Ultrasonic Intensity Measurement Techniques

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Abstract –

The search for a means of measuring cavitation intensity as an indicator of the effectiveness of an ultrasonic cleaning system has been ongoing for decades. Although many devices and schemes have been explored, none has emerged as the definitive "yardstick" for this evaluation. In this presentation, we will explore several of the means that have been employed to indicate the intensity of an ultrasonic field in a liquid. Each will be described in detail and discussed and evaluated with regard to its value as a tool to measure cleaning effectiveness.

Introduction –

The quest for a means to measure the intensity of an ultrasonic field has been ongoing at least since the mid-1960's when the Ultrasonic Manufacturer's Association initiated an effort to develop standards for their industry. The goal of that effort was to establish a universal standard against which ultrasonic cleaners could be evaluated for performance. One of the notable works was authored by Shih-Ping Liu and was published in The Journal of the Acoustical Society of America in November of 1965[1]. In the paper, Shih-Ping Liu explores the Chlorine-Release Test as an indicator of ultrasonic activity intensity and relates the results of the Chlorine-Release Test to cleaning effectiveness as measured using the ceramic ring test initially developed by Gilbert G. Brown of The American Sterilizer Company. In summary, it was concluded that the Chlorine-Release Test is a good relative indicator of ultrasonic intensity and that its results correlate well with cleaning effectiveness as indicated by the ceramic ring test for cleaning. This test was never adopted as a standard having been abandoned when it was discovered that a number of parameters including ultrasonic frequency significantly affected the validity of correlation between the test result and cleaning performance.

The issue of correlating any measure of ultrasonic energy or "cavitation intensity" to ultrasonic cleaning performance has been the downfall of any number of proposed protocols which assume that there is a direct relationship between the two. In fact, even the most elegant (and accurate) measure of ultrasonic intensity, it seems, falls short of predicting cleaning performance. The effectiveness of a cavitation field can be varied without varying its overall intensity. For example, a cavitation field made up of a large number of small cavitation bubbles (less intensity per cavitation and implosion event) may not be as effective in some instances as a cavitation field with the same overall

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[1] Chlorine-Release Test for Cavitation-Activity Measurements, Shih-Ping Liu, Journal of the Acoustical Society of America, Volume 38, Number 5, November 1965, pp 817-823.

intensity but made up of fewer bubbles with relatively higher intensity per event and vice versa. This issue will be addressed in more detail later in this paper.

Ultrasonics –

The basic principles of ultrasonic cavitation and its application to cleaning are well-known. Cavitation "bubbles" are created in liquids in the rarefaction portion of an ultrasonic sound wave. These "bubbles" then collapse in the following compression cycle of the sound wave generating minute areas of high temperature and pressure. This enhances the cleaning process in two ways. First, by causing the physical displacement of contaminants due to the force generated by the imploding cavitation bubble. Secondly, by forcing liquid exchange across interface boundaries thereby promoting dissolution of soluble contaminants by suitable "solvents." It is logical to assume that the effectiveness of the cleaning process is related to the intensity of the ultrasonic field and resulting implosions of cavitation bubbles. Cavitation intensity, therefore, was identified as a parameter of interest to indicate cleaning effectiveness.

Before we go on, it is important to note that cavitation alone does little to enhance cleaning. "Stable" cavitation bubbles which do not implode with violent force can be created in a liquid due to the passage of mechanical waves. Any device intended to measure the cleaning ability of a system must address the implosions of cavitation bubbles, not just their formation. In the following, the term "cavitation intensity" will be used to characterize "transient" cavitation bubbles which result in implosions useful in enhancing the cleaning effect.

Cleanliness vs. Cavitation Intensity –

The focus of this paper is measurement of cavitation implosion intensity as a contributory factor in the ultrasonic cleaning process. It is difficult not to argue that cleanliness itself can be used as a measure of cavitation intensity. In fact, it is this confusion that leads us to pursue a true measure of cavitation intensity. Without such a measure it is not possible to establish a correlation between cleaning effectiveness and cavitation intensity.

The following is a summary of various techniques which have been advanced as measures of cavitation intensity.

