

Development of Techniques to Investigate Sonoluminescence as a Source of Energy Harvesting

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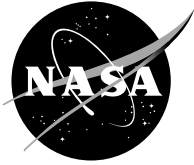
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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

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Abstract

Instrumentation techniques are being developed at NASA Glenn Research Center to measure optical, radiation, and thermal properties of the phenomena of sonoluminescence, the light generated using acoustic cavitation. Initial efforts have been directed to the generation of the effect and the imaging of the glow in water and solvents. Several images have been produced of the effect showing the location within containers, without the additions of light enhancers to the liquid. Evidence of high energy generation in the modification of thin films from sonoluminescence in heavy water was seen that was not seen in light water. Bright, localized sonoluminescence was generated using glycerin for possible applications to energy harvesting. Issues to be resolved for an energy harvesting concept will be addressed.

Introduction

Sonoluminescence has risen to be a source of interest to those outside of the ultrasonic community over the last decade (ref. 1). The processes of understanding the effect lead to the challenge of utilizing some of its more interesting properties in practical applications.

The sonoluminescence phenomena is defined as the generation of light from sound waves, first discovered in the 1930s as a by-product of early work on sonar (ref. 2). The report in 1992 of the ultrasonic trapping of a single glowing bubble in a flask of water generated a cascade of research (ref. 3). The glow from the bubble was found to be generated in bubbles compressed to at least 150 kPa in an extremely short duration flash (<12 psec), and had temperatures of at least 25,000 K for the single bubble (refs. 4 and 5). Bubbles of noble gases were seen to flash brighter, but the nature of the liquid was also seen as playing a large role in the flashes as well (refs. 6 to 8).

Shortly after research results on trapped single bubbles were published, models were developed to explain these measurements. Simple shock calculations showed that peak temperatures inside the sonoluminescent bubbles could reach 3×10^8 K based on the collapse of an ideal spherical gas bubble (ref. 9). Assuming a non-spherical collapse, the high speed jet striking the opposite side of the bubble gave rise to the possibility of the water being fractured on the molecular scale and generating light as fracto-luminescence (refs. 10 and 11). The extremely rapid collapse of the bubble led to the theoretical examination of sonoluminescence as an effect of quantum vacuum radiation (ref. 12). The lack of an after-glow suggested a cooperative optical emission, like that of an optical laser or superradiance (refs. 13 and 14). The actual process may be a combination of any of the above (refs. 15 to 18). A simplified schematic of the current model of the process is shown in figure 1 (after ref. 1).

Initial examination of the phenomenon by the National Aeronautics and Space Administration (NASA) involved sponsoring measurements of single-bubble sonoluminescence in microgravity (0g vertical acceleration) and hypergravity (2g vertical acceleration) performed on a KC-135 parabolic research flight by the University of Washington. The researchers discovered that light emission brightened promptly by 20 percent and increased continually under microgravity, suggesting buoyancy-driven instabilities are a critical limitation to the effect (ref. 19). Flight hardware for an ensuing experiment on ISS was under development in 2003 (shown in fig. 2), but was cancelled following a redirection in NASA's space exploration efforts.

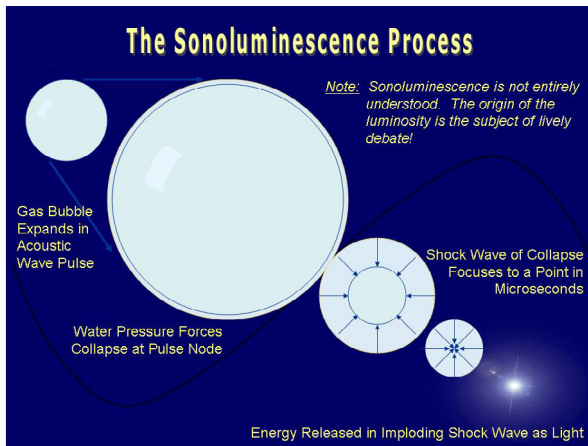


Figure 1.—A schematic of the sonoluminescence process (after ref. 1).

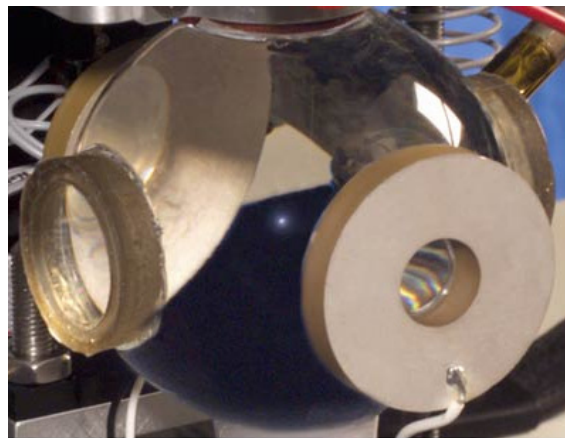


Figure 2.—Sonoluminescence flight hardware testing in 2003.

Even as these theories are being explored, applications for the effect are taking shape, from fusion containment (refs. 10 and 20 to 22) to thin film deposition systems (ref. 23). Recently, Purdue University researchers at Oak Ridge National Laboratory claimed to have demonstrated thermonuclear fusion using sonoluminescence in deuterated acetone (refs. 24 to 28).

If realized, harnessing the high energy release in safe, emission-free ultrasonic processes would lead to the development of revolutionary power systems for in-flight use for both aircraft and spacecraft. The benefits of an on-board fusion power system will be in the reduced fuel consumption, lower emissions and reduced noise for many types of aircraft. A practical fusion power source would replace the conventional gas turbine auxiliary power units and electrical generators in aircraft, and fuel cells and batteries in spacecraft, improving flight and mission capability. Longer-term use of the power source will have both an environmental benefit and act as a positive contributor to the country's energy diversification, as well as enable new missions for both air and space.

NASA Glenn Research Center (GRC) is developing instrumentation technologies for the support of the mission to pioneer the future in space exploration, scientific discovery, and aeronautics research. These technologies also enable the capabilities for long duration, more distant human and robotic missions for the Vision for Space Exploration.

As part of our mission to conduct basic and applied research on advanced instrumentation technologies, GRC has begun an examination of sonoluminescence for instrumentation and measurement technique development. The objective of the effort is to investigate claims and theories of power generation based on sonoluminescence. The approach will initially determine whether there is any difference in the emission from bubbles in light water and heavy water then other solvents. Eventually conclusions on sonoluminescence-based power generation concepts will be formulated utilizing the data from our experiments. In this paper, we report on progress made to date on our investigation of the phenomena of sonoluminescence in terms of its generation and imaging.

