the surface area wetted with the hydophobe, reducing the scrubbing energy for removal (**Figure 5**).

The ultrasonic cavitations play an important role in initiating and finishing the removal of such hydrophobic contaminants. The shock wave (the micro streaming currents) greatly speed up the breaking of the hanging contaminants, enhancing displacement with the detergent film. The removed contaminants are then encapsulated in the micellic aggregates, thus preventing their redeposition. The net result is that ultrasonic cavitations accelerate the displacement of contaminants form the surface of the substrate and also facilitate their dispersion throughout the cleaning system.

Particles, in general, have irregular shapes. All the adhesion forces - van der Waals, electrical double layer, capillary and electrostatic - in theory are directly proportional in magnitude to the size of the particle. One would expect that the energy of detachment would decrease with the size of particles. However, the smaller particles are always more difficult to detach. This is mainly due to the lodging effect. Smaller particles tend to get trapped in the valleys of a rough surface.

The mechanism of particle removal involves shifting the free energy of detachment to be near or smaller than zero, according to Gibbs adsorption equation (**Figure 6**). Surfactants play a very important role in decreasing by adsorption at particle and substrate interfaces and with the bath.

The wettability of the surface plays an important role in achieving this step. The ultrasonic cavitation's role is to provide the necessary agitation energy for the detachment (i.e., the removal force). At high frequency (60-70 kHz) ultrasonics, the detachment or the removal efficiency of one micron particles, measured in deionized water, was found to be 95 percent , equaling the efficiency obtained by using the megasonics at about 850 kHz, versus 88 percent at 40 kHz. This is

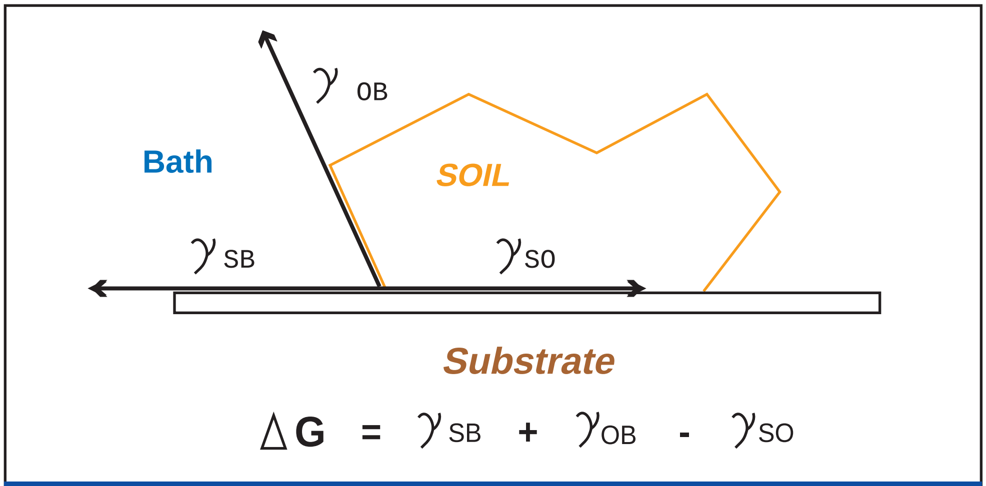

Figure 6 **Particulate Soil**

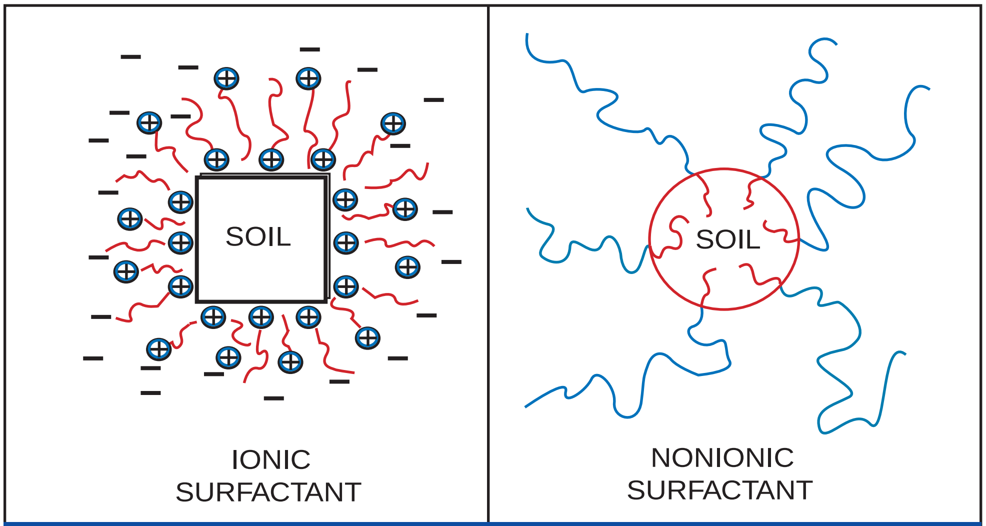

Figure 7 **Antiredeposition**

expected in light of the fact that cavitation size is smaller at higher frequencies and can reach deeper into the surface valleys. One would then anticipate that by using a combination of the high frequency ultrasonics at 65-68 kHz and the appropriate chemistry, the removal efficiency of various particles can be further optimized.

Redeposition of Contaminants

Redeposition of contaminants is inhibited by another mechanism, by forming a barrier between the removed contaminant and the cleaned surface. In solvent cleaning, the absorbed solvent layers on the substrate surface and the contaminants provide a film barrier. In aqueous cleaning, a good surfactant system is capable of encapsulating contaminants inside their micellic structure (**Figure 7**). Thus, redeposition of the encapsulated contaminants (soils) onto the surface is prevented via stearic hindrance for nonionic surfactants, while anionic surfactants prevent redepositon via electrical repulsive barrier.

Encapsulation can be permanent or transient, based on the nature of the used surfactants. Transient encapsulation is superior to emulsification, as it allows better filtration and/or phase separation of contaminants. The potential of reversing the redeposition step by the sonic shock waves on loaded micelles results in partial re-adhesion. Therefore, allowing the increase in the soil load in a cleaning solution to reach saturation point, without good filtration, will result in a significant decrease in the detergent cleaning efficiency, at which point the cleaning action may cease. To ensure steady cleaning efficiency, the dispersed contaminants must be removed by means of continuous filtration or separation of contaminants, along with maintaining the recommended concentration of the cleaning chemical.

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About the Author

Dr. Sami Awad is VP of Technology at Crest Ultrasonics (Trenton, NJ). He has more than 15 years experience in developing new chemistries and processes for precision cleaning, surface treatment and metal forming. Dr. Awad is the author of more than 25 scientific academic papers in organic synthesis and reaction mechanisms, and has served on the teaching faculties of Drexel University (Philadelphia, PA) and Cairo University, Egypt. Dr. Awad is a member of ACS, Ultrasonic Industry Association (UIA), IDEMA and ASM. He holds a Ph.D. in organic chemistry, and may be reached at (609) 883-4000, or by fax at (609) 883-3331.

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FUNDAMENTALS

OF

ULTRASONIC CLEANING

By James R Hesson HESSONIC ULTRASONIC

HESSONIC

HIGH ENERGY SOUND SUPERSONICS

INDEX

INTRODUCTION

Ultrasonic cleaning offers several advantages over conventional methods. Ultrasonic waves generate and evenly distribute cavitation implosions in a liquid medium. The released energies reach and penetrate deep into crevices, blind holes, and areas that are inaccessible by other cleaning methods. The removal of contaminants is consistent and uniform regardless the complexity and geometry of the part being cleaned.

ADDITIONAL FEATURES:

1) SPEED, cleaning usually completed in 1 to 3 minutes
2) LABOR, Tremendous labors savings over conventional cleaning methods.
3) CHEMICAL, use lower concentration and milder chemicals to complete cleaning task. Does no have to be a low foaming chemical as required in most spray, agitation cleaners.

NOTE:

This paper is written in two parts. Part one contains information for basic knowledge on ultrasonic theory and chemistry. An asterisk (*) with a number will be found throughout part one on certain topics, these asterisks (*) with matching numbers will also be found in part two and will give additional information on the specific topic for those who require more in depth detail.

WHAT DOES ULTRASONIC MEAN

Before we go into the theory of ultrasonics lets first get a better understanding of what me mean by ultrasonic. A sound wave (may also be expressed as an acoustical pulse or pressure wave), which is beyond the range audible to human hearing, is the point at which ultrasonic begins. Since 18,000 Hertz (18,000 cycles) per second is the approximate upper limit or the human hearing range it is considered the point at which ultrasonic begins. Most like to refer to the ultrasonic range as a sound wave equal to or greater than 20 KHz or 20 Kilo Hertz, Kilo meaning thousand and Hertz (after H.R.Hertz) meaning cycle per second. Ultrasonic cleaning indicates it uses sound waves at or above the 18/20 KHz range.

PART ONE

Every ultrasonic cleaning system consists of three components.

1) ULTRASONIC GENERATOR
   The function of the ultrasonic generator is to utilize the available electrical power, usually 120 or 240 volt 60/50 Hertz, and convert it into a higher voltage and faster cycle to activate the transducer, usually 2000 volts at 40,000 Hertz for a 40KHz cleaning system.
2) TRANSDUCER
   The function of the transducer is to take a signal in one form (electrical) and convert it into a signal of another form (a sound wave, which also may be expressed as a acoustics pulse or pressure wave). A good example would be a microphone and speaker. We speak into a microphone and produce a sound wave or acoustic pulse that is then converted by the microphone transducer into an electrical signal. This electrical signal is transmitted to a speaker transducer that converts this electrical signal back into a sound wave.
   The function of the transducer used in ultrasonic cleaning is to convert the electrical pulses from the generator into a sound wave or pressure wave. When this sound wave/pressure wave is driven through a liquid with appropriate amplitude it will cause the formation of a cavitation vapor/vacuum cavity, which is the scrubbing force found in ultrasonic cleaning systems.
3) TANK OR VESSEL
   The transducer must be bonded to the sides or bottom or immersed into (using an immersible Transducer) a tank or vessel filled with a liquid to remove the high intensity pressure wave from the Transducer. Ultrasonic cleaning transducers cannot be operated dry or series damage may result to both the generator and the transducer. (*2)

TRANSDUCERS (*1)

Ultrasonic transducers may be made from a number of materials. The most common piezoelectric material used is a ceramic called lead zerconate titanate. During the manufacturing process the ceramic is subjected to a high electrical potential causing the ceramic to develop dipoles (*2) and become polarized (to have a positive and negative side). This polarization will give the ceramic a unique feature. When the transducer ceramic is put into service and has an electrical potential applied to it from an ultrasonic generator it will swell and change dimension. When the electrical potential is removed the ceramic will return to its original state and will continue to expand and contract or resonate (like a tuning fork) until it self dampens and stops. Each time the transducer expands it emits a sound wave or pressure wave. Both the resonant frequency that the transducer was manufactured for, and the output frequency of the generator determine the frequency of this pressure wave.

The generator must be designed to emit an electrical pulse at precise intervals so as to compliment the movement of the transducer, not to hinder its movement; this is referred to as automatic tuning.

TRANSDUCER BONDING (*3)

Two types of transducer bonding are used to secure the transducers to the cleaning tank or immersible, one being epoxy (aircraft quality) and the other being brazed. The most common bonding practice used today is epoxy do to the large surface contact area and lightweight of the piezoelectric transducer sandwich. (*1)

With the epoxy bonding technique the transducer may be designed with electrical isolation from the tank or cleaning system (no high voltage potential will be grounded through the tank or cleaning system).

The epoxy adhesion is more than sufficient for bonding the piezoelectric transducer to the tank wall or bottom and gives uniform attachment on surfaces that are not perfectly flat or level. Epoxy bonding is so reliable that most manufacturers will guarantee the bond for 10 years or longer.

The second type is braze bonding. This technique was first used to bond the heavy electromagnetic (magnetrostrictive) transducers (*1) do to their heavy weight and small surface contact area. This bonding technique was carried over to some piezoelectric transducers with no real advantage over epoxy bonding because the bonding strength was not required and there may be a reduction in cleaning performance do to the higher-pressure readings. (*3). Brazing also indicates the transducer sandwich mounting surface is steel not aluminum. The acoustical velocity (mm/microseconds) in steel is 5.79 as compared to aluminum at 6.45. This indicates a significant energy loss by using steel in place of aluminum. Also a brazed transducer cannot be easily isolated from being grounded to the tank.

ULTRASONIC GENERATORS (*4) * SEE DRAWING A

Ultrasonic generators differ in the waveforms they emit and their output ratings. Three forms of output may be used, full wave, half wave, and continuous wave. When discussing generator output power always refer to the average output power, not the peak output those without electrical knowledge may be easily misled so again request average power output.

The manufacturer or supplier of the cleaning system should have a frequency/watt meter available to verify the output frequency and output wattage of the generator. Checking the input power to the ultrasonic generator is of little value when you are interested in the output power, don’t be fooled.

To protect the generator from electrical fluctuations and spikes the generator output may be de tuned by as much as 10% but never any more. The frequency/watt meter is the best way to check output frequency and wattage.

1) Virtually all-Industrial ultrasonic generators have automatic frequency tuning.
2) Generators with constant power output hold power output when input voltage changes.
3) Generators should have a power intensity control to control output power.
4) It is advisable to have sweep frequency (*7)
5) It is advisable to have a control to adjust the sweep repetition rate.

ULTRASONIC POWER (*5)

For water at ambient temperature the minimum amount of energy needed to achieve cavitation was estimated to be 0.3 to 0.5 watts per square centimeter for the transducer-radiating surface operating at 40 KHz. What this means is we must supply adequate power to the transducer to initiate cavitation. Cavitation, the scrubbing force in ultrasonic cleaning will be covered at a later time.

Take a given tank filled with a liquid and introduce a pressure wave derived from 100 watts of generator output power, the pressure wave travels through the liquid uneventfully. Now increase the generator to 200 watts output power and once again the pressure wave travels through the liquid uneventfully. Now increase the generator output power to 300 watts. Now as the pressure wave travels through the liquid it has enough amplitude to reduce the local pressure below the point of vaporization and form a cavitation bubble, this is referred to as the threshold of cavitation. Now increase the generator output to 500 watts and one might conclude we increase the power in each cavitation bubble, but this is not the case. After initiating cavitation as we increase power to the ultrasonic tank we increase the number of cavitation bubbles (Referred to as events) we do not affect the energy in the cavitation events. The operating frequency determines the size of the cavitation event and among other factors the energy released.

FREQUENCY (*5)

- The lower the operating frequency the larger the implosion bubble.
- The higher the operating frequency the smaller the implosion bubble.

As we lower the operating frequency the implosion bubble becomes larger and releases more energy when they implode but we also lower the number or amount of events. As we increase the operating frequency we reduce the size of the implosion bubble releasing less energy when they implode but we also increase the number or amount of events.

The maximum size of the cavitation event is proportional to the applied frequency. At equal power inputs to a 25 KHz tank, a 40 KHz tank, and a 68 KHz tank the 40 KHz tank will have 60% higher number of events than the 25KHz tank, and the 68 KHz tank will have 70% higher number of events than the 40 KHz tank. As we increase the frequency we increase the amount of cleaning events and cleaning is more homogeneous but less power is released in each event so cleaning ability may be reduced.

20 KHz to 25 KHz

At 25 KHz and lower there will be fewer events than the higher frequencies but these events will store and release considerably more energy when they implode resulting in more aggressive scrubbing. The cautions to be noted are there is increased potential for damage to the part being cleaned and do to the longer wave length one may notice less homogeneous cleaning results.

Ultrasonic cleaners operating at these lower frequencies will emit stray frequencies or sub harmonics that will be more noticeable and audible to the personal operating the cleaner and in some cases be quite irritating. Frequencies operating at 20 KHz and lower may require the operating personal to wear some type of ear protection do to the potential unknown hazards that this low frequency may have. .

The lower frequencies do to the high intensity of the implosion event will show more rapid signs of cavitation erosion on the transducer-radiating surface. Cavitation erosion is the under cutting and removal of metal from the stainless steel radiating surface.

40 KHz

At 40 KHz the softer implosion forces are usually adequate for most cleaning applications, has better overall cleaning uniformity do to the higher number of cavitation events and there is less chance of damaging the product being cleaned by the imploding bubble.

At 40 KHz the stray frequencies or sub harmonics are further from the hearing range and have little noticeable noise output. Do to the softer implosion force less cavitation erosion will result on the transducer-radiating surface, (also referred to as the transducer diaphragm). 40 KHz is the most wildly used frequency for ultrasonic cleaning.

60 KHz to 80 KHz

At 60 KHz to 80 KHz the implosion forces are much weaker than the lower frequencies and will not have sufficient implosion forces for adequate cleaning in the majority of applications. Do to the shorter wavelength and higher number of cavitation events increase uniformity in cleaning will be noted. With the softer implosion force there is virtually no cavitation erosion and being so far from the human hearing range noise from stray frequencies of sub harmonics are of no concern.

NOTE: Even with the low cavitation implosion forces these higher frequencies can out performs the lower frequencies in certain applications. (*6)

400 KHz to 800 KHz and higher

At 400 KHz to 800 KHz and higher cavitation events have virtually no cleaning ability do to their weak cavitation implosion force. Any cleaning achieved at these frequencies is do to liquid movement or fluid dynamics produced by the pressure wave traveling through the liquid. These high frequencies, as the lower 60 KHz to 80 KHz frequencies, do not lend themselves to most ultrasonic cleaning applications but are used by electronic component manufacturers on special cleaning applications (*6)

MULTI FREQUENCY / SWEEP FREQUENCY (*7) * see drawing B

Multi frequency suggests more than one frequency being introduced into the cleaning tank. A given transducer is manufactured to operate at a fixed frequency (resonant frequency) the transducer must be operated at its resonant frequency or within plus or minus 1 to 2 KHz from its resonant frequency. If a transducer is driven at more than 2 KHz from its manufactured frequency a reduction in output power will result. If transducers of different frequency and bonded to a tank only the transducers driven at or close to their resonant frequency will be operating at maximum efficiency, the remaining transducer will have poor power output and could over heat do to the miss matched frequency.

Sweep frequency suggests changing the generator output through a frequency band by sweeping from a lower frequency to a higher frequency. This sweep must be no more than plus/minus 1 to 2 KHz from the fundamental frequency of the transducers. By exciting the transducers in this manner pressure waves of different frequencies will be introduced into the liquid causing better overall cleaning and less dead spots or standing waves

STANDING WAVES (*7)

Within the cleaning bath fixed points of maximum and minimum amplitude of one completed cycle can be found. The point of maximum amplitude is called the antinode; the point of minimum amplitude is called node. Cavitation takes place primarily at the antinode point and virtually none at the node point. By changing the frequency we shorten or lengthen the wavelength and so change the antinode/node locations helping to eliminate the dead spots (standing waves) within the bath giving better overall cleaning results. Sweeping the frequency is the best way to reduce the negative results of a standing wave.

CAVITATION * see drawing C & E

What is cavitation? Now that we have some knowledge about ultrasonic cleaning and that the ultrasonic generator and transducer are required to produce cavitation in an ultrasonic cleaning bath and that it is the scrubbing force found in ultrasonic cleaning, how is it formed?

To develop a cavitation event we must transmit a high intensity pressure wave from the transducer into a liquid with enough amplitude so as to tear the liquid apart in the rarefaction half cycle and drop the pressure within the liquid below its point of vaporization. When this has been achieved we will develop millions of minute vacuum bubbles called cavitation events. Every half cycle we develop these vacuum bubbles which store their developing energy and then collapse or implode in the compression half cycle releasing their energy. This causes the shear forces they release to break the bonds holding a particle to the item being cleaned. At 40 KHz this cleaning cycle will repeat itself 40,000 times a second.

Cavitation development and amount of energy released relies on a number of factors such as

1) Ultrasonic power.
2) Density.

3) Vapor pressure.
4) Temperature
5) Condition of the liquid (Will be covered in the liquid properties for ultrasonic cleaning section.)

The imploding cavitation bubble conducts the majority of the cleaning by the development of shearing forces but is aided by what is known as micro streaming within the liquid the maximum size of the cavitation bubble is proportional to the applied frequency. As we lower the frequency the larger the imploding bubble will grow. The larger the imploding bubble the greater the implosion force. As we lower the frequency we also lower the number of cavitation events. As we increase the frequency we decrease the size of the cavitation bubble and weaken or soften the implosion force. As we increase the frequency we also increase the number the number of cavitation events

At 40 KHz there are 60 % more cavitation implosions than at 25 KHz
At 68 KHz there are 70 % more cavitation implosions than at 40 KHz. * See drawing C

The characteristic size of a cavitation bubble in water under normal atmospheric pressure is roughly given by F x R = 300, with the frequency being F in Hertz and the equilibrium bubble radius R in (cm). For F= 30 KHz R will be 100UM.
All the above relates to what size cavitation implosion bubble do we want to do our cleaning task without damage to the Item being cleaned, and receive the best overall cleaning results in the shortest time frame.

LIQUID PROPERTIES BEST SUITED FOR ULTRASONIC CLEANING.

VISCOSITY (*8)
In an ultrasonic cleaning bath viscosity should be low to promote cavitation. A thick viscous, syrup type solution would not lend itself to good cavitation, the higher the viscosity the more energy is needed for transmission of the ultrasonic pressure wave.

DENSITY
Density should be high to create intense cavitation events although high-density liquids require additional energy to initiate cavitation. If density is to high cavitation may not be initiated. If cavitation is initiated The imploding cavitation bubble would have tremendous amounts of energy to be released.

In an aqueous cleaning system the viscosity and density are both in a good range for ultrasonic cleaning and should be of little concern.

VAPOR PRESSURE

A vapor pressure of medium value is most suitable for ultrasonic cleaning. Remember we have to go below the point of vaporization of the liquid to initiate cavitation. If the vapor pressure of the liquid is low it will take more power to reach the point of vaporization and in some cases the required power may not be available, so cavitation will never be initiated. Under these conditions if enough power was available the cavitation bubble will store and release extremely high levels of energy.
High vapor pressure will develop cavitation bubbles with ease do to the fact it will be easier to go below the point of vaporization so little power is required, this means less power will be stored and less energy will released. Water in an average temperature range and a middle range for vapor pressure is favorable for most ultrasonic cleaning applications.

SURFACE TENSION

Like vapor pressure the surface tension should be moderate.
With high surface tension the cavitation bubbles have less elasticity so are very hard to develop. Under these conditions of we have enough power to initiate cavitation development tremendous amounts of energy will be stored and released.
With low surface tension the bubbles have more elasticity so are easy to develop. Because of the ease of development the cavitation bubbles will require lower power levels to initiate cavitation development and so will store and release lower implosion forces.
Tap water without additives is hard to cavitate do to high surface tension. If we add a small amount of wetting agent to reduce the surface tension (make the water wetter) we will have noticeable more cavitation activity. If we add to many wetting agents we can lower the surface tension to a point that we will begin losing cavitation intensity. Most chemicals formulated for use in an ultrasonic cleaning bath have the required wetting agents.
NOTE: We must also wet the product being cleaned to achieve proper cleaning. Without a wetting agent to lower the surface tension in water proper contact between the product and the water cannot be achieved.

SCENARIO

Trying to develop a cavitation bubble in water with high surface tension is like trying to blow up a balloon for the first time. You have to exert a tremendous force to initiate expansion. If expansion is accomplished a tremendous amount of energy will be stored, If ample power is not available no cavitation will be developed. (Now add a wetting agent to reduce surface tension) Now compare this to a balloon that has been blown up numerous times, it takes less exertion to initiate expansion so the balloon will blow up quite easily so less energy will be stored, but cavitation will be easy to initiate to begin the cleaning process. Surface tension not only affects the cavitation intensity but also allows the Item being cleaned to have better water contact for improved cleaning. Expression- makes the water wetter.

LIQUID TEMPERATURE

The liquid temperature affects the cavitation quantity, intensity and chemical cleaning action. The cooler the liquid the more difficult to go below the point of vaporization to begin the cavitation development process, this is do to the differential between the low temperature and the boiling point of the liquid. The applied energy must be sufficient to drop the pressure within the liquid below its vapor pressure point. If the liquid is to cold and the applied energy is insufficient under these conditions no cavitation cavities will be developed. If we increase the input power enough to initiate cavitation tremendous amounts of energy will be stored and released when the cavitation bubble implodes in the compression half cycle.
If we increase the liquid temperature it makes it easier to go below the point of vaporization so we initiate cavitation with less energy. The number of cavitation events will increase as the temperature is increased but the energy being stored in the cavitation bubble will decrease. As we approach the boiling point cavitation intensity steadily diminishes and cease or becomes ineffective for most cleaning applications at the boiling point of the liquid.
The liquid temperature will also affect the chemical cleaning ability. Some chemicals work best at elevated temperatures; while others will break down so require lower temperatures. If the temperature is to low the chemical may have trouble dissolving or dispersing. As we increase the liquid temperature most chemicals get more aggressive but we lower the cavitation implosion force. We have to find a temperature / cavitation Balance that is right for the application.

SCENARIO

Picture a seesaw with cavitation intensity on one side and temperature on the other side. As we lower the temperature side we raise the cavitation intensity side. As we raise the temperature side we lower the cavitation intensity side.

The temperature of an ultrasonic bath may vary from 80 degrees Fahrenheit (27 Celsius) or lower to 180 degrees Fahrenheit (82 Celsius) or higher depending on the application. 140 degrees Fahrenheit (60 Celsius) are the average temperature for most ultrasonic cleaning applications.

DEGASSING

Before cavitation can become effective in an ultrasonic bath dissolved gases trapped in the liquid must be removed. If not removed the cavitation vacuum bubbles being formed will fill with this gas cushioning the implosion force In some cases the cavitation bubble will sequentially grow with each cycle and when large enough float to the liquid surface without performing any cleaning task.

Unwanted gases may also be introduced into the liquid in a number of ways, all of which should be avoided if possible.

RHEOLOGICAL PROPERTIES TO BE AVOIDED

1) Pumping the solution at to fast a rate and returning above the liquid
2) Introducing the product being cleaned into the bath to rapidly.
3) Moving the product around to fast while in the bath
4) Repeatedly introducing and removing the product from the bath.
5) Continuously pumping the liquid. to a secondary tank and back

DEGASSING SUGGESTIONS

1) Switch the generator to a half wave mode
2) Shutting the generator off and on at 3 second intervals, 3 on, 3 off etc.
3) Elevate the liquid temperature
4) Fill the tank the night before and let stand until the next day.
5) Once the water is degassed and left inactive subsequent use will require little or no degassing.

WATER CONDITONS

Most alkaline detergents can soften water with up to 10 grains of hardness. If the available water is harder than this consider using a water softener.

Distilled or highly polished water is not recommended for most ultrasonic cleaning applications do to the lack of nuclei in the water from which the vacuum bubble is formed. By adding a soap or detergent to the water will help this condition to some degree but using (not so clean) water will help insure you of having the needed nuclei.

ALKALINE DETERGENTS (8*)

Before a proper chemical can be selected we must first be familiar with the soil or soils to be removed and the sensitivity of the item being cleaned in regards to temperature limitations and metal /material /coating compatibility.

Three common types of contamination are classified as ORGANIC, INORGANIC, and PARTICULAR.

ORGANIC contamination such as oil, greases, waxes and adhesives are solvent soluble.

INORGANIC contamination is insoluble in solvents and requires water-based solutions.

PARTICULAR contamination is usually insoluble.

WATER is the best universal cleaner for both organic and inorganic soils when treated with the proper cleaning chemical. In most cases particular contamination is best removed with water and ultrasonics rather than solvents. The cavitation intensity in water can be 10 to 100 times greater the cavitation intensity in most solvents.

The major active ingredients in alkaline detergents are
1) SAPONIFIERS
2) WETTING AGENTS
3) DEFLOCCULANTS
4) SEQUESTERING or CHELATING AGENTS
5) BUFFERING AGENTS
6) INHIBITORS

The proper selection of ingredients must be tailored to the contamination being removed for best cleaning results.

ACIDIC DETERGENTS SEE DRAWING F

Acidic solutions are seldom used in ultrasonic cleaning systems. If the contamination is not suitable for alkaline detergent cleaning acids may be used if the stainless steel tank (usually 316L) is compatible with the acid at the concentration being used.

If the acid is not compatible with the tank stainless consider using a tank or insert made from a different grade of stainless or consider quartz, glass, tantalum, titanium, PVC, polypropylene, or a compatible plastic. * See drawing E

The least desirable would be the plastics do to the dampening effects of the plastics when used as an insert tank. An insert tank approach is also the most common way to use different chemicals for different cleaning applications without draining the main ultrasonic cleaning bath.

After the contamination has been identified a detergent may be formulated with consideration of not damaging or attacking the item being cleaned and the temperature limitations of both the item being cleaned and the detergent. Remember the hotter the solution the more aggressive the detergent will usually be but the ultrasonic cavitation intensity will be lowered. As we reduce the liquid temperature we increase the cavitation implosion force, we have to find that balance best suited for the application. One of the most important ingredients required for the best cleaning results in an ultrasonic cleaner is the wetting agent. When the surface tension is to high cavitation development will be difficult, and cavitation erosion may be more rapid on the radiating surface. If we don’t properly wet the part being cleaned we cannot expect to properly wet the contamination for removal.

Ultrasonic cleaning can also be a great asset when used in a final rinse to aid detergent removal.

Ultrasonic cleaning systems cannot be fully effective as a cleaner without the aid of chemicals or a wetting age

SUMMARY

ULTRASONIC GENERATORS
1. Refer to the average output power only, not peak power
2. Verify output power and frequency
3. Request a power intensity control on the generator.
4. Request sweep frequency, verify if true sweep and not a temporary wobble at the start of the cycle.
5. Request an adjustable sweep repetition control.
6 Check longevity of ultrasonic manufacturer.