Chlorine Release Test

This test, which was one of the first, utilizes the ability of ultrasonic cavitation to decompose carbon tetrachloride to release free chlorine as an indicator of the intensity of ultrasonic cavitation. A potassium iodide solution is prepared and saturated with carbon tetrachloride. Chlorine released as the carbon tetrachloride decomposes liberates iodine from the potassium iodide which can then be measured as an indicator of ultrasonic cavitation intensity.

$$\begin{gathered} CCl_4 + H_2O \rightarrow Cl_2 + CO + 2HCl, \\ 2HCl + [O] \rightarrow Cl_2 + H_2O, \\ Cl_2 + 2KI \rightarrow 2KCl + I_2 \end{gathered}$$

A small sample (typically 200ml) of the potassium iodide solution saturated with carbon tetrachloride is placed in a plastic bag and scanned along the surface of the tank to be tested using a prescribed, uniform technique. The increase in free iodine in the solution after a given exposure time is measured using a spectrophotometer or titration with starch to indicate cavitation intensity.

Although proven repeatable under standardized conditions, this test was eventually abandoned and withdrawn as a candidate as a standard when it was demonstrated that higher frequencies (greater than 40 kHz) promoted the release of chlorine but did not produce corresponding cleaning results. Also, other, simpler alternatives emerged which the ultrasonic community felt could be made workable. It was clear that the "Chlorine Release Test" provided a valid comparison only when the units being compared were operating at the same frequency and in the 20 to 50Khz range of frequencies. Other variables including solution level in the tank and surfactant concentration were shown to have a major effect on the test result making standardization more difficult than initially expected.

Standardized Soil Test

Although this could be best described as a cleaning test, the procedure was intended to freeze all relevant parameters to allow cleaning effectiveness to be an indicator of cavitation intensity. This first attempt at a standardized "cleaning" test utilized ceramic rings contaminated with a reference "soil."

In preparing this paper, I was unable to find the formula for the "soil" but my recollection is that it contained a solvent, dye, paraffin and a number of other ingredients. The soil was applied to the flat surfaces of the ceramic rings which were then placed soiled face to soiled face in pairs which were held together with twisted wire. After the pairs were assembled, they were baked to dry the soil and weighed. Cleaning was done in a prescribed manner with the ring pairs suspended on "load bars" sized to provide a reference cleaning load for each specific size tank. After cleaning using standardized conditions of time, temperature and chemistry, the ceramic ring pairs were again weighed to determine the weight of soil removed by the cleaning process. The difference in weight was seen as an indicator of cleaning effectiveness.

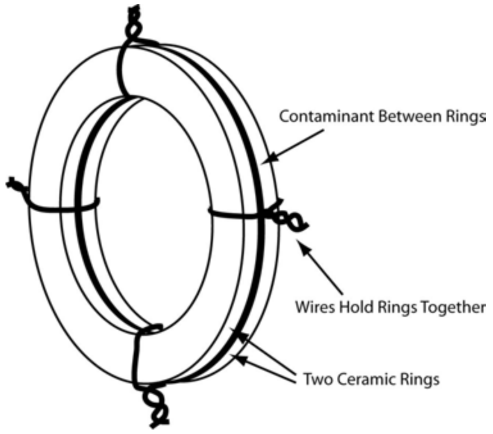


Illustration 1 - Two ceramic rings are contaminated with a "standard soil" and held tightly face to face for cleaning. Effectiveness is measured based on the amount of soil removed from between the rings.

This test, although it showed promise as a true test of the cleaning ability of a system, was extremely cumbersome and sensitive to such variables as the tightness of the twisted wires, the method of applying the soil, placement of the rings during cleaning and so on. It was eventually abandoned when the general consensus was that a simpler standard was required.

Aluminum Foil Test

In this test, a piece of aluminum foil is positioned vertically in the ultrasonically activated tank. The foil may be supported by a framework to prevent distortion due to currents within the liquid. After exposure under specific conditions and for a defined length of time, the foil is examined for pits and/or holes caused by the implosion of cavitation bubbles in proximity to the foil surface. The pattern of foil damage is said to indicate the distribution of ultrasonic energy within the liquid while the severity of damage and deformation is used to indicate the intensity of the ultrasonic cavitation field.

