Publication No. UP-805

ULTRASOUND POWER IN MEDICINE

Principles Of Ultrasound Power Measurement

ohmic instruments co.

EASTON, MARYLAND 21601

TOLL-FREE
800-626-7713

FAX
(410) 822-9633

(410) 820-5111

ULTRASOUND POWER IN MEDICINE

Principles Of Ultrasound Power Measurement

by

The Engineering Staff of
Ohmic Instruments Co.

Published By

Ohmic Instruments Co.

ULTRASOUND POWER IN MEDICINE

CONTENTS

ULTRASOUND POWER IN MEDICINE

INTRODUCTION.

Sonics is the science and technology of acoustical waves. Its practical medical application in solids and fluids extends below the human perception into the infrasonic region of 15 to 20 Hz. This frequency region is where behavior patterns can be influenced and in some animals, such as elephants, communications is accomplished. Low frequency mechanical waves from a few tenths of a cycle to 20 Hz are encountered in oceanographic and seismic work. The audible spectrum continues through the 12 to 20 KHz range for humans, depending on age, and up to 50 to 100 KHz for small insects and animals. This is followed by the broad range of ultrasound continuous up to several hundred megahertz.

Beyond sonic frequencies of 500 megahertz, the term "hypersonic" has been used. To avoid confusion with hypersonic speeds, the term, "pretersonic" was introduced meaning, "ultrasonic frequency higher than 500 megahertz". (See IEEE Standard Dictionary of Electrical and Electronic Terms. John Wiley & Sons, Inc. publishers.) The sonic spectrum continues through gigahertz (10^9 Hz) to terahertz (10^{12} Hz). At very low wave lengths, the x-ray counterpart of the electromagnetic spectrum, crystal lattice vibration takes place. Due to the x-ray's short wave length, it is measurable only by x-ray spectrometry.

BASIC PROPERTIES OF ULTRASOUND

Sound Velocity = Frequency x Wavelength.

The relationship between sound velocity, frequency, and wavelength is of fundamental importance. Sound velocity equals the product of frequency and wave length. Sound velocity in water is 1494 meters per second (m/sec) at +70°F., hence, at 1 megahertz, a therapeutic head has the wave length of 1494 x 10^{-6} meter or 0.15 centimeter (cm) length for one cycle. Figure 1 shows the relationship of sound velocity, frequency, and wavelengths of gases, liquids, and metals. To reduce reflection and standing wave errors in power measurements, a 10 to 1 wave length ratio should be maintained, that is, with a 1-megahertz applicator, a 1.5 cm or over one-half inch between the transducer/target absorbing media is to be maintained.

Temperature Effects in Water.

Propagation velocity of ultrasound in water is the function of temperature, pressure, oxygen content, and other variables. Pure water below +74°C. has a positive temperature coefficient. Its sound velocity increases from 1422 m/sec. at 0°C. to 1557 m/sec. at +74°C., a +9.3 percent change. In the acoustic classification of liquids, some have positive, others negative, temperature coefficients. Therefore, it is possible to make sound velocity in water independent of temperature over a wide range. For example, when mixing 18% ethyl alcohol by volume to water, the sound velocity will become independent of temperature over the range of +5°C. to +45°C.

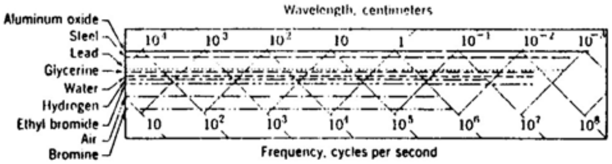


Figure 1. Sound Velocity in gases, liquids, and metals.

Pressure Effects in Water.

The compressibility of liquids by ultrasound is determined by their elastic properties, that is, their expansion and contraction of molecules and redistribution of their mutual orientation. The lattice structure is more compact when the liquid is compressed and a more lax distribution exists during expansion. Hence, when sound waves pass as through water, a small increase and decrease in pressure is superimposed on the static pressure. As the pressure increases, the sound velocity also increases and cavitation forces decrease. For example, at 6,000 atmosphere pressure, the sound velocity in water at +30°C. increases over 50% and the compressibility by a factor of 3, with respect to ambient atmospheric pressure.

When the ambient pressure is lowered below 1 atmosphere at high sonic intensity levels, the cavitational pressure threshold becomes significant since cavitation means formation of vapor-filled bubbles and cavities in the water due to

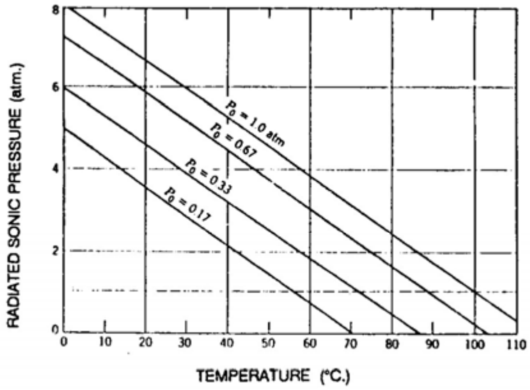


Figure 2. Radiated Sonic Pressure vs. Temperature.

reduction of pressure below a critical value without change in the ambient temperature. Figure 2 shows the Radiated Sonic Pressure vs. Temperature at atmospheric pressure levels between $P_O = 0.17$ to 1 atmosphere in degassed water with applied sonic pressure of 60 kilohertz (KHz). As the sonic frequency increases, the slopes become more steep.

Surface Tension of Water.

Surface tension is a force within the fluid acting on its surface to minimize the area of its surface. The internal pressure in a gas bubble within water is a function of surface tension and when it collapses, the bubble gives up kinetic energy and is converted into a smaller size. At higher surface tension there is more energy expended. Water has a very high surface tension and can produce damaging cavitation, that is, when water is combined with oxygen under high pressure and temperature, pits and surface damage to the walls of high pressure containers can occur. The oxygen acts in water as a catalytic agent. To avoid damage in high pressure boilers, additives called, Oxygen Scavengers, are used. These scavengers combine with the free oxygen in water to decrease surface tension and reduce oxygen content to a few tenths of a part per million (ppm).

Cavitation - Transient And Stable

Cavitation is the formation of gas or vapor-filled cavities within liquids by sonic or mechanical forces. It is a process where the fluid vapor pressure is reduced to a critical temperature without change in ambient temperature. Transient cavitation is a rapid burst of cavities in the fluid media to sonic forces. Stable cavitation is stable periodic function due to the interaction of the sonic intensity with the fluid and surrounding media, such as, the vibrating air bubbles or streaming. The basic parameters causing cavitation in fluids are many and are interrelated. The threshold of cavitation can vary widely depending on the fluid's viscosity, surface tension, density, purity, dissolved gases, temperature, pressure and the applied ultrasound frequency. At low sonic frequencies, under 100 KHz, the effect of pop noise and bubble growth is pronounced. Above 5 to 10 MHz, cavitational threshold levels decrease.

Some Cavitation Mechanisms

As low as a few hundred milliwatts per square centimeter, sonic waves in fluids have sufficient energy to produce large pressure amplitude variations. In the low pressure phase, even in degassed water, thermal agitation may override the cohesive forces. Boiling bubbles burst and give up their kinetic energy; others go into a stable periodic cavitation and oscillate. This cavitational oscillation depends on the bubble size and fluid pressure. Therefore, for a bubble diameter (d) in inches at a pressure (p) in feet, the resonant frequency (f_r) in hertz is $f_r = 44.6\, p^{1/2} / d$. For a typical bubble size of ten thousandths of and inch diameter submersed under 4 inches of water, the bubble resonance is approximately 2.6 kilohertz.

Bubbles that reach resonant size are power sources and usually are accompanied by strong acoustical fields and non-linear effects caused by bursting, change in radiation pressure and streaming. Vibrating groups of air bubbles can cause violent motion within biological cells. Bubble-induced shear stresses can cause hemolysis of red blood cells.

Another undesirable effect of bubbles in fluid media is the change in velocity of the sound through reflection and refraction. In addition, the nature of air bubbles as reflectors are different from that of solid or liquid particles. Air bubbles are much more compressible then the surrounding water, so they pulsate at larger amplitude when exposed to sonic fields.