TRANSDUCERS
1. Piezoelectric ceramic transducer.
2. Epoxy bond.
3 Operating frequency

FREQUENCY

1 18 KHz to 25 KHz (most aggressive)
2 40 KHz (most highly used frequency for general cleaning applications)
3 60 KHz to 80 KHz (best for removing sub micron particles. Common use in electronic manufacturing)

400KHz to 800KHz and higher (same as 60 KHz to 80 KHz)

LIQUID PROPERTIES

1 Liquid temperature.
2 Viscosity
3 Density
4 Vapor pressure

Surface tension, wetness of water, best around 30 dyn/cm

ALKALINE DETERGENTS

First identify the contamination and classify. Formulate a detergent as required with consideration to temperature limitations. Proper wetting agents as required to satisfy the ultrasonic needs and to properly wet the product being cleaned.

CAVITATION

1 The lower the frequency the more aggressive the cavitation implosion.
2 The lower the frequency the fewer cavitation events
3 The higher the frequency the softer the cavitation implosion.
4 The higher the frequency the more cavitation events.
5 The cooler the liquid temperature the harder to initiate effective cavitation.
6 The hotter the liquid temperature the easier to initiate effective cavitation.
7 Wetting agents affect both the quantity and the quality of the cavitation event.
8 Three steps for cavitation are nucleation, growth and violent collapse or implosion.

STANDING WAVES

Dead spots within the cleaning bath which is evident in all ultrasonic cleaners. To reduce the effects use sweep frequency. The product may also be slowly moved up and down in the liquid for at least one wavelength during the cleaning process to insure that the part is fully and equally exposed to the antinodes.

EROSION

The undercutting and removal of metal from the radiating surface, more evident at the lower frequencies. By adding titanium nitride coating to the radiating surface erosion will be greatly reduced.

ULTRASONIC POWER

1 Must have adequate power to initiate and maintain cavitation under most work conditions.
2 If we try to introduce too much ultrasonic power into a tank a barrier will form at the liquid/radiating surface interface that will block additional input power and will cause advanced cavitation erosion.
3 If we do not have adequate ultrasonic power initiating cavitation will be difficult, maintaining cavitation will be difficult, and cleaning at best will be marginal. A low power level will also greatly reduce the cleaning applications the tank will be able to perform.
4 When considering purchasing a special ultrasonic cleaning system for a specific cleaning application FIRST Contact someone who is knowledgeable in ultrasonic design.
SECOND. Send a sample of the item to be cleaned to their testing lab for evaluation. THIRD. Request information on tank design best suited for the application.

DEGASSING

Removal of unwanted gas from the liquid. Must be completed before cavitation can be fully Effective.

END OF PART ONE

PART TWO

TRANSDUCERS (*1)

Transducers are available in two varieties, MAGNETOSTRICTIVE and ELECTROISTRICTIVE. The magnetostrictive type transducers contain ferromagnetic nickel laminations surrounded by electrical coils. During operation a varying magnetic field causes the laminations to alternately expand and contract generating a sound wave or pressure wave that is driven into the liquid of an ultrasonic tank. Magnetrostrictive transducers are a low frequency transducer and cannot operate practically at frequencies higher than approximately 20 KHz. Magnetostrictive transducers can lose up to 50 % of their applied energy in the form of heat making it difficult to maintain a low temperature in the ultrasonic bath. Magnetostrictive transducers are a low voltage, high current device that requires polarization. Do to the low operating frequency sub harmonics from the fundamental frequency are at a high amplitude in the human hearing range and usually will require ear protection by operating personal or other precautions will have to be taken.

Electrostrictive (piezoelectric) transducers have ceramic crystals, which similarly expand, and contract (vibrate) in a varying electrical field. First quartz was used, then barium titanate. The draw back with the quartz was the high cost. The draw back with the barium titanate was the low operating temperature of 160 degrees Fahrenheit (70 Celsius) maximum, or the transducer would become de polarized and destroyed. The new lead zerconate titanate ceramic transducer element can withstand temperatures in excess of 250 degrees Fahrenheit (120 Celsius). These piezoelectric transducers are a high voltage low current device and are far more efficient in energy conversion (in excess of 90 %). The piezoelectric ceramic can be manufactured to virtually any operating frequency making in the most widely used material used for ultrasonic applications. The transducer ceramic crystal is compressed into a "sandwich " consisting of a steel back plate and a steel or aluminum face plate for protecting the fragile ceramic, to aid in mounting to the tank wall, and to adjust the fundamental frequency by compression forces of the sandwich assembly. The advantages of ceramic technology in stacking ultrasonic transducers within the sandwich are overwhelming. Silicon carbide, second only to diamonds in hardness and acoustically the best ceramic in the world to transmit a sound wave should be used to enhance the transmission of ultrasonic sound wave from the transducer sandwich assembly.

TRANSDUCER CONSTRUCTION (*2) SEE DRAWING G

During the manufacturing process the lead zerconate titanate ceramic is subjected to a very high electrical field causing the formation of dipoles within the ceramic. A dipole is a small infinitesimal group of molecules bonded together within the ceramic. These dipoles display a unique feature when polarized. The dipoles will now have a polarity of opposite potential on the opposing sides. When an electrical potential from the ultrasonic generator is applied to the transducer, positive-to-positive and negative-to-negative the dipoles will compress or shrink. When the electrical potential from the ultrasonic generator is reversed and applied to the transducer, positive to negative and positive to negative the dipoles will expand or grow in length. * See drawing F

These dipoles are located throughout the ceramic crystal with all their positive polarities facing in one direction and all their negative polarities facing in the opposite direction. When an electrical potential is applied to the polarized ceramic crystal all the dipoles work in unison causing the ceramic disc to expand or contract. Each time the crystal expands it emits a movement of molecules in the form of a sound wave or pressure wave.

With a better understanding of the dipole and how in works should be evident how a transducer functions. The transducer will take a signal in one form (electrical) and convert it into a signal of another form, (Mechanical movement) to produce a sound wave or pressure wave. This is the principal of electrical to mechanical conversion.

If a transducer is subjected to extremely high temperatures (above the curing temperature of the ceramic) The dipoles could slip out of alignment and the transducer will become de polarized and will no longer function properly. If an ultrasonic cleaning transducer is run dry (no water in tank) permanent damage can result. Without a liquid coupling to disperse the high intensity sound wave the transducer may chip or fragment causing a frequency change. Never test a dry ultrasonic cleaner by a quick buzz of power, with a quick two second buzz on a 40 KHz tank the transducer has just operated (without water) 80,000 times, this is not a recommended procedure!

TRANSDUCER BONDING (*3)

A recent comparison by a Silicon Valley, Ca. Computer disc drive giant showed 25 to 30 % higher pressure readings when comparing a leading manufacturers epoxy bonded transducer to a vacuum brazed transducer from another leading manufacturer.
Additional test was conducted using a Hewlett-Packard Co. digital signal analyzer, which also indicated 29 % superiority for the epoxy-bonded transducer.

ULTRASONIC GENERATORS (*4) SEE DRAWING A

Ultrasonic generators are the power source for providing electrical power to the transducer at the voltage required for operation. Each generator is designed to drive a designated number of transducers. A 500-watt generator is normally connected to 12 transducer elements or 6 pairs, supplying each with approximately 40 watts of power. The crystals are capable of accepting additional power but this would cause significantly more cavitation erosion on the radiating surface, especially at the lower frequencies. Also by driving more power to the transducers fewer would be required, causing poor transducer distribution on the radiating surface.
Generators differ in the waveforms they emit. The three waveforms are full wave, half wave, and continuous wave, of these, full and half wave are most common.
FULL WAVE
Peak power is twice the avenge power.
HALF WAVE.
Peak power is four times the average power
CONTINUOUS WAVE
Peak power and average power are the same.

Always refer to the generator average output power when discussing power.

All Industrial ultrasonic generators have FCC suppression filters. The FCC filter prevents the modulated RF signal from entering the electrical supply line.

Generators with constant output power will self adjust to compensate for voltage fluctuations.

Generators with an electronic feedback loop changes the generator output power whenever the tank is loaded or the liquid level is changed and in most cases leads to erratic cleaning.

*NOTE: Ultrasonic generators and transducers from one manufacturer cannot be mixed with generators and transducers from another manufacturer. When selecting ultrasonic cleaning equipment longevity of the manufacturer should be your number one priority. What good is a 10-year guarantee on the transducer if the Company has only been in business for a few years? Anyone can give a guarantee but only a few will honor it. If a small manufacturer is forcer into a recall because of a defective part this manufacturer will suddenly disappear leaving you with a very expensive non-working and non-repairable ultrasonic cleaning system. If a manufacturer has been in business for 30 or 40 years be assured of getting service far into the future.

ULTRASONIC POWER (*5)

To determine if we have adequate ultrasonic power in a tank we must know both the wattage per square inch of the transducer-radiating surface and the cubic volume measurement of the liquid being ultrasonically activated.

1) If the ultrasonic tank bottom measures 10 inch by 14 inch this would give us a radiating surface of 140 square inch. If this tank were driven by a 500-watt generator the watt density would be 3.6 watts per square inch (500-divided by140) on the radiating surface.
2) If we fill this 10 by 14-inch tank to a depth of 10 inch we will now have 1400 cubic inches of liquid (6.1 gallons).
   If a 500-watt generator drives this tank the volume density would be .36 watts per Cubic inch of liquid. This would be considered a standard intensity ultrasonic tank.

   If we now install a 1000 watt generator to drive this tank the watt density per square inch on the Radiating surface would be 7.2 watts per square inch on the radiating surface and .72 watts per cubic inch of liquid; this would be considered a high intensity ultrasonic tank.

   Now lets take this 10-inch by 14 ultrasonic tank and increase is volume by filling it to up to a depth of 36 inches.(22 gallon). If this tank is once again connected to a 500-watt generator the watt density is again 3.6watts per square inch, but the watt density per cubic inch has dropped from .36 watts per cubic inch to (.099) watts per cubic inch. This is a reduction from 1/3 watt per cubic inch to 1/10 watt per cubic inch of liquid. The generator may have enough power to initiate cavitation in the first or second wavelength but will loose amplitude as it travels through this much liquid and will have trouble initiating and maintaining cavitation in the remainder of the tank.
   Do to the low ultrasonic power level the only way to help satisfy this condition is to elevate the tank temperature. At the elevated temperature of 180 degrees Fahrenheit the tank will eventually degas and cavitation will be initiated. The precaution that must be taken with this tank is that the high temperature must be retained and the load being cleaned must be kept small or the tank will stall and cavitation will be lost.

Ultrasonic power may be rated as <u>low intensity, medium intensity, standard intensity,</u> and <u>high intensity.</u>
It should be obvious that we can not expect to use the same ultrasonic power level as used in the blind cleaner, (usually in the area of 1500 watts for 25 to 30 gallons) and expect to install this same amount of power into a tank containing 95 or 100 gallons and expect to achieve effective ultrasonic cleaning. If a person is not familiar with ultrasonic activity and power levels one may be deceived into thinking their tank is:

1) **WORKING THE WAY IT SHOULD**
2) **THE CLEANING TASK IS TO DIFFERCULT**
3) **THE LOAD IS TO LARGE FOR THE TANK**
4) **I MUST BE USING THE WRONG CHEMICAL**

As the capacity of an ultrasonic tank increases, the increase in ultrasonic power is <u>not linear.</u> If we drive a 10-gallon tank with 750 watts of power we do not have to drive a 90-gallon tank with 6750 watts of power to archive the same cleaning results.

If we change the configuration of a tank but retain the same volume the ultrasonic power requirements may also change. A tank with dimensions of 24 inch x 24 inch x 9 inch deep (22 gallon) may only require 750 watts of ultrasonic power where a tank with dimensions of 12 inch x 12 inch x 36 inch deep (22 gallon) may require 1500 watts of ultrasonic power to achieve the same cleaning results.
When interested in purchasing a special ultrasonic cleaning tank go to a qualified ultrasonic design engineer for specifications.
If you have a special cleaning application it is recommended that you send a sample to a qualified ultrasonic cleaning lab for evaluation and tank design specifications.

FREQUENCY (*6)

The lower frequencies are more widely used when the product being cleaned is not susceptible to damage by the aggressive cavitation. This aggressive nature of the lower frequencies is best suited for removal of insoluble particles in the middle to upper micron range, and for removal of tenacious deposits.
Ultrasonic intensity is an integral function of the frequency and amplitude of the radiating wave.

1. A 20 KHz radiating wave will be approximately twice the intensity of a 40 KHz wave for a given average power output.
2. The diameter range of a 20 KHz cavitation bubbles is 50/200 micron.
3. The diameter range of a 25 KHz cavitation bubbles is 35/150 micron.
4. At 20 KHz the impact range is 35/70- K Pascal with a streaming velocity of 400 km/hr.
5. At 20 KHz the node, antinode points are one half-wave length or two inches apart.

40 KHz is the most widely used frequency for most ultrasonic cleaning applications. At 40 KHz the node, antinode points are one half wavelength or one inch apart.

60 KHz to 80 KHz is more commonly used in the electronic Industry. Removal efficiency of a one micron and sub micron particle is increased with the higher frequencies. At 65 KHz the removal efficient on a one-micron particle is 95 % compared to 88 % for 40 KHz. The size of a one-micron particle is one thousandth of a millimeter or one millionth of a meter, much to small to see with the human eye without magnification. Under most general ultrasonic cleaning applications these small micron and sub micron particles are of little concern so the lower frequencies are favored. The higher frequencies are favored for use in the electronic Industry for cleaning hybrids; substrates, surface mounts, and disc drive components. This Industry is very concerned with these small micron and sub micron particles and being very susceptible to damage welcome the weak cavitation implosion force of the higher frequencies.

At the higher frequencies of 400 KHz to 800 KHz and higher the removal efficiency of a one micron particle is virtually the same as the 60 KHz and 80 KHz frequencies. These frequencies are also used exclusively by the electronic and optical Industries.

One might expect that the lower frequencies, with their more aggressive cavitation implosion forces to have a greater detachment effect for all particles no matter what their micron size.
Small particles are harder to remove do to both their force of attraction and their ability for lodging into small areas. The weight of the particle is also a major factor in detachment. Although the force between a particle and an adjacent surface decreases with particle size it becomes more difficult to remove a solid particle from a solid surface because of the value of the ratio Fa/W where Fa is the force of attraction and W is the weight of the particle. The value of Fa/W increases rapidly as the diameter of the particle decreases.
Even highly polished surfaces have some valleys and irregular areas where small micron and sub micron particles can lodge. The low frequency of 20 KHz has a cavitation bubble range size of 50 to 200 microns in diameter. These cavitation bubbles have little chance of penetrating into these small irregular areas to remove small micron particles. The higher frequencies of 60 KHz and 80 KHz with its smaller range of cavitation bubbles and higher number of cavitation events have a better chance of penetrating these areas and removing more of the particles.
On items being cleaned characteristic viscous and thermal boundary layers exist. At 30 KHz the viscous boundary layer thickness is 4.4 millionths of a meter, the thermal boundary layer is 1.1 millionths of a meter.
At the lower frequencies the acoustic field does not perpetrate these boundary layers significantly so small micron and sub micron particles do not always feel the effects of the acoustic field
The boundary layer thickness is inversely proportional to the square root of the frequency.
The best means of penetrating this boundary layer is to increase the operating frequency. At 900 KHz the viscous boundary layer is to 0.8 millionths of a meter thus increasing the removal efficiency of small micron and sub micron particles.

SWEEP FREQUENCY (*7) * see drawing D

Caution should be taken when talking about sweep frequency, Some refer to a sweep frequency when in fact it is nothing more than a unpredictable frequency “wobble” during the first 5 to 10 % of the modulated cycle. This occurs because at the beginning of the cycle the voltage is to low to lock onto the fundamental frequency so is in a searching or wandering mode until the voltage reaches operational levels. At about 10 % into the modulated cycle the circuit locks on to the fundamental frequency for the balance of the cycle. During the first 10 % of the modulated cycle the energy level accounts for less than 2 % of the total energy delivered during a single modulated cycle.

THIS PHENOMENON IS EVEDENT IN ALL ULTRASONIC SYSTEMS, THIS IS NOT A SWEEP FREQUENCY.

A true sweep frequency is when the ultrasonic is operating at its fundamental frequency, lets say 40 KHz and then changes its output to 39 KHz, then back to 40 KHz, then to 41 KHz, then back to 40 KHz and so on through the full modulated cycle. This generator would have a sweep of plus or minus 1 KHz around the fundamental frequency of 40 KHz.

An additional feature that aids in cleaning is an adjustable sweep repetition rate control. Under non-adjustable conditions the sweep will be set at a fixed repetition rate of 100 to 125 sweeps per second. With the adjustable sweep the repetition rate may be changed from 30 sweeps per second to 250 sweeps per second. The changing of the sweep repetition rate is very valuable in reducing damage to certain sensitive parts being cleaned.

ALKALINE DETERGENTS (*8)

The most common aqueous cleaning media, alkaline detergents are widely used to remove a wide verity of contaminants from metals to plastics to glass. Some alkaline detergents may be used at high temperatures while others are temperature limited.

These cleaning agents utilize alkaline salts as sodium hydroxide, sodium metasilicate, orthosilicate or trisilicate, sodium carbonate, sodium tetraborate, trisodium phosphate, tetrasodium pyrophosphate, or sodium polyphosphates.

Rather than dissolving soils like solvents alkaline detergents displace and suspend them, emulsify them, or react with them to form water-soluble soaps. Selection of a specific cleaner should be based on work piece materials, soil composition, cleanliness standards and water conditions (especially hardness)

The major active ingredients in alkaline detergents are **saponifiers, wetting agents, deflocculants, water softeners, buffering agents** and **inhibitors.**

SAPONIFIERS

Saponifiers are strong alkalines, which convert oils and greases into water-soluble soaps.

WETTING AGENTS

Wetting agents are surface-active synthetic detergents, which lower the surface tension of the cleaning solution. Simply immersing a solid item into a liquid doesn’t mean that the item is sufficiently wetted for cleaning. In order to penetrate the surface of a contaminate layer the liquid must have a lower surface tension than that of the contaminant. EXPRESSION (make the water wetter).

The normal difference in surface tension between water and oil may be illustrated when a drop of water is placed on top of an oily surface and the water will bead up and remain there. If a wetting agent is added to this water droplet to reduce the surface tension to that of the oil film the droplet will spread out over the oil and will cause the water to penetrate and displace the oil, sending the oil droplets to the surface of the water.

DEFLOCCULANTS

Deflocculants are sub-microscopic colloidal particles that are added to a cleaning solution. The deflocculants do not dissolve in the water, but remain suspended and exhibit constant Brownian movement. Deflocculants aid cleaning through attraction of oppositely charged fine soil particles clinging to part surfaces. When their attraction is greater than the surface charge attraction the particles leave the surface and become suspended, with little tendency for redeposition.

WATER SOFTENERS

Water softeners are sequestering or chelating agents that combine with metallic ions to form water-soluble Nonionic structures. Most alkaline detergents can softer water up to 10 grains of hardness. If available water is harder than this the use of deionized water is recommended.

SEQUESTERING or CHELATING AGENTS.

Sequestering or chelating agents are similar in action except sequestering agents are limited to maximum temperatures of 180 degrees F (82 C). They are composed of polyphosphates, usually sodium tripolyphosphate, tetraphosphate or hexametaphosphate.

CHELATING AGENTS

Chelating agents are generally organic sodium salts of one of various acids. Unlike the polyphosphates they do not break down or lose potency at high temperatures. Moreover they enable alkaline cleaners to solubilize metallic compounds such s rust, scale, iron, and zinc phosphate conversion coatings, and drawing compounds.

BUFFERING AGENTS

Buffering agents or buffer salts maintain the optimum pH range for maximum detergency of soaps and other surface-active agents. Each cleaning solution has a particular pH range of greater effectiveness. Buffering agents are designed to keep the solution within this range despite contamination by acidic or alkaline soils during cleaning.

INHIBITORS

Inhibitors are silicates or chromates added to highly alkaline detergents to allow their use with non-ferrous metals such as aluminum, copper, lead, zinc and tin. They are not required when working pieces are composed of ferrous metals of titanium and magnesium alloys. During cleaning inhibitors deposit a thin protective film on the bare metal surfaces as soon as soils are removed to protect attack, pitting or tarnishing.

END

Any questions, comments, suggestions or request for cleaning application laboratory tests please direct to:

HESSONIC ULTRASONIC DISTRICT OFFICE

751 Majestic Dr. Washington, UT. 84780 1125 N Kraemer Pl. Anaheim, CA. 92806

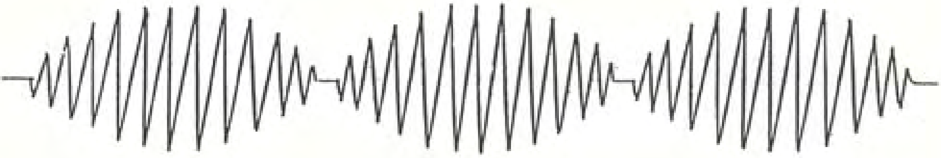
Tel. 435-627-2460 TF 800-552-0372 Fax 435-627-2465

E-mail Hessonic@aol.com Web site www.hessonic.com

DRAWING A

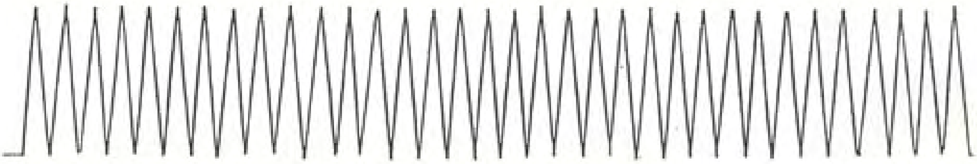
FORMS OF ULTRASONIC GENERATOR OUTPUTS

* FULL WAVE



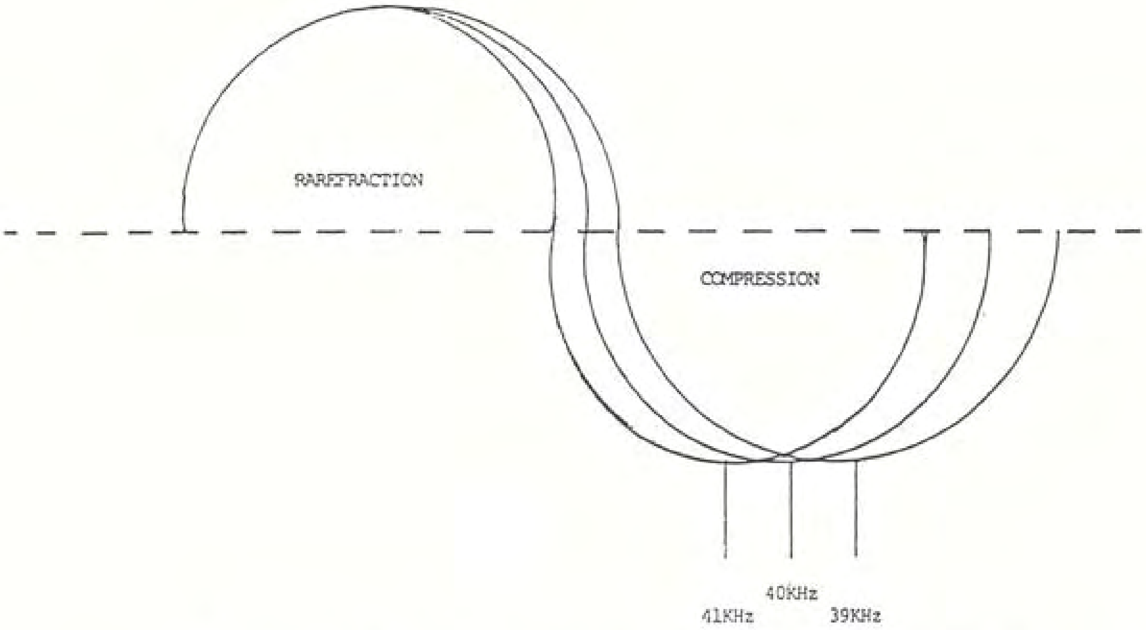
* HALF WAVE

* CONTINUOUS WAVE



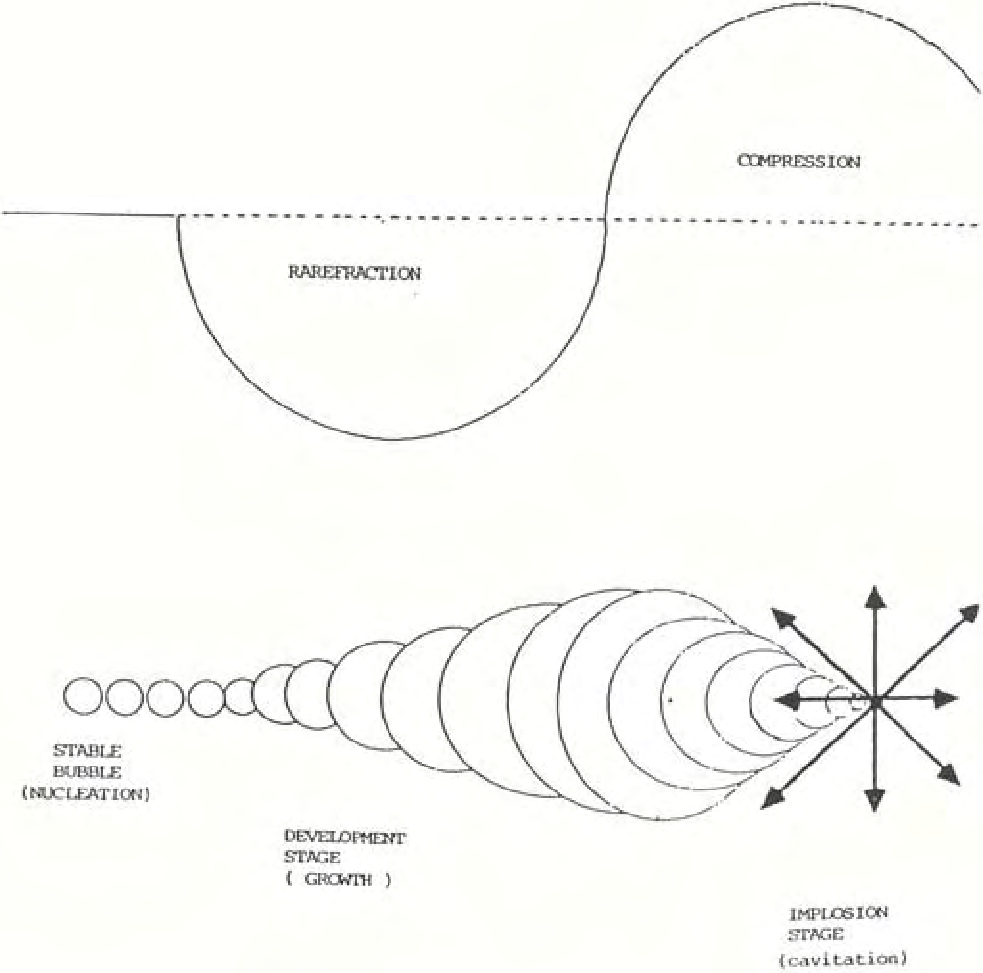
DRAWING B

*SWEEP FREQUENCY



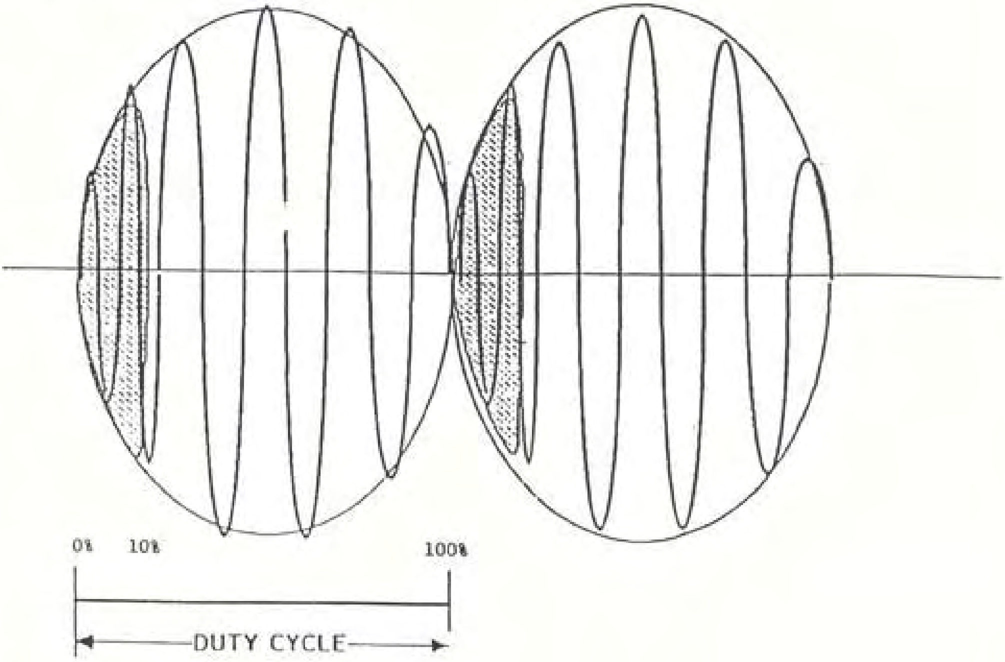
BY CHANGING THE GENERATOR OUTPUT FREQUENCY (WITHIN LIMITS) WE CHANGE THE LOCATION OF THE NODE, ANTINODE HELPING TO ELIMINATE DEAD SPOTS (STANDING WAVES)