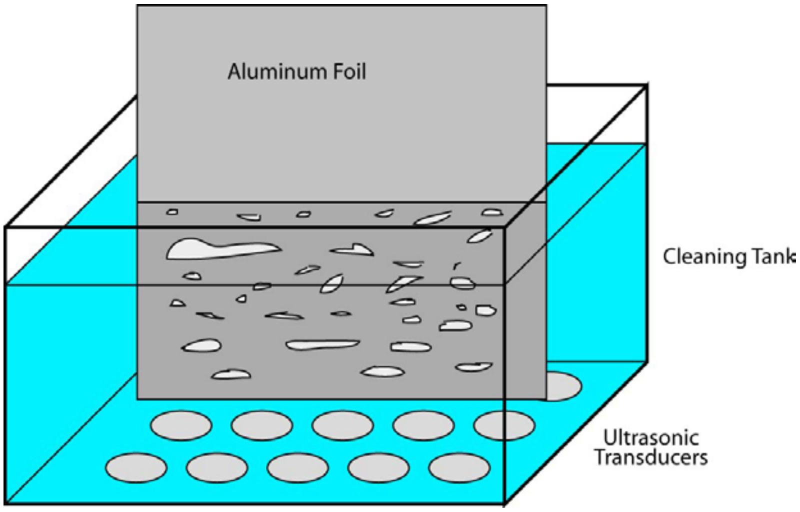
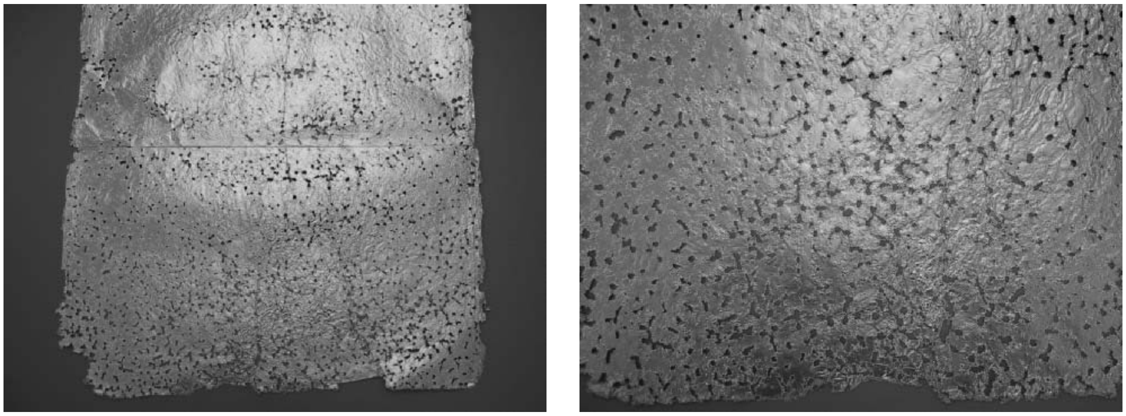


Illustration 2 – Aluminum foil is placed vertically in an ultrasonically activated tank. Tank effectiveness is based on the erosion density and pattern seen on the foil after exposure.



Illustrations 3 and 3a – Cavitation patterns on aluminum foil. The left picture above shows the entire width of a piece of foil. The picture on the right shows a closeup of the pattern produced. The black areas in the foil are actually holes.

There have been attempts to standardize the test by developing a set of specifications for the foil and for interpreting the results once the foil has been exposed to the ultrasonic field. Microscopic examination and measurement of the size of dents in the foil, measurement of light transmission through the holes produced in the foil, mapping of the eroded foil areas using a variety of tools such as a planimeter and computer integration have all been proposed as means of evaluation.

The results of the foil test are very sensitive to precise placement of the foil, ultrasonic frequency, temperature, and a variety of other variables in the ultrasonic field. In the end, this is a very subjective test the interpretation of which is a bit like reading tea leaves. Other problems include the fact that eroded bits of aluminum contaminate the bath being tested often making it unsuitable for use after testing. In spite of its problems, the aluminum foil test continues to be a popular and useful qualitative test in a number of instances.