Apparatus

The basic equipment for sonoluminescence consists of a flask containing the liquid, ultrasonic transducers, a piezoceramic amplifier and a function generator (ref. 4). Schematics of our test apparatus are shown in figures 3 and 4. The transducers are driven by an amplified signal from the function generator to saturate the fluid with ultrasonic waves. The voltage and current flowing across the transducers can be monitored, and instrumentation (such as a microphone, spectrometer and a photomultiplier tube) can be positioned to monitor the resulting sonoluminescence.

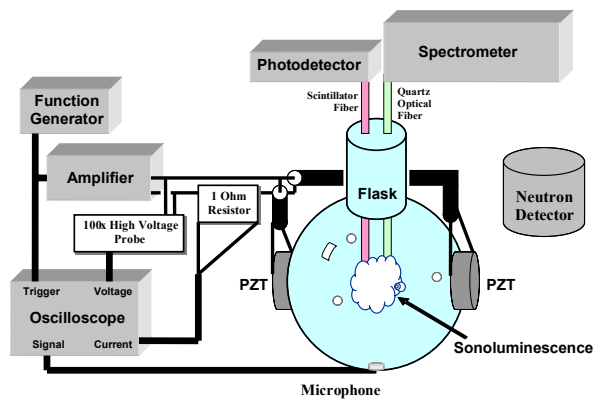


Figure 3.—Resonating test apparatus and associated equipment.

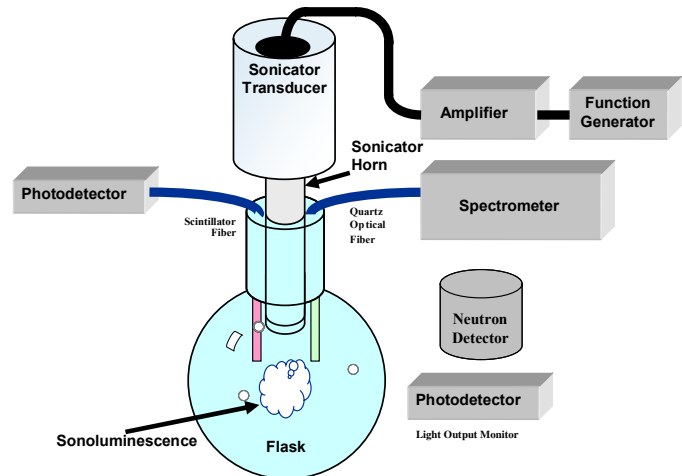


Figure 4.—Sonicator test apparatus and associated equipment.

If the ultrasonic energy from the transducers can be concentrated into a small enough uniform spot, and the liquid does not contain a large amount of dissolved gas, the liquid can be ruptured in cavitation that is controlled. The cavitation can cause a single glowing bubble to appear that is reasonably stable, known as single-bubble sonoluminescence (SBSL) (ref. 4). If the liquid is nearly saturated with dissolved gas, the cavitation forms filamentary patterns that are chaotic as the input energy is distributed throughout the flask. A cloud of glowing bubbles can result, which is referred to as multi-bubble sonoluminescence (MBSL) (ref. 29). Either way, the sonoluminescence is located at or near regions of maximum pressure (ref. 29).

Imaging

The initial apparatus for our tests was a resonating test apparatus as shown in figure 3, consisting of a 250 ml round borosilicate glass flask with a pair of piezoceramics attached with epoxy on opposite sides and filled with refrigerated ($\sim 17^\circ\text{C}$) distilled water. Patterns of MBSL were produced at various frequencies. Although most of the patterns were chaotic, two stable geometric patterns were reproducible. The patterns of interest were rings having four and eight nodules at 68.5 and 93.0 kHz, respectively. The MBSL patterns were faint, requiring the observers 20 min of dark adaptation in the lab to see them. To determine the placement of fiber optic instrumentation for future investigations, the position of the MBSL in relation to the sides of the flask needed to be recorded.

A low lux astronomical video camera was purchased to image the patterns. The camera was set to maximum sensitivity and images were recorded using a 2-sec-frame integration setting. Images were recorded with and without the frequency generator on, and with and without room lights on. The resulting compilation of these is seen in figure 5. Only three of the nodules of the four-nodule ring are seen in the image. The eight-nodule ring was too faint to be resolved by this method.

To help increase visibility of the MBSL, a sonoluminescence setup using a high power Sonicator (ultrasonic liquid processor and cell disrupter, Misonix, Inc.) test apparatus as shown in figure 4. The test cell used initially were a 100 ml borosilicate glass beaker filled with refrigerated distilled water, but later a 50 ml quartz flask was used. Each used a titanium high intensity ultrasonic transducer horn probe in line with the signal generator and amplifier instead of piezoceramics. As seen in figure 4, the transducer horn was inserted into the open top of the beaker and flask. Besides capable of delivering high acoustic power, the Sonicator test apparatus has the added benefit that the transducer is not physically attached to the test cell as in the resonating test apparatus.

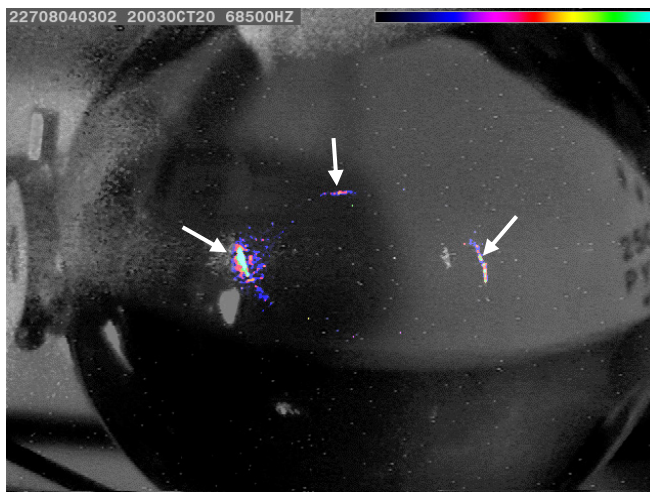


Figure 5.—Enhanced false-color image taken from video of a ring of MBSL. The arrows indicate the three visible nodules.

With the resonating test apparatus, the previously reported (ref. 10) effect was observed of brighter sonoluminescence glow in cooler water at the same driving voltage. In order to keep the water temperature cool and the cells stable, a Peltier cooler box was modified from a commercial kit and aluminum support rings were machined for use with the Sonicator test apparatus. The MBSL patterns were generated in the both beaker and quartz flask cells with and without support rings by this method. However, the patterns were not as defined as in the 250 ml flask, and the video camera was not able to detect the patterns as well as the ring patterns with the resonating test apparatus.