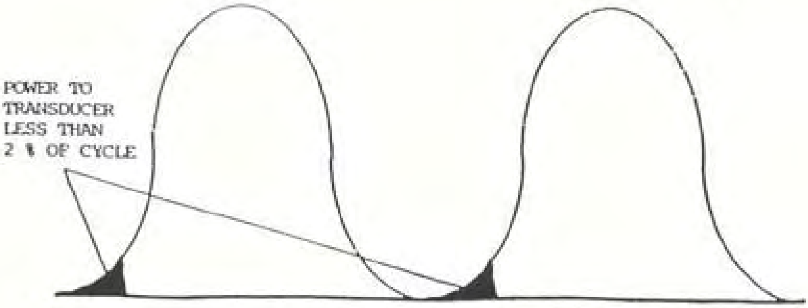
DRAWING C


COMPRESSION
RAREFRACTION
STABLE BUBBLE (NUCLEATION)
DEVELOPMENT STAGE (GROWTH)
IMPLOSION STAGE (cavitation)

DRAWING D

* THIS IS NOT SWEEP FREQUENCY

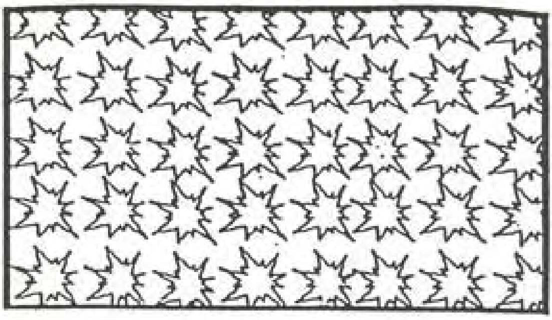




DRAWING E

68 kHz

70% more implosions than 40 kHz



Cavitations at 68 kHz

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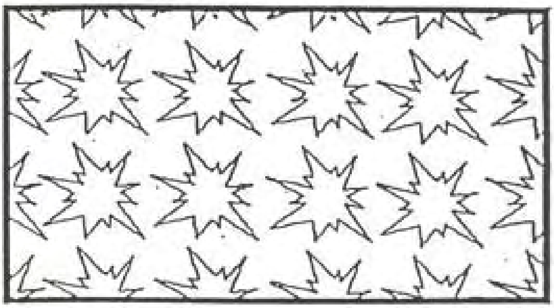
40 kHz

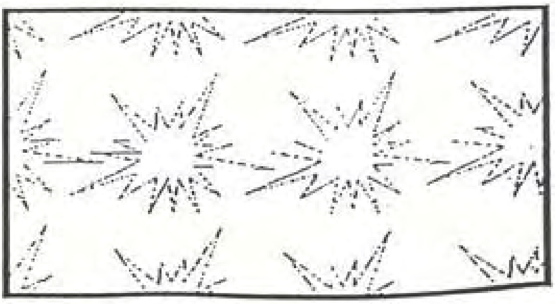
60% more implosions than 25 kHz



Cavitations at 40 kHz

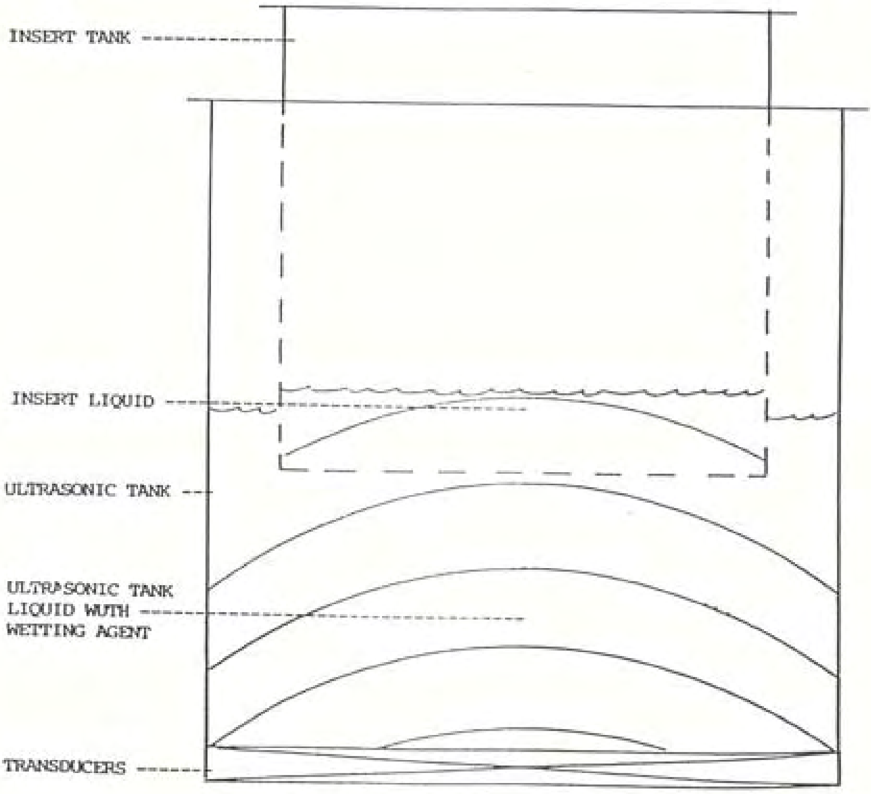
---

25 kHz



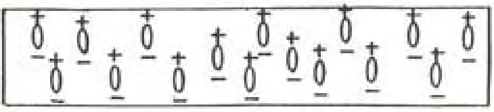
Cavitations at 25 kHz

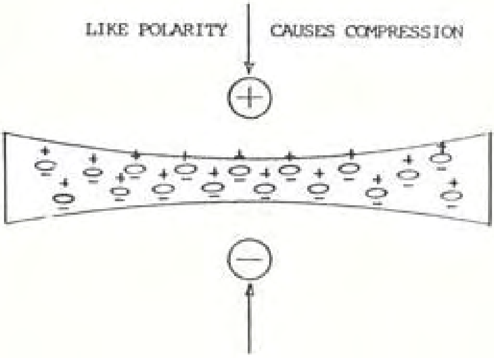
USE OF AN INSERT TANK TO CAVITATE A SECONDARY SOLUTION

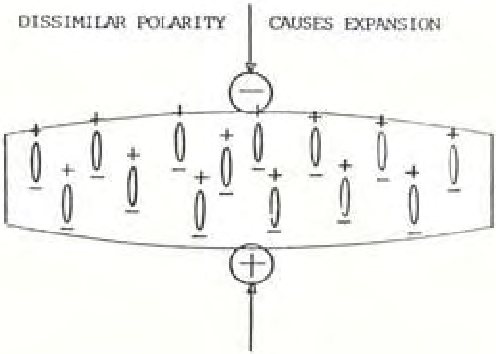


DRAWING G

POLARIZED PIEZOELECTRIC CERAMIC WITH DIPOLES







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Abstract

A presentation describing the theory of ultrasonics and how ultrasonic technology is applied to precision cleaning. This presentation will explore the importance and application of ultrasonics in precision cleaning along with explanations of ultrasonic cleaning equipment and its application. Process parameters for ultrasonic cleaning will be discussed along with procedures for proper operation of ultrasonic cleaning equipment to achieve maximum results.

Introduction

Cleaning technology is in a state of change. Vapor degreasing using chlorinated and fluorinated solvents, long the standard for most of industry, is being phased out in the interest of the ecology of our planet. At the same time, cleaning requirements are continually increasing. Cleanliness has become an important issue in many industries where it never was in the past. In industries such as electronics where cleanliness was always important, it has become more critical in support of growing technology. It seems that each advance in technology demands greater and greater attention to cleanliness for its success. As a result, the cleaning industry has been challenged to deliver the needed cleanliness and has done so through rapid innovation over the past several years. Many of these advances have involved the use of ultrasonic technology.

The cleaning industry is currently in a struggle to replace solvent degreasing with alternative "environmentally friendly" means of cleaning. Although substitute water-based, semi-aqueous and petroleum based chemistries are available, they are often somewhat less effective as cleaners than the solvents and may not perform adequately in some applications unless a mechanical energy boost is added to assure the required levels of cleanliness. Ultrasonic energy is now used extensively in critical cleaning applications to both speed and enhance the cleaning effect of the alternative chemistries. This paper is intended to familiarize the reader with the basic theory of ultrasonics and how ultrasonic energy can be most effectively applied to enhance a variety of cleaning processes.

What is "Ultrasonics?"

Ultrasonics is the science of sound waves above the limits of human audibility. The frequency of a sound wave determines its tone or pitch. Low frequencies produce low or bass tones. High frequencies produce high or treble tones. Ultrasound is a sound with a pitch so high that it can not be heard by the human ear. Frequencies above 18 Kilohertz are usually considered to be ultrasonic. The frequencies used for ultrasonic cleaning range from 20,000 cycles per second or kilohertz (KHz) to over 100,000 KHz. The most commonly used frequencies for industrial cleaning are those between 20 KHz and 50KHz. Frequencies above 50KHz are more commonly used in small tabletop ultrasonic cleaners such as those found in jewelry stores and dental offices.

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The Theory of Sound Waves

In order to understand the mechanics of ultrasonics, it is necessary to first have a basic understanding of sound waves, how they are generated and how they travel through a conducting medium. The dictionary defines sound as the transmission of vibration through an elastic medium which may be a solid, liquid, or a gas. Sound Wave Generation - A sound wave is produced when a solitary or repeating displacement is generated in a sound conducting medium, such as by a "shock" event or "vibratory" movement. The displacement of air by the cone of a radio speaker is a good example of "vibratory" sound waves generated by mechanical movement. As the speaker cone moves back and forth, the air in front of the cone is alternately compressed and rarefied to produce sound waves, which travel through the air until they are finally dissipated. We are probably most familiar with sound waves generated by alternating mechanical motion. There are also sound waves which are created by a single "shock" event. An example is thunder which is generated as air instantaneously changes volume as a result of an electrical discharge (lightning). Another example of a shock event might be the sound created as a wooden board falls with its face against a cement floor. Shock events are sources of a single compression wave which radiates from the source.

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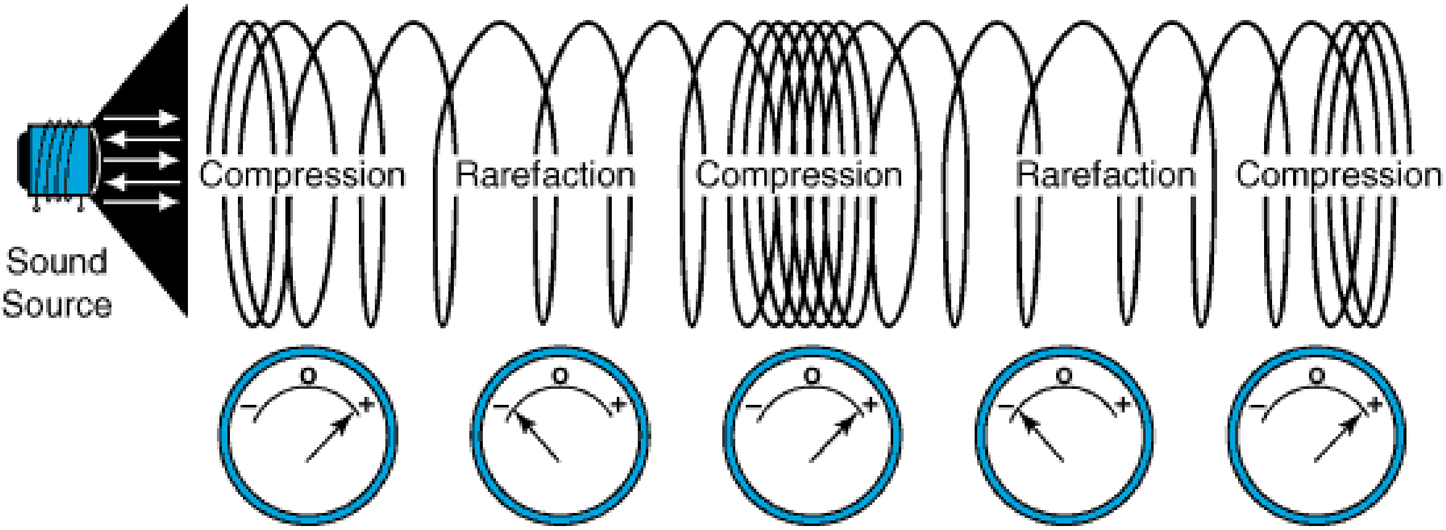

The Nature of Sound Waves

The diagram above uses the coils of a spring similar to a Slinky toy to represent individual molecules of a sound conducting medium. The molecules in the medium are influenced by adjacent molecules in much the same way that the coils of the spring influence one another. The source of the sound in the model is at the left. The compression generated by the sound source as it moves propagates down the length of the spring as each adjacent coil of the spring pushes against its neighbor. It is important to note that, although the wave travels from one end of the spring to the other, the individual coils remain in their same relative positions, being displaced first one way and then the other as the sound wave passes. As a result, each coil is first part of a compression as it is pushed toward the next coil and then part of a rarefaction as it recedes from the adjacent coil. In much the same way, any point in a sound conducting medium is alternately subjected to compression and then rarefaction. At a point in the area of a compression, the pressure in the medium is positive. At a point in the area of a rarefaction, the pressure in the medium is negative.

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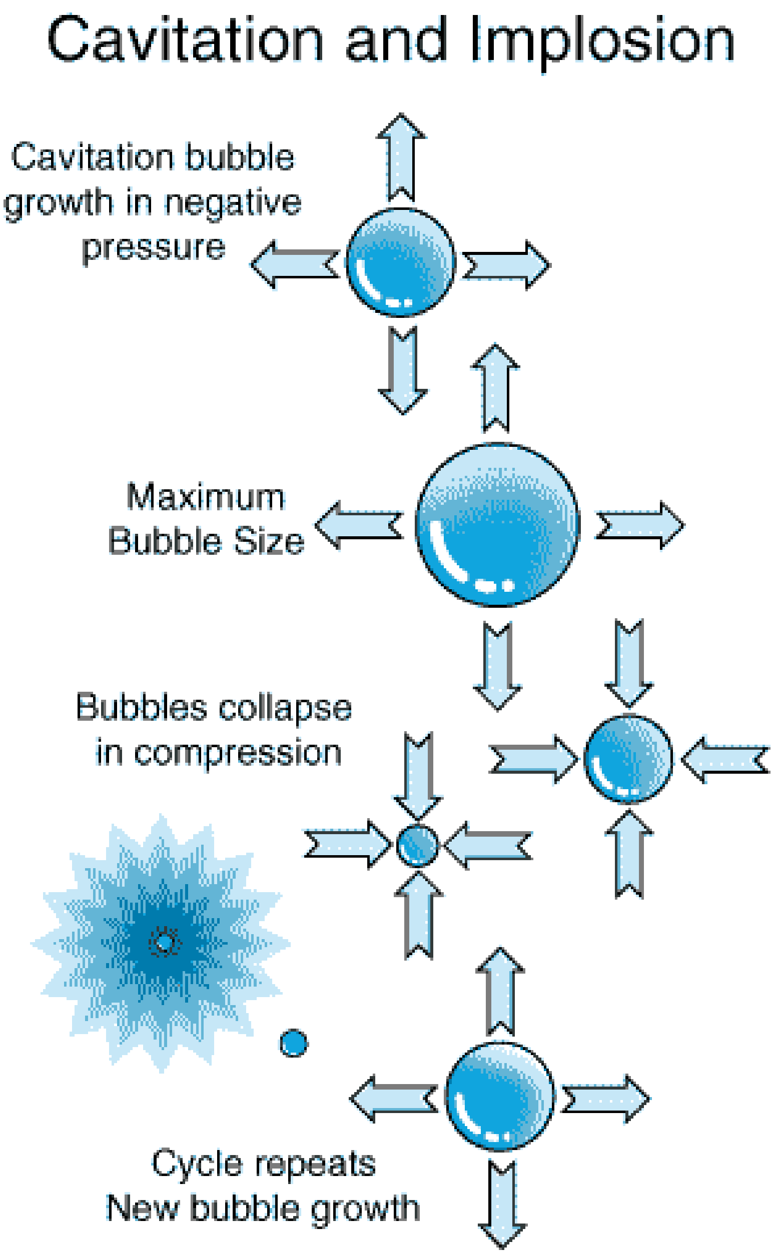

In elastic media such as air and most solids, there is a continuous transition as a sound wave is transmitted. In non-elastic media such as water and most liquids, there is continuous transition as long as the amplitude or "loudness" of the sound is relatively low. As amplitude is increased, however, the magnitude of the negative pressure in the areas of rarefaction eventually becomes sufficient to cause the liquid to fracture because of the negative pressure, causing a phenomenon known as cavitation. Cavitation "bubbles" are created at sites of rarefaction as the liquid fractures or tears because of the negative pressure of the sound wave in the liquid. As the wave fronts pass, the cavitation "bubbles" oscillate under the influence of positive pressure, eventually growing to an unstable size. Finally, the violent collapse of the cavitation "bubbles" results in implosions, which cause shock waves to be radiated from the sites of the collapse. The collapse and implosion of myriad cavitation "bubbles" throughout an ultrasonically activated liquid result in the effect commonly associated with ultrasonics. It has been calculated that temperatures in excess of 10,000°F and pressures in excess of 10,000 PSI are generated at the implosion sites of cavitation bubbles.

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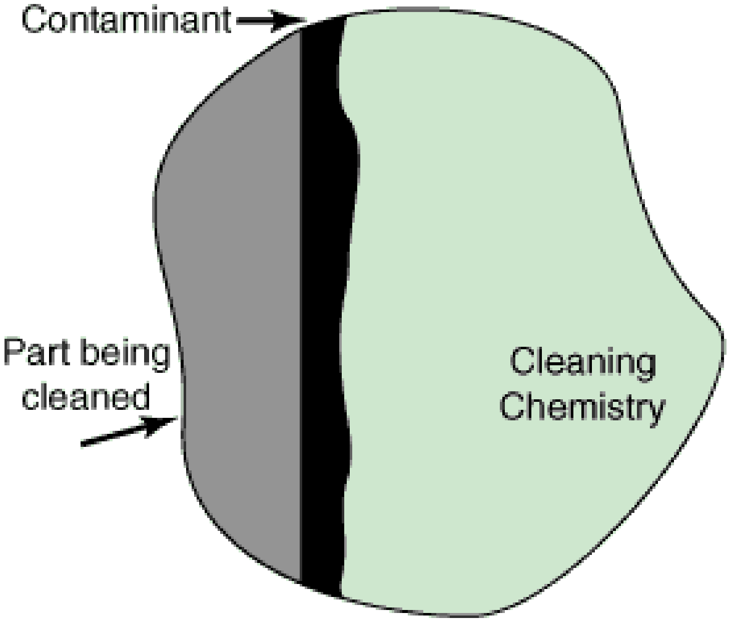
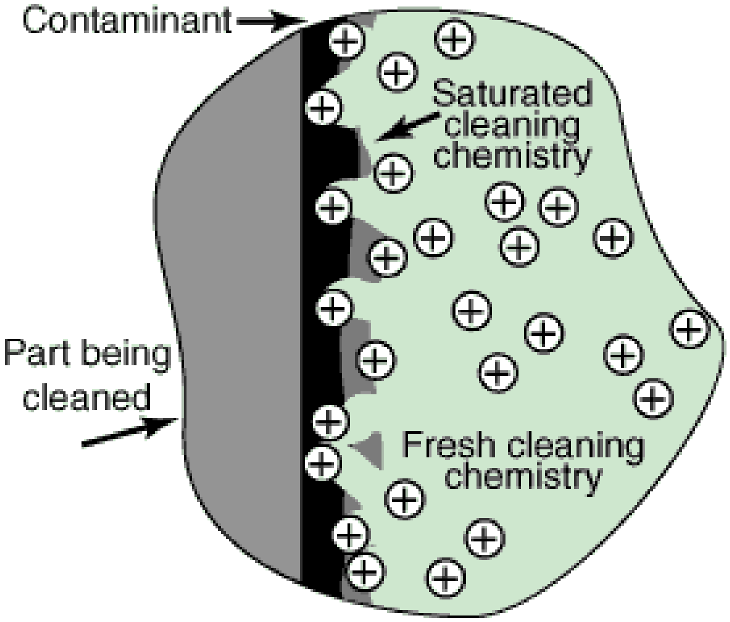
Benefits of Ultrasonics in the Cleaning and Rinsing Processes

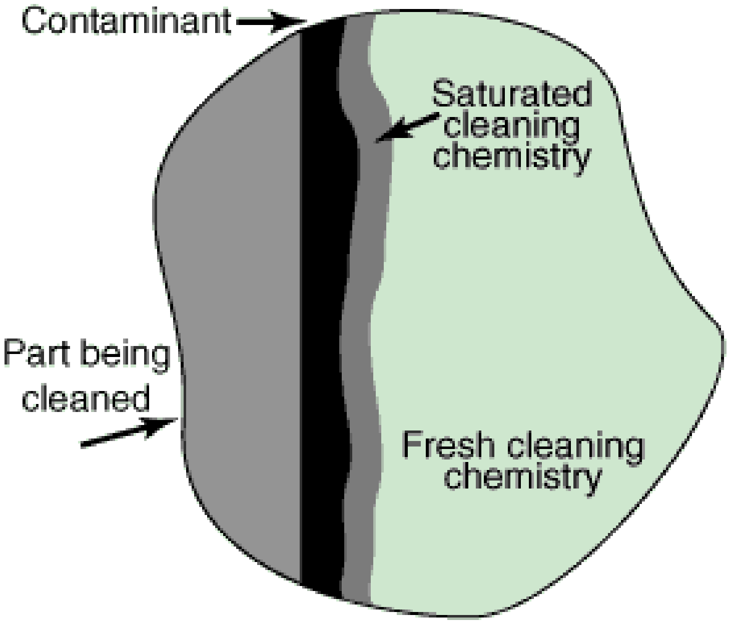
Cleaning in most instances requires that a contaminant be dissolved (as in the case of a soluble soil), displaced (as in the case of a non-soluble soil) or both dissolved and displaced (as in the case of insoluble particles being held by a soluble binder such as oil or grease). The mechanical effect of ultrasonic energy can be helpful in both speeding dissolution and displacing particles. Just as it is beneficial in cleaning, ultrasonics is also beneficial in the rinsing process. Residual cleaning chemicals are removed quickly and completely by ultrasonic rinsing.



In removing a contaminant by dissolution, it is necessary for the solvent to come into contact with and dissolve the contaminant. The cleaning activity takes place only at the interface between the cleaning chemistry and the contaminant.

As the cleaning chemistry dissolves the contaminant, a saturated layer develops at the interface between the fresh cleaning chemistry and the contaminant. Once this has happened, cleaning action stops as the saturated chemistry can no longer attack the contaminant. Fresh chemistry cannot reach the contaminant.





Ultrasonic cavitation and implosion effectively displace the saturated layer to allow fresh chemistry to come into contact with the contaminant remaining to be removed. This is especially beneficial when irregular surfaces or internal passageways are to be cleaned.

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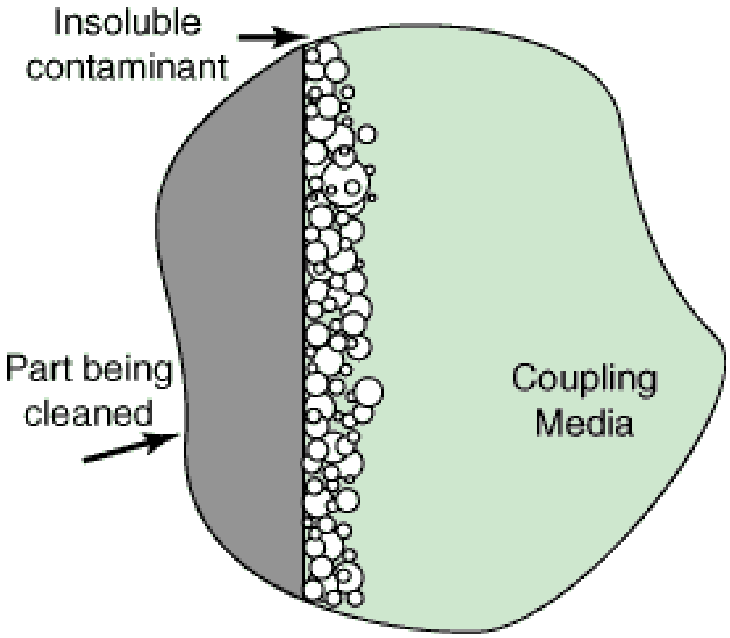
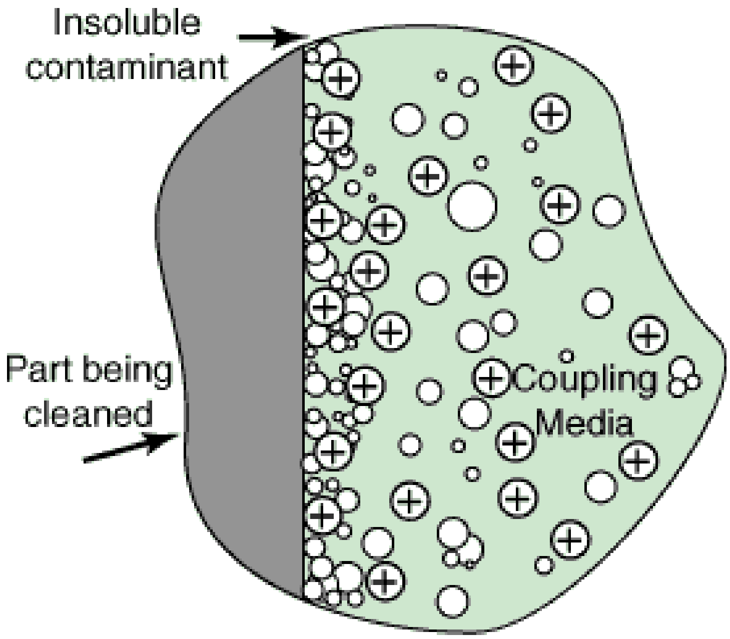
Ultrasonics Speeds Cleaning by Dissolution



Some contaminants are comprised of insoluble particles loosely attached and held in place by ionic or cohesive forces. These particles need only be displaced sufficiently to break the attractive forces to be removed.



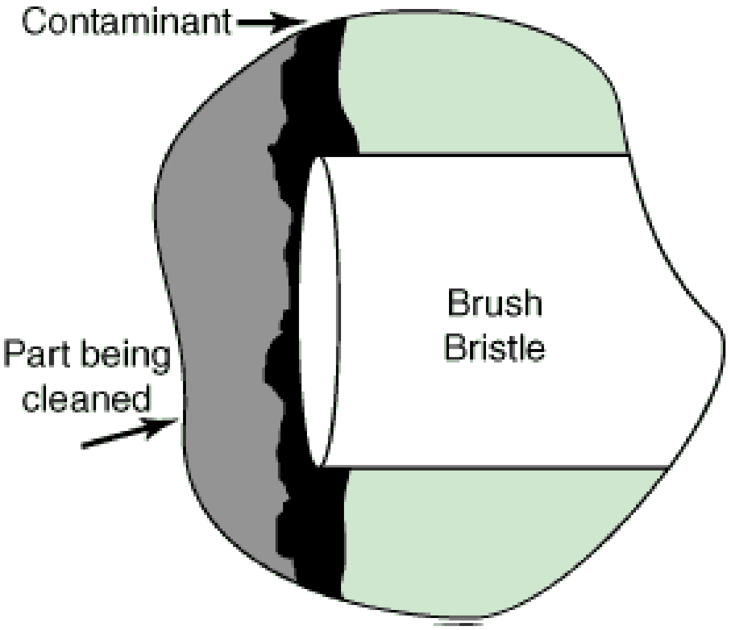
Cavitation and implosion as a result of ultrasonic activity displace and remove loosely held contaminants such as dust from surfaces. For this to be effective, it is necessary that the coupling medium be capable of wetting the particles to be removed.

Complex Contaminants

Contaminations can also, of course, be more complex in nature, consisting of combination soils made up of both soluble and insoluble components. The effect of ultrasonics is substantially the same in these cases, as the mechanical micro-agitation helps speed both the dissolution of soluble contaminants and the displacement of insoluble particles. Ultrasonic activity has also been demonstrated to speed or enhance the effect of many chemical reactions. This is probably caused mostly by the high energy levels created as high pressures and temperatures are created at the implosion sites. It is likely that the superior results achieved in many ultrasonic cleaning operations may be at least partially attributed to the sonochemistry effect.

A Superior Process

In the above illustrations, the surface of the part being cleaned has been represented as a flat. In reality, surfaces are seldom flat, instead being comprised of hills, valleys and convolutions of all description. The illustration at the right shows why ultrasonic energy has been proven to be more effective at enhancing cleaning than other alternatives, including spray washing, brushing, turbulation, air agitation, and even electro-cleaning in many applications. The ability of ultrasonic activity to penetrate and assist the cleaning of interior surfaces of complex parts is also especially noteworthy.