Ceramic Ring Test

A derivative of the standardized soil test described earlier, this test was first proposed by G. G. Brown of American Sterilizer Company. It employs ceramic rings contaminated with graphite applied using a pencil as the test object. The graphite contaminant can not be effectively removed from the porous ceramic surface by rubbing, brushing or spraying techniques and, being relatively inert, is not easily removed by chemical means. Removal of graphite from the ceramic ring seems directly related to the action of ultrasonic cavitation and implosion. The coated rings are exposed to the ultrasonic field using a standardized procedure and then evaluated for cleanliness by comparing them to a reference photograph of rings graded on a numerical scale.

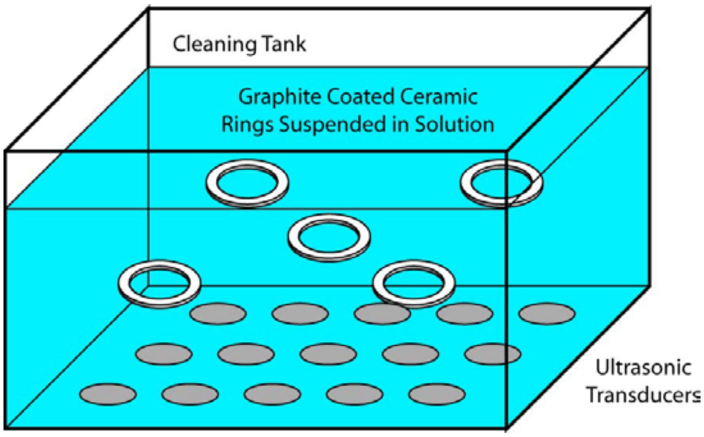


Illustration 4 – Ceramic rings contaminated with graphite from a pencil are suspended in an ultrasonic cleaning tank using a fixture or basket. The rings are “graded” using a photograph similar to the one shown below for comparison. Larger numbers indicate better performance.

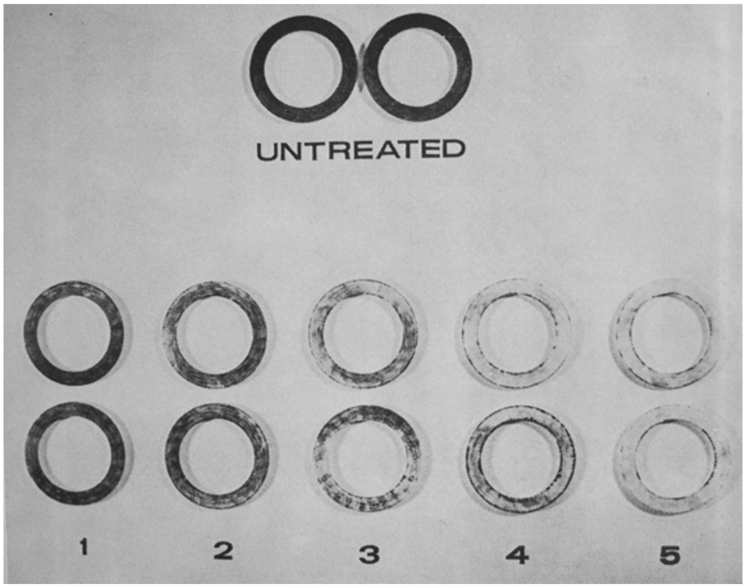


Illustration 5 - Comparative reference for the ceramic ring test.

This test was found useful and is still employed as a standard by several manufacturers and users of ultrasonic cleaners. Downfalls include its sensitivity to ultrasonic frequency, temperature and other variables difficult to control. Evaluation of the results is also very subjective requiring judgment on the part of the person doing the evaluation. On the positive side, this is one of the few tests based on an actual mechanical cleaning effect.

Hydrophone Test

Hydrophones or underwater microphones or "probes" have been used extensively to detect cavitation and implosion events resulting from ultrasonic activity. There are several challenges in using these devices for this application including sorting out what portion of the signal generated by the probe is a result of useful cavitation and which part is simply the ultrasonic frequency and other noise introduced into the liquid. To this end, the output of the sensing device is usually sent to a signal processor which is meant to separate out the signal characteristic of that produced by imploding cavitation bubbles (generally described as "white noise").