A 16-bit-grayscale CCD imaging system for terrestrial still deep-space astrophotography was purchased to image the MBSL. Unlike the compiled image of figure 5 from three separate images, only brightness and contrast level enhancement and the application of a noise filter was needed to achieve the images shown in figures 6 to 10. The MBSL filament feature on the bottom of the flask in figure 6(b) is approximately 25 mm wide by 1 mm thick, making the resolution approximately 100 $\mu\text{m}/\text{pixel}$. The filament structure is revealed with a gradient map on the edges of sonoluminescence intensity as false color in figures 7(b) to 10(b).

The sonoluminescence filaments seen in figures 7 and 8 follow a conical pattern from the horn to the base of the beaker and flask. The filament pattern has been reported elsewhere (ref. 29), but in our images, the container is clearly visible, and no brightening agent was introduced into the water. The 50 ml flask produced the brightest MBSL shown in figure 8, possibly due to the small volume and thus increased concentration of the applied ultrasonic power.

The CCD imaging system was turned on the rings formed by the resonating test apparatus using the 250 ml flask, which had been at room temperature for several months. The ring patterns were reproduced, as shown in figures 9 and 10, but dimmer and at higher frequencies than in figure 5 due to the room temperature water. The rings in the images are smeared due the variation of the nodules positions about the pressure maximums. The images reveal the rings as a “wavy” ring, with nodules near the piezoceramics.

The nodules of the eight-nodule ring are revealed as pairs of nodules shifting about the four maximums of the four-nodule ring (only six of the eight nodules are visible in figure 10). In addition, in comparing figures 9 and 10, the four-nodule ring forms in the center of the flask, but the eight-nodule ring forms slightly lower. The shift in position is not apparent to the dark-adapted observer since the flask is not clearly visible in the darkened lab. Thus, this ability to image the flask and the sonoluminescence effect together is demonstrated to be necessary if any precision is desired for the placement of in situ instrumentation.

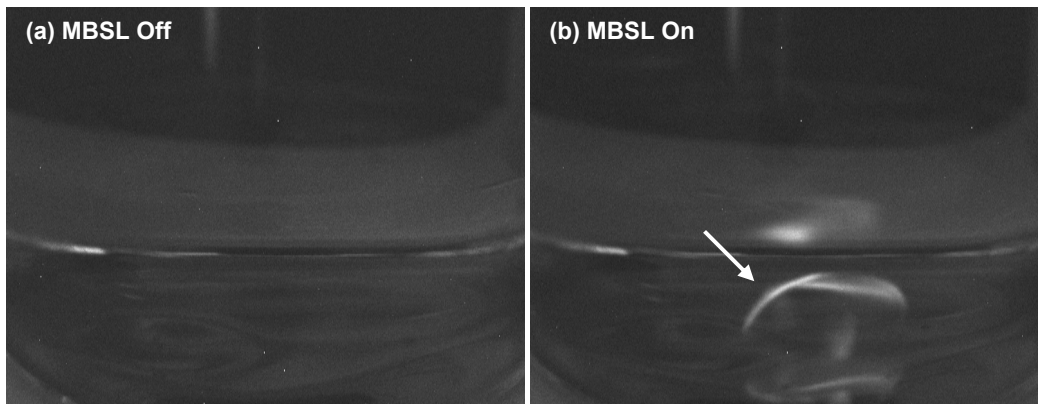


Figure 6.—The bottom of a 100 ml beaker with the transducer horn (a) off and (b) on. The MBSL filament appears centered at the bottom of the beaker (arrow). Both pictures are 1-min exposures at $f/1.2$.

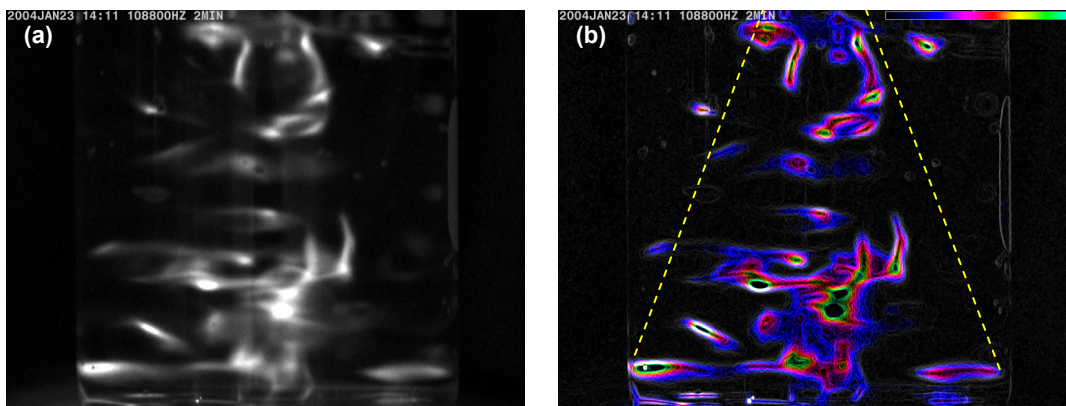


Figure 7.—Enhanced image of MBSL at 108.8 kHz in the 100 ml beaker. Exposure time was 2 min at $f/2.8$. The field of view is 6.6 by 5.1 cm. Image shown in (a) grayscale and (b) false color highlighting filament structure with guides to outline the conical pattern.

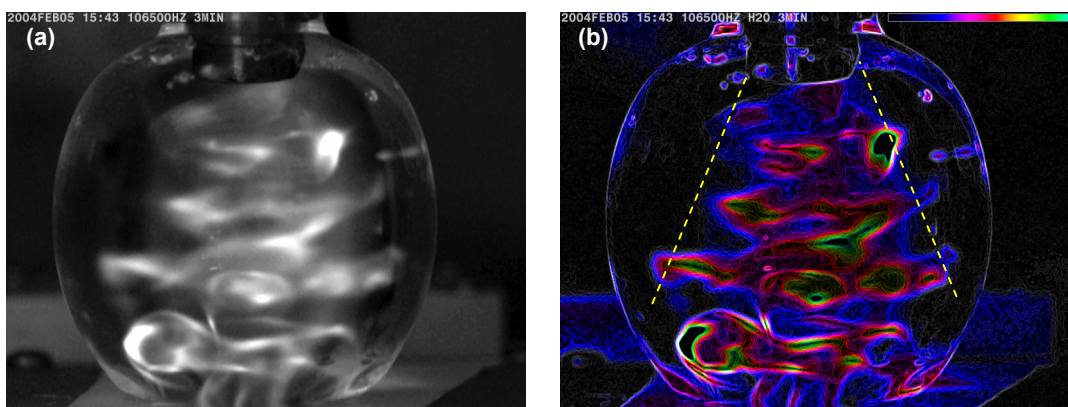


Figure 8.—Enhanced images of MBSL at 106.5 kHz in the 50 ml flask. Exposure time was 3 min at $f/2.8$. The field of view is 7.1 by 5.4 cm. Image shown in (a) grayscale and (b) false color highlighting filament structure with guides to outline the conical pattern.