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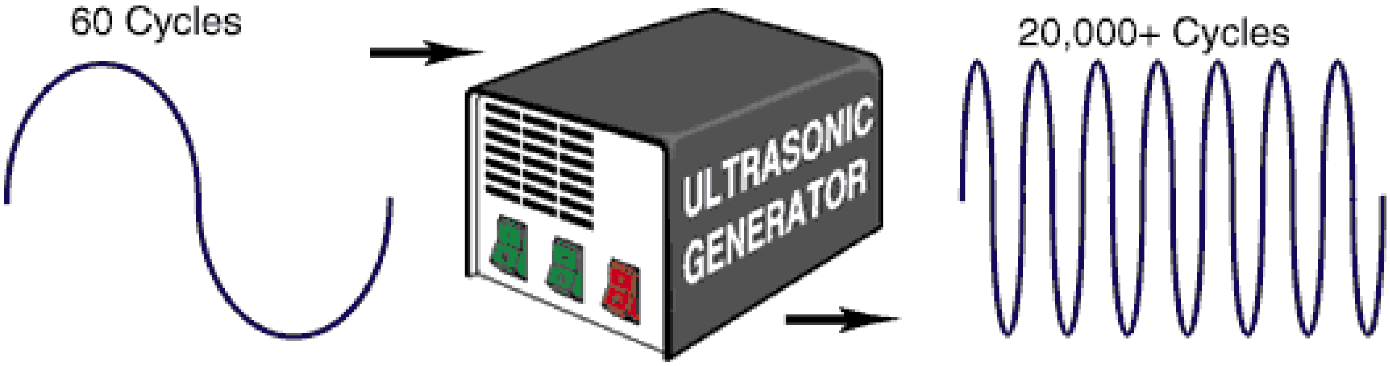
Ultrasonic Equipment

To introduce ultrasonic energy into a cleaning system requires an ultrasonic transducer and an ultrasonic power supply or "generator." The generator supplies electrical energy at the desired ultrasonic frequency. The ultrasonic transducer converts the electrical energy from the ultrasonic generator into mechanical vibrations.

Ultrasonic Generator

The ultrasonic generator converts electrical energy from the line which is typically alternating current at 50 or 60Hz to electrical energy at the ultrasonic frequency. This is accomplished in a number of ways by various equipment manufacturers. Current ultrasonic generators nearly all use solid state technology.



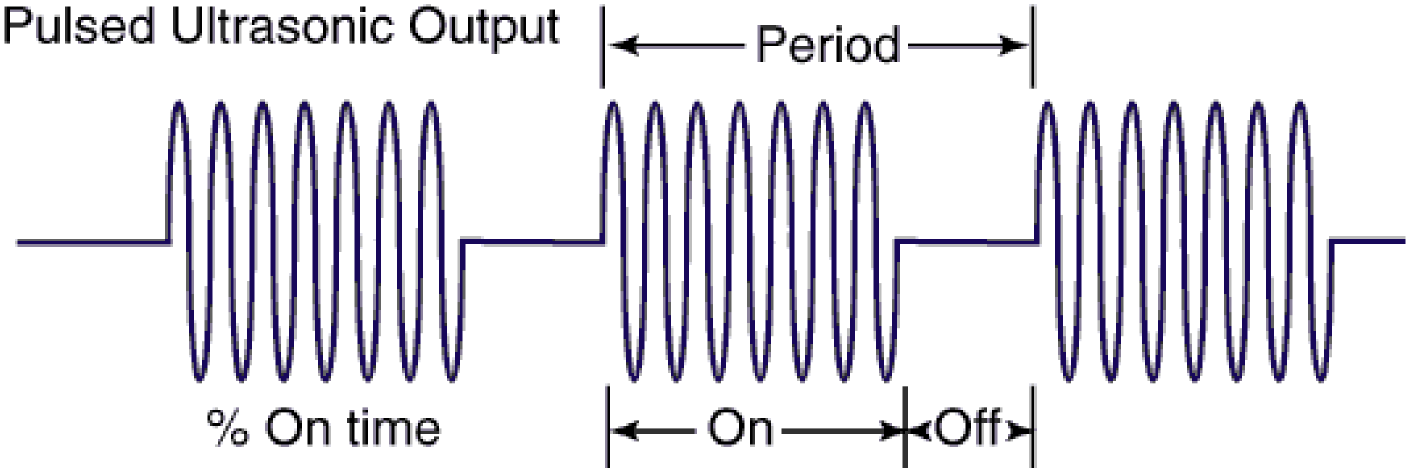
There have been several relatively recent innovations in ultrasonic generator technology which may enhance the effectiveness of ultrasonic cleaning equipment. These include square wave outputs, slowly or rapidly pulsing the ultrasonic energy on and off and modulating or "sweeping" the frequency of the generator output around the central operating frequency. The most advanced ultrasonic generators have provisions for adjusting a variety of output parameters to customize the ultrasonic energy output for the task.

Square Wave Output

Applying a square wave signal to an ultrasonic transducer results in an acoustic output rich in harmonics. The result is a multi-frequency cleaning system which vibrates simultaneously at several frequencies which are harmonics of the fundamental frequency. Multi-frequency operation offers the benefits of all frequencies combined in a single ultrasonic cleaning tank.

Pulse

In pulse operation, the ultrasonic energy is turned on and off at a rate which may vary from once every several seconds to several hundred times per second.



The percentage of time that the ultrasonic energy is on may also be changed to produce varied results. At slower pulse rates, more rapid degassing of liquids occurs as coalescing bubbles of air are given an opportunity to rise to the surface of the liquid during the time the ultrasonic energy is off. At more rapid pulse rates the cleaning process may be enhanced as repeated high energy "bursts" of ultrasonic energy occur each time the energy source is turned on.

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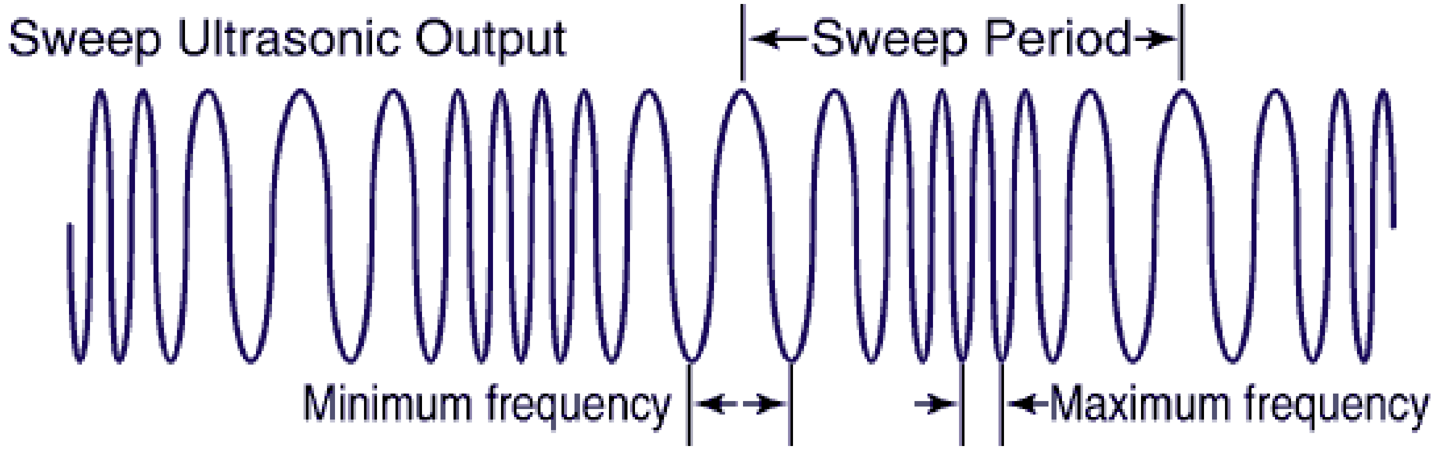
Frequency Sweep

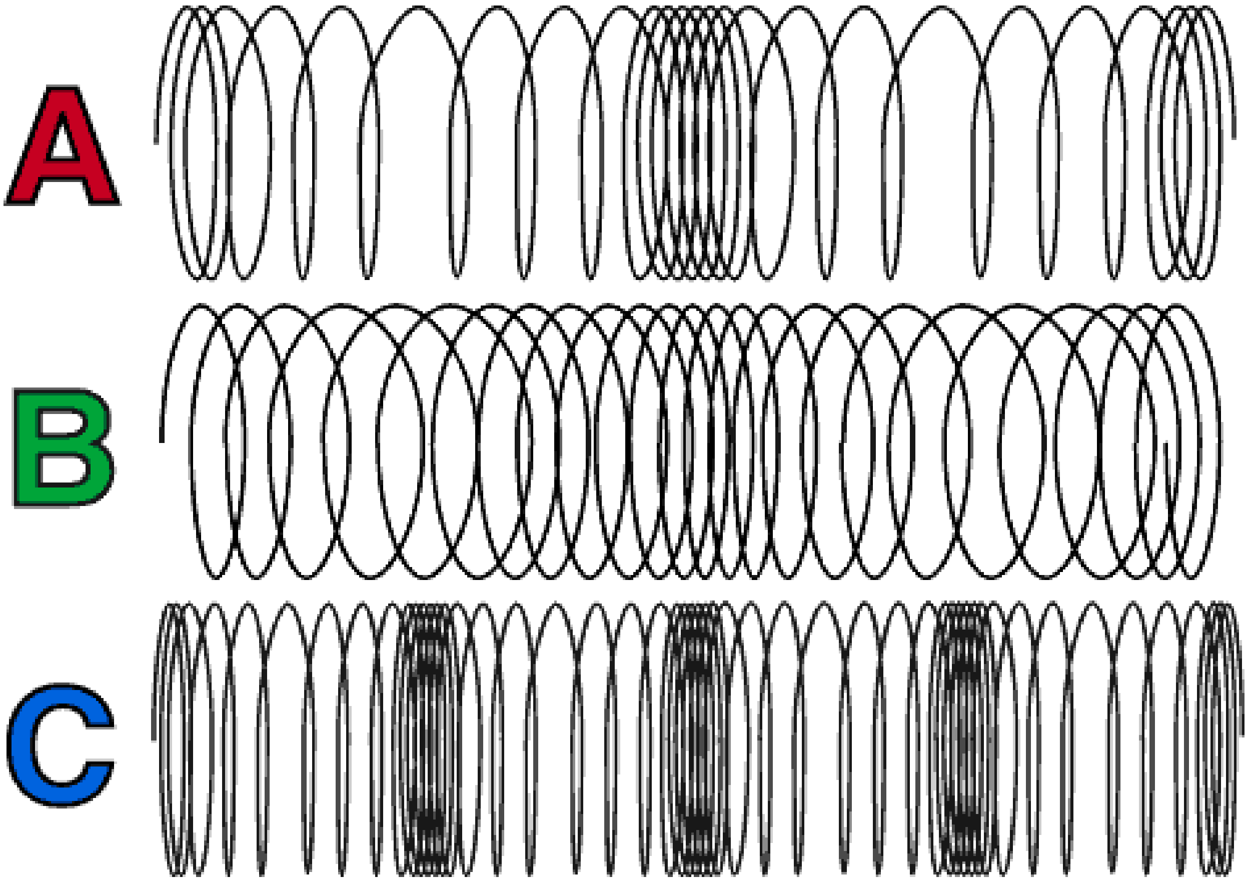
In sweep operation, the frequency of the output of the ultrasonic generator is modulated around a central frequency which may itself be adjustable.



Various effects are produced by changing the speed and magnitude of the frequency modulation. The frequency may be modulated from once every several seconds to several hundred times per second with the magnitude of variation ranging from several hertz to several kilohertz. Sweep may be used to prevent damage to extremely delicate parts or to reduce the effects of standing waves in cleaning tanks. Sweep operation may also be found especially useful in facilitating the cavitation of terpenes and petroleum based chemistries. A combination of Pulse and sweep operation may provide even better results when the cavitation of terpenes and petroleum based chemistries is required.

Frequency and Amplitude

Frequency and amplitude are properties of sound waves. The illustrations below demonstrate frequency and amplitude using the spring model introduced earlier. In the diagram, if **A** is the base sound wave, **B** with less displacement of the media (less intense compression and rarefaction) as the wave front passes, represents a sound wave of less amplitude or "loudness." **C** represents a sound wave of higher frequency indicated by more wave fronts passing a given point within a given period of time.



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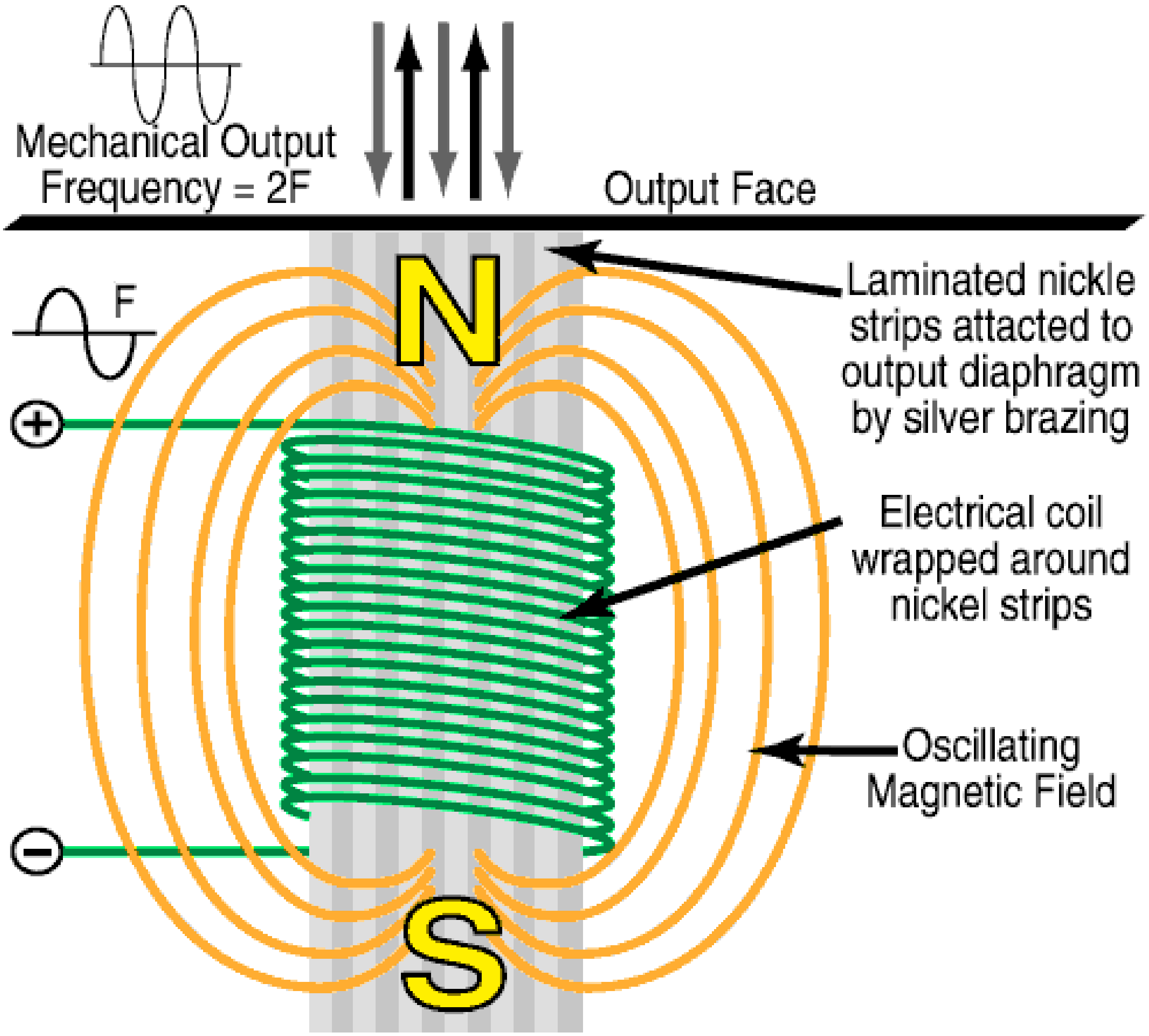
Ultrasonic Transducers

There are two general types of ultrasonic transducers in use today: Magnetostrictive and piezoelectric. Both accomplish the same task of converting alternating electrical energy to vibratory mechanical energy but do it through the use of different means.

Magnetostrictive

Magnetostrictive transducers utilize the principle of magnetostriction in which certain materials expand and contract when placed in an alternating magnetic field.



Alternating electrical energy from the ultrasonic generator is first converted into an alternating magnetic field through the use of a coil of wire. The alternating magnetic field is then used to induce mechanical vibrations at the ultrasonic frequency in resonant strips of nickel or other magnetostrictive material which are attached to the surface to be vibrated. Because magnetostrictive materials behave identically to a magnetic field of either polarity, the frequency of the electrical energy applied to the transducer is 1/2 of the desired output frequency. Magnetostrictive transducers were first to supply a robust source of ultrasonic vibrations for high power applications such as ultrasonic cleaning.

Because of inherent mechanical constraints on the physical size of the hardware as well as electrical and magnetic complications, high power magnetostrictive transducers seldom operate at frequencies much above 20 kilohertz. Piezoelectric transducers, on the other hand, can easily operate well into the megahertz range.

Magnetostrictive transducers are generally less efficient than their piezoelectric counterparts. This is due primarily to the fact that the magnetostrictive transducer requires a dual energy conversion from electrical to magnetic and then from magnetic to mechanical. Some efficiency is lost in each conversion. Magnetic hysteresis effects also detract from the efficiency of the magnetostrictive transducer.

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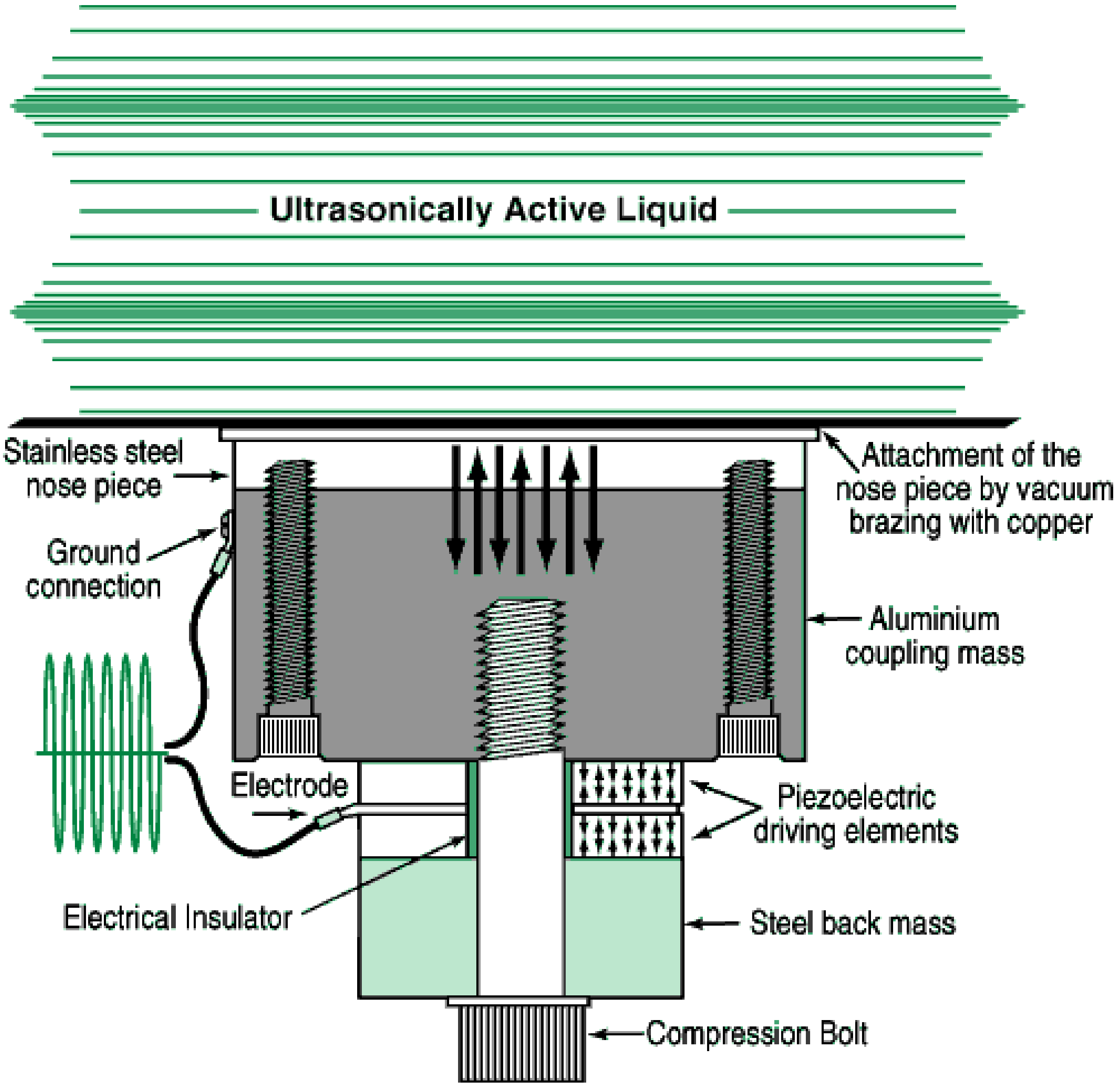
Piezoelectric

Piezoelectric transducers convert alternating electrical energy directly to mechanical energy through use of the piezoelectric effect in which certain materials change dimension when an electrical charge is applied to them.



Electrical energy at the ultrasonic frequency is supplied to the transducer by the ultrasonic generator. This electrical energy is applied to piezoelectric element(s) in the transducer which vibrate. These vibrations are amplified by the resonant masses of the transducer and directed into the liquid through the radiating plate. Early piezoelectric transducers utilized such piezoelectric materials as naturally occurring quartz crystals and barium titanate which were fragile and unstable. Early piezoelectric transducers were, therefore, unreliable. Today's transducers incorporate stronger, more efficient and highly stable ceramic piezoelectric materials which were develops as a result of the efforts of the US Navy and its research to develop advanced sonar transponders in the 1940's. The vast majority of transducers used today for ultrasonic cleaning utilize the piezoelectric effect.

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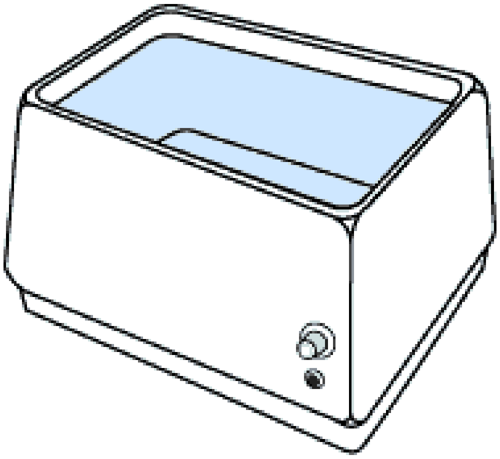
Ultrasonic Cleaning Equipment

Ultrasonic cleaning equipment ranges from the small tabletop units often found in dental offices or jewelry stores to huge systems with capacities of several thousand gallons used in a variety of industrial applications. Selection or design of the proper equipment is paramount in the success of any ultrasonic cleaning application.

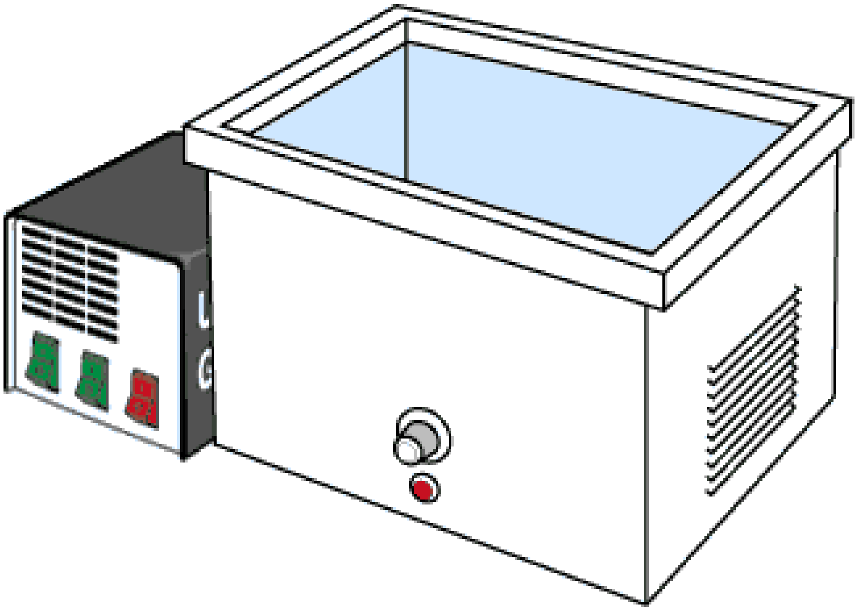
The simplest application may require only a simple heated tank cleaner with rinsing to be done in a sink or in a separate container. More sophisticated cleaning systems include one or more rinses, added process tanks and hot air dryers. Automation is often added to reduce labor and guarantee process consistency.

The largest installations utilize immersible ultrasonic transducers which can be mounted on the sides or bottom of cleaning tanks of nearly any size. Immersible ultrasonic transducers offer maximum flexibility and ease of installation and service.



Small, self-contained cleaners are used in doctors' offices and jewelry stores.

Heated tank cleaning systems are used in laboratories and for small batch cleaning needs.



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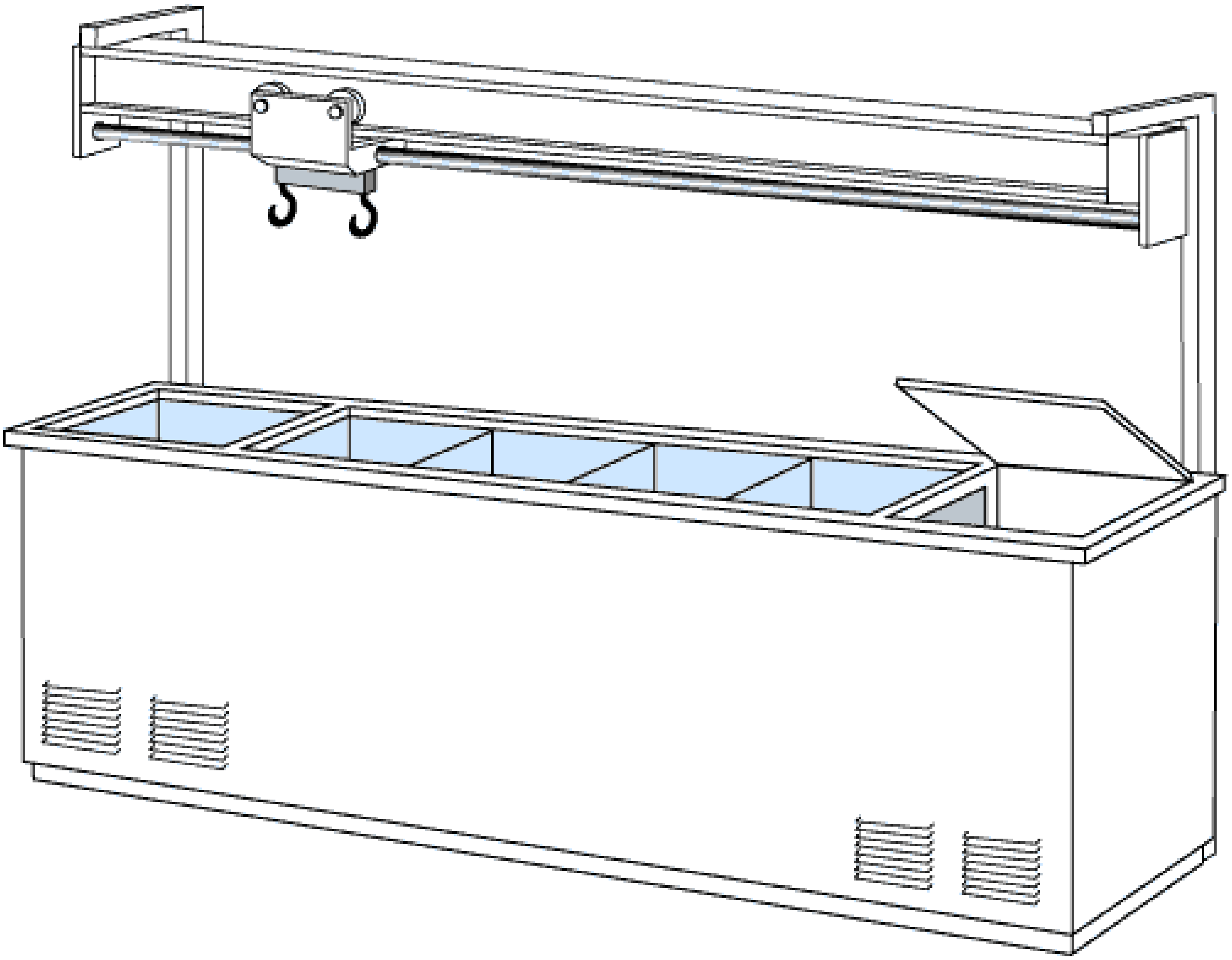
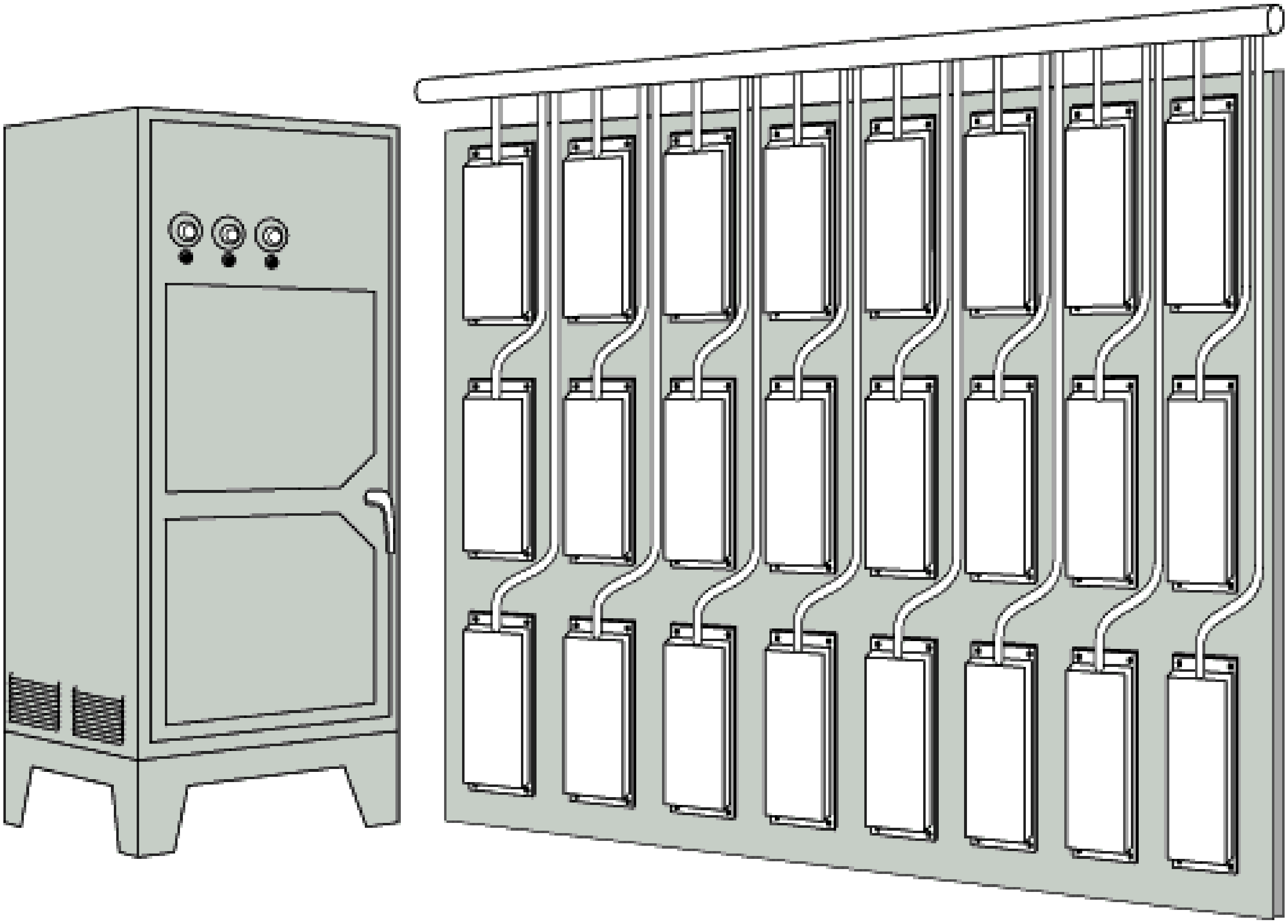
Ultrasonic Cleaning Equipment *cont.*

Console cleaning systems integrate ultrasonic cleaning tank(s), rinse tank(s) and a dryer for batch cleaning. Systems can be automated through the use of a PLC controlled material handling system.