To Reduce Cavitational Effects:

1. De-gas distilled water to a few parts per million O_2 content. The water should have minimum impurities and suspended materials.
2. Decrease the energy level by lowering the ambient temperature to the 30° to 40° F. range.
3. Seal water surface area to avoid oxygen transfusion through air.
4. Pulse ultrasound to lessen effects of cavitation.
5. Use chemical additives to decrease surface tension.
6. Raise the ambient pressure.
7. Change test media to higher density fluid, such as, degassed castor oil.

Pulse Duration Vs. Cavitation in Water.

Pulsed ultrasound offers advantages as there is a time delay between the applied ultrasonic intensity and the onset of cavitation. A five to ten-second delay may occur at high power levels before effects of cavitation is noticed. In general, the longer the water is exposed to intense sound, the lower the cavitation level. This time delay is due to the finite speed of bubble growth by diffusion and other slow responding periodic effects: reflections, standing waves, etc. Even after 10 to 20 seconds, threshold levels can affect measurements. Figure 3 shows the Dependence of Cavitational Threshold Vs. Pulse Length of degassed and tap water.

At high power levels, to reduce cavitational effects, pulsed operation with duty cycle of 10% to 50% time duration can be used then averaged and corrected. A change of water media to more viscous type fluid, such as, degassed castor oil, as used with underwater sonar transmitters will reduce cavitational effects.

Absorption of Sound in Water.

A general definition of absorption is the taking up of energy from sonic or electromagnetic radiation by the media through which the radiation is passing. The acoustic energy in water is converted to heat, due to friction and impurities in the water media. Figure 4 shows how energy absorption per unit distance varies with frequency at temperatures of +5°C., +15°C., and +22.5°C. Note that when the transducer frequency is increased from 1 megahertz to 5 megahertz, the ultrasonic energy absorption increases approximately 25 times, an inverse square law relation.

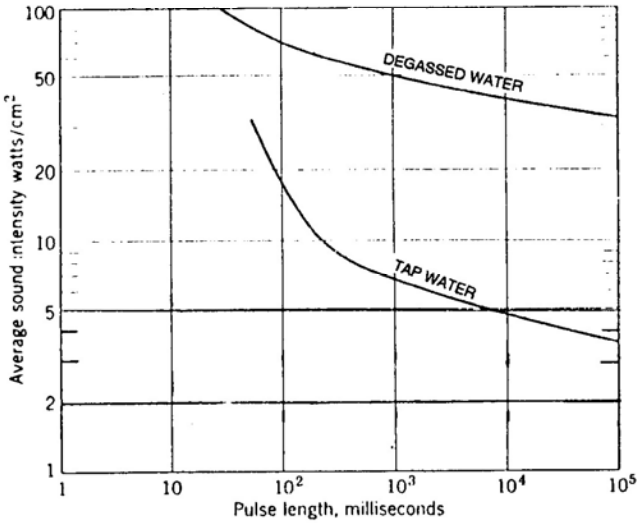


Figure 3. Cavitational Threshold vs. Pulse Length

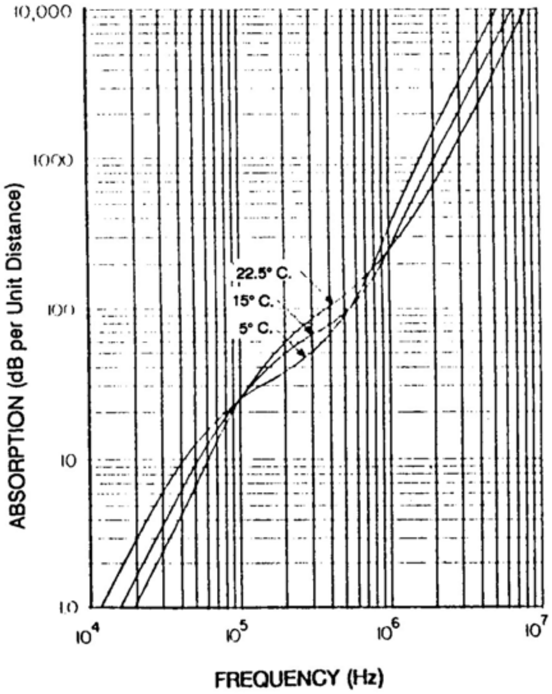


Figure 4. Energy Absorption Vs. Frequency

Reflections, Echo, Audible Power Levels

Acoustical reflection is the return of waves from surfaces on which they are incident. If an audible wave is reflected with sufficient delay and its magnitude is to be perceived as a signal from that directly transmitted, it is called an echo.

In air, the sound velocity is 331.5 meters per second at 0°C. The human ear can only differentiate a tenth of a second time delay, so the distance between the reflector and sound source should be over 17 meters before echo can be heard. The high limit of human perception to sound wave length is 1.6 centimeters or 20 KHz, yet, in terms of power sensitivity, the human ear outperforms in sensitivity ultrasound power measurement limits. Sound power levels are also expressed in watts and sound intensity in watts per unit area. A human ear threshold level of hearing a 1 kHz tone, perpendicular to the propagation of energy is 10^{-12} watts. Normal speech is 10^{-5} watts (or 10 microwatts). Shouting is 1 milliwatt, a car horn is 5 watts, and a large siren is 1000 watts. Due to its logarithmic sound response, the human ear can cover close to 15 decades.

SONIC POWER MEASUREMENTS.

Power, Intensity, and Beam Profile

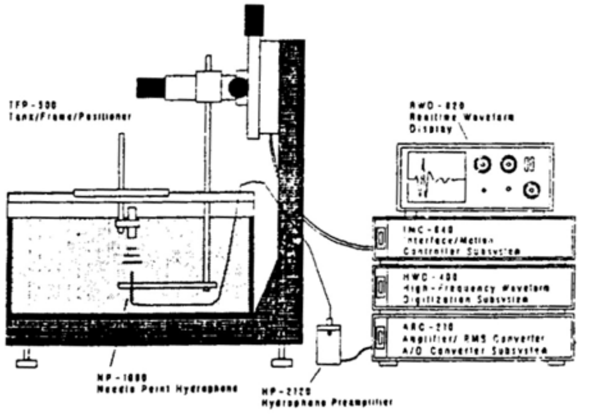
Power (W) is the time rate of doing work. In a mechanical system, power is equal to the time average product of force and velocity. Similarly, ultrasound power is the time average of the total force exerted over an area multiplied by the sound velocity in water.

Intensity (I) is the instantaneous acoustic power transmitted by the sonic wave across a unit area perpendicular to the wave. $I = P^2cd$ where (P) is the instantaneous acoustic pressure, (c) is sound velocity, and (d) is the density of the medium. Most sound fields are not uniformly distributed over the transducer surface, therefore, it is important to measure the power that is transmitted over a very small area and then autoscan in the focal plane.

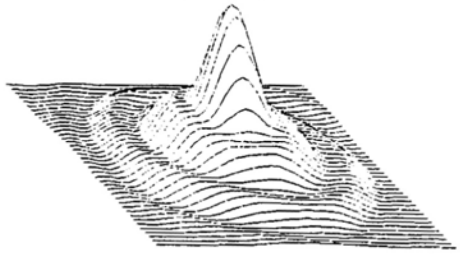
The power is measured using a small transducer with an area that is approximately equal to the sound velocity (c) divided by the transducer frequency (f) then squared; $(c/f)^2$. For a 2.5 megahertz transducer in water (c = 1500 meter/sec), the transducer area is 0.36 mm^2 and the diameter is 0.68 mm. The generally accepted pin probe to plot beam profiles has a 0.5 mm diameter. With a computer controlled x-y plotter, a three-dimensional beam profile can be generated. Figure 5 shows a test tank, miniature transducer, x-y plotter, and a beam profile.

Manufacturers of medical ultrasound transducers are required to submit beam profile information to the F.D.A. to verify safe ratios of peak-to-average acoustical power intensities.

From the beam profile, the total transducer energy can be integrated and power measurement can be compared against the Radiation Force Balance method.



Courtesy of NTR Systems



3-D Plot - Ultrasound Transducer Beam Profile

Figure 5. Plotting a transducer beam profile.

Principles of Radiation Force Balance (R.F.B.)