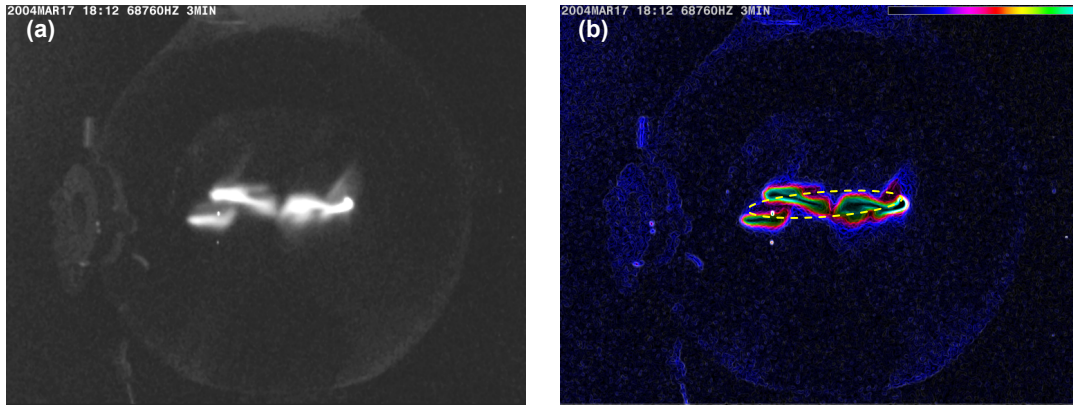


Figure 9.—Enhanced images of MBSL at 68.76 kHz in the 250 ml flask. Exposure time was 3 min at f/2.8. The field of view is 11.4 by 8.8 cm. Image shown in (a) grayscale and (b) false color highlighting filament structure with a guide to outline the ring pattern.

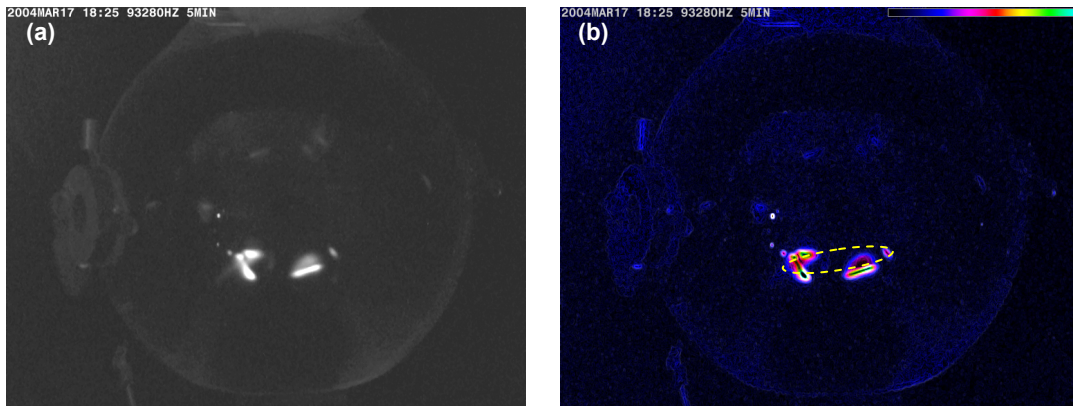


Figure 10.—Enhanced images of MBSL at 93.28 kHz in the 250 ml flask. Exposure time was 5 min. at f/2.8. The field of view is 11.4 by 8.8 cm. MBSL shown in (a) grayscale and (b) false color highlighting filament structure with a guide to outline the ring pattern.



Figure 11.—True-color picture of sonoluminescence in light water (contrast-enhanced). Exposure time was 2 min. at f/2.8.

A 16-bit three-color CCD imaging system for terrestrial still deep-space astrophotography was purchased for color imaging the MSBL. The camera was calibrated using a color rendition chart. The image of the MBSL in a 50 ml flask is shown in figure 11 with contrast enhanced but at true color. Red light scattering from the LED's of the support equipment help reveal the transducer horn and flask.

Indications of High Temperature Generation

The formation of cavitation bubbles is the vaporization of the liquid due to changes in pressure. The liquid transitions to its vapor phase around nucleation points that arise from a breakdown in surface tension of the liquid. This breakdown can be initiated by the random mechanical motion of the liquid molecules, container geometry, impurities (liquid or gaseous) and cosmic radiation. The vaporization can translate into high temperatures. The highly localized nature of sonoluminescence makes a direct measurement of the bubble temperature extremely difficult with thermocouples or RTD probe. One method of comparing the temperatures of two different environments is to compare the surface modification of materials exposed to the different environments. Leveraging our expertise in thin films for high temperature sensing applications, the effect of sonoluminescent bubbles on thin films was investigated to determine differences in the temperature of sonoluminescence in light water (H_2O) and heavy water (D_2O).

The effect of exposure of thin films to sonoluminescence in light water and heavy water was compared using several 1 mm thick, 6.1 by 6.1 mm² substrates of alumina (Al_2O_3) coated with thin films. The first two samples had 3 μm of platinum deposited on the alumina substrates and were not annealed. The first sample was exposed to MBSL in heavy water, and the second was exposed to MBSL in light water. Images taken by SEM are shown in figure 12, and both samples have similar features. Each sample had the general appearance of as-deposited platinum film. However, occasional small ($\sim 1 \mu m$ diameter) pellets were observed on the heavy water sample. These pellets appear to be slightly larger conglomerations of platinum grain pellets, but it is not clear if they are post-sonoluminescence film features. If the pellets were created from exposure to sonoluminescence, their appearance would be an indication that the sonoluminescence in heavy water generated higher temperatures than the sonoluminescence in light water.