A wide range of options may be offered in custom designed systems. Large scale installations or retrofitting of existing tanks in plating lines, etc., can be achieved through the use of modular immersible ultrasonic transducers. Ultrasonic generators are often housed in climate-controlled enclosures.



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Maximizing the Ultrasonic Cleaning Process

Process Parameters

Effective application of the ultrasonic cleaning process requires consideration of a number of parameters. While time, temperature and chemical remain important in ultrasonic cleaning as they are in other cleaning technologies, there are other factors which must be considered to maximize the effectiveness of the process. Especially important are those variables which affect the intensity of ultrasonic cavitation in the liquid.

Maximizing Cavitation

Maximizing cavitation of the cleaning liquid is obviously very important to the success of the ultrasonic cleaning process. Several variables affect cavitation intensity.

Temperature is the most important single parameter to be considered in maximizing cavitation intensity. This is because so many liquid properties affecting cavitation intensity are related to temperature. Changes in temperature result in changes in viscosity, the solubility of gas in the liquid, the diffusion rate of dissolved gasses in the liquid, and vapor pressure, all of which affect cavitation intensity. In pure water, the cavitation effect is maximized at approximately 160°F.

The viscosity of a liquid must be minimized for maximum cavitation effect. Viscous liquids are sluggish and cannot respond quickly enough to form cavitation bubbles and violent implosion. The viscosity of most liquids is reduced as temperature is increased.

For most effective cavitation, the cleaning liquid must contain as little dissolved gas as possible. Gas dissolved in the liquid is released during the bubble growth phase of cavitation and prevents its violent implosion which is required for the desired ultrasonic effect. The amount of dissolved gas in a liquid is reduced as the liquid temperature is increased.

The diffusion rate of dissolved gasses in a liquid is increased at higher temperatures. This means that liquids at higher temperatures give up dissolved gasses more readily than those at lower temperatures, which aids in minimizing the amount of dissolved gas in the liquid.

A moderate increase in the temperature of a liquid brings it closer to its vapor pressure, meaning that vaporous cavitation is more easily achieved. Vaporous cavitation, in which the cavitation bubbles are filled with the vapor of the cavitating liquid, is the most effective form of cavitation. As the boiling temperature is approached, however, the cavitation intensity is reduced as the liquid starts to boil at the cavitation sites.

Cavitation intensity is directly related to **Ultrasonic Power** at the power levels generally used in ultrasonic cleaning systems. As power is increased substantially above the cavitation threshold, cavitation intensity levels off and can only be further increased through the use of focusing techniques.

Cavitation intensity is inversely related to **Ultrasonic Frequency**. As the ultrasonic frequency is increased, cavitation intensity is reduced because of the smaller size of the cavitation bubbles and their resultant less violent implosion. The reduction in cavitation effect at higher frequencies may be overcome by increasing the ultrasonic power.

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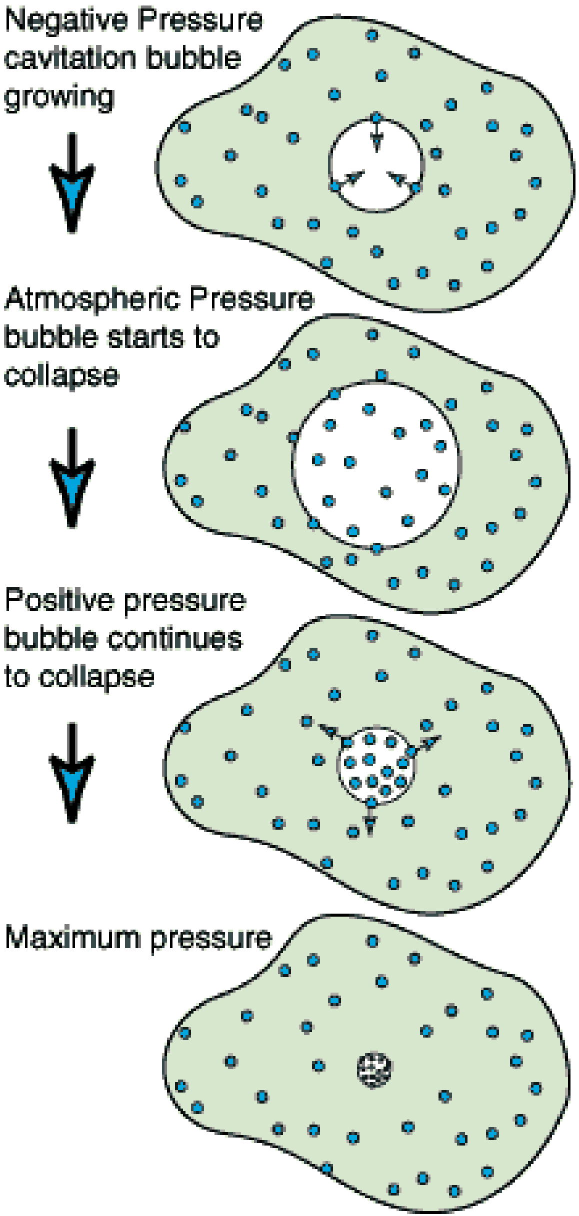
Importance of Minimizing Dissolved Gas

During the negative pressure portion of the sound wave, the liquid is torn apart and cavitation bubbles start to form. As a negative pressure develops within the bubble, gasses dissolved in the cavitating liquid start to diffuse across the boundary into the bubble. As negative pressure is reduced due to the passing of the rarefaction portion of the sound wave and atmospheric pressure is reached, the cavitation bubble starts to collapse due to its own surface tension. During the compression portion of the sound wave, any gas which diffused into the bubble is compressed and finally starts to diffuse across the boundary again to re-enter the liquid. This process, however, is never complete as long as the bubble contains gas since the diffusion out of the bubble does not start until the bubble is compressed. And once the bubble is compressed, the boundary surface available for diffusion is reduced. As a result, cavitation bubbles formed in liquids containing gas do not collapse all the way to implosion but rather result in a small pocket of compressed gas in the liquid. This phenomenon can be useful in degassing liquids.



The small gas bubbles group together until they finally become sufficiently buoyant to come to the surface of the liquid.

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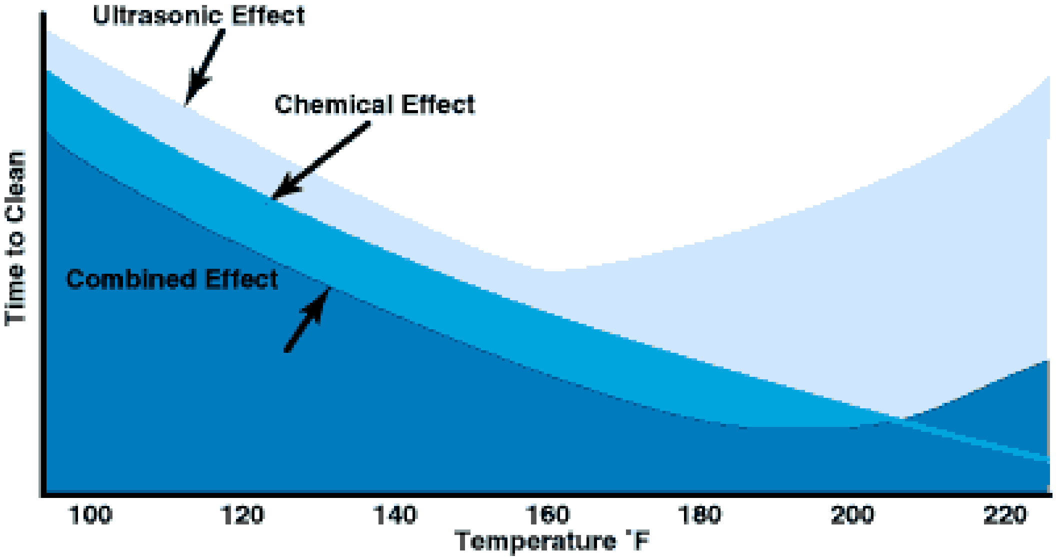
Maximizing Overall Cleaning Effect

Cleaning Chemical selection is extremely important to the overall success of the ultrasonic cleaning process. The selected chemical must be compatible with the base metal being cleaned and have the capability to remove the soils which are present. It must also cavitate well. Most cleaning chemicals can be used satisfactorily with ultrasonics. Some are formulated especially for use with ultrasonics. However, avoid the non-foaming formulations normally used in spray washing applications. Highly wetted formulations are preferred. Many of the new petroleum cleaners, as well as petroleum and terpene based semi-aqueous cleaners, are compatible with ultrasonics. Use of these formulations may require some special equipment considerations, including increased ultrasonic power, to be effective.



Temperature was mentioned earlier as being important to achieving maximum cavitation. The effectiveness of the cleaning chemical is also related to temperature. Although the cavitation effect is maximized in pure water at a temperature of approximately 160°F, optimum cleaning is often seen at higher or lower temperatures because of the effect that temperature has on the cleaning chemical. As a general rule, each chemical will perform best at its recommended process temperature regardless of the temperature effect on the ultrasonics. For example, although the maximum ultrasonic effect is achieved at 160°F, most highly caustic cleaners are used at a temperatures of 180°F to 190°F because the chemical effect is greatly enhanced by the added temperature. Other cleaners may be found to break down and lose their effectiveness if used at temperatures in excess of as low as 140°F. The best practice is to use a chemical at its maximum recommended temperature not exceeding 190°F

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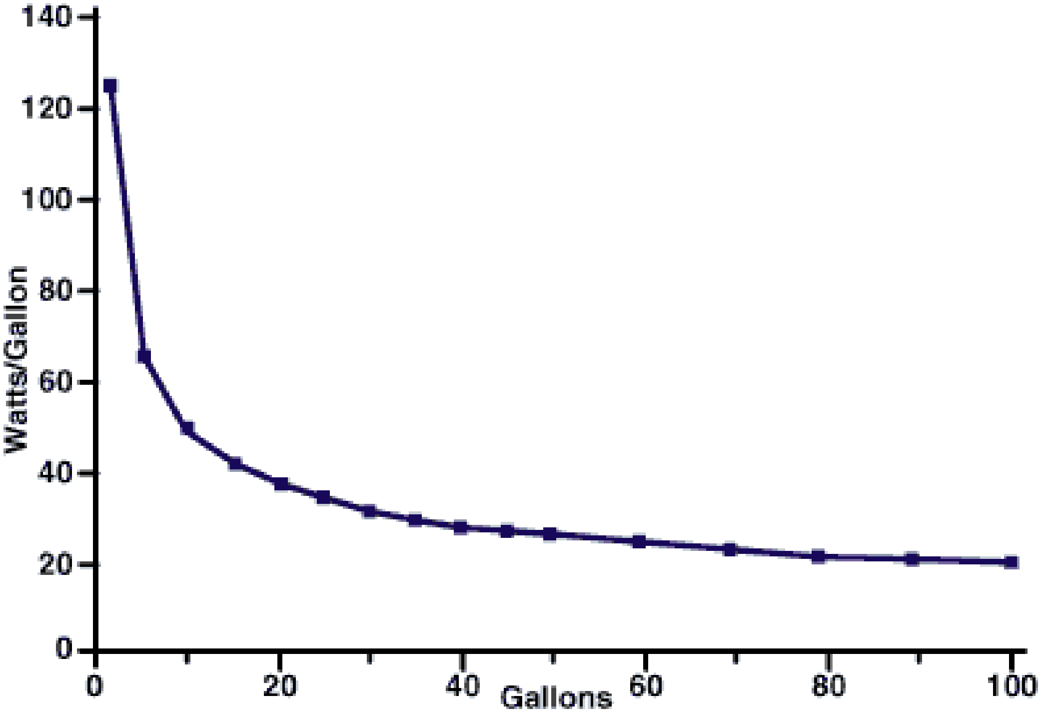
Maximizing Overall Cleaning Effect *cont.*

Degassing of cleaning solutions is extremely important in achieving satisfactory cleaning results. Fresh solutions or solutions which have cooled must be degassed before proceeding with cleaning. Degassing is done after the chemical is added and is accomplished by operating the ultrasonic energy and raising the solution temperature. The time required for degassing varies considerably, based on tank capacity and solution temperature, and may range from several minutes for a small tank to an hour or more for a large tank. An unheated tank may require several hours to degas. Degassing is complete when small bubbles of gas cannot be seen rising to the surface of the liquid and a pattern of ripples can be seen.

The **Ultrasonic Power** delivered to the cleaning tank must be adequate to cavitate the entire volume of liquid with the workload in place. Watts per gallon is a unit of measure often used to measure the level of ultrasonic power in a cleaning tank. As tank volume is increased, the number of watts per gallon required to achieve the required performance is reduced. Cleaning parts that are very massive or that have a high ratio of surface to mass may require additional ultrasonic power. Excessive power may cause cavitation erosion or "burning" on soft metal parts. If a wide variety of parts is to be cleaned in a single cleaning system, an ultrasonic power control is recommended to allow the power to be adjusted as required for various cleaning needs. Part Exposure to both the cleaning chemical and ultrasonic energy is important for effective cleaning. Care must be taken to ensure that all areas of the parts being cleaned are flooded with the cleaning liquid. Parts baskets and fixtures must be designed to allow penetration of ultrasonic energy and to position the parts to assure that they are exposed to the ultrasonic energy. It is often necessary to individually rack parts in a specific



orientation or rotate them during the cleaning process to thoroughly clean internal passages and blind holes.

Conclusion

Properly utilized, ultrasonic energy can contribute significantly to the speed and effectiveness of many immersion cleaning and rinsing processes. It is especially beneficial in increasing the effectiveness of today's preferred aqueous cleaning chemistries and, in fact, is necessary in many applications to achieve the desired level of cleanliness. With ultrasonics, aqueous chemistries can often give results surpassing those previously achieved using solvents. Ultrasonics is not a technology of the future -- it is very much a technology of today.

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Ultrasonic Cleaning: Fundamental Theory and Application

By F. John Fuchs

Director, Applications Engineering
CAE Ultrasonics

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PMR Systems, Inc.
2024 W. 1st Street, Ste 104
TEMPE, AZ 85281
Phone: (480) 829-8170
Fax: (480) 829-8238
E-MAIL: sales@pmrsystems.com

PMR Systems, Inc. was established in 1994 as a distribution company, serving the Surface Mount Industry as well as the Microelectronic Assembly community.

We are a customer focused organization - committed to supplying unsurpassed quality, reliability and value to our customers. Developing and distributing market-driven products and services is our mission.

Our models 3500 and 5000 Ultrasonic Stencil Cleaning Systems found a wide acceptance in the industry and have been installed worldwide to the satisfaction of our customers.

PMR Systems, Inc. is located in a new building, 5 Min. from the Phoenix Sky Harbor Airport.

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A supply kit of system - compatible, readily disposable cleaning agents, specially formulated to remove adhesives, solder paste and inks.

- SMT Concentrate Adhesive Detergent
- SMT Concentrate Solder Paste Detergent, etc.

All supplies are now available for immediate shipment.

PMR Systems, Inc. has started an advertisement campaign nationwide to promote our models 3500 and 5000.

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Ultrasonic SMT Stencil Cleaning Systems

The Challenge: *Safely and efficiently cleaning SMT stencils, fine-pitch screens, PCBs, blades, dispensing nozzles and other tools without the use of solvents, alcohol or hand-wiping.*

The Answer: Aqueous ultrasonic cleaning *to thoroughly remove flux, solder paste and adhesives without harming the part or generating hazardous waste.*

PMR Systems presents a highly efficient, easy to use and environmentally benign cleaning system developed exclusively for use with PCB stencils and related components. In partnership with **CAE Ultrasonics,** the leader in advanced ultrasonic cleaning technology, PMR Systems offers this economical, hazard-free alternative to conventional solvent cleaning methods.

The **PMR 3500** and **PMR 5000** are sleek, two-tank units featuring 40 kHz **ultrasonics, heat, filtration** and **ergonomically-**

Water Eater Model 85E

The Model 85E is an electrically heated wastewater evaporator.PMR Systems is an authorized dealer for EMC products.

designed operator controls and fixtures for ease of use and thorough cleaning results. The ultrasonic washing process permits penetration of minute crevices to remove solder paste, flux or SMD adhesives more efficiently than spray washing or hand-wiping and without the use of harmful solvents or aggressive chemicals.

Choose from **two standard models** to accomodate any size of stencil. **Options** include custom-designed parts-holding racks and a supply of our specially blended cleaning agents formulated for use in the PMR ultrasonic stencil cleaning systems.

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Ultrasonic SMT Stencil Cleaning System

Control Panel

Filters

Tanks

Standard Features

- Ultrasonic wash + rinse using CAE Ultrasonic's 40 kHz piezoelectric, metallurgically bonded transducers for superior performance and durability.
- All-stainless steel construction
- Temperature-controlled heat in both wash and rinse tanks
- Solder trap for easy disposal of heavy sediments
- Circulation pump and your choice of 10µ or 5µ particulate filter with pressure gauge on wash tank
- Low liquid level protection
- De-Gas cycle start
- Ergonomically-arranged operator controls
- Sliding Cover
- Full Warranty

Options and Accessories

- A supply of system-compatible, readily disposable cleaning agents Specially-formulated to remove adhesives, solder paste and inks
- Custom-engineered stainless parts baskets for racking stencils, PCBs, dispensing nozzles or other components
- Alternative 380, 480 or 575V, 3Ø, 50/60Hz power supplies
- Installation supervision and

training

Two Standard Models

Model	Capacity (gals.)	Tank Dimensions (LRxFBxLiquid Level)	Unit Dimensions (LRxFBxHeight)	Ultrasonic Power (Watts RMS)	Heating Power (Watts per tank)	Power Supply
PMR 3500	21	30" X 8" X 23.5"	41" X 29" X 36"	1,440	2,000	220V, 1Ø, 60HZ, 45A
PMR 5000	40	34" X 8" X 34"	53" X 29" X 48"	2,000	4,000	220V, 1Ø, 60HZ, 45A

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DETERGENTS

PMR Systems, Inc. offers the SC - 125 Detergent for the use with ultrasonic stencil cleaning system.

The SC - 125 is formulated to remove RA, RMA, No clean and OA solder paste from screens, stencils, misprinted substrates and tooling commonly used in surface mount technology (SMT) assembly.

Also, removing wet SMD adhesives from stencils and misprinted substrates as well as removing flux residue from PCB's, flex circuits, wave-solder pallets and tooling can be accomplished effectively with the SC - 125.

Of course, the SC - 125 is a tested and certified detergent as the MATERIAL SAFETY DATA SHEET (MSDS) will show.
If you want to see the entire 2 page MSDS, please click here and fillout the Request Form.

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FAQ

Ultrasonic SMT Stencil Cleaning Systems

Frequently Asked Questions

1) How important is the chemistry as part of the stencil cleaning process?

The chemistry is the heart of the cleaning process! This is true not only in stencil cleaning but also in virtually any ultrasonic cleaning process. The purpose of ultrasonics is to speed and enhance the action of the cleaning chemistry. In this case, CAE Blackstone and PMR Systems conferred with several potential chemistry formulators before a chemistry was developed which had the ability to meet the wide range of cleaning applications inherent to the printed circuit board fabrication process.

2) Since PMR Systems uses heaters, can the heat de-bond the glue holding the stencil together or distort the apertures of a fine-pitch stencil due to expansion / contraction of the stainless steel?

The specially formulated chemistry offered by CAE Blackstone and PMR Systems is used at various temperatures for a variety of applications. The temperature that is recommended for stencil cleaning in the operator instruction manual is 115 degrees Fahrenheit. Heaters add versatility to the unit allowing faster start-up and solution degassing especially at the beginning of a process day. Many stencil manufactures use MERECO

7) Why does the PMR unit use 220 Volt electrical instead of standard 115 Volt?

Since the maximum practical current draw from a non-dedicated 120-volt outlet is 15 amps, and the PMR Systems unit features a 1,000 watt ultrasonic generator and a filter pump as standard, the limits of a 120 volt outlet are reached prior to the addition of heaters. Since the heaters help provide additional capability to the system especially in adhesive removal, they were considered necessary as part of the standard offering by PMR Systems. However, in the event that only 120-volt power is available, the system can be configured to "time share" the various features making it operable from a 120-volt source if necessary.

8) The PMR 5000 has a 40-gallon wash tank. Will it require more chemistry than a smaller tank?

Only volume and throughput limit the "life" of a chemistry. Double the chemistry will process twice the work. In addition, chemistry life is extended in the PMR Systems unit through the use of a filtration system to remove contaminants likely to foul the

Technologies Group MERECO 3212 epoxy resin for attaching stencils to the mesh and frame. Their data of Overlap Shear Testing (ASTM D 1002-72) verifies immersing a stencil in water for 30 days @ 120 degrees Fahrenheit results in a shear strength of 4700 PSI compared to 30 days @ 72 degrees Fahrenheit in air with Relative Humidity of 50% with a shear strength of 5100 PSI. This is only a reduction in shear strength of 7% NOT a de-bonding issue. Mind you this 7% loss was achieved only after 30 days of continuous immersion at 120 degrees Fahrenheit. Stencils in the PMR Systems typically only see 12 minutes @ 115 degrees Fahrenheit per cleaning cycle. Since most stencils are made of stainless steel, and the apertures are created with lasers exceeding temperatures of 3000 degrees Fahrenheit there is no concern of apertures warping at 115 degrees Fahrenheit.

3) Is the PMR Systems chemical, environmentally safe?

YES, The chemistry is a an aqueous detergent, that can be easily disposed. We offer several methods of disposal, dependant upon municipal laws.

4) Is the chemistry offered by PMR Systems suitable for evaporation?

The chemistry offered by PMR Systems and CAE Blackstone contains NO saponifiers, NO VOC's or hazardous materials and is suitable for reduction by evaporation.

5) Does the PMR Systems Stencil Cleaner require a fume hood because of the heated tanks?

The PMR Systems stencil cleaners are

process. This filtration system is in addition to the "solder trap". The chemistry offered by CAE Blackstone and PMR Systems is buffered to prevent the need for continuing additions to maintain the required bath concentration. PMR Systems does not advocate the approach of replacing the chemistry weekly no matter how many cleaning operations have been performed because it wasteful and costly.

9) Can chemistry offered by CAE Blackstone and PMR Systems also clean SMD adhesives and flux residue from pallets and tooling.

Because the CAE Blackstone / PMR Systems chemistry is further enhanced by heating, it is the only detergent chemistry that has been demonstrated capable of cleaning operations on all SMD Adhesives (Heraus, Loctite, CibaGiga, & Emerson Cummings), solder pastes (no clean, RMA, Water Soluble, etc) and conductive epoxies with guaranteed results.

In conclusion, PMR Systems and CAE Blackstone are proud of the chemical and equipment package they have developed. As a primary manufacturer of ultrasonic cleaning equipment for nearly 50 years, CAE Blackstone has developed and demonstrated the capability to build world class ultrasonic equipment which holds up under the rigid requirements of industrial cleaning operations. "Blackstone" is

supplied with a cover to limit evaporation to those brief times when a stencil or other work is actually being introduced into or removed from the cleaner. There is no reason for a fume hood over this unit as over time there will be no more evaporation than there would be from an open-covered unit operating at room temperature.

6) PMR Systems designed its rinsing to perform immersion rinsing instead of spray rinsing. Does this mean that the user will use more water for rinsing?

The PMR Systems equipment offers ultrasonic immersion rinsing in addition to optional spray rinsing and air blow-off. Ultrasonic rinsing has been demonstrated to do a better job of removing the last traces of chemistry following cleaning. The combination of ultrasonic immersion rinsing and use of the optional spray rinse will result in more thorough rinsing using less water. Furthermore, the rinse water can be recycled into the cleaning tank once it is contaminated thereby eliminating the fresh water required for mixing with the chemistry.

a leading name in the ultrasonic cleaning industry respected around the world with literally thousands of installations.

PMR Systems has vast experience in the field of printed circuit board manufacturing having worked in that industry along with major electronics companies. The logical pairing of PMR Systems and CAE Blackstone provides the potential user of the Ultrasonic Stencil Cleaning System the best possible support through two companies "in tune" with their customers' needs.

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Other/Describe:

Number of employees in your company:

1 - 49 ○ 50 + ○ 100 + ○ 500 + ○

What are you cleaning?

solder paste ☐ adhesives ☐
Other/Describe:

What are the typical Dimensions of the pieces to be cleaned? (Inches)

L ☐ x W ☐ x H ☐

When do you plan to purchase?

0 - 3 months ○ 3 - 6 months ○ 6 + months ○

Briefly describe your product interest:

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Ultrasonic Cleaning

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Abstract

A presentation describing the theory of ultrasonics and how ultrasonic technology is applied to precision cleaning. This presentation will explore the importance and application of ultrasonics in precision cleaning along with explanations of ultrasonic cleaning equipment and its application. Process parameters for ultrasonic cleaning will be discussed along with procedures for proper operation of ultrasonic cleaning equipment to achieve maximum results.

Introduction

Cleaning technology is in a state of change. Vapor degreasing using chlorinated and fluorinated solvents, long the standard for most of industry, is being phased out in the interest of the ecology of our planet. At the same time, cleaning requirements are continually increasing. Cleanliness has become an important issue in many industries where it never was in the past. In industries such as electronics where cleanliness was always important, it has become more critical in support of growing technology. It seems that each advance in technology demands greater and greater attention to cleanliness for its success. As a result, the cleaning industry has been challenged to deliver the needed cleanliness and has done so through rapid innovation over the past several years. Many of these advances have involved the use of ultrasonic technology.

The cleaning industry is currently in a struggle to replace solvent degreasing with alternative "environmentally friendly" means of cleaning. Although substitute water-based, semi-aqueous and petroleum based chemistries are available, they are often somewhat less effective as cleaners than the solvents and may not perform adequately in some applications unless a mechanical energy boost is added to assure the required levels of cleanliness. Ultrasonic energy is now used extensively in critical cleaning applications to both speed and enhance the cleaning effect of the alternative chemistries. This paper is intended to familiarize the reader with the basic theory of ultrasonics and how ultrasonic energy can be most effectively applied to enhance a variety of cleaning processes.

What is "Ultrasonics?"

Ultrasonics is the science of sound waves above the limits of human audibility. The frequency of a sound wave determines its tone or pitch. Low frequencies produce low or bass tones. High frequencies produce high or treble tones. Ultrasound is a sound with a pitch so high that it can not be heard by the human ear. Frequencies above 18 Kilohertz are usually considered to be ultrasonic. The frequencies used for ultrasonic cleaning range from 20,000 cycles per second or kilohertz (KHz) to over 100,000 KHz. The most commonly used frequencies for industrial cleaning are those between 20 KHz and 50KHz. Frequencies above 50KHz are more commonly used in small tabletop ultrasonic cleaners such as those found in jewelry stores and dental offices.