To test average power output levels of therapeutic and diagnostic transducers, the Radiation Force Balance (R.F.B.) method is used. See The American Institute of Ultrasound in Medicine, "Safety Standard for Diagnostic Ultrasound Equipment", AIUM/NEMA Standard Publication No. UL-1-1981 Section D 1.3. which states "The radiation force balance was chosen for measurement of ultrasound power because it is conceptually simple, relatively easy to build and use, and provides a measurement which can be referred to the National Bureau of Standards".

This method is called R.F.B. because the applied sonic force radiated from the transducer under test (T.U.T.) exerts a force proportional to the radiated sonic energy when it is intercepted by the target. This force is measured on a mechanical or electronic scale.

For accurate R.F.B. measurements, the following are required:

1. A transducer having perfect coupling to degassed water which radiates into an infinite non-reflective media.
2. Water that does not introduce any reflection or attenuation caused by air bubbles or other sonic interference paths.
3. A perfect 45° cone geometry and construction to avoid errors, reflections, or acoustic flexing.
4. A perfect sonic absorber which does not reflect energy.
5. A precision scale to measure exact force on the cone.
6. A disturbance-free environment.

RADIATION FORCE BALANCE (R.F.B) CONSTRUCTION.

The R.F.B. consists of the following blocks as shown in Figure 6, with numbers indicated as follows:

1. Test Tank
2. Sonic Sound Absorber
3. Test Media: Degassed Water
4. Sonic Target
5. Coupling Target to Scale
6. Transducer Under Test (T.U.T.) Positioning and Support
7. Scale to Measure Force Exerted on Target.

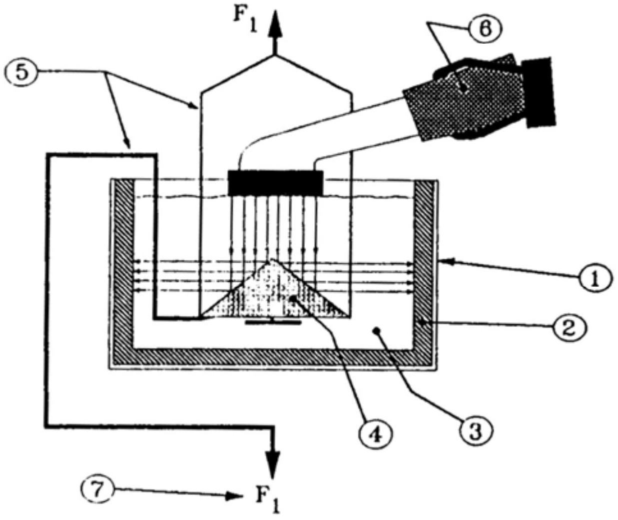


Figure 6. The Radiation Force Balance (R.F.B.) Method

The Test Tank.

The ideal test tank should have large enough water volume and solid mechanical construction to give accurate power measurements. A test tank size around 1,000 milliliters (1 liter) was found to be adequate. A smaller test tank volume above one-half liter may be used for low power level measurements. The smaller the water volume, the more important becomes the quality of the degassed water and the sound absorbent liner.

All UPM Series radiation force balance (R.F.B.) units use the one-liter, or larger, water test tanks. For lower power level measurements, the 600-ml type is available to customer requirements. A faster water settlement time, easier handling, requiring less degassed water justifies having the smaller tank size. All test tanks have a half-inch rubber lining to absorb the sonic reflections. Interfering resonant effects in all types of ultrasound tests may occur during measurements. These effects can show up as unstable power readings with variations as much as 10%. The resonant effects can be caused by: 1) water that is not sufficiently degassed or has absorbed oxygen during test; 2) air pocket formations on the transducer or cone; 3) incorrect transducer positioning or unbalanced cone; 4) transducer overheating at high power levels; 5) sustained low level air or mechanical turbulence; 6) uneven surface for the R.F.B.; 7) reflections, resonances and standing waves caused by sonic fields between T.U.T., target, absorber or from the water surface. To analyze the source, first, reduce the ultrasound power level until the readings become stable. Note the power level, then change the water, clean cone, transducer and liner from bubble buildup. Vary the position and distance between T.U.T. and target then continue with these steps until the readings become stable. If the water volume is lowered in the test tank to less than one-half liter, a critical level is reached and cannot support sonic forces usually due to heat gradients, cavitation, or media sonic reverberation. This will cause the readings to fluctuate.

Sonic Sound Absorbers.

The purpose of the rubber liner in the test tank is to absorb sonic energy. The effectiveness of the absorption is rated by the material's ability to dissipate radiation and it is measured in percent called Reflection Coefficient and defined as: The ratio of the amplitude of a wave reflected from a surface to the amplitude of the incident wave. A simple test for sonic reflection is shown in Figure 7. For example, a 2.5 megahertz transducer is pulsed underwater toward a reflector and the received signal is normalized as 100%, followed by the insertion of the rubber absorber in front of it. The return echo gives the percent of reflection ($V_2/V_1 \times 100$). There are many different materials which can be used to absorb sonic forces. Most of them are made of synthetic rubber. Some materials use glass air bubble beads with various layers of different absorbing media to enhance the sonic absorption and diffusion.

The UPM Series power meter tanks are lined with one-half inch neoprene rubber having a durometer value of 30. Durometer measurements range from 0 to 100 and are used to rate rubber material for its degree of softness: the lower the durometer reading, the softer the material. Figure 8 shows a typical durometer measurement.

Additional improvements by providing miniature pyramid shapes in the narrow 180° three-dimensional frame of the wall absorber will further enhance trapping of unwanted reflections.

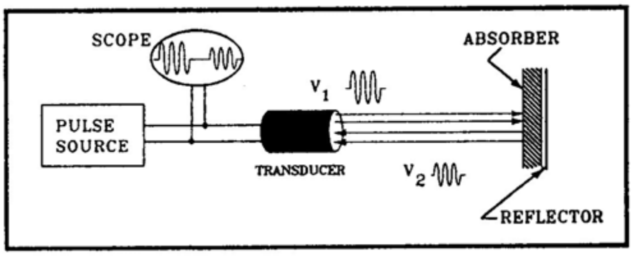


Figure 7. Testing for sonic reflection.

Degassed Water.

Air bubbles in water deflect sonic energy and change propagation time (velocity) and, thereby, the measurement accuracy of ultrasound power will be affected. Degassed water containing less than five parts per million (ppm) free oxygen is recommended for use in the test tank. One method of obtaining water with low oxygen level is to boil distilled water for 30 minutes in a Mason-type glass jar without the lid. After the 30 minutes, immediately place thin plastic over the lid, cover with the metal screw cap, tighten, and

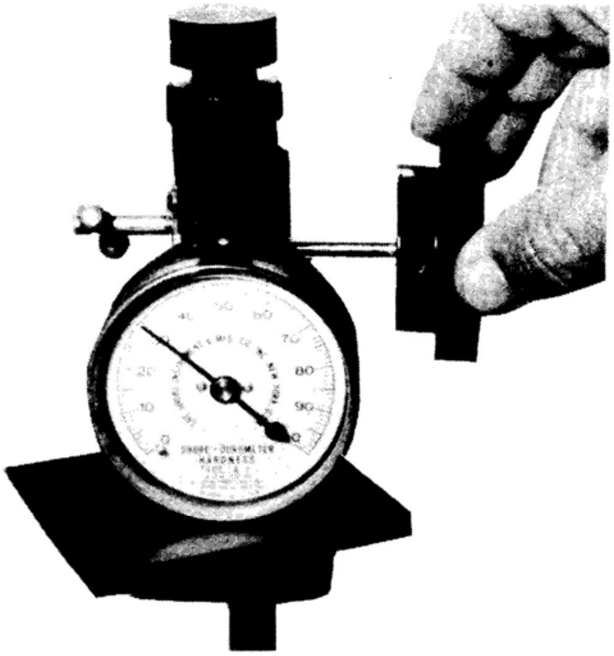


Figure 8. Durometer testing of neoprene rubber.

refrigerate until cool. As it cools, a vacuum will develop within the container. Another method of degassing water is to heat it to boiling point then place under vacuum for 5 to 10 minutes. Avoid double transferring the boiled degassed water from one container to another because even with minimum turbulence, it degrades the water quality.