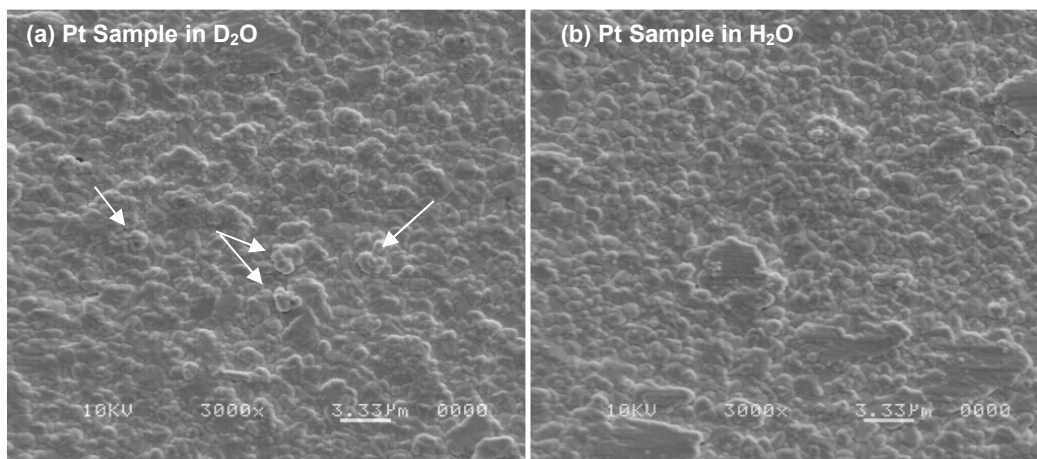


Figure 12.—SEM image comparison of as-deposited, 3- μm -thick films of pure platinum coating alumina substrates exposed to sonoluminescence with (a) D_2O , and (b) H_2O . The arrows indicate possible pellets generated in the exposure to sonoluminescence.

In expectation for miniature instrumentation applications, the three new samples first patterned a 1- μm -thick sputter-deposited platinum (Pt) resistance temperature detector and annealed at 1000 °C for 8 hr. The samples were then over-coated with a 3 μm layer of palladium alloy with 13 percent chromium (PdCr). The PdCr alloy film is typically used as a strain gauge in high temperature environments. For this instance, the alloy was used due to the affinity of palladium to hydrogen to allow the attraction sonoluminescence (which supposedly contains hydrogen ions (ref. 31)) and the high adhesion strength of the chromium to the oxide substrate. Though the Pt itself has some limited affinity to hydrogen, the film does not adhere well to alumina at high temperatures, and failures of the Pt film were seen prior to PdCr deposition after annealing.

One of the new samples was exposed to MBSL in light water and another to MBSL in heavy water. Under SEM, the sample exposed to MBSL in light water showed no significant modification of the film. The sample exposed to MBSL in heavy water showed 4- to 5- μm -diameter craters in the PdCr film overcoating the Pt film under SEM. As the Pt film was already failing, the third sample was exposed to MBSL in both light water and heavy water. Images of the exposures are shown in figure 13 showing that the sample was exposed to sonoluminescence directly at the tip of the Sonicator horn. Again, the sample exposed to light water showed no modification of the film, but after the heavy water MBSL exposure, the 4- to 5- μm -diameter craters in the film were apparent under SEM. No craters in the PdCr film directly deposited on the alumina substrate were seen. Figure 14 gives a side-by-side comparison of the film at different magnifications after the light water exposure and after the heavy water exposure.

Table I gives a summary of some properties of the materials used in the samples (refs. 32 and 33). Delaminating of films is considered a zero order affect of mismatches between the two materials Coefficient of Thermal Expansion (CTE). The grain failures are seen in the film with PdCr on Pt and not the PdCr suggests that the expansion of the PdCr on Pt is greater than that of the PdCr compared to alumina. However, table I indicates that the adhering PdCr has a greater CTE mismatch to the alumina substrate than the Pt film that was delaminating.

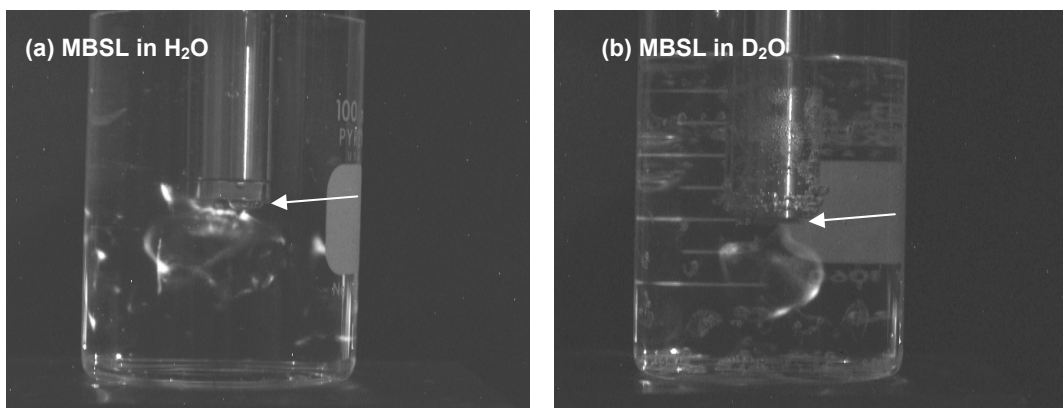


Figure 13.—Film sample on Sonicator horn tip (arrows) exposed to SL in (a) H₂O and (b) D₂O at 56kHz in 100 ml beakers.

TABLE I.—SAMPLE SUBSTRATE AND FILM PROPERTIES (REFS. 32 AND 33)

Material	Density, g/cm ³	Melting point, K	Heat of fusion, J/g	Specific heat, J/gK	Thermal conductivity, W/mK	Thermal diffusivity, mm ² /s	Coefficient of thermal expansion, (CTE) (10 ⁻⁶ /°C)	Heat of oxide formation, kJ/mol
Al ₂ O ₃	3.92	2300	16,435	0.880	30.0	8.70	8	----
Pt	21.5	2141	113.6	0.113	71.6	29.5	10	-173
Pd - 13%Cr	11.39	>1828	189.4	0.271	71.8	23.3	15	-468