Illustration 6 – Two “probe” type instruments. The one on the left is circa 1958 while the one on the right represents the latest technology (courtesy of ppb, 740 13th St., Ste. 326, San Diego, CA 92101). Devices of this type are suitable for measuring day to day consistency in a given tank or for comparisons of tanks of similar manufacture.

Devices of this type have several characteristics that make it difficult to obtain repeatable readings which can be used as a reliable indicator of comparative ultrasonic cavitation intensity. Their response is generally highly frequency sensitive with at least one resonant frequency in the ultrasonic frequency spectrum. If the primary ultrasonic frequency of the cleaning bath being profiled happens to be relatively close the resonant frequency of the sensor, meaningful readings are virtually impossible. They are also temperature sensitive with resonant frequency and impedance varying with temperature. Signal processors capable of anticipating and compensating for the variety of primary frequencies and waveforms utilized in ultrasonic cleaning systems is a challenge which has not yet been demonstrably overcome. Most signal processors use an averaging or integrating scheme which may register extremely high instantaneous peak power as cavitation while not measuring sustained cavitation accurately. Repeatable readings may be difficult to achieve even under controlled laboratory conditions.

Even with their problems, hydrophone techniques have and will continue to be used to indicate day to day fluctuations in performance in a controlled ultrasonic bath and also to compare similar baths for performance.

Lead Erosion

The mechanical force generated by the collapse of cavitation bubbles is capable of etching or eroding aluminum, brass and other soft metals including lead. The lead erosion test uses standardized lead coupons positioned in a prescribed way within a cleaning bath. The weight loss of the coupons due to ultrasonic exposure is used to indicate the intensity of ultrasonic cavitation in the bath.

It is difficult to miss the similarities between this test and the foil erosion test described above. The Lead erosion test has the advantage of providing a quantitative result through measurement of weight loss as opposed to the subjective result of the aluminum foil test.

This test is sensitive to variations in temperature, chemistry and, along with other parameters, ultrasonic frequency. Ultrasonic erosion does not occur readily at higher frequencies. Although it was never widely used, the lead erosion test is practically non-existent as a measurement technique today due to the environmental sensitivity to lead contamination.

Calorimetric Test

Calorimetric tests are based on the fact that energy can not be created or destroyed. It is well known that ultrasonically activated liquids increase in temperature. Ultrasonic energy introduced into a liquid results in cavitation and implosion which in turn results in heat energy being dissipated into the liquid. The increase in temperature is used as an indicator of cavitation intensity.

In fact, it is difficult to ascribe which portion of any temperature increase is due to cavitation and which portion is due to frictional losses within the liquid. Even simple stirring of a liquid will, of course, increase its temperature. It is also difficult to account for additional heat input due to losses in the ultrasonic transducers which are attached to the cleaning tank and random heat losses through the tank walls and cooling due to evaporation of liquid from the surface of the bath. Without a means of differentiating between heat generated by friction and that resulting from the working implosions of ultrasonically induced cavitation bubbles, any calorimetric test serves, at best, as a relative indicator of total mechanical input to the system.

Test Validity

In summary, none of the above really fills the bill as the definitive measure of the performance of an ultrasonic cleaning system . Within limits, some of the schemes may be reasonably accurate indicators of relative cavitation intensity under controlled conditions. It is troubling, however, that it can be easily demonstrated that different testing schemes give drastically differing results under virtually identical conditions. One test, the aluminum foil test for example, may show very high ultrasonic activity in a given tank while another test, perhaps the ceramic ring test, will show very weak activity. The actual cleaning performance of the tank may be good or bad depending on the actual cleaning task presented.

The Ideal Yardstick –

For the moment let us assume that the goal of detecting and quantifying cavitation intensity is a noble one and that the effectiveness of an ultrasonic cleaning system is directly related to the intensity of the ultrasonic cavitation field it generates. This allows evaluation of an ultrasonic cleaning system to be based on a measurement of cavitation intensity alone making the challenge one of finding the ideal detector for measuring ultrasonic cavitation intensity. To assure accuracy of measurement of the desired parameter, cavitation intensity, we seek an instrument with the following properties - -

<u>Essential</u> Properties

- Responsive to Cavitation Intensity Alone
    - Insensitive to Sound Waves and Other Vibrations Not Producing Cavitation Resulting in Useful Implosion Events

    - Insensitive to Temperature
    - Insensitive to Frequency

      (Ideally able to detect the intensity of individual cavitation events and the number of events in a given volume of liquid in a given period of time.)
- Calibrated to an Absolute Reference Standard
- Repeatable Result

Wish List

- Non-invasive
    - Small
    - Transparent to Sound Waves
    - Low Mass
- Easy to Operate
    - Automatic
    - "Goof Proof"
- Portable
    - Small
    - Light Weight

So What ARE the Problems?