Store the degassed water only in glass or non-porous plastic containers. The half-gallon carbonated liquid bottles are suitable. Soft polystyrene quart or gallon milk/water containers are not suitable as they will, in time, allow oxygen to enter and degrade the water quality.

Ideally, the water during tests are to be maintained below 5 ppm oxygen content. See Figure 9 for typical errors. The straight line is degassed water below 5 ppm. Tap water "A" has 25 ppm and water "B", over 35 ppm. Distilled water, depending on shelf-life, may have up to 20 ppm oxygen content. Sterile distilled water used for irrigation purposes in hospitals is available from most hospital supply centers. It is acceptable for use and, usually, contains less than 4 ppm of oxygen. It is advisable to periodically verify the oxygen content of the degassed water. Test kits are available containing vials having reagent to absorb a water sample once the vacuum vile tip is broken. After a few minutes, the change in color determines whether the ppm reading is 0 to 15 according to the supplied chart. The colors are from 0/yellow to 15/dark blue. These test kits are available from Chemetrics, Inc., Warrenton, VA. Direct reading dissolved oxygen meters, such as Model DOT-20 available from Ohmic Instruments Co., St. Michaels, MD, provide a less complicated testing alternative.

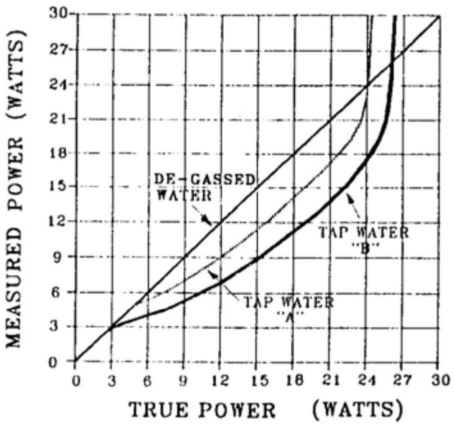


Figure 9. Effect of water type on sonic power.

Degassed water is to be poured into the test tank only shortly before a test with a minimum of turbulence. Hold the tank in tilted position while pouring. During tests, the water will absorb oxygen and each test should be limited to less than one minute duration. Periodic change of degassed water is recommended. A visual inspection will aid to judge whether air bubble accumulation is excessive on the cone, rubber lining, or T.U.T. See Figure 11 and 12.

Figure 10. A dissolved oxygen test kit.

Figure 11. Bubble formation on the sonic target.

Sonic Targets for R.F.B.

The total energy radiated from the transducer under test (T.U.T.) is to be fully intercepted by the 45° conical target. A target can be made of either reflective or absorptive material. The ideal target converts all radiated energy to ultrasonic power output in grams. To achieve precise measurement, a <u>reflective</u> type target should have an exact 45° cone geometry and deflect all sonic energy into the tank liner. A few tenths of a degree target angle deviation introduces measurement errors. Construction, imperfections in material and thickness, surface finish, or backing media can also introduce additional errors. The inside of the cone is called "target backing". It either contains air or is lined with polystyrene foam. Figure 13 shows the various cone size assemblies as used in Ohmic ultrasound power meters. The 45° rubber strip on the vertical coupling arm to the cone acts as a diffuser over the narrow angle where sonic reflection between the cone and arm may occur. Transducer head sizes up to 3 inches (optional 6 in.) in diameter may be tested.

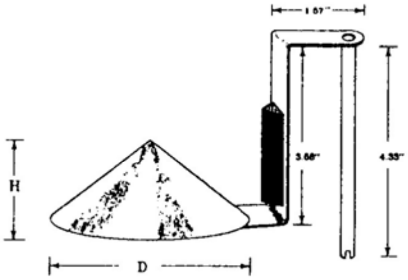
Figure 12. Transducer positioned in test tank. (Notice bubbles.)

To reduce reflections, a 45° cone can be jacketed with 1/8-inch neoprene rubber, which makes it an <u>absorbing</u> target. A small percentage of sonic energy is therefore reflected and absorbed by the tank's rubber lining. This absorptive type target performs well at high power levels as the reflections caused by bubbles are better attenuated between the cone and liner. The readings of the absorptive target correlate closely with the readings of the 45° reflective type target. Figure 14 on the left shows a reflective cone of UPM-30 and on the right, an absorptive target that may be used at high power level with the UPM-DT Series.

Coupling Target to Scale.

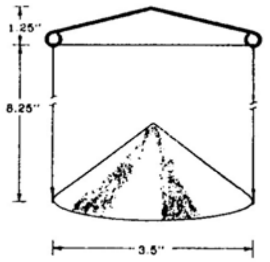
To measure the sonic force on the cone target, a non-frictional direct transfer to the scale is required. Any coupling method may be used as long as it does not degrade the accuracy of measurement. In the case of the Model UPM-30, suspension of the cone is by nylon string. This method is used as the string does not absorb moisture or introduce friction. String suspension requires an exact positioning of the cone as well as leveling of the power meter unit. At higher power level testing, the string suspension requires more care in positioning.

	D	H	Tank Dia.	Tank Vol.
Small Cone	2.6"	1.37"	5.1"	600 ml.
Large Cone	3.3"	1.65"	6"	1100 ml.



UPM–DT TARGETS

Tank Dia.	Tank Vol.
6"	



UPM–30 TARGET

Figure 13. Sonic target cone sizes.

At 20 to 30-watts, a radiant force over 2 grams is put out by the T.U.T. causing motion of the cone or displacement up to a few tenths of an inch. This motion will be averaged out by the scale and does not introduce any measurable difference as long as all the radiated power is bounced off the cone to the absorbing rubber target. At low power measurements, the digital R.F.B. requires a solid target suspension, as the least cone movement could introduce 10 to 50 milliwatts error.

Transducer Under Test (T.U.T.) Positioning and Support.

Before a test, check that the transducer head is clean. Surface contamination such as oil smudges, dust or other particles should be removed. When clean, tilt the transducer head at a 45° angle while it is inserted into the water to minimize air trapping. Remove the head to verify that the surface is fully and uniformly wetted. If not, wipe dry, clean the transducer surface and re-enter the transducer head into the water. When the transducer is approximately ¼ inch below the water line, position it parallel to the water surface and place it directly over the center of the target. If it is not centered, variations in the reading may occur. A large variation in reading will occur if the entire sonic beam is not intercepted by the cone target. Positioning errors can be verified by moving the transducer head off the cone center and take some readings. To facilitate centering T.U.T. above the cone, the Model UPM-30 is supplied with a positioning jig as illustrated in Figure 15. For the digital Model UPM-DT, a positioning jig and an air turbulence shield are also available.

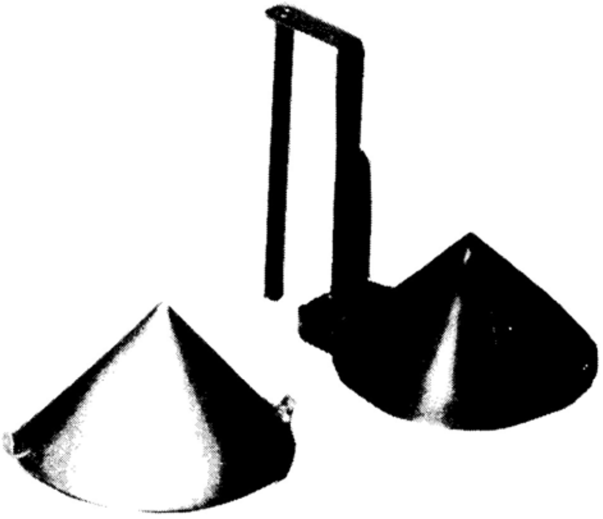


Figure 14. Reflective Cone (left) and Absorptive Cone (right).

The T.U.T. is supported by a clamp and positioning arm adjustable with thumbscrews in the X-Y-Z planes as shown in Figure 12. Always try to maintain a ¼ to ½ inch of distance between T.U.T. and the point of the cone.