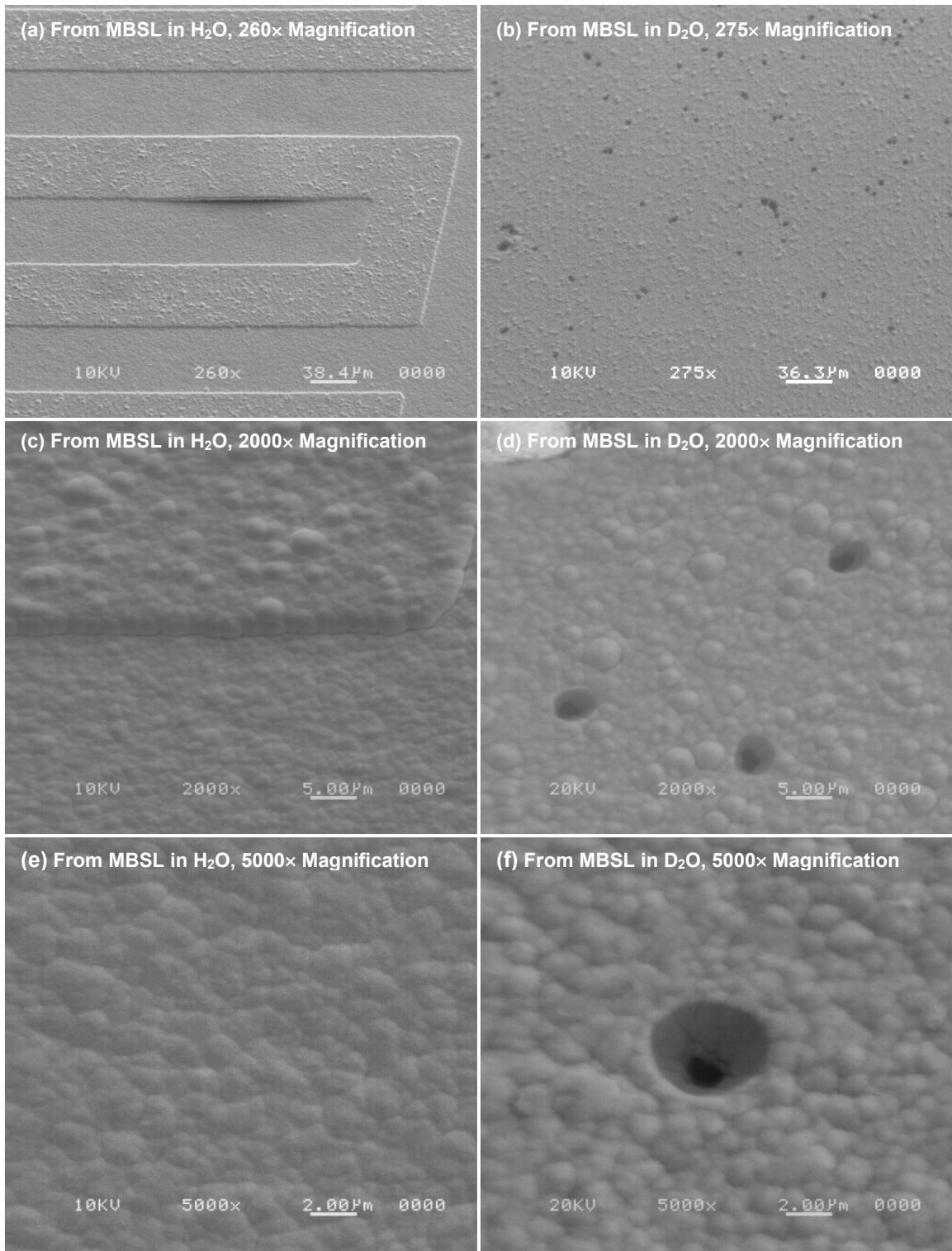


Figure 14.—Surface of the 3- μm -thick PdCr films on 1- μm -thick Pt patterns seen by SEM under increasing magnification. The black surface at the bottom of the craters is non-conducting alumina. The films on the left (a, c, and e) were exposed to MBSL in H_2O , and on the right (b, d, and f) to MBSL in D_2O .

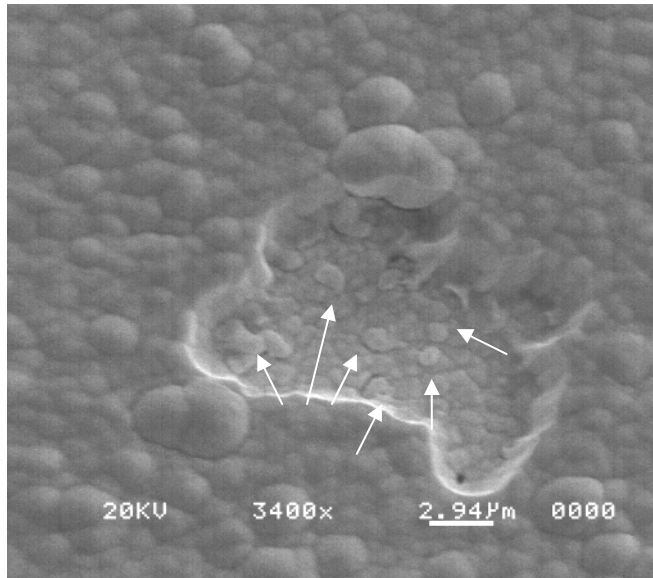


Figure 15.—A large 20 by 10 μm failure of the PdCr film over Pt film. Globules of PdCr are seen (arrows) on the 1- μm -thick Pt film that is still adhering.

A first order estimate of the relative adhesion strength of films on oxides is the energy involved in forming an oxide of the film (or heat of oxide formation). Table I shows that the PdCr alloy film has a more negative heat of oxide formation, and thus more favorable to adhesion on the alumina than platinum. The energy imparted to the film at the sonoluminescence point locations could be enough to vaporize or melt the film when not adhering to the substrate but not enough to vaporize or melt the film when it is adhering to the substrate.

The adhesion of the film to the substrate may be allowing the substrate to absorb the energy via phonon vibrations, and the delaminating film does not allow the energy to be transferred directly into the bulk substrate material. Alternatively, the loose islands may have heated up and “popped” off due to thermal expansion. This effect was seen on two separate samples in the heavy water runs and not seen in the light water runs. The craters did not occur in the as-deposited Pt films in either light or heavy water.

Some failures of the PdCr film that did not involve failure of the Pt film were observed after exposure to heavy water. The SEM image of the largest volume (14 by 8 by 3 μm^3) is shown in figure 15. Analysis by EDX of the failure area indicates that remnants of the PdCr film remain at the exposed Pt surface, presumably in the form of several 0.375 μm radius globules observed in the SEM image. From table I, at least 6.9 kJ/cm^3 (or 605 J/g) (from table I) is required to melt PdCr from 20 $^\circ\text{C}$, and 7.1 kJ/cm^3 (or 332 J/g) for platinum. The craters and the PdCr film damage may be due to the same heating process of the PdCr film. The lack of damage induced in the Pt film suggests the heating is not directly from excessively high energy density of the MBSL in heavy water as compared to light water.