As mentioned at the outset, the above tests were advanced and have been promoted as means to measure the intensity and/or pattern of ultrasonic cavitation and implosion in a liquid. The real reason to measure ultrasonic cavitation intensity, however, is to use it as an indicator of the effectiveness of an ultrasonic cleaning system with intensity being related to the speed and thoroughness of cleaning and distribution related to the uniformity of cleaning. So far, none of the techniques advanced really meets the challenge. There are several "stumbling blocks" yet to be overcome.

The Empty Tank Phenomenon –

It is safe to say that ultrasonic cleaning is NEVER performed in an empty cleaning tank. There must always be an item to be cleaned in place before cleaning can be performed. Yet, many of the above tests are typically (and some may ONLY be) performed in a tank without a cleaning load in place and therefore can not represent conditions as they will exist when cleaning is actually taking place. It can be easily demonstrated that the cleaning load is a significant factor to consider in the performance of a cleaning system and should be considered. Weight, surface area, base material, contaminant, placement, parts basket or rack, chemistry, and agitation all impact cavitation intensity and distribution and, as a result, cleaning effectiveness.

This is not to say that a standardized cleaning load could not be introduced into a cleaning system under test. But - - what would it consist of and what effect would the selection have on the outcome of tests using different testing schemes.

Lack of Standard Conditions –

Many of the above tests do not address standard conditions of temperature, chemistry, liquid depth while others do so only casually. The list of parameters which affect cavitation intensity is lengthy and is still growing. Any test meant to indicate cavitation intensity as a result of ultrasonic energy input must freeze all other parameters.

Early researchers didn't recognize the effects of variables including chemistry, gas content of the liquid, etc. In fact, even today we are discovering that previously unrecognized variables such as particulate content have a huge effect on the ability of a liquid to cavitate and provide useful implosions. To this end, there is excellent work being done by the National Physics Laboratory in England which recognizes the need for a standardized liquid as one of the essentials in any comparative measurement of cavitation intensity.

Although we recognize that the ideal tool does not exist, let's pretend for a moment that it did exist and was being used to measure cavitation intensity as a measure of the cleaning ability of a system. It wouldn't be long before we started tweaking other variables, not just the ultrasonic hardware, to maximize the numbers. It would become apparent in short order that there are tradeoffs in everything. Changing one variable, let's say temperature, in the interest of increased cavitation intensity readings might in some cases prove an overall detriment to the process. Cavitation would be seen as just one of a number of tools essential to good cleaning.

Part Damage –

It has been common practice for years to use higher frequency ultrasonics to clean delicate parts to prevent cavitation damage. Higher frequency ultrasonic energy has also been reported more effective in the removal of small particles from surfaces, including those which are sub-micron in size.

Conversely, low frequency ultrasonic energy has been proven effective in many applications which can not be accomplished with higher frequencies. Some applications, it seems, require a certain threshold level of intensity to be released in the collapse of the cavitation bubble in order to produce the desired effect.

More recently, precise control of frequency, frequency sweep bandwidth and rate, amplitude modulation (pulse), and other waveform parameters has been used to eliminate detrimental effects of ultrasonic cleaning due to part resonance.

So - - Is cavitation intensity the real measure of the usefulness and effectiveness of an ultrasonic cleaning system? In a word - - NO. In the final analysis, the ultimate measure of cleaning performance is yield. How many good, clean parts are produced – and this may not be related at all to the intensity of cavitation in the cleaning tank.

Where Do We Go From Here?