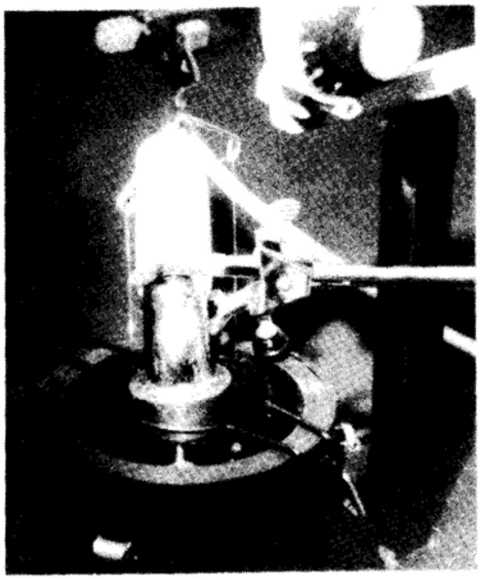


Figure 15. Positioning Jig and Air Turbulence Shield.

SCALES TO MEASURE FORCE.

Mechanical Scales.

The Food and Drug Administration (F.D.A.) specifies for therapeutic heads at 10 watts an accuracy of ± 2 watts. A ten times better scale resolution is desirable. Resolving ±0.2 watt with a mechanical scale is practical as ±10 milligrams equals ±150 milliwatts. The mechanical scale has a built-in integration time and depending on the skill of the operator, usually, the sonic forces can be balanced within 10 to 20 seconds. Some advantages of the mechanical units are : 1) Simplicity; 2) Requires no electrical power; 3) Gives sufficient accuracy to test therapeutic power heads; 4) Lower cost than electronic units. The mechanical models require the operator to manually balance and read the scale in grams then multiply the gram measurement by a constant of 14.65. The lower cost, however, offsets these minor inconveniences. Figure 16 shows the UPM-30 mechanical scale and vernier dial uses to make the gram/power measurement.

Figure 16. UPM-30 vernier scale to measure ultrasound power.

Electronic Balances.

The electronic balances are capable of resolving ultrasonic power levels of a few milliwatts. Features include: 1) Variable integration time; 2) Averaging selected number of consecutive readings over a fixed time period. Averaging increases accuracy. The microprocessor-based scale takes 100 readings in 15 seconds and displays the average reading; 3) Bar graph. A fifty-segment bar graph is programmed from 0 to 30 watts to display applied power level; 4) Auto-tracking. This feature reduces errors caused by minor vibrations, air currents or ripples on the water; 5) Bi-directional RS-232 output with variable baud rate from 110 to 9600; 6) Computer interface using a 9-pin sub-miniature D connector. Figure 17 shows some typical digital display readings.

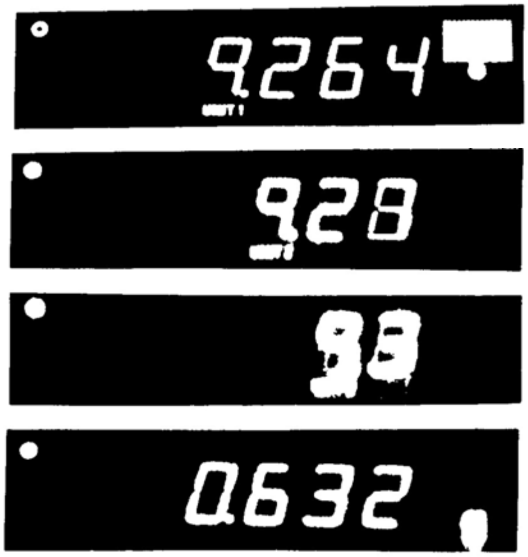


Figure 17. UPM-DT digital units displays.

Scale Locks.

All Ohmic R.F.B. are portable and housed in a carrying case. The pivot points are locked or suspended during transportation. The practical design of the digital units allows placing the carrying case over the R.F.B. only if the pivot lift bar is depressed.

Ambient Environment

A quiet disturbance-free environment is essential for low power measurements. The following factors are to be considered:

1. Temperature. For testing, use +70°F. (±5°F.). For large deviation, see correction chart in Figure 18. Avoid high intensity light or other large ambient temperature gradients in the nearby area where measurements are being taken as they may set up a slow moving air current.
2. Mechanical Stability. Minimum background vibrations made by carts, cars, refrigerators, etc. are to be avoided. A solid, stable table on a concrete floor is preferred. Always place the R.F.B. in a horizontal level position. Tilting will increase or introduce possible errors.
3. Acoustical Vibrations. With a ±68 microgram resolution for each ±1 milliwatt, loud speech, high level radio or other acoustical noise sources close to the R.F.B. can affect readings.
4. Air Turbulence. Air conditioning ducts, fans, open windows or doors, convection air currents, etc. can cause errors in readings. A shield made using an open manila folder or cardboard around the R.F.B. can be used as a draft deterrent.
5. Magnetic Fields. The electromagnetic restoring force used by the electronic balance is affected by magnetic fields and is corrected for the average earth's magnetic field. Avoid conducting tests in areas where power lines or other media can generate strong magnetic fields.
6. High Humidity. Storing the R.F.B. over a long period of time in an 80% relative humidity environment, above +70°F. will affect the calibration accuracy of the electronic balance within a few years. It is advisable to store the unit in a clean, cool environment of below 60% relative humidity and 75°F. ambient temperature.

EVALUATION OF ULTRASOUND POWER METERS

Calibration Accuracy - Model UPM-30.

In mid-year of 1978, the U.S. Bureau of Radiological Health made a detailed evaluation of Ohmic Instruments Company's Ultrasound Power Meter, Model UPM-30, and found that the accuracy was within the U.S. National Bureau of Standard (NBS) calibration uncertainty of ± 6%. See Table 1 for an excerpt from their report.

The Ohmic wattmeter (Model UPM-30) was calibrated by NBS at approximately 5, 10, 20, 25, and 30 watts and the following data reported.

True Power (W)	Measured Power (W)	% Error
5.38	5.64	+4.8
11.81	12.23	+3.6
17.28	18.02	+4.3
23.05	24.25	+5.2
27.10	28.71	+5.9
33.27	35.01	+5.2
		+4.84 Avg.

As determined by an NBS designed modulated radiation force system. This represents the average difference between Ohmic and NBS calibrations, and is within NBS's stated source uncertainty of ±6%.

Table 1. Excerpt from NBS evaluation on Model UPM-30.

A positive average error of +4.85% was found due to: 1) absorption material reflection; 2) target geometry; and 3) scale uncertainty. As stated in the F.D.A. report, the errors are not random and can be corrected. Since the publication of this report, the recommended improvements were incorporated and these errors have been reduced. The measurements were made on an NBS-designed Modulated Radiation Force Balance (R.F.B.). It is called Modulated R.F.B. because the applied test frequency to the transducer under test (T.U.T.) is 90% amplitude modulated at a 30 hertz rate. This method allows synchronous signal processing with higher accuracy to rebalance with magnetic force within a closed feedback loop, the sonic energy exerted on the cone. (For a copy of the evaluation, see HEW Publication No. FDA 79-8075, Nov. 1978).

The purpose of this second evaluation is to show that if the measurement accuracy is to be extended from ± 150-milliwatt level of the UPM-30 compared with the 2 and 10-milliwatt sensitivity of the electronic units, a more careful evaluation of the variables affecting accuracy at low power levels is required.

DESIGN UPDATE CONSIDERATIONS.

Replacing the Mechanical Scale.

The demand for higher accuracy at lower power level measurements in the 20-milliwatt to 2-watt range requires increased scale sensitivity. To resolve milliwatts means measurements to the nearest ± 68 micrograms or 0.068 milligram for each ± 1 milliwatt force exerted on the cone. Therefore, the mechanical scale of the UPM-30 was replaced with an electronic balance having a last digit resolution of 68 micrograms.

Tests gave reproducible readings within ± 5 milliwatts variation up to several watts. Over 10 watts, the slightest cone motion due to the string suspension system and variation in transducer positioning, gave uncertainty and increased the reading fluctuation to ± 50 milliwatts. Unbalancing the transducer over the target at 20 to 30 watts introduced swing errors of ± 0.2 watt. Tests show that the UPM-30 performs its designed function down to the ± 150-milliwatt level. The string suspension system when used with the electronic scale is the limiting factor for low power measurements.

Replacing the String Suspension.