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The Theory of Sound Waves

In order to understand the mechanics of ultrasonics, it is necessary to first have a basic understanding of sound waves, how they are generated and how they travel through a conducting medium. The dictionary defines sound as the transmission of vibration through an elastic medium which may be a solid, liquid, or a gas. Sound Wave Generation - A sound wave is produced when a solitary or repeating displacement is generated in a sound conducting medium, such as by a "shock" event or "vibratory" movement. The displacement of air by the cone of a radio speaker is a good example of "vibratory" sound waves generated by mechanical movement. As the speaker cone moves back and forth, the air in front of the cone is alternately compressed and rarefied to produce sound waves, which travel through the air until they are finally dissipated. We are probably most familiar with sound waves generated by alternating mechanical motion. There are also sound waves which are created by a single "shock" event. An example is thunder which is generated as air instantaneously changes volume as a result of an electrical discharge (lightning). Another example of a shock event might be the sound created as a wooden board falls with its face against a cement floor. Shock events are sources of a single compression wave which radiates from the source.

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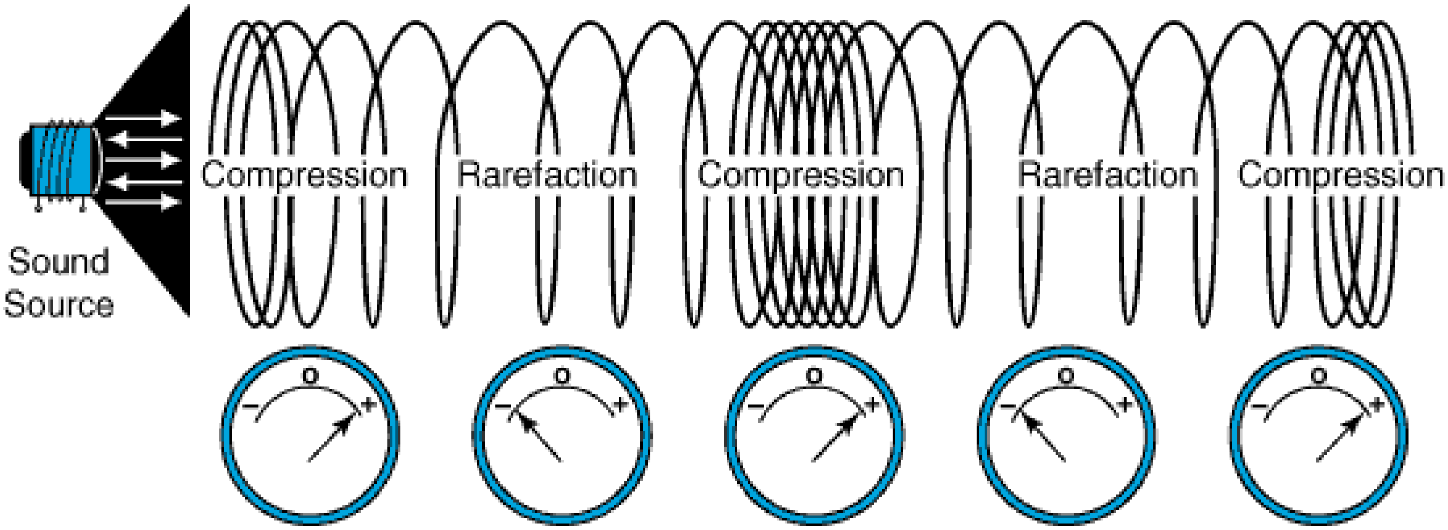

The Nature of Sound Waves

The diagram above uses the coils of a spring similar to a Slinky toy to represent individual molecules of a sound conducting medium. The molecules in the medium are influenced by adjacent molecules in much the same way that the coils of the spring influence one another. The source of the sound in the model is at the left. The compression generated by the sound source as it moves propagates down the length of the spring as each adjacent coil of the spring pushes against its neighbor. It is important to note that, although the wave travels from one end of the spring to the other, the individual coils remain in their same relative positions, being displaced first one way and then the other as the sound wave passes. As a result, each coil is first part of a compression as it is pushed toward the next coil and then part of a rarefaction as it recedes from the adjacent coil. In much the same way, any point in a sound conducting medium is alternately subjected to compression and then rarefaction. At a point in the area of a compression, the pressure in the medium is positive. At a point in the area of a rarefaction, the pressure in the medium is negative.

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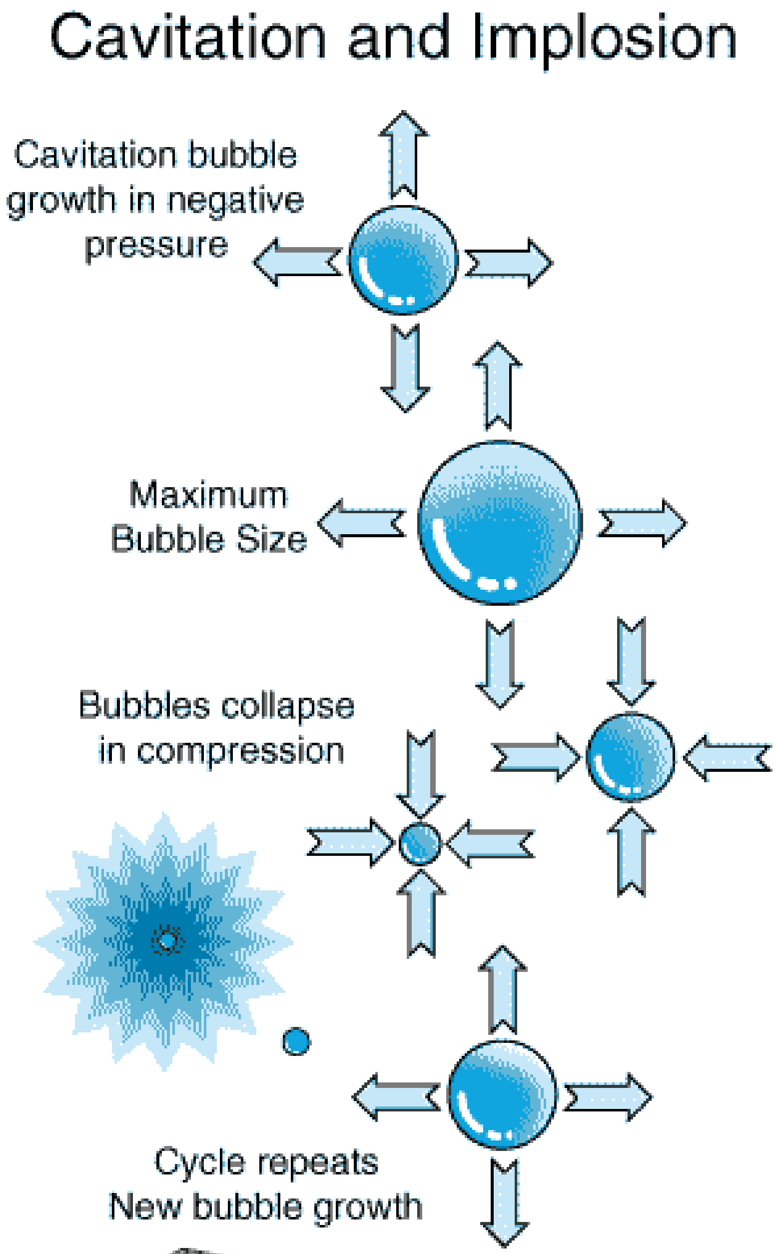

In elastic media such as air and most solids, there is a continuous transition as a sound wave is transmitted. In non-elastic media such as water and most liquids, there is continuous transition as long as the amplitude or "loudness" of the sound is relatively low. As amplitude is increased, however, the magnitude of the negative pressure in the areas of rarefaction eventually becomes sufficient to cause the liquid to fracture because of the negative pressure, causing a phenomenon known as cavitation. Cavitation "bubbles" are created at sites of rarefaction as the liquid fractures or tears because of the negative pressure of the sound wave in the liquid. As the wave fronts pass, the cavitation "bubbles" oscillate under the influence of positive pressure, eventually growing to an unstable size. Finally, the violent collapse of the cavitation "bubbles" results in implosions, which cause shock waves to be radiated from the sites of the collapse. The collapse and implosion of myriad cavitation "bubbles" throughout an ultrasonically activated liquid result in the effect commonly associated with ultrasonics. It has been calculated that temperatures in excess of 10,000°F and pressures in excess of 10,000 PSI are generated at the implosion sites of cavitation bubbles.

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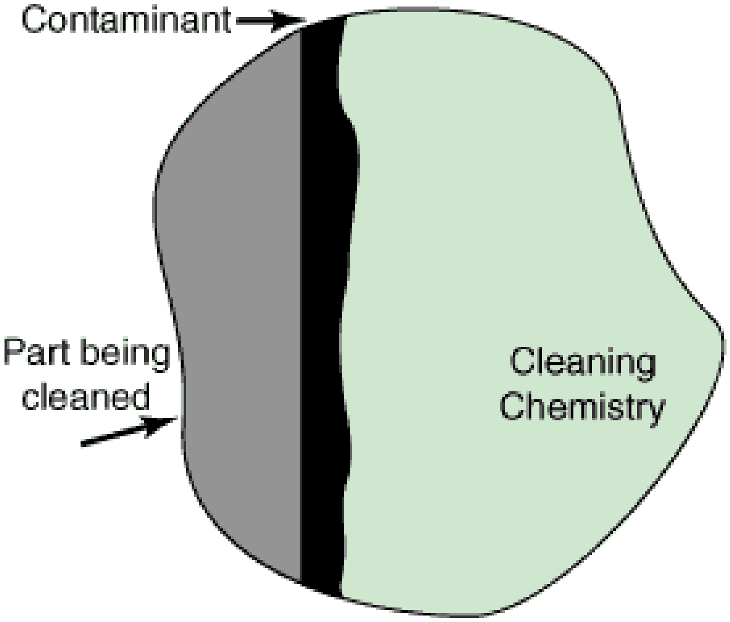
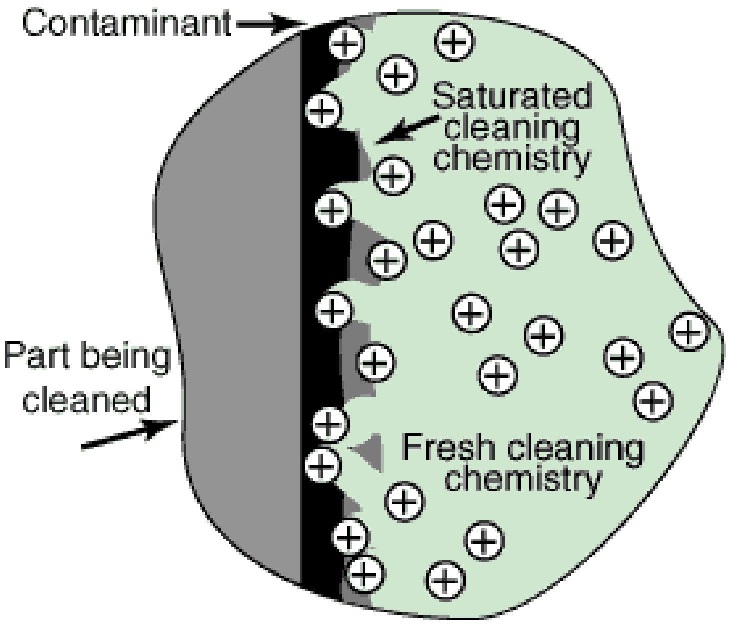
Benefits of Ultrasonics in the Cleaning and Rinsing Processes

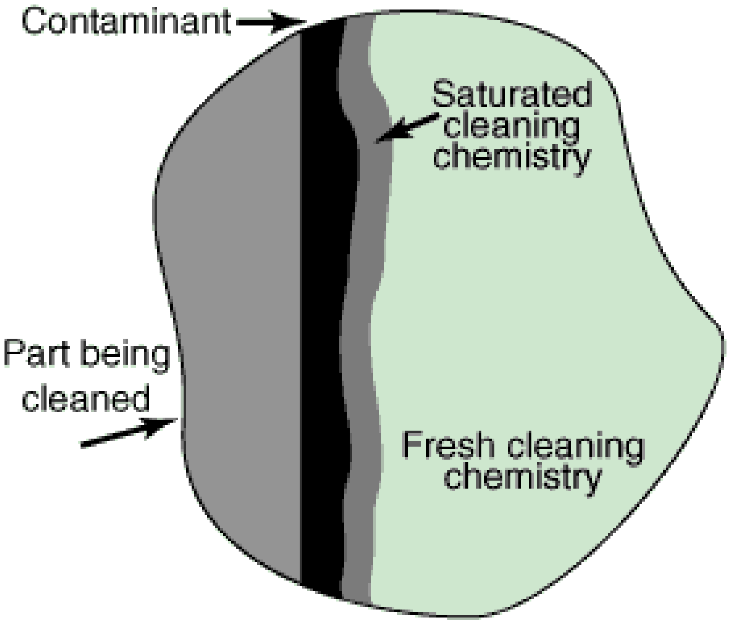
Cleaning in most instances requires that a contaminant be dissolved (as in the case of a soluble soil), displaced (as in the case of a non-soluble soil) or both dissolved and displaced (as in the case of insoluble particles being held by a soluble binder such as oil or grease). The mechanical effect of ultrasonic energy can be helpful in both speeding dissolution and displacing particles. Just as it is beneficial in cleaning, ultrasonics is also beneficial in the rinsing process. Residual cleaning chemicals are removed quickly and completely by ultrasonic rinsing.



In removing a contaminant by dissolution, it is necessary for the solvent to come into contact with and dissolve the contaminant. The cleaning activity takes place only at the interface between the cleaning chemistry and the contaminant.

As the cleaning chemistry dissolves the contaminant, a saturated layer develops at the interface between the fresh cleaning chemistry and the contaminant. Once this has happened, cleaning action stops as the saturated chemistry can no longer attack the contaminant. Fresh chemistry cannot reach the contaminant.





Ultrasonic cavitation and implosion effectively displace the saturated layer to allow fresh chemistry to come into contact with the contaminant remaining to be removed. This is especially beneficial when irregular surfaces or internal passageways are to be cleaned.

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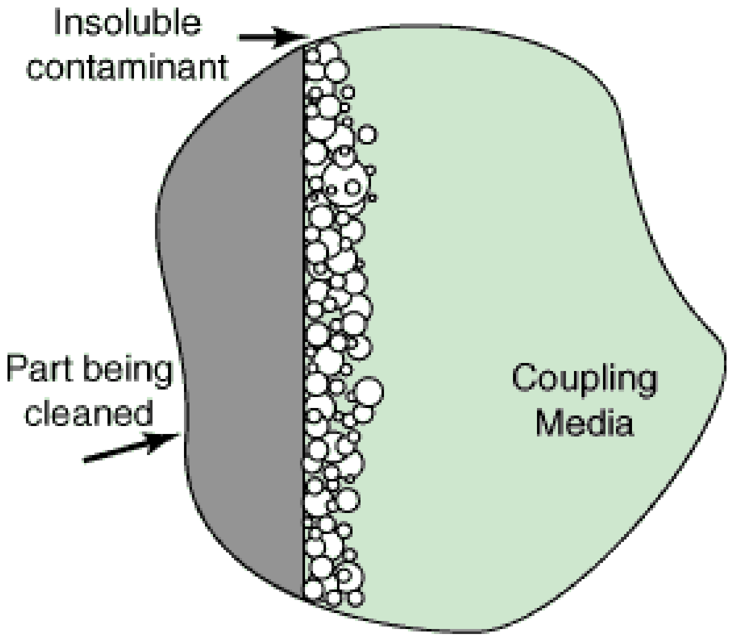
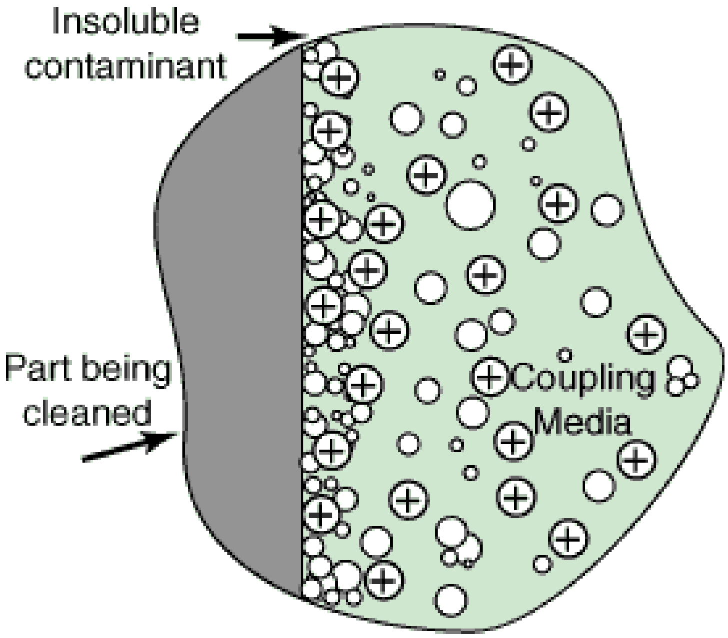
Ultrasonics Speeds Cleaning by Dissolution



Some contaminants are comprised of insoluble particles loosely attached and held in place by ionic or cohesive forces. These particles need only be displaced sufficiently to break the attractive forces to be removed.

Cavitation and implosion as a result of ultrasonic activity displace and remove loosely held contaminants such as dust from surfaces. For this to be effective, it is necessary that the coupling medium be capable of wetting the particles to be removed.

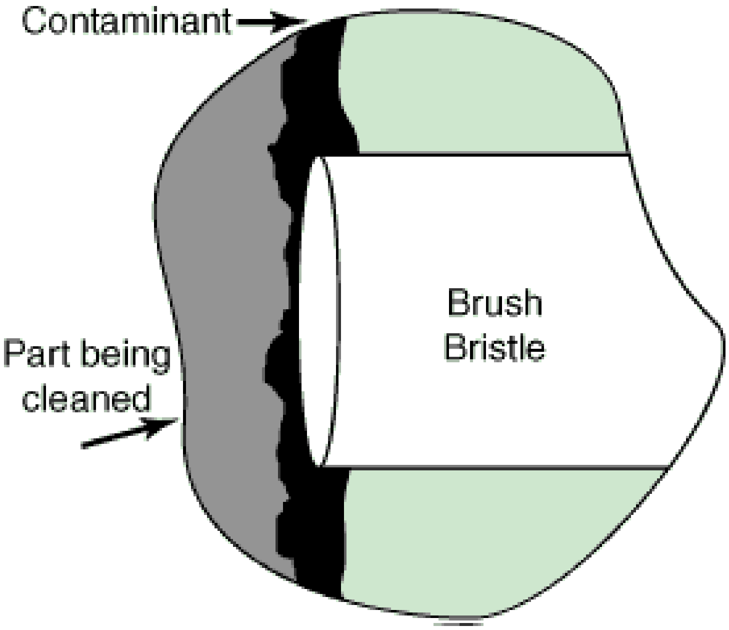


Complex Contaminants

Contaminations can also, of course, be more complex in nature, consisting of combination soils made up of both soluble and insoluble components. The effect of ultrasonics is substantially the same in these cases, as the mechanical micro-agitation helps speed both the dissolution of soluble contaminants and the displacement of insoluble particles. Ultrasonic activity has also been demonstrated to speed or enhance the effect of many chemical reactions. This is probably caused mostly by the high energy levels created as high pressures and temperatures are created at the implosion sites. It is likely that the superior results achieved in many ultrasonic cleaning operations may be at least partially attributed to the sonochemistry effect.

A Superior Process

In the above illustrations, the surface of the part being cleaned has been represented as a flat. In reality, surfaces are seldom flat, instead being comprised of hills, valleys and convolutions of all description. The illustration at the right shows why ultrasonic energy has been proven to be more effective at enhancing cleaning than other alternatives, including spray washing, brushing, turbulation, air agitation, and even electro-cleaning in many applications. The ability of ultrasonic activity to penetrate and assist the cleaning of interior surfaces of complex parts is also especially noteworthy.



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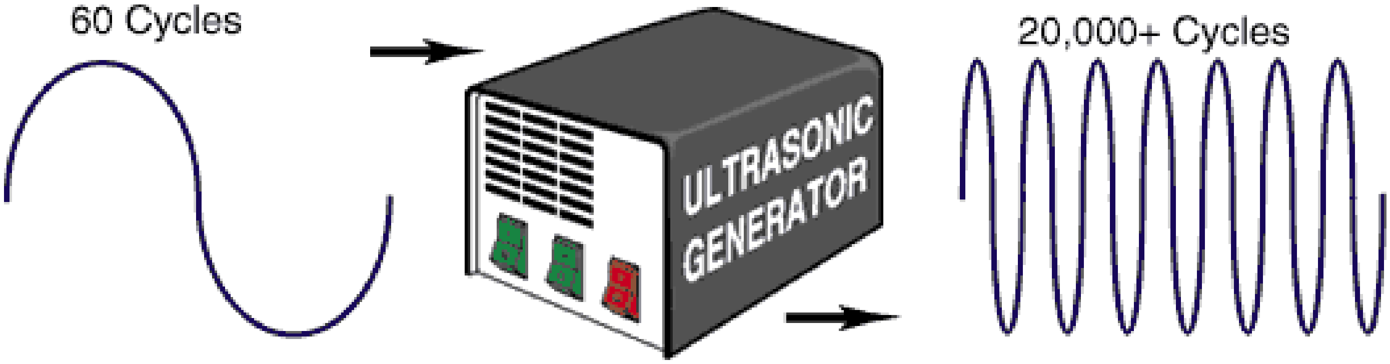
Ultrasonic Equipment

To introduce ultrasonic energy into a cleaning system requires an ultrasonic transducer and an ultrasonic power supply or "generator." The generator supplies electrical energy at the desired ultrasonic frequency. The ultrasonic transducer converts the electrical energy from the ultrasonic generator into mechanical vibrations.

Ultrasonic Generator

The ultrasonic generator converts electrical energy from the line which is typically alternating current at 50 or 60Hz to electrical energy at the ultrasonic frequency. This is accomplished in a number of ways by various equipment manufacturers. Current ultrasonic generators nearly all use solid state technology.



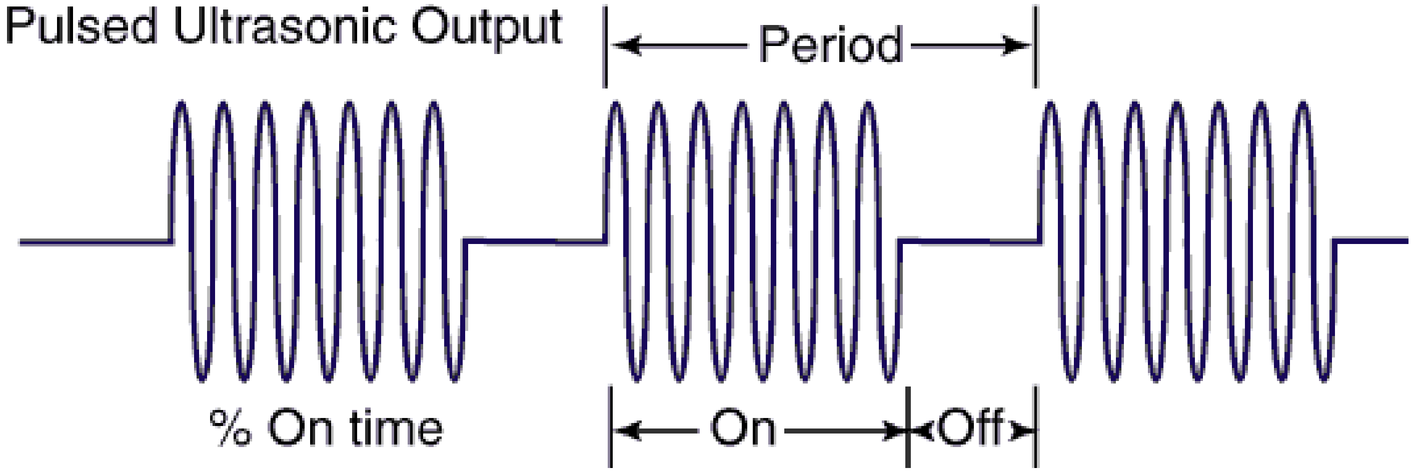
There have been several relatively recent innovations in ultrasonic generator technology which may enhance the effectiveness of ultrasonic cleaning equipment. These include square wave outputs, slowly or rapidly pulsing the ultrasonic energy on and off and modulating or "sweeping" the frequency of the generator output around the central operating frequency. The most advanced ultrasonic generators have provisions for adjusting a variety of output parameters to customize the ultrasonic energy output for the task.

Square Wave Output

Applying a square wave signal to an ultrasonic transducer results in an acoustic output rich in harmonics. The result is a multi-frequency cleaning system which vibrates simultaneously at several frequencies which are harmonics of the fundamental frequency. Multi-frequency operation offers the benefits of all frequencies combined in a single ultrasonic cleaning tank.

Pulse

In pulse operation, the ultrasonic energy is turned on and off at a rate which may vary from once every several seconds to several hundred times per second.



The percentage of time that the ultrasonic energy is on may also be changed to produce varied results. At slower pulse rates, more rapid degassing of liquids occurs as coalescing bubbles of air are given an opportunity to rise to the surface of the liquid during the time the ultrasonic energy is off. At more rapid pulse rates the cleaning process may be enhanced as repeated high energy "bursts" of ultrasonic energy occur each time the energy source is turned on.

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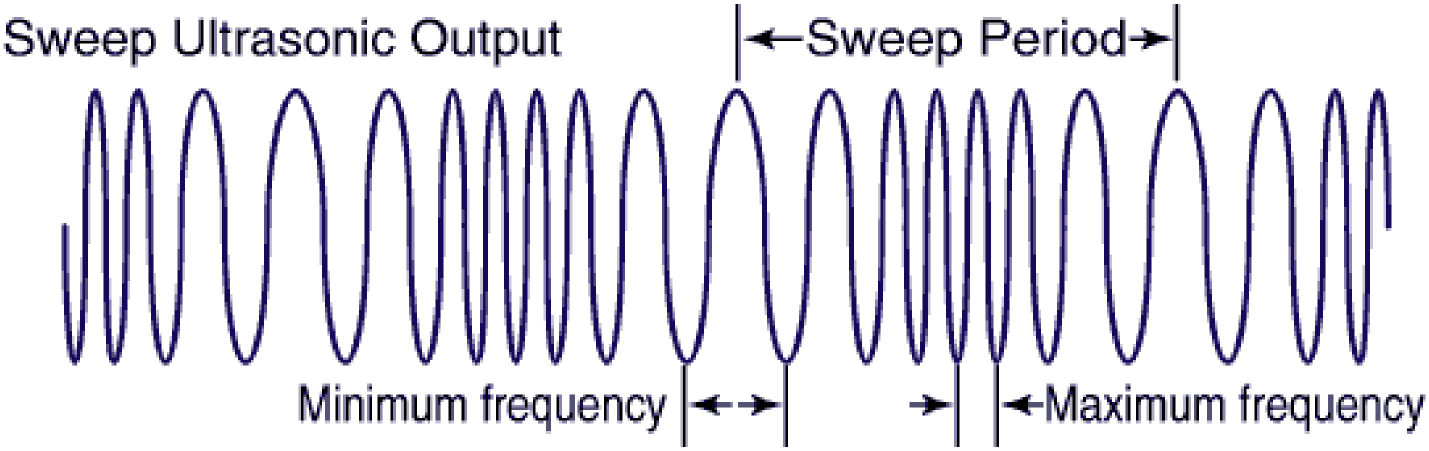
Frequency Sweep

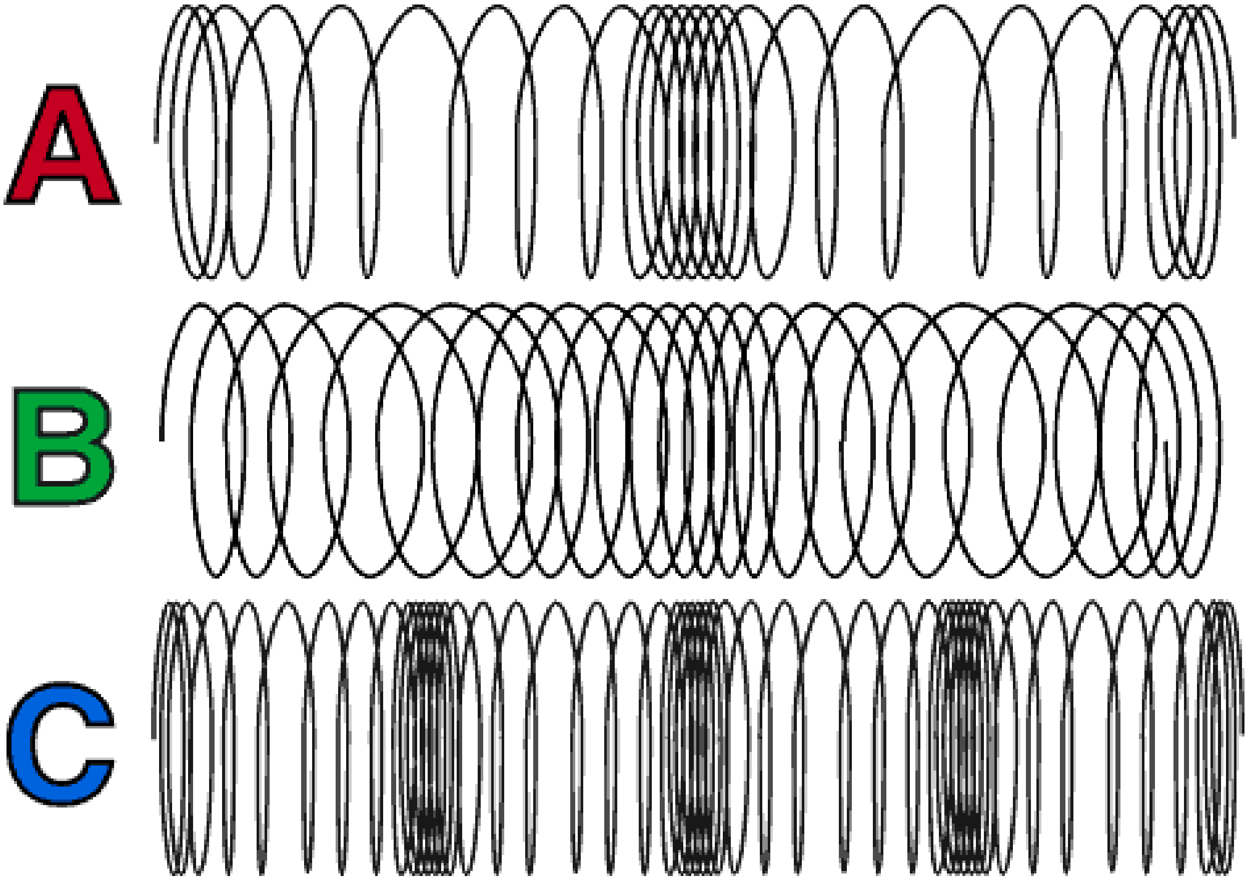
In sweep operation, the frequency of the output of the ultrasonic generator is modulated around a central frequency which may itself be adjustable.