The primary result of these tests revealed that modification of PdCr films was observed by MBSL generated in heavy water but not light water. The film modification indicates high energy densities are generated, though not high enough to indicate net energy generation by the MBSL itself. No effect was observed on platinum films in heavy or light water.

Sonoluminescence in Solvents

Previous studies of sonoluminescence brightness in various solvents give empirical relationships of the brightness varying with the liquid's viscosity, surface tension, inverse of the vapor pressure or a combination of these properties (ref. 31). Properties of several solvents are reported in table II that have been identified as producing some form of sonoluminescence (ref. 30 and 31). The stability of the sonoluminescence light output with temperature is also reported to be dependent on the molar heat of vaporization of the liquid divided by the boiling point. Table II shows that the brighter sonoluminescence should be seen in the solvents with higher boiling points (>100 °C), however a higher boiling point also indicates a greater sensitivity to temperature.

From the information in table II, pure glycerin appears to be the best solvent for use in sonoluminescence studies. Like the other higher boiling point solvents, glycerin is notoriously hygroscopic, eventually absorbing water from the ambient air to stabilize as the 80 percent glycerin to 20 percent water mixture listed in table II. As glycerin is relatively safe and more readily available than the other solvents, GRC began sonoluminescence studies using glycerin. Note that acetone and other low boiling point solvents being explored elsewhere (refs. 24, 26, and 28) were rejected based on low viscosity and high vapor pressure properties that are considered detrimental to sonoluminescence intensity.

A cloud of cavitation was generated with a Sonicator setup (fig. 4) that corresponded to sonoluminescence in the liquid as seen under dark conditions, as shown in figure 16. The cavitation was particularly localized, allowing for a promising target for the spectroscopy and radiation studies that are planned.

TABLE II.—PROPERTIES IMPORTANT TO SONOLUMINESCENCE FOR DIFFERENT SOLVENTS AT 20 °C (REF. 30)

Solvent	Boiling point, °C	Density, ρ (g/cm ³)	Mol. wt. (g/mole)	Viscosity, μ (cP)	Surface tension, γ (dynes/cm)	Vapor pressure, P_v (Torr)	Molar heat of vaporization, ΔH_v (kJ/mole)	Calculated MBSL intensity (γ^2/P_v relative to water)	Intensity stability with temperature, $dI/(IdT)$ (°C ⁻¹)
Methanol	64.7	0.415	32.04	0.597	22.6	93.3	35.2	0.0180	-0.072
Ethanol	78.5	0.789	46.07	1.2	22.8	44	39.3	0.0386	-0.078
Acetone	56.5	0.792	58.08	0.326	23.7	186	30.3	0.0099	-0.064
Cyclohexane	81.4	0.779	84.16	1.02	25.5	84.8	29.9	0.0251	-0.059
Carbon tetrachloride	76.8	1.595	153.84	0.969	27.0	91.3	29.9	0.0261	-0.059
Benzene	80.1	0.879	78.11	0.652	28.9	74.3	30.8	0.0369	-0.060
Light water	100.0	1.00	18.02	1.00	73.1	17.5	40.7	1	-0.076
Heavy water	101.4	1.11	20.03	1.25	73.1	16.6	42.1	1.13	-0.078
80% glycerin + 20% water	121	1.209	77.28	60.1	66.6	3.5	85.7	4.16	-0.151
Ethylene glycol	197	1.116	62.07	19.9	47.7	0.08	49.6	93.3	-0.073
Sulfuric acid	290	1.788	184.15	25.4	55.1	6.00E-05	94.1	166000	-0.116
Glycerin	290	1.261	92.09	1490	63.4	0.001	87.9	13200	-0.108

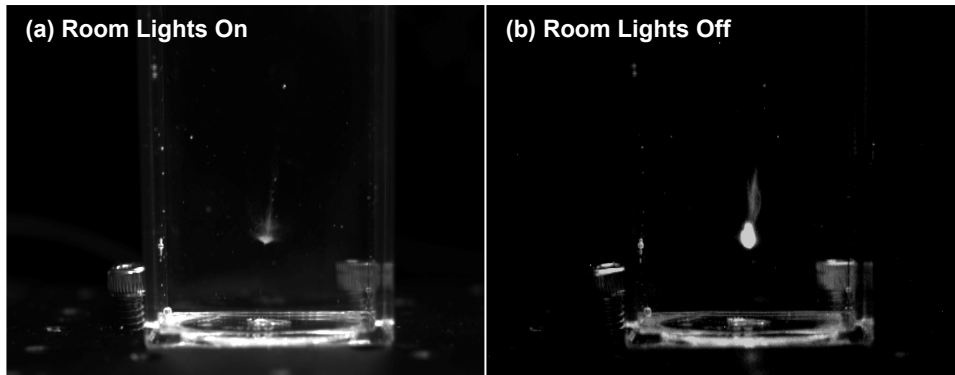


Figure 16.—Cavitation in Glycerin with (a) room lights on, and (b) room lights off (contrast enhanced) showing localized sonoluminescence in a 40 ml container. The Sonicator transducer was set to 56 kHz.

TABLE III.—ENERGIES OF REACTIONS OF INTEREST

Reaction	Product	Rest mass, MeV/c ² (D = 1875.6128 MeV/c ²)	Kinetic energy, keV
D(d,n) ³ He	³ He	2808.3914	822
	n	939.5536	2458
D(d,p)T	T	2807.9027	1265
	p	938.2720	3786
D(d,γ) ⁴ He	⁴ He	3727.3792	75.7
	γ	-----	23,771

Radiation Detection

There have been several claims of fusion reactions occurring in sonoluminescence (refs. 20, 21, 24, and 26). The reactions cited are those that fuse two deuterium atoms to form (1) helium-3 and a neutron (D(d,n)³He), (2) tritium and a proton (D(d,p)T), or (3) helium-4 and a gamma ray (D(d,γ)⁴He). These reactions either can occur in a sonoluminescent bubble alone or interacting with a palladium catalyst (Pd:D(d,b)Y reactions). See table III for the calculated energies of the products of these reactions.

The detection of the fusion reactions in the sonoluminescence test cells is made difficult by the nature of the liquids used to generate the reactions. The low level ionizing radiation levels are difficult to detect through water and heavy water due to their nuclear properties. The liquids can be analyzed for tritium production or the detection of helium-3 and helium-4 out-gassing during the tests, but background impurities and the diffusive nature of the gases makes such analysis slow and difficult. However, some success have been reported using liquid scintillators and track detectors (ref. 28).