To avoid errors generated by cone movement, the string suspension used in the UPM-30, has been replaced with a solid suspension (See Figure 6, Item 7) for transfer of force to the electronic balance. With this modification, the cone can move only in the horizontal plane a few degrees. At this point, the UPM-30 becomes, with identical characteristics, a sensitive electronic power meter capable of resolving milliwatts up to 30 watts. The electronic scale enhances reading accuracy by integrating 100 readings in 15 seconds. It also provides, in addition to the gram scale, three ranges of 0.1, 0.01 and 0.002 watt, a full scale bar graph and an RS-232C bi-directional interface.

Temperature Effects.

The operating temperature limits of the R.F.B. were tested by placing units in +35°F. to +140°F. ambient temperatures. After stabilization time, power measurements were made and compared against reference standards. Data was taken three times and averaged. The difference between readings of the UPM-30 and DT-1 was within +3% over the full range. From +35°F. to +60°F. there were no noticeable changes in power readings. With an ambient temperature of +140°F., the deviation at 20 watts was -3 watts. Deviations are linear with power level, for example, at 10 watts, -1.5 watts at +140°F., Figure 18, shows the experimental data and the expected correction factor to be applied if high accuracy measurement is to be made outside the +65°F. to +75°F. temperature range.

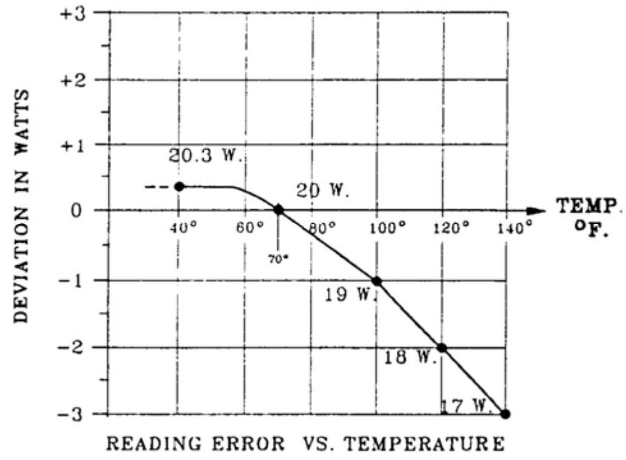


Figure 18. Effect of temperature on power measurements.

Water Media Errors.

Table 2 shows test data of power readings against reference power standards at 5, 10, 15, and 20 watts with 5 ppm degassed water in the test tank (Column A). Power was measured with UPM-30 and UPM-DT-1. Both units read within ±3% accuracy of the standards. Next, both power meters were left at ambient in same condition for 24 hours and readings were repeated (See Column B). The abnormally high readings were expected after visual examination as both the liner, cone, and the transducer had bubble distribution on their surfaces. This is the slow mechanism of diffusion of air into water through its surface. Next, the cone, liner and transducer were wiped off with the same water in the tank and, by this time, 15 ppm O_2 readings were repeated as shown in Column D, while the errors increased they were still within reasonable limits for routine tests. Figure 9 shows expected reading errors when measurements are made with tap water A, or with the more air-saturated B version. Both are in the 20 to 30 ppm range. As the trapped air content is reduced, the curves move in gradually to the degassed straight line. The good quality distilled water lies close to the degassed line up to 20 watts. Tests show that the water quality and a bubble-free environment are critical. Low carbonated water seltzer water, was used to fill the test tank and readings were taken without sonic power applied. Within a 10-minute period, readings varied within ± 50 watts. The CO_2 bubbles adhered quickly to the cone and rubber liner and rapidly changed their positions by deflating and re-combining on the top and bottom of the cone, transducer face and the liner. With time, many of the bubbles united and formed air pockets.

A	B	C	D
True Power (Using Ref. Std)	Measured Power (Initial reading)	Measured Power (Bubbles formed 1 Day later)	Re-Measured Power (with Bubbles removed)
5	4.96	7.8	4.8
10	9.85	14.5	9.5
15	14.7	20.4	14.2
20	19.5	25.3	18.5

Table 2. Test data showing effect of bubble formation on sonic power readings.

Low and High Power Readings.

The quantity of air bubbles in the water on T.U.T, cone, and the absorbing wall liner determines mainly the ±reading deviations. Both deviations are likely depending upon the prevailing conditions. The positive deviation occurs, if the 1) absorbing rubber liner becomes less effective due to bubble build-up causing multiple reflections from the bubble interface. The sonic radiated force deflected by the cone tends to drive the bubbles to the surface of the liner. Energy will bounce back and forth between the target and liner; 2) Bubble build-up on the target and the T.U.T. degrades the ideal cone performance and starts reflecting energy between them. If sufficient target bubbles radiate energy back to the transducer, they can set up standing waves and give high or unstable readings. The negative deviation occurs if, 1) there are air pockets on the T.U.T. surface; 2) there are air bubbles between T.U.T and the target; and 3) if there are air bubbles on the target or between the target and the liner/absorber. High power level readings are also affected by thermal turbulence and gradients usually producing minus deviations.

Positioning And Repeatability.

The HEW evaluation report of the UPM-30 positioning sensitivity versus repeatability was also tested and data summarized. In the report, it was suggested that a positioning device be enclosed with the units to reduce random errors. Since 1979, all UPM-30 units include a positioning jig. See the illustration of this positioning jig in Figure 15. For the digital unit, a positioning jig is available. In addition to positioning, the plastic cover also acts as an air shield over the tank.

Limits of Accuracy.

The F.D.A. 1968 Radiation Control For Health and Safety Act specifies that the temporal average ultrasonic power be indicated on each therapy unit within ±20% for all emissions greater than 10% of the maximum emission. At 10 watts, the ±2-watt tolerance limit dictates at least a ten-to-one or three-to-one safety factor, that is, the accuracy of measurement, including all uncertainties, should be within ±0.2 or ±0.66 watt of uncertainty. 10% maximum emission of most therapeutic units is 2 watts and ten-fold safety factor would require ±20 milliwatts measurement accuracy including scale uncertainty. This accuracy is possible with Model UPM-DT-10 but not with Model UPM-30. If the same percentage accuracy is to be maintained at 100-milliwatt levels, the limits become ±2 or ±6.6 milliwatts. The electronic R.F.B. Model UPM-DT-1 can meet these limits of accuracy. Since this unit integrates 100 readings in 15 seconds, meaningful power measurements are possible below 50 milliwatts. Figure 19 shows the UPM-DT-1, UPM-DT-10, and UPM-30 Ultrasound Power Meters and Short Performance Data.

This report was prepared by Ohmic Instruments Company engineering staff in response to some of the questions and problems encountered with sonic power measurements in the past ten years. We express our appreciation to both the F.D.A. Acoustics Branch and the U.S. National Bureau of Standards for their valuable suggestions to improve power measurement accuracy.

EVALUATION BY THE NATIONAL BUREAU OF STANDARDS OF MODELS UPM-DT-1 AND UPM-DT-10

In early 1988, Ohmic submitted two digital power meters to the National Bureau of Standards for verification of their accuracy. The NBS transducer calibration standards have a maximum uncertainty of ±3%. Both power meters performed within the ±3%, at their low/high power measurement ranges as outlined in the following excerpts from the two NBS reports:

March 30, 1988

U.S. Department of Commerce
National Bureau of Standards
Gaithersburg, MD 20899

EXCERPTS FROM THE TEST REPORT
OF
ULTRASOUND POWER METER
Model UPM-DT-1, S/N 207

Introduction

The ultrasound power meter was tested pursuant to the manufacturer's request for an evaluation of the stability and accuracy of the instrument when used to measure ultrasonic power over a wide range of power levels. The instrument was tested by using it to measure known levels of ultrasonic power ranging from 5 mW to 1 W; the test procedures were designed to generate data useful in determining the range of measured values over which reasonable accuracy might be expected, and the average accuracy obtained for this range of measured values.

Test Procedures

The ultrasound used in these tests was generated by a half-wave resonant, air-backed lithium niobate transducer 1.6 cm in active diameter. Single-frequency continuous-wave excitation at 4.768 MHz was used. The magnitude and stability of the ultrasonic power thus generated was known from prior transducer calibration data obtained using the National Bureau of Standards (NBS) radiation force balance and procedures described in NBS Internal Report 78-1520. The known values of applied power cited herein are believed to differ from the values actually applied to the instrument under test by an amount no greater than three percent of the cited values. The instrument was used with the setup parameters programmed by its manufacturer.