Various effects are produced by changing the speed and magnitude of the frequency modulation. The frequency may be modulated from once every several seconds to several hundred times per second with the magnitude of variation ranging from several hertz to several kilohertz. Sweep may be used to prevent damage to extremely delicate parts or to reduce the effects of standing waves in cleaning tanks. Sweep operation may also be found especially useful in facilitating the cavitation of terpenes and petroleum based chemistries. A combination of Pulse and sweep operation may provide even better results when the cavitation of terpenes and petroleum based chemistries is required.

Frequency and Amplitude

Frequency and amplitude are properties of sound waves. The illustrations below demonstrate frequency and amplitude using the spring model introduced earlier. In the diagram, if **A** is the base sound wave, **B** with less displacement of the media (less intense compression and rarefaction) as the wave front passes, represents a sound wave of less amplitude or "loudness." **C** represents a sound wave of higher frequency indicated by more wave fronts passing a given point within a given period of time.



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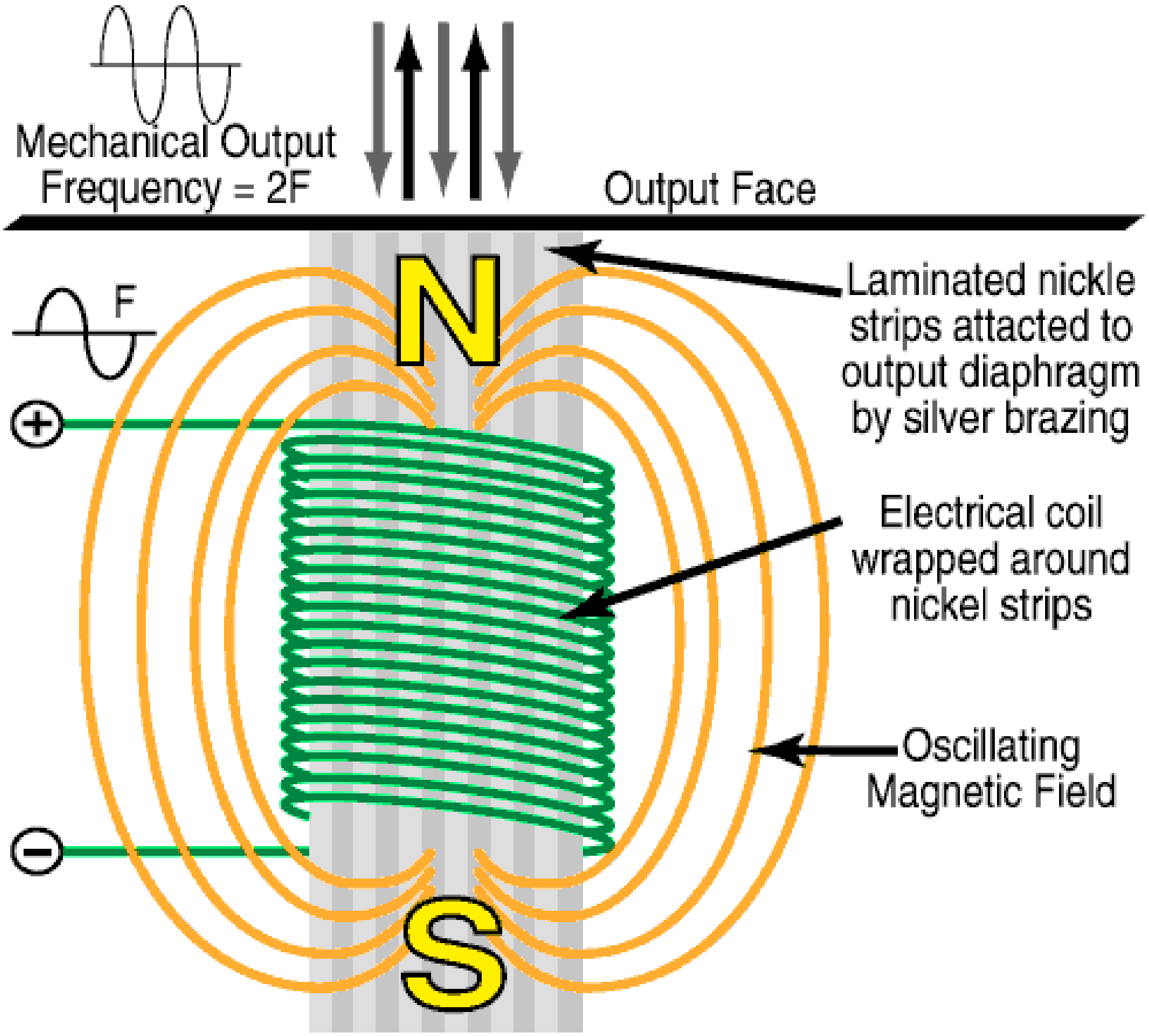
Ultrasonic Transducers

There are two general types of ultrasonic transducers in use today: Magnetostrictive and piezoelectric. Both accomplish the same task of converting alternating electrical energy to vibratory mechanical energy but do it through the use of different means.

Magnetostrictive

Magnetostrictive transducers utilize the principle of magnetostriction in which certain materials expand and contract when placed in an alternating magnetic field.



Alternating electrical energy from the ultrasonic generator is first converted into an alternating magnetic field through the use of a coil of wire. The alternating magnetic field is then used to induce mechanical vibrations at the ultrasonic frequency in resonant strips of nickel or other magnetostrictive material which are attached to the surface to be vibrated. Because magnetostrictive materials behave identically to a magnetic field of either polarity, the frequency of the electrical energy applied to the transducer is 1/2 of the desired output frequency. Magnetostrictive transducers were first to supply a robust source of ultrasonic vibrations for high power applications such as ultrasonic cleaning.

Because of inherent mechanical constraints on the physical size of the hardware as well as electrical and magnetic complications, high power magnetostrictive transducers seldom operate at frequencies much above 20 kilohertz. Piezoelectric transducers, on the other hand, can easily operate well into the megahertz range.

Magnetostrictive transducers are generally less efficient than their piezoelectric counterparts. This is due primarily to the fact that the magnetostrictive transducer requires a dual energy conversion from electrical to magnetic and then from magnetic to mechanical. Some efficiency is lost in each conversion. Magnetic hysteresis effects also detract from the efficiency of the magnetostrictive transducer.

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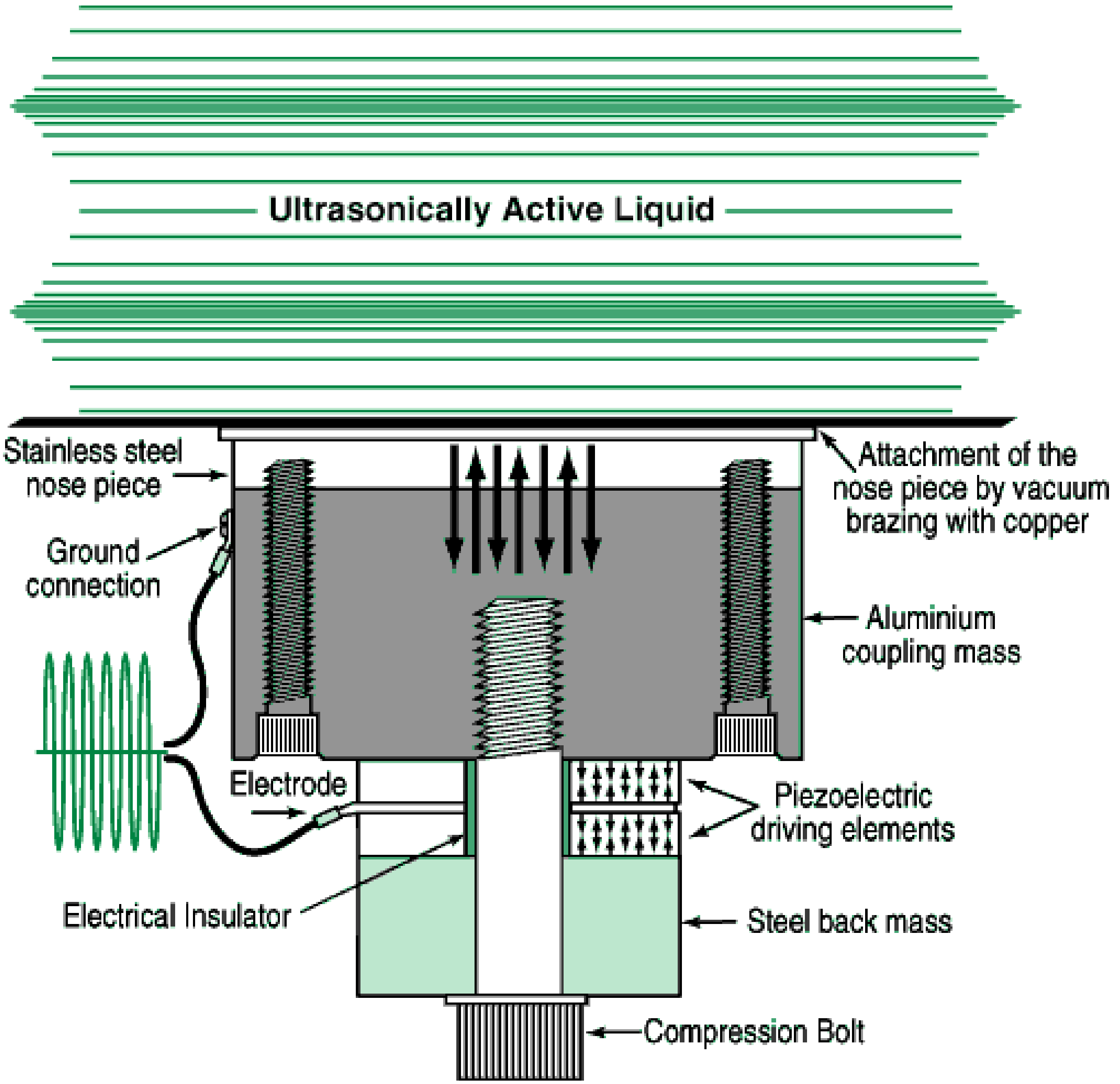
Piezoelectric

Piezoelectric transducers convert alternating electrical energy directly to mechanical energy through use of the piezoelectric effect in which certain materials change dimension when an electrical charge is applied to them.



Electrical energy at the ultrasonic frequency is supplied to the transducer by the ultrasonic generator. This electrical energy is applied to piezoelectric element(s) in the transducer which vibrate. These vibrations are amplified by the resonant masses of the transducer and directed into the liquid through the radiating plate. Early piezoelectric transducers utilized such piezoelectric materials as naturally occurring quartz crystals and barium titanate which were fragile and unstable. Early piezoelectric transducers were, therefore, unreliable. Today's transducers incorporate stronger, more efficient and highly stable ceramic piezoelectric materials which were develops as a result of the efforts of the US Navy and its research to develop advanced sonar transponders in the 1940's. The vast majority of transducers used today for ultrasonic cleaning utilize the piezoelectric effect.

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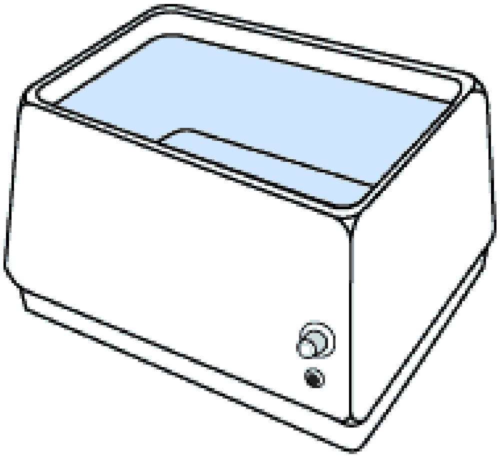
Ultrasonic Cleaning Equipment

Ultrasonic cleaning equipment ranges from the small tabletop units often found in dental offices or jewelry stores to huge systems with capacities of several thousand gallons used in a variety of industrial applications. Selection or design of the proper equipment is paramount in the success of any ultrasonic cleaning application.

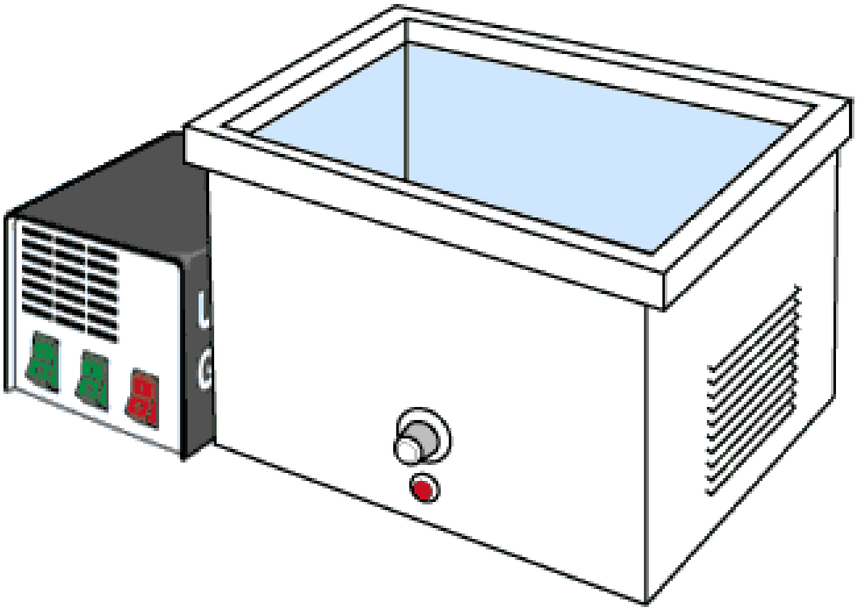
The simplest application may require only a simple heated tank cleaner with rinsing to be done in a sink or in a separate container. More sophisticated cleaning systems include one or more rinses, added process tanks and hot air dryers. Automation is often added to reduce labor and guarantee process consistency.

The largest installations utilize immersible ultrasonic transducers which can be mounted on the sides or bottom of cleaning tanks of nearly any size. Immersible ultrasonic transducers offer maximum flexibility and ease of installation and service.



Small, self-contained cleaners are used in doctors' offices and jewelry stores.

Heated tank cleaning systems are used in laboratories and for small batch cleaning needs.



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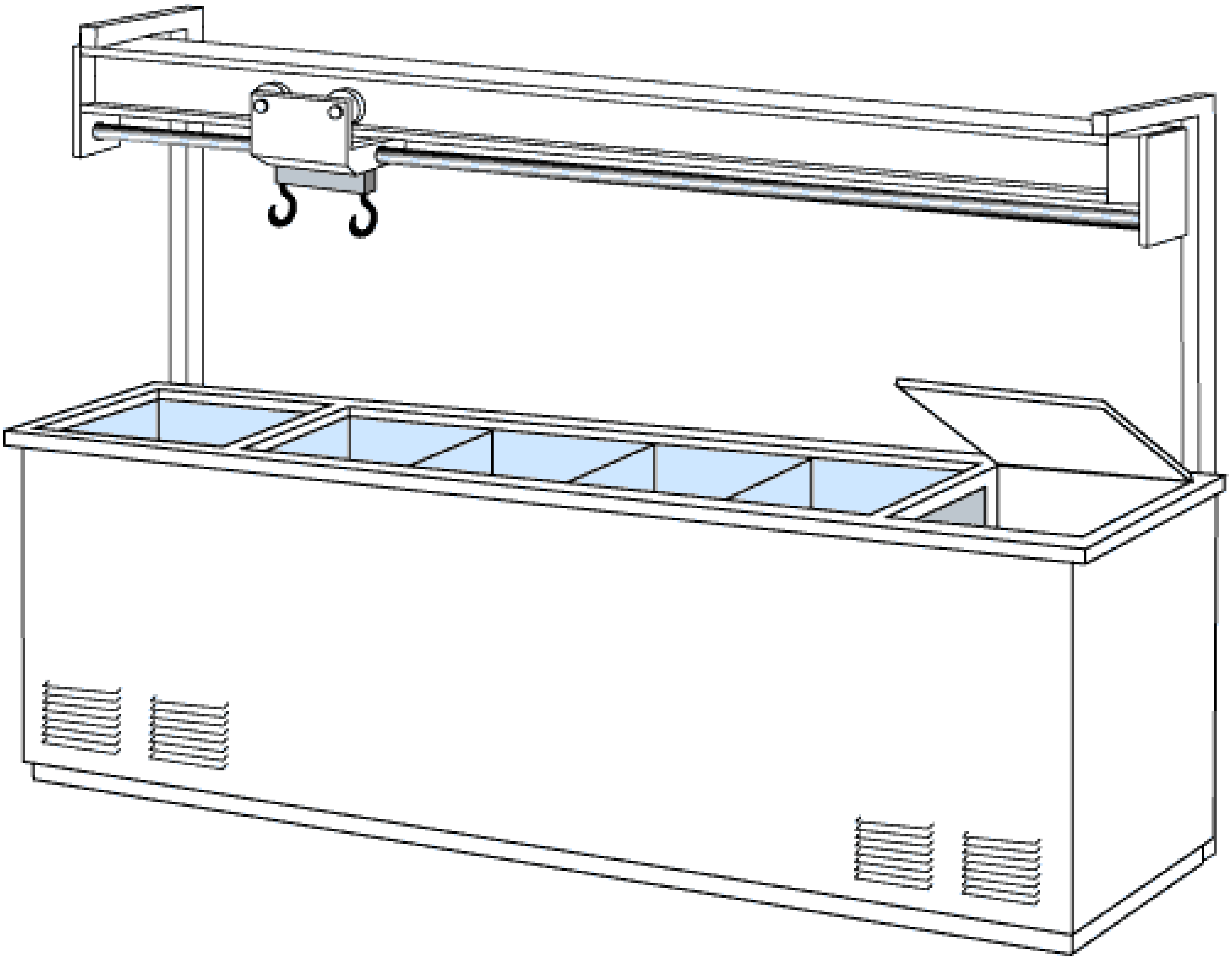
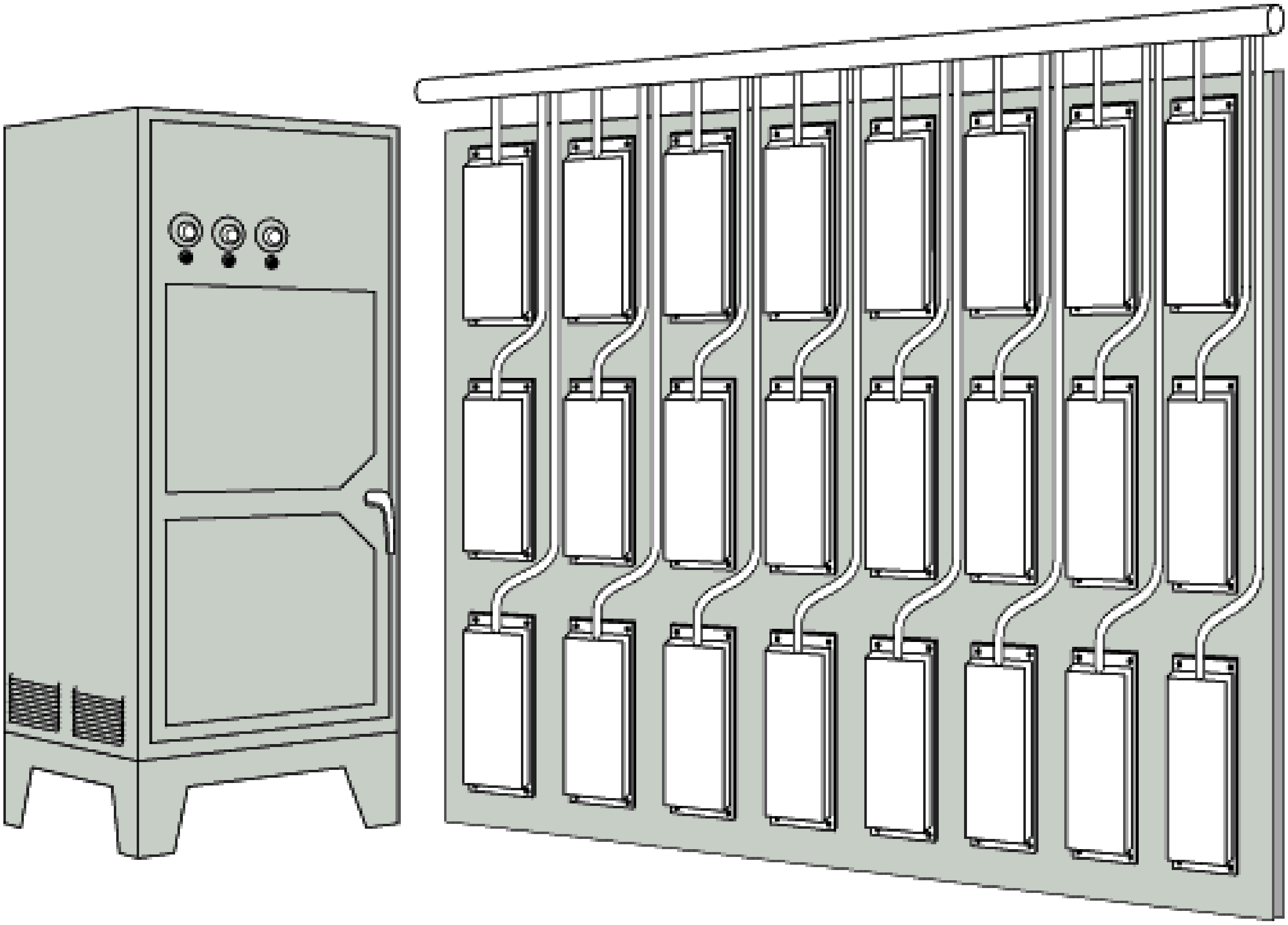
Ultrasonic Cleaning Equipment *cont.*

Console cleaning systems integrate ultrasonic cleaning tank(s), rinse tank(s) and a dryer for batch cleaning. Systems can be automated through the use of a PLC controlled material handling system.



A wide range of options may be offered in custom designed systems. Large scale installations or retrofitting of existing tanks in plating lines, etc., can be achieved through the use of modular immersible ultrasonic transducers. Ultrasonic generators are often housed in climate-controlled enclosures.



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Maximizing the Ultrasonic Cleaning Process

Process Parameters

Effective application of the ultrasonic cleaning process requires consideration of a number of parameters. While time, temperature and chemical remain important in ultrasonic cleaning as they are in other cleaning technologies, there are other factors which must be considered to maximize the effectiveness of the process. Especially important are those variables which affect the intensity of ultrasonic cavitation in the liquid.

Maximizing Cavitation

Maximizing cavitation of the cleaning liquid is obviously very important to the success of the ultrasonic cleaning process. Several variables affect cavitation intensity.

Temperature is the most important single parameter to be considered in maximizing cavitation intensity. This is because so many liquid properties affecting cavitation intensity are related to temperature. Changes in temperature result in changes in viscosity, the solubility of gas in the liquid, the diffusion rate of dissolved gasses in the liquid, and vapor pressure, all of which affect cavitation intensity. In pure water, the cavitation effect is maximized at approximately 160°F.

The viscosity of a liquid must be minimized for maximum cavitation effect. Viscous liquids are sluggish and cannot respond quickly enough to form cavitation bubbles and violent implosion. The viscosity of most liquids is reduced as temperature is increased.

For most effective cavitation, the cleaning liquid must contain as little dissolved gas as possible. Gas dissolved in the liquid is released during the bubble growth phase of cavitation and prevents its violent implosion which is required for the desired ultrasonic effect. The amount of dissolved gas in a liquid is reduced as the liquid temperature is increased.

The diffusion rate of dissolved gasses in a liquid is increased at higher temperatures. This means that liquids at higher temperatures give up dissolved gasses more readily than those at lower temperatures, which aids in minimizing the amount of dissolved gas in the liquid.

A moderate increase in the temperature of a liquid brings it closer to its vapor pressure, meaning that vaporous cavitation is more easily achieved. Vaporous cavitation, in which the cavitation bubbles are filled with the vapor of the cavitating liquid, is the most effective form of cavitation. As the boiling temperature is approached, however, the cavitation intensity is reduced as the liquid starts to boil at the cavitation sites.

Cavitation intensity is directly related to **Ultrasonic Power** at the power levels generally used in ultrasonic cleaning systems. As power is increased substantially above the cavitation threshold, cavitation intensity levels off and can only be further increased through the use of focusing techniques.

Cavitation intensity is inversely related to **Ultrasonic Frequency**. As the ultrasonic frequency is increased, cavitation intensity is reduced because of the smaller size of the cavitation bubbles and their resultant less violent implosion. The reduction in cavitation effect at higher frequencies may be overcome by increasing the ultrasonic power.

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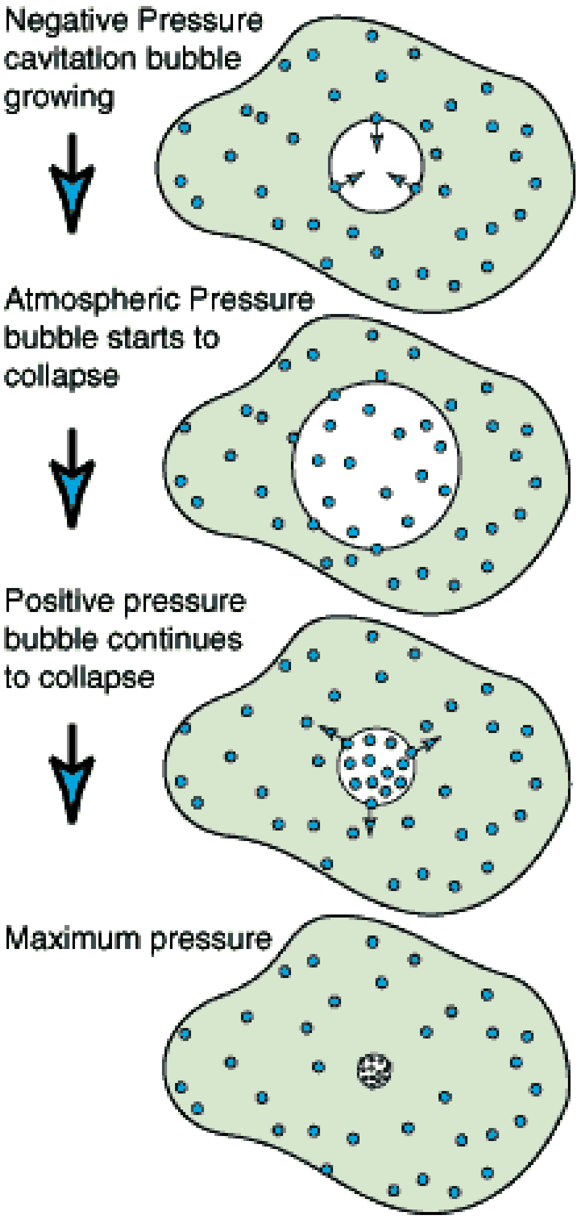
Importance of Minimizing Dissolved Gas



During the negative pressure portion of the sound wave, the liquid is torn apart and cavitation bubbles start to form. As a negative pressure develops within the bubble, gasses dissolved in the cavitating liquid start to diffuse across the boundary into the bubble. As negative pressure is reduced due to the passing of the rarefaction portion of the sound wave and atmospheric pressure is reached, the cavitation bubble starts to collapse due to its own surface tension. During the compression portion of the sound wave, any gas which diffused into the bubble is compressed and finally starts to diffuse across the boundary again to re-enter the liquid. This process, however, is never complete as long as the bubble contains gas since the diffusion out of the bubble does not start until the bubble is compressed. And once the bubble is compressed, the boundary surface available for diffusion is reduced. As a result, cavitation bubbles formed in liquids containing gas do not collapse all the way to implosion but rather result in a small pocket of compressed gas in the liquid. This phenomenon can be useful in degassing liquids. The small gas bubbles group together until they finally become sufficiently buoyant to come to the surface of the liquid.