First of all, it should be stated that the measurement tools described above are not, after all, worthless. It's just that one must realize exactly what is being measured and the level of importance that should be placed on the data collected. Some of them are useful for day to day comparisons of ultrasonic performance provided that conditions are standardized. In these days of digitally synthesized waveforms and a technology that is being asked to provide surfaces orders of magnitude cleaner than was even imagined as little as three decades ago, characterization of cavitation intensity is more than a simple, all encompassing number indicating cavitation intensity.

Today, we are concerned not only with cavitation intensity but with the size of the cavitation bubbles and the number that are produced. A given level of intensity, after all, can be achieved through the implosion of a small number of large bubbles or a larger number of smaller bubbles. A simple measure of intensity can not, then, characterize the sound field in this case. The frequency envelope for ultrasonic cleaning continues to extend higher and higher as critical particle sizes become smaller and smaller. A balance must be achieved between cleaning and part damage due to cavitation erosion or part resonance. Combinations of frequencies have been demonstrated effective in removing a range of particle sizes in difficult cleaning applications.

So what started out as an art in search of science is turning into a science in search of art.

So, the "ideal" yardstick for measuring cavitation intensity today appears to be much more sophisticated than that sought (and not found) in the past. Add to our previous list of "Essentials" the following - -

- Ability to quantify the number of cavitation/implosion events taking place in a given volume of liquid in a certain period of time.
- Ability to quantify the amount of energy released in each cavitation/implosion event.

To the "Wish List" add - -

- The ability to collect the above date in real time to allow feedback to the ultrasonic source allowing corrections for part loading, temperature, tank level and the myriad of other parameters that we now know have an effect on the cleaning process.

This device does not exist!

Summary

Any instrument produced to date has a limited scope of application. It is heartening that in only a few increasingly rare cases do the manufacturers and sellers of these instruments make claims for them beyond their demonstrated capability. It is clearly indicated, for example, that measurements are "relative" and that even a calibrated device does not give an absolute value to be used as a measure of anything. The ongoing risk is that the users of these instruments will put more faith in them than they are due.

Some of the present instruments may be put to good use in providing day to day comparisons of performance under controlled cleaning conditions. Use in other than scientifically controlled conditions, however, can only lead to inconclusive if not misleading results and should be avoided.

Hopefully, we can in the future, come to the realization that the “cavitation meter” by itself is not an instrument capable if indicating a competitive advantage of one ultrasonic cleaning system over another. If found, an accurate and reliable measure of cavitation intensity could be put to good use by scientists and engineers in search of the most efficient and effective means of delivering sound energy to a liquid. This would likely be employed in the area of transducer development under the controlled conditions required for such measurements.

Cavitation Evaluation Techniques

Test	**Ease of Application**	**Equipment Requirement**	**Unit of Measurement**	**Repeatability**	**Relationship to Cleaning**	**Bath Contamination**	**Provides Distribution Information**
Standardized Soil	Difficult and Time Consuming	Laboratory, analytical balance, other equipment	Yes – Weight Loss	Good using standardized technique	Relates well to some cleaning tasks	Yes	Minimum
Chlorine Release	Difficult and Time Consuming	Laboratory, special equipment	Yes – Chlorine Released	Good using standardized technique	Relates well to some cleaning tasks	No	No. Test is designed to average results
Aluminum Foil Test	Very Easy	Aluminum Foil, holding frame	No – Subjective, Comparative	Varies depending on conditions and interpretation	Relates well to some cleaning tasks	Yes Aluminum particles	Yes
Ceramic Ring Test	Easy	Rings, pencil, comparison chart	No – Subjective, Comparative	Varies depending on conditions and interpretation	Relates well to some mechanical cleaning tasks	Yes (minimum graphite residue)	Minimum
Hydrophone	Moderately easy to difficult	Hydrophone and analysis device. Positioning equipment in some cases	Relative Scale related to Watts/In^2 or Watts/Gallon	Varies depending on conditions and procedure	Questionable	No	Yes when mapping procedures are used
Lead Erosion	Easy	Lead coupons, analytical balance	Yes – Weight Loss per unit of Time	Moderate to good depending on conditions and procedures	Relates well to some cleaning tasks	Yes Lead particles	Minimum
Calorimetric	Varies	Temperature measuring device	Yes – Temperature Increase per Unit of Time	Good using standardized technique	None	No	No