Nine levels of power, ranging from 50 mW to 1 W, were used in obtaining the data from which an estimate of overall instrumental uncertainty was developed. The choice of these levels was facilitated by use of the results of earlier experiments intended to determine the magnitude of **the smallest level of power that could be detected (but not necessarily accurately measured) and to determine the magnitude of the smallest change in power level that could be measured with reasonable accuracy.** By switching small amounts of ultrasound on and off, and carefully watching the readout, **it was found that 5 mW of power could be detected reliably, but lower values could not.** This value is consistent with the 2-count truncation of displayed values established by setup parameters. In order to further check instrumental performance with small changes of input, the applied power was switched between 40 mW and 50 mW, and display readings were recorded as soon as they became stable. The process was repeated to allow computation of 13 successive differences, and 10 mW was subtracted from each successive difference. The average absolute value of these 13 values is 2.2 mW. **This result suggests that, for values of applied power large enough to allow the instrument to operate at full accuracy, the precision of the measured values is about 2 mW.**

Repeated measurements were made for each of 12 levels of applied power ranging from 25 mW to 1 W. For each measurement, the re-zero button was pushed and the transducer was energized just after the readout indicated zero. The display was read just after the stability lamp came on, except when the lamp had failed to extinguish while the displayed values increased. In this circumstance, it was necessary to continuously watch the display and take the reading the first time a stable indication was obtained. The transducer was de-energized just after reading the display and another reading taken when the display had again settled. This procedure was repeated at least ten times for each level. Average measured values were computed for and compared to each known value of applied power. **The fractional errors for three levels of power below 50 mW ranged from 7% to 13%, while the fractional errors for the nine levels between 50 mW and 1 W ranged from 0.1% to 3.67%, with an average absolute value of 1.7%.** From this dichotomy it is inferred that the lower power limit for operation with full accuracy is 50 mW. The measurements just discussed were made without use of the Average Display feature; another set of measurements was made between 100 mW and 1 W in order to determine the benefits of using this feature. The average absolute fractional error for the measurements made with the Average Display feature was 3.0%, and the corresponding value for data taken without it was 1.4%. These results are taken to indicate that no significant advantage was obtained by use of the Average Display feature.

Conclusions

An experimental investigation of the operating characteristics of the ultrasound power meter designated UPM-DT-1 S/N 207 has allowed estimation of its accuracy while undergoing testing. Because NBS has no knowledge or control of the degree to which the performance of other equipment might approach that of the instrument tested, nor of the degree to which performance might vary over time, the uncertainty estimate cited herein should be construed to apply only to the designated device while tested and no other time, and should not be considered relevant to the performance of any other equipment during any period of time. **From the test results for the instrument designed UPM-DT-1 S/N 207, it is estimated that measured values differed from the true values of applied ultrasonic power by an amount not greater than the sum of 0.002 W and three percent of the true values, for true values between 0.05 W and 1.0 W.** The present investigators know of no way to predict accuracy or stability for operation under conditions different from the ones described.

Signed by:

Donald G. Eitzen, Group Leader
Steven E. Fick, Electrical Engineer
Ultrasonic Standards
Automated Production Technology Division
Center for Manufacturing Engineering

February 24, 1988

U.S. Department of Commerce
National Bureau of Standards
Gaithersburg, MD 20899

EXCERPTS FROM THE N.B.S. TEST REPORT
OF
ULTRASOUND POWER METER
Model UPM-DT-10, S/N 188

Introduction

The instrument designated UPM-DT-10 S/N 188, which will hereinafter be called DT-10 for the sake of brevity, was found to behave as might be expected of a device of its type. That is, the discrepancies between indicated and actually applied levels of power were consistent with the number of displayed digits, and no unusual behavior was observed during the course of testing.

Test Procedures

For all test reported here, the magnitude and stability of the applied ultrasonic power were independently known from data generated in transfer calibrations from the National Bureau of Standards (NBS) radiation force balance described in NBS Internal Report 78-1520. Levels of power from 0.05 W to 1.0 W were generated using a standard source transducer operated at 4.768 MHz, while levels between 2 W and 10 W, inclusive, were obtained using a commercial transducer operating at 0.926 MHz. Single-frequency continuous wave rf excitation was used in all cases. The known values of applied power cited herein are believed to differ from the values actually generated by an amount no greater than three percent of the cited values. The power meters were set for the highest possible display resolution in milliwatts and were used with the other operational settings (e.g., averaging mode) unchanged from those established by the manufacturer. Distilled, recently-degassed water was the test medium. The instruments were allowed to warm up overnight before each test.

Furnished with the instruments were conical targets of two designs. The target hereinafter called the "metal" one exposed bare sheet metal to the incident ultrasound, while the "rubber" target was covered with a material similar in appearance to sheet neoprene. The response of the two instruments to sudden, large changes in incident power was tested with both types of target installed in each instrument. Ten levels of power ranging from 0.1 W to 10.0 W were used for these tests. For each measurement, the re-zero button was pushed and the transducer was energized just after the readout indicated zero. The display was read just after the stability lamp came on, except when the lamp had failed to extinguish while the displayed values increased. In this circumstance, it was necessary to continuously watch the display and take the reading the first time a stable indication obtained. The transducer was de-energized just after reading the display and another reading taken when the display had again settled. This procedure was repeated at least five times for each of the ten levels of power used in testing each instrument with both targets.

Conclusions

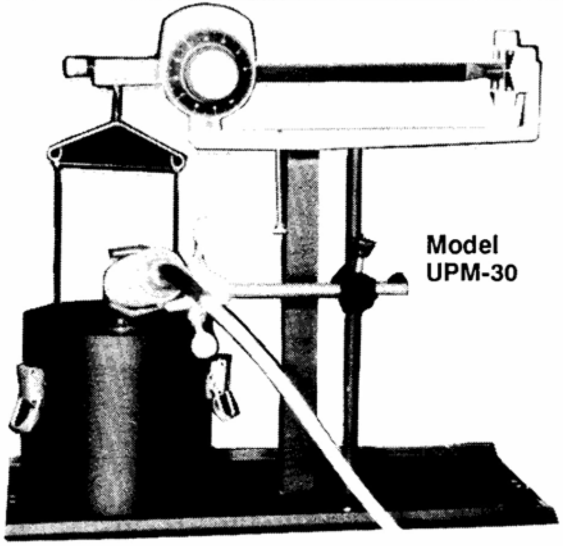
An experimental investigation of the operating characteristics of the ultrasound power meter designated UPM-DT-10 S/N 188 has allowed formulation of uncertainty estimate and of the operating conditions under which the estimates are valid. Because NBS has no knowledge or control of the degree to which the performance of other equipment might approach that of the instruments tested, nor of the degree to which performance might vary over time, the uncertainty estimate cited herein should be construed to apply only to the designated devices while tested and at no other times, and should not be considered relevant to the performance of any other equipment during any period of time. From the test results for the instrument designed UPM-DT-10 S/N 188, it is estimated that measured values differed from the true values of applied ultrasonic power by an amount not greater than the sum of 0.01 W and three percent of the true values, for true values between 0.16 W and 10 W. The present investigators know of no way to predict accuracy or stability for operation under conditions different from the ones described for each instrument.