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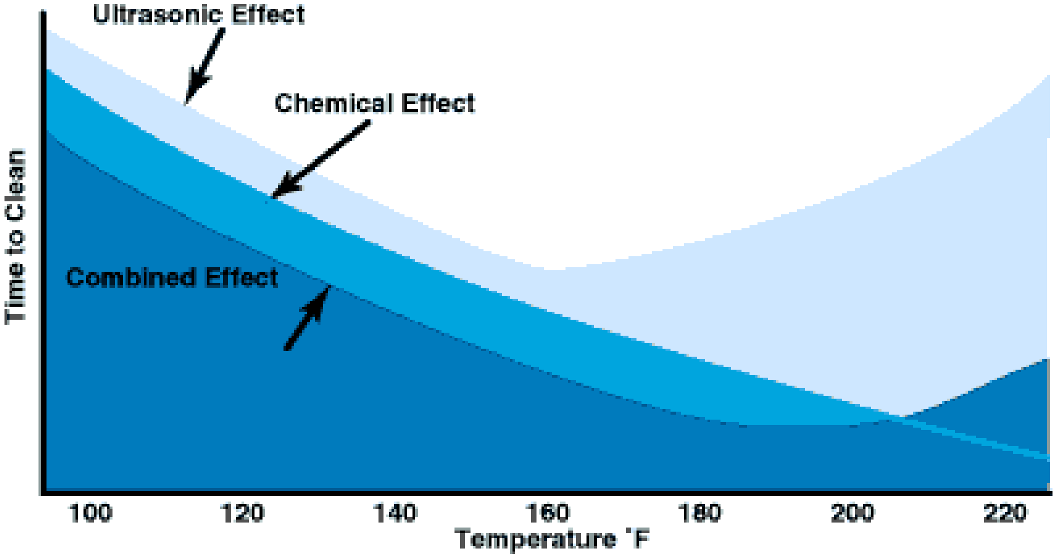
Maximizing Overall Cleaning Effect

Cleaning Chemical selection is extremely important to the overall success of the ultrasonic cleaning process. The selected chemical must be compatible with the base metal being cleaned and have the capability to remove the soils which are present. It must also cavitate well. Most cleaning chemicals can be used satisfactorily with ultrasonics. Some are formulated especially for use with ultrasonics. However, avoid the non-foaming formulations normally used in spray washing applications. Highly wetted formulations are preferred. Many of the new petroleum cleaners, as well as petroleum and terpene based semi-aqueous cleaners, are compatible with ultrasonics. Use of these formulations may require some special equipment considerations, including increased ultrasonic power, to be effective.



Temperature was mentioned earlier as being important to achieving maximum cavitation. The effectiveness of the cleaning chemical is also related to temperature. Although the cavitation effect is maximized in pure water at a temperature of approximately 160°F, optimum cleaning is often seen at higher or lower temperatures because of the effect that temperature has on the cleaning chemical. As a general rule, each chemical will perform best at its recommended process temperature regardless of the temperature effect on the ultrasonics. For example, although the maximum ultrasonic effect is achieved at 160°F, most highly caustic cleaners are used at a temperatures of 180°F to 190°F because the chemical effect is greatly enhanced by the added temperature. Other cleaners may be found to break down and lose their effectiveness if used at temperatures in excess of as low as 140°F. The best practice is to use a chemical at its maximum recommended temperature not exceeding 190°F

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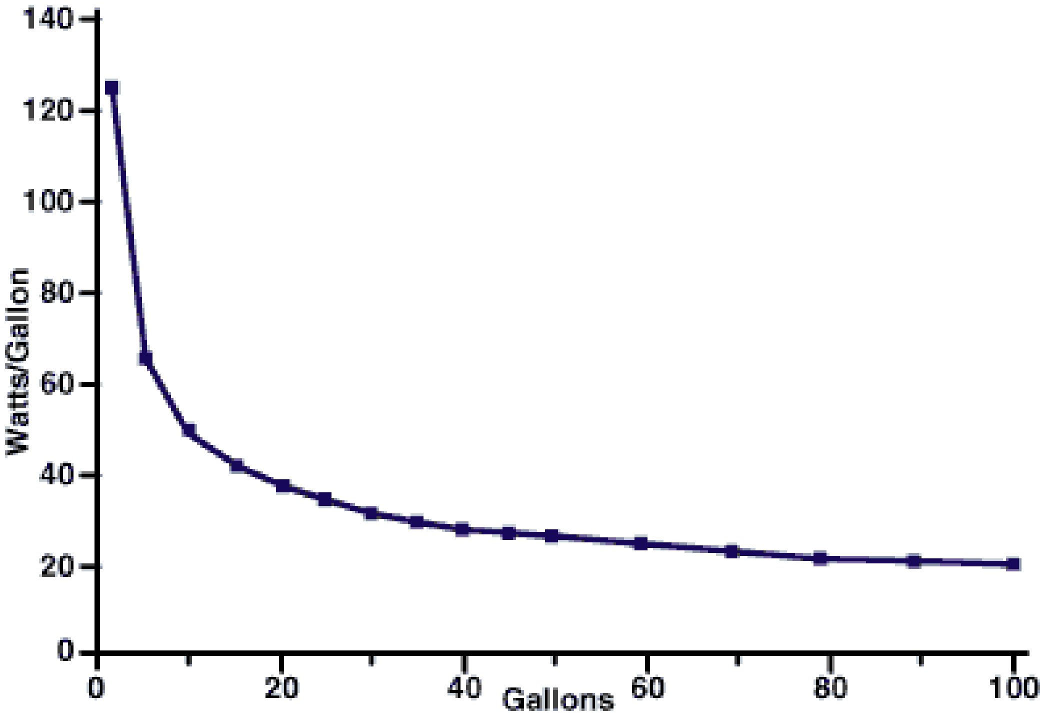
Maximizing Overall Cleaning Effect *cont.*

Degassing of cleaning solutions is extremely important in achieving satisfactory cleaning results. Fresh solutions or solutions which have cooled must be degassed before proceeding with cleaning. Degassing is done after the chemical is added and is accomplished by operating the ultrasonic energy and raising the solution temperature. The time required for degassing varies considerably, based on tank capacity and solution temperature, and may range from several minutes for a small tank to an hour or more for a large tank. An unheated tank may require several hours to degas. Degassing is complete when small bubbles of gas cannot be seen rising to the surface of the liquid and a pattern of ripples can be seen.



The **Ultrasonic Power** delivered to the cleaning tank must be adequate to cavitate the entire volume of liquid with the workload in place. Watts per gallon is a unit of measure often used to measure the level of ultrasonic power in a cleaning tank. As tank volume is increased, the number of watts per gallon required to achieve the required performance is reduced. Cleaning parts that are very massive or that have a high ratio of surface to mass may require additional ultrasonic power. Excessive power may cause cavitation erosion or "burning" on soft metal parts. If a wide variety of parts is to be cleaned in a single cleaning system, an ultrasonic power control is recommended to allow the power to be adjusted as required for various cleaning needs. Part Exposure to both the cleaning chemical and ultrasonic energy is important for effective cleaning. Care must be taken to ensure that all areas of the parts being cleaned are flooded with the cleaning liquid. Parts baskets and fixtures must be designed to allow penetration of ultrasonic energy and to position the parts to assure that they are exposed to the ultrasonic energy. It is often necessary to individually rack parts in a specific orientation or rotate them during the cleaning process to thoroughly clean internal passages and blind holes.

Conclusion

Properly utilized, ultrasonic energy can contribute significantly to the speed and effectiveness of many immersion cleaning and rinsing processes. It is especially beneficial in increasing the effectiveness of today's preferred aqueous cleaning chemistries and, in fact, is necessary in many applications to achieve the desired level of cleanliness. With ultrasonics, aqueous chemistries can often give results surpassing those previously achieved using solvents. Ultrasonics is not a technology of the future -- it is very much a technology of today.

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Ultrasonic Cleaning

Jeff Hancock
Blue Wave Ultrasonics

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ASM HANDBOOK®
Volume 5 : Surface Engineering

Navigation:

Introduction

ULTRASONIC CLEANING involves the use of high-frequency sound waves (above the upper range of human hearing, or about 18 kHz) to remove a variety of contaminants from parts immersed in aqueous media. The contaminants can be dirt, oil, grease, buffing/ polishing compounds, and mold release agents, just to name a few. Materials that can be cleaned include metals, glass, ceramics, and so on. Ultrasonic agitation can be used with a variety of cleaning agents: detailed information about these agents is available in the other articles on surface cleaning in this Section of the Handbook.

Typical applications found in the metals industry are removing chips and cutting oils from cutting and machining operations, removing buffing and polishing compounds prior to plating operations, and cleaning greases and sludge from rebuilt components for automotive and aircraft applications.

Ultrasonic cleaning is powerful enough to remove tough contaminants, yet gentle enough not to damage the substrate. It provides excellent penetration and cleaning in the smallest crevices and between tightly spaced parts in a cleaning tank.

The use of ultrasonics in cleaning has become increasingly popular due to the restrictions on the use of chlorofluorocarbons such as 1,1,1-trichloroethane. Because of these restrictions, many manufacturers and surface treaters are now using immersion cleaning technologies rather than solvent-based vapor degreasing. The use of ultrasonics enables the cleaning of intricately shaped parts with an effectiveness that corresponds to that achieved by vapor degreasing. Additional information about the regulation of surface cleaning chemicals is contained in the article "Environmental Regulation of Surface Engineering" in this Volume. The article "Vapor Degreasing Alternatives" in this Volume includes descriptions of cleaning systems (some using ultrasonics) that have been designed to meet regulatory requirements while at the same time providing effective surface cleaning.

Process Description

In a process termed cavitation, micron-size bubbles form and grow due to alternating positive and negative pressure waves in a solution. The bubbles subjected to these alternating pressure waves continue to grow until they reach resonant size. Just prior to the bubble implosion (Fig. 1), there is a tremendous amount of energy stored inside the bubble itself.

Figure 1

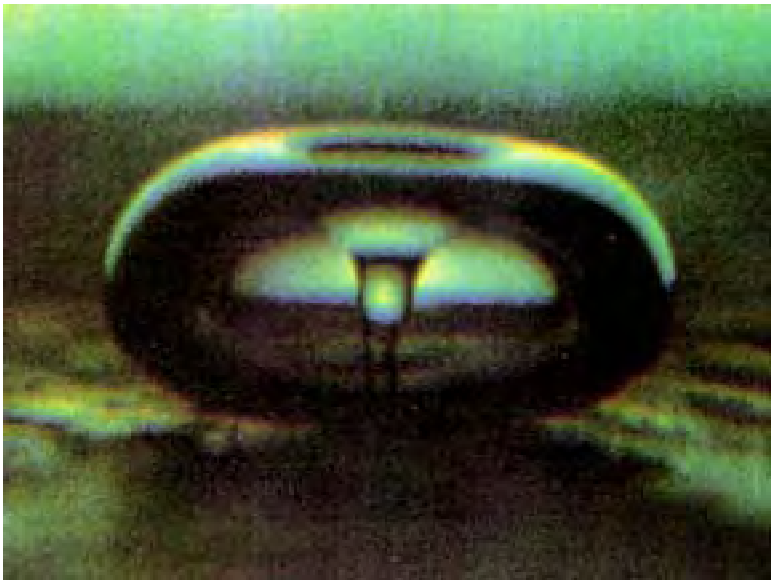

Fig. 1- Imploding cavity in a liquid irradiated with ultrasound captured in a high-speed flash photomicrograph. Courtesy of National Center for Physical Acoustics, University of Mississippi.

Temperature inside a cavitating bubble can be extremely high, with pressures up to 500 atm. The implosion event, when it occurs near a hard surface, changes the bubble into a jet about one-tenth the bubble size, which travels at speeds up to 400 km/hr toward the hard surface. With the combination of pressure, temperature, and velocity, the jet frees contaminants from their bonds with the substrate. Because of the inherently small size of the jet and the relatively large energy, ultrasonic cleaning has the ability to reach into small crevices and remove entrapped soils very effectively.

An excellent demonstration of this phenomenon is to take two flat glass microscope slides, put lipstick on a side of one, place the other slide over top, and wrap the slides with a rubber band. When the slides are placed into an ultrasonic bath with nothing more than a mild detergent and hot water, within a few minutes the process of cavitation will work the lipstick out from between the slide assembly. It is the powerful scrubbing action and the extremely small size of the jet action that enable this to happen.

Ultrasound Generation. In order to produce the positive and negative pressure waves in the aqueous medium, a mechanical vibrating device is required. Ultrasonic manufacturers make use of a diaphragm attached to high-frequency transducers. The transducers, which vibrate at their resonant frequency due to a high-frequency electronic generator source, induce amplified vibration of the diaphragm. This amplified vibration is the source of positive and negative pressure waves that propagate through the solution in the tank. The operation is similar to the operation of a loudspeaker except that it occurs at higher frequencies. When transmitted through water, these pressure waves create the cavitation processes.

The resonant frequency of the transducer determines the size and magnitude of the resonant bubbles. Typically, ultrasonic transducers used in the cleaning industry range in frequency from 20 to 80 kHz. The lower frequencies create larger bubbles with more energy, as can be seen by dipping a piece of heavy-duty aluminum foil in a tank. The lower-frequency cleaners will tend to form larger dents, whereas higher-frequency cleaners form much smaller dents.

Equipment

The basic components of an ultrasonic cleaning system include a bank of ultrasonic transducers mounted to a radiating diaphragm, an electrical generator, and a tank filled with aqueous solution. A key component is the transducer that generates the high-frequency mechanical energy. There are two types of ultrasonic transducers used in the industry, piezoelectric and magnetostrictive. Both have the same functional objective, but the two types have dramatically different performance characteristics.

Piezoelectric transducers are made up of several components. The ceramic (usually lead zirconate) crystal is sandwiched between two strips of tin. When voltage is applied across the strips it creates a displacement in the crystal, known as the piezoelectric effect. When these transducers are mounted to a diaphragm (wall or bottom of the tank), the displacement in the crystal causes a movement of the diaphragm, which in turn causes a pressure wave to be transmitted through the aqueous solution in the tank. Because the mass of the crystal is not well matched to the mass of the stainless steel diaphragm, an intermediate aluminum block is used to improve impedance matching for more efficient transmission of vibratory energy to the diaphragm. The assembly is inexpensive to manufacture due to low material and labor costs. This low cost makes piezoelectric technology desirable for ultrasonic cleaning. For industrial cleaning, however, piezoelectric transducers have several shortcomings.

The most common problem is that the performance of a piezoelectric unit deteriorates over time. This can occur for several reasons. The crystal tends to depolarize itself over time and with use, which causes a substantial reduction in the strain characteristics of the crystal. As the crystal itself expands less, it cannot displace the diaphragm as much. Less vibratory energy is produced, and a decrease in cavitation is noticed in the tank. Additionally, piezoelectric transducers are often mounted to the tank with an epoxy adhesive, which is subject to fatigue at the high frequencies and high heat generated by the transducer and solution. The epoxy bond eventually loosens, rendering the transducer useless. The capacitance of the crystal also changes over time and with use, affecting the resonant frequency and causing the generator to be out of tune with the crystal resonant circuit.

Energy transfer of a piezoelectric transducer is another factor. Because the energy is absorbed by the parts that are immersed in an ultrasonic bath, there must be a substantial amount of energy in the tank to support cavitation. If this is not the case, the tank will be "load-sensitive" and cavitation will be limited, degrading cleaning performance. Although the piezoelectric transducers utilize an aluminum insert to improve impedance matching (and therefore energy transfer into the radiating diaphragm), they still have relatively low mass. This low mass limits the amount of energy transfer into the tank (as can be seen from the basic equation for kinetic energy, $mv2$). Due to the low mass of the piezoelectric transducers, manufacturers must use thin diaphragms in their tanks. A thick plate simply will not flex (and therefore cause a pressure wave) given the relatively low energy output of the piezoelectric transducer. However, there are several problems with using a thin diaphragm. A thin diaphragm driven at a certain frequency tends to oscillate at the upper harmonic frequencies as well, which creates smaller implosions. Another problem is that cavitation erosion, a common occurrence in ultrasonic cleaners, can wear through a thin-wall diaphragm. Once the diaphragm is penetrated, the solution will damage the transducers and wiring, leaving the unit useless and requiring major repair expense.

Magnetostrictive Transducers are known for their ruggedness and durability in industrial applications. Zero-space magnetostrictive transducers consist of nickel laminations attached tightly together with an electrical coil placed over the nickel stack. When current flows through the coil it creates a magnetic field. This is analogous to deformation of a piezoelectric crystal when it is subjected to voltage. When an alternating current is sent through the magnetostrictive coil, the stack vibrates at the frequency of the current.

The nickel stack of the magnetostrictive transducer is silver brazed directly to the resonating diaphragm. This has several advantages over an epoxy bond. The silver braze creates a solid metallic joint between the transducer and the diaphragm that will never loosen. The silver braze also efficiently couples the transducer and the diaphragm together, eliminating the damping effect that an epoxy bond creates. The use of nickel in the transducers means there will be no degradation of the transducers over time; nickel maintains its magnetostrictive properties on a constant level throughout the lifetime of the unit. Magnetostrictive transducers also provide more mass, which is a major factor in the transmission of energy into the solution in the ultrasonic tank. Zero-space magnetostrictive transducers have more mass than piezoelectric transducers, so they drive more power into the tank, and this makes them less load-sensitive than piezoelectric systems.

A radiating diaphragm that uses zero-space magnetostrictive transducers is usually 5 mm (3/16 in.) or greater in thickness, eliminating any chance for cavitation erosion wearthrough. Heavy nickel stacks can drive a plate of this thickness and still get excellent pressure wave transmission into the aqueous solution.

In summary, the advantages of zero-space magnetostrictive transducers are:

- They are silver brazed for permanent bonding with no damping effect
- They provide consistent performance throughout the life of the unit with no degradation of transducers
- Their high mass results in high energy in the tank and less load sensitivity
- Their thick diaphragm prevents erosion wear-through

The magnetostrictive transducer is not as efficient as a piezoelectric transducer. That is, for a given voltage or current displacement, the piezoelectric transducer will exhibit more deflection than the magnetostrictive transducer. This is a valid observation; however, it has offsetting disadvantages. The efficiency of concern should be that of the entire transducing system, including not only the transducer but also the elements that make up the transducer, as well as the diaphragm. It is the inferior mounting and impedance matching of a piezoelectric-driven diaphragm that reduces its overall transducing efficiency relative to that of a magnetostrictive transducer.

The **ultrasonic generator** converts a standard electrical frequency of 60 Hz into the high frequencies required in ultrasonic transmission, generally in the range of 20 to 80 kHz. Many of the better generators today use advanced technologies such as sweep frequency and autofollow circuitry. Frequency sweep circuitry drives the transducers between a bandwidth slightly greater and slightly less than the center frequency. For example, a transducer designed to run at 30 kHz will be driven by a generator that sweeps between 29 and 31 kHz. This technology eliminates the standing waves and hot spots in the tank that are characteristic of older, fixed-frequency generators. Autofollow circuitry is designed to maintain the center frequency when the ultrasonic tank is subjected to varying load conditions. When parts are placed in the tank or when the water level changes, the load on the generator changes. With autofollow circuitry, the generator matches electrically with the mechanical load, providing optimum output at all times to the ultrasonic tank.

Ultrasonic tanks are generally rectangular and can be manufactured in just about any size. Transducers are usually placed in the bottom or on the sides, or sometimes both when watt density (watts per gallon) is a concern. The transducers can be welded directly into the tank, or watertight immersible units can be placed directly into the aqueous solution. In some instances the immersibles may be mounted at the top of the tank, facing down. For applications such as strip cleaning, one immersible is placed on top and one on the bottom, with minimal distance between them. The strip is then run through the very high energy field. A tank should be sturdy in construction, ranging from 11 to 14 gauge in thickness. Larger, heavy-duty industrial tanks should be 11 to 12 gauge and should contain the proper stiffeners for support due to the weight of the solution.

Solution

The solution used in ultrasonic cleaning is a very important consideration. Solvents such as 1,1,1-trichloroethane and freon have been used effectively for many years, with and without ultrasonics. However, with the advent of the Montreal protocol, which calls for elimination of key ozone-depleting substances by 1996, companies are searching for more environmentally friendly methods to clean their parts. Chemical formulators are developing products that meet the demands of cleaning operations, yet are compatible with the health and well-being of society.

Whenever possible, it is best to use a water-based detergent in the ultrasonic cleaning process. Water is an excellent solvent, nontoxic, nonflammable, and environmentally friendly. However, it can be difficult and expensive to dispose of soiled water. Rinsing and drying can also be difficult without detergents. High surface tension exists in solutions without detergents, thus making rinsing difficult in hard-to-reach areas. Detergents can therefore be added to lower the surface tension and provide the necessary wetting action to loosen the bond of a contaminant to a substrate. As an added bonus, the cavitation energy in a water-based solution is more intense than in an organic solvent.

Table 1 is a guide for selection of appropriate cleaning agents for use with ultrasonic cleaning. Additional information about many of these agents is available in the other articles in this Section of the Handbook.

Solution temperature has a profound effect on ultrasonic cleaning effectiveness. In general, higher temperatures will result in higher cavitation intensity and better cleaning. However, if the temperature too closely approaches the boiling point of the solution, the liquid will boil in the negative pressure areas of the sound waves, reducing or eliminating cavitation. Water cavitates most effectively at about 70ºC (160ºF); a caustic/water solution, on the other hand, cleans most effectively at about 82ºC (180ºF) because of the increased effectiveness of the chemicals at the higher temperature. Solvents should be used at temperatures at least 6ºC (10ºF) below their boiling points (Ref 2).

Table 1

Solutions Used With Ultrasonic Cleaning Of Various Parts (Source: Ref. 1)

Material of construction	Types of parts	Contaminants	Suitable cleaning agent
Iron, Steel, Stainless steel	Castings, stamping, machined parts, drawn wire, diesel fuel injectors	Chips, lubricants, light oxides	High caustic with chelating agents
Iron, Steel, Stainless steel	Oil-quenched, used automotive parts; fine mesh and sintered filters	Carbonized oil grease, carbon smut, heavy grime deposits	High caustic, silicated
Iron, Steel, Stainless steel	Bearing rings, pump parts, knife blades, drill taps, valves	Chips; grinding, lapping and honing compounds; oils; waxes and abrasives	Moderately alkaline
Iron, Steel, Stainless steel	Roller bearings, electronic components that are affected by water or pose dryer problems, knife blades, sintered filters	Buffing and polishing compounds; miscellaneous machining, shop and other soils	Chlorinated-solvent degreaser (inhibited trichloroethylene, for example)
Aluminum and zinc	Castings, open-mesh air filters, used automotive carburetor parts, valves, switch components, drawn wire	Chips, lubricants and general grime	Moderately alkaline, specially inhibited to prevent etching of metal, or neutral synthetic (usually in liquid form)

Copper and brass (also silver, gold, tin, lead, and solder)	Printed circuit boards, waveguides, switch components, instrument connector pins, jewelry (before and after plating), ring bearings	Chips, shop dirt, lubricants, light oxides, fingerprints, flux residues, buffing and lapping compounds	Moderately alkaline, silicated, or neutral synthetic (possibly with ammonium hydroxide for copper oxide removal)
Magnesium	Castings, machined parts	Chips, lubricants, shop dirt	High caustic with chelating agents
Various metals	Heat treated tools, used automotive parts, copper-clad printed circuit boards, used fine-mesh filters	Oxide coatings	Moderately to strong inhibited proprietary acid mixtures specific for the oxide and base metal of the part to be cleaned (except magnesium)
Glass and ceramics	Television tubes, electronic tubes, laboratory apparatus, coated and uncoated photographic and optical lenses	Chips, fingerprints, lint, shop dirt	Moderately alkaline or neutral synthetic
Plastics	Lenses, tubing, plates, switch components	Chips, fingerprints, lint, shop dirt	Moderately alkaline or neutral synthetic
Various metals, plastics (nylon, Teflon, epoxy, etc.), and organic coatings when water solutions cannot be tolerated	Precision gears, bearings, switches, painted housings, printed circuit boards, miniature servomotors, computer components	Lint, other particulate matter, and other light oils	Trichlorotrifluoroethane (fluorocarbon solvent), sonic-vapor degreaser

System Design

Considerations in the design of any cleaning system include the contaminants on the part (s), the required cleanliness level, the geometry and material of the part(s), the quantity to be processed, and the previous system design and layout (if applicable). The part geometry, production rate, and cleaning time required will determine the size of the cleaning system, once the overall process has been decided. Typical tanks range from 20 to 400 L (5 to 1000 gal), and some are even larger.

Industrial, heavy-duty applications require industrial, heavy-duty ultrasonic equipment. Other factors that need to be considered are cleaning solutions and temperatures, rinsing (with or without ultrasonics), drying, automation, and load requirements. Most manufacturers of ultrasonic cleaning systems will assist in these decisions and will offer laboratory services and technical expertise. A typical system is shown in Fig. 2.

Figure 2

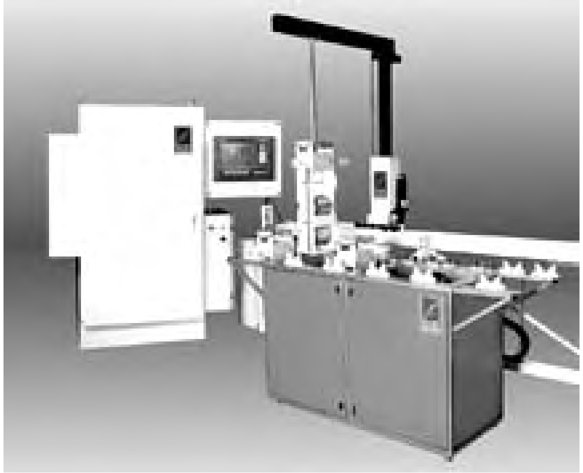

Fig. 2- Automated ultrasonic cleaning system. This system is designed to clean intricate metal hearing-aid components using a neutral-pH solution at 60ºC (140ºF) and three rinse stages at 70ºC (160ºF). Basket rotation (1 to 3 rpm) is used during each stage to ensure adequate cleaning and rinsing. The system computer controls all functions, including the hoist, and allows for storage of different process parameters for different types of parts. Courtesy of Blue Wave Ultrasonics.

Cleanliness Considerations. In a typical aqueous ultrasonic cleaning system, it is the cleaning stage(s) that will remove or loosen the contaminants. The following rinse stage(s) remove any remaining loosened soils and residual detergent, and a dryer removes any remaining rinse water. The overall process of the system is usually determined experimentally. Most reputable industrial cleaning equipment manufacturers have an applications lab where, through a process of experience, trial, and error, a properly designed cleaning process can be determined to meet the cleanliness levels specified.

There are a variety of ways to check for cleanliness. Some are as simple as a water break test on the part to see if most oil has been removed. Others are as elaborate as surface quality monitoring that uses optically stimulated electron emission technology to measure thin films of contaminants down to the Angstrom level.

Changing Existing Systems. If a current system exists, such as a vapor degreaser or soak tank, several things need to be considered. It may be practical, and possibly most economical, to retrofit the existing unit from one that uses solvent an organic solvent to one that uses an aqueous cleaner. Ultrasonic transducers can be added to an existing tank by cutting a hole in the tank and welding the transducer(s) in, or by simply dropping a watertight immersible unit into the tank. The latter method will take up some room in the tank, but it requires less labor. Additional work may have to be done to the tank, such as removing the cooling coils from the vapor degreaser, adding additional fittings for a filtration system, and so on.

In some existing systems, there is a large inventory of stainless steel baskets for handling the parts throughout the cleaning system. If possible, it is best to use these baskets due to the relatively high cost of replacement. In ultrasonic cleaning, the mesh size or hole configuration of the basket is very important. Some mesh sizes will inhibit the cavitation process inside the basket, thereby affecting the overall cleaning capability. Mesh sizes greater than 200 mesh or less than 10 mesh work best. An interesting note is that ultrasonic activity will pass through a variety of media. For example, solution A placed in a Pyrex beaker will cavitate if placed in solution B, which is cavitating in an ultrasonic tank.

Additional information on adapting vapor degreasing systems for ultrasonic immersion cleaning is provided in the article "Vapor Degreasing Alternatives" in this volume.

Part Handling. The geometry of the parts must be carefully analyzed to determine how they will be placed in the cleaning tank. Large parts, such as engine blocks, can be suspended directly from a hoist, whereas smaller parts will usually be placed in a basket. The most important factor in parts placement is to be sure that air is not trapped anywhere inside the part. If an air pocket is allowed to form, such as in a blind hole that would be facing downward toward the bottom of the tank, the cleaning solution and effects of cavitation will not be able to reach this particular area. The part will have to be rotated somehow in the tank during the cleaning process to allow the cleaning solution to reach the area where air was previously trapped. This can be accomplished either manually, by the attending operator, or by a rotating arm on an automated lift mechanism.

It is best if small parts can be physically separated when placed in a basket. An example would be to place machined valve bodies in a basket with some type of divider or locator for each one. Many times, however, in high output lines it is not possible to separate parts physically, such as in the manufacture of electrical connector pins where thousands of parts may need to be cleaned at one time because of the high production output and the small size. Ultrasonic agitation will be able to reach between these parts and allow the solution's scrubbing power to remove the contaminants, even if the parts are stacked on top of one another. On the other hand, rinse water may not remove all of the residual detergent , and a dryer has a very hard time removing moisture from embedded parts. The problem is easily solved by having an automated hoist with a constant rotating fixture on the arm that allows the basket to tumble at 1 to 3 rpm. This rotation allows the parts to tumble slowly and exposes the embedded pieces for proper rinsing and drying.

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Blue Wave Ultrasonics

Phone: (563) 322-0144 / Fax: (563) 322-7180

Toll Free (800) 373-0144