Signed by:

Donald G. Eitzen, Group Leader
Steven E. Fick, Electrical Engineer
Ultrasonic Standards Group
Automated Production Technology Division
Center for Manufacturing Engineering

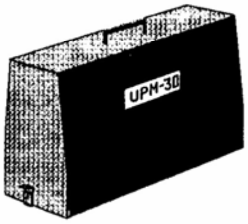
Power Meter Specifications: Models UPM-30, UPM-DT-1, and UPM-DT-10

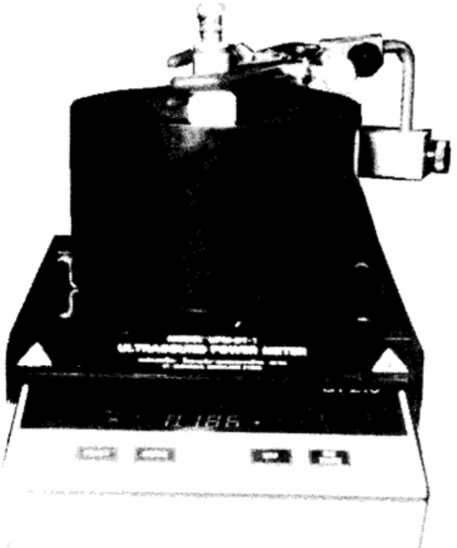
MODEL:	UPM-30	UPM-DT-1	UPM-DT-10
Power Range:	150 mW. to 30 W.	±2 mW. to 30 W.	±10 mW. to 30 W.
Resolution:	±150 mW.	±2 mW.	±10 mW.
Min. Detectable Power Level:	±150 mW.	±4 mW.	±20 mW.
Min. Accuracy:	±5%	±5% Above 50 mW.	±5% Above 200 mW.
Expected Accuracy:	±4%	±3% Above 100 mW.	±3% Above 500 mW.
Display Ranges:	1	4	2
Display Sensitivity:	±0.01 g. or ±150 mW.	0.002/0.01/0.1 Watt 0.001 Gram	0.01 Watt 0.01 Gram
Zeroing:	Manually Adjusted	Automatic	Automatic
Bar Graph Display:	N/A	0 to 30 Watts	None
Integration Times:	N/A	Min/Reduced/Norm/Max	Low/Med/High
Stability Level:	N/A	0 to 3	None
Averaged Display:	N/A	1 to 100 readings in 15 sec.	None
Baud Rates:	N/A	110 to 9600	300
Line Power:	Not Required	100/120/220/240 V.A.C.	100/120/220/240 V.A.C.
Shipping Weight:	18 lbs.	26 lbs.	26 lbs.



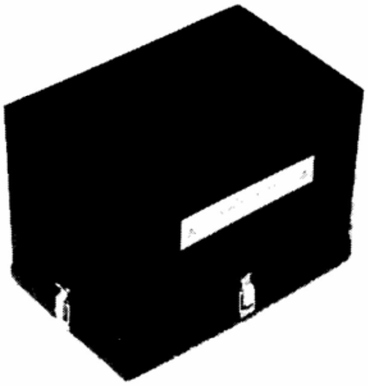
Model UPM-30

UPM-30 Carrying Case
(19"H x 17"L x 7"W)





Model UPM-DT-1



DT Series Carrying Case
(10"H x 14"L x 9"W)

Model UPM-DT-10

GLOSSARY OF ULTRASOUND TERMS

ABSORPTION. The radiated sound intensity in water decays in proportion to the square of the distance from the source. Additional reduction in intensity occurs due to the imperfection in the media, causing the acoustical energy to be converted into heat. This loss in intensity is called absorption.

ACOUSTICAL POWER OUTPUT INDICATIONS. Meter display provides continuous indication of the absolute ultrasonic power, or percentage of maximum ultrasonic power, being delivered by the instrument through the transducer into the patient, with typical ± 25% accuracy.

ACOUSTIC IMPEDANCE. The ratio of sonic pressure to volume velocity expressed in acoustic ohms. If the plane wave propagation is in one direction and there is no return wave, it is called characteristic impedance. It is a pure resistance as there is no imaginary part in the expression.

ACOUSTIC STREAMING. Non-linear effects in a fluid media, such as, microbubbles and non-uniform fluid turbulence introduced by a sonic field.

ATTENUATION REDUCTION. A decreases in sonic intensity caused by discontinuities, absorption, variation in temperature and impurities in the water.

BOILING/HOT SPOTS. A fixed temperature and pressure where transition from liquid to the gaseous phase occurs and bubbles form.

CAVITATION POP NOISE. Noise resulting from the collapse of air or vapor bubbles in liquids due to the sonic or mechanical forces.

CAVITATION - TRANSIENT/STABLE. Formation of gas or vapor-filled cavities within liquids by sonic or mechanical forces. It is a process where the fluid vapor pressure is reduced to a critical temperature without change in ambient temperature. **Transient cavitation** is a rapid burst of cavities in the fluid media to sonic forces. **Stable cavitation** is stable periodic function due to the interaction of the sonic intensity with the fluid and surrounding media, such as, the vibrating air bubbles or streaming.

DECADE. The interval between any two quantities having the ratio of 10 to 1.

DENSITY. The mass of a given substance per unit volume.

DIFFRACTION. Redistribution in space of the sonic wave intensity that results from the presence of an object causing variations of either the amplitude or phase of the wave.

ECHO. An intercepted sound power re-radiated as a secondary sound. Part of the intercepted energy is converted to heat and rest reflected as sound. A wave that has been reflected with sufficient delay and magnitude to be perceived as a signal distinct from that directly transmitted.

EXPOSURE TIME. The amount of time the transducer assembly delivers continuous or pulsed ultrasonic power.

FAR FIELD. The region of the field in which the acoustic energy flow proceeds essentially as though coming from a point source located in the vicinity of the transducer assembly.

FREE FIELD. An isotropic (having identical properties in all directions) homogenous sound field, that is, free from all bounding surfaces without any interaction with other fields or sources.

INTENSITY. The power transmitted by a sound wave across a unit area perpendicular to the wave.

REFLECTION. The return of waves or particles from surfaces on which they are incident.

REFRACTION. The change of direction of sound transmission due to the spatial variation of the wave velocity in the medium.

REVERBERATION-SCATTERING. Reverberation is unwanted sound waves arriving from several indirect paths, instead of direct reflections from the target. Unwanted background noise that does not contain meaningful information is often called "scattering".

SCATTERING. The irregular reflection, or diffusion of sonic waves in different directions.

SENSITIVITY-ACOUSTIC AXIS. The sensitivity of the transducer is expressed as the output voltage across its terminals for each unit of sound pressure. Most transducers are not equally sensitive in all directions; the axis along which the maximum sensitivity is obtained is called the acoustical axis of the transducer.

SOUND VELOCITY. The velocity of sound in degassed water at + 24°C is 1494 meters per second. This mean average will vary with temperature, pressure, salinity, organ or tissue composition, impurities, etc.

SPATIAL-AVERAGE/TEMPORAL-AVERAGE INTENSITY (SATA). For auto-scanning systems, means the temporal average intensity averaged over the scan cross-sectional area on the surface specified (may be approximated as the ratio of ultrasonic power to the scan cross-sectional area, or as the mean value of that ratio if it is not the same for each scan). For non-auto-scanning systems, SATA means the temporal average intensity averaged over the beam cross-sectional area (may be approximated as the ratio of ultrasonic power to the beam cross-sectional area).

SPATIAL-PEAK/PULSE-AVERAGE INTENSITY (SPPA). The value of the pulse average intensity at the point in the acoustic field where the pulse average intensity is a maximum, or is a local maximum within a specified region.

SPATIAL-PEAK/TEMPORAL-AVERAGE INTENSITY (SPTA). The value of the temporal average intensity at the point in the acoustic field where the temporal average intensity is a maximum, or is a local maximum within a specified region.

SPATIAL-PEAK/TEMPORAL-PEAK INTENSITY (SPTP). The value of the temporal-peak intensity at the point in the acoustic field where the temporal-peak intensity is a maximum, or is a local maximum within a specified region.STANDING WAVE. A wave in which the ratio of an instantaneous value at one point to that at any other point does not vary with time.

SUPERHEATING. Heating of a substance above the temperature at which change of state would ordinarily take place without such a change of state occurring, e.g., heating of water above its boiling point without boiling taking place.

TEMPERATURE COEFFICIENT. The rate of change of some physical quantity, such as, ultrasound power output of a transducer with respect to temperature.

TEMPERATURE vs DEPTH. For propagation-time measurements in water, temperature is an important consideration, as sound velocity decreases with the decrease in temperature. A 0°-10° change causes a 3% change in the sound velocity.

TOTAL DELIVERED ACOUSTICAL ENERGY. The product of ultrasonic power and exposure time. The longer the measurement time, the higher is the measurement accuracy.

ULTRASONIC RADIATION INTENSITY. The strength or the amount of energy radiated across a unit area perpendicular to the sonic wave. Intensity can be also considered as pressure or radiation levels.

ULTRASONICS. A science of ultrasonic sound waves.

VISCOSITY. Flow resistance or internal friction. Energy dissipation and generation of stresses in a fluid by the distortion of fluid elements.