A direct method to verify the reaction processes is by sampling the ionizing radiation in situ with scintillation detectors. A thin film coated scintillating detector is under development to identify fusion reactions occurring in sonoluminescence. The detector consists of a coated scintillating cube or fiber, a waveshifting optical fiber, a fiber optic connector, and a photomultiplier (PMT) module. A schematic is shown in figure 17.

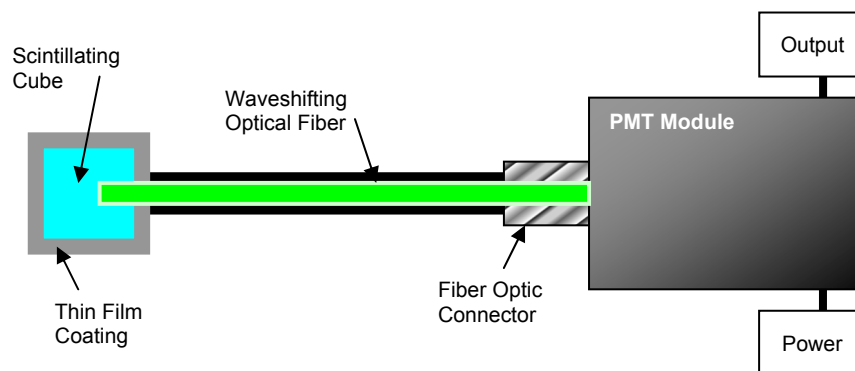


Figure 17.—Schematic of thin film coated scintillating detector.

TABLE IV.—NUCLEAR PROPERTIES OF SCINTILLATOR AND COATINGS (REFS. 34 AND 35)

Material	Density, g/cm ³	Atomic mass, amu	Thermal neutron absorption cross section, barns	76 keV alpha particle range, μm	3.75 MeV proton range, μm	2.5 MeV electron range, mm
Scintillator	1.032	6.25	0.35	0.7914	208.6	12.34
Rh	12.41	102.91	144.8	0.2724	42.34	1.480
Cu	8.96	63.546	3.78	0.2076	48.68	1.953
Pd	12.02	106.4	6.9	0.1797	44.83	1.552

The polyvinyltoluene (PVT)-based scintillator (Bicron BC-408 (Saint-Gobain Ceramics & Plastics, Inc. for their inorganic and organic scintillators)) was used in the prototype detector design, generates a pulse of light if an ionizing particle interacts inside it, depositing energy. The intensity of the light is directly proportional to the energy deposited by the interacting particle with the ionization potential based on the particle's atomic number. The scintillator used is reported to be insensitive to photons with energies over 100 keV as well as neutral particles. A thin film coating of rhodium (Rh), copper (Cu) or palladium (Pd) on the scintillator functions as either an attenuator or a convertor to allow possible fusion products to react with the scintillator, and also prevents the sonoluminescence light from generating false readings. The nuclear properties of the scintillator and the coatings are given in table IV (refs. 34 and 35).

The relative response of the scintillator with coatings for each reaction was calculated using the Monte Carlo program SRIM (ref. 36). For each coating (Rh, Cu, Pd) and ion (p, T, ³He, ⁴He), 10,000 input particles were used, and the balance of the energy of the particles transmitted through the coatings was assumed deposited into the scintillator. The sum of the deposited energies were scaled based on the reported scintillator response to determine the light output.

For each fusion reaction scenario, the output of the detectors is normalized to the detector with the largest signal. The results are shown in table V. Thus, comparing the response of each detector will allow a reasonable identification of the reaction occurring in the cell. In this way, the fusion reactions that appear (or not) in sonoluminescent conditions can be determined, limited by the statistics of the actual counts and background radiation.

The output for the D(d,n)³He reaction was determined from the helium-3 ion transport in SRIM, as well as utilizing a 3-μm-thick rhodium film as a neutron convertor. Rhodium emits 2.44 MeV electrons in the beta decay of captured neutrons, and has an excellent thermal neutron absorption cross section of 145 barns/atom, which will capture about 0.1 percent of the neutron flux per micron thickness of film. The emitted electron will be easily detectable as the scintillator sensitivity to electrons is reported to be five times that for protons of equivalent energy.

TABLE V.—RELATIVE SENSITIVITIES OF DETECTORS TO REACTIONS OF INTEREST

Detector film coating	D(d,p)T	D(d,n) ³ He	D(d,γ) ⁴ He	Pd:D(d,p)T	Pd:D(d,n) ³ He	Pd:D(d,γ) ⁴ He
3.0 μm Rh	0.89	0.04				
0.3 μm Cu	0.86	1.00	1.00			
0.3 μm Pd	1.00	0.94		1.00	1.00	1.00
0.3 μm Pd/3.0 μm Rh	0.84	0.04		0.87	0.03	

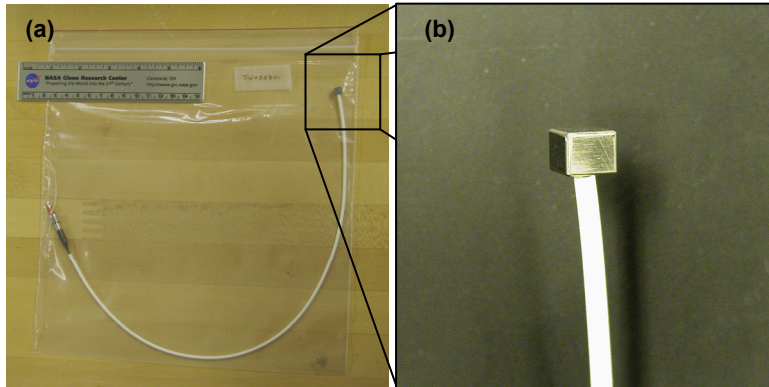


Figure 18.—Prototype thin film coated scintillating detector (a) assembly; (b) close-up of coated ¼-in. scintillator cube with a thin film of Pd.

The use of palladium in ultrasonic systems as well as our observations in figures 13 and 14 suggests that the metal should be considered in radiation detection. All three of the deuterium-deuterium reactions will be tested with a palladium film included on the detectors as well as without. If palladium has a catalytic role in fusion reactions, then the detectors with the palladium will be more sensitive as the reactions are occurring inside the palladium film. The sensitivity was modeled in SRIM assuming the reactions occur at the bottom of the 0.3 μm Pd layer, based on the 0.375 μm radius globules seen in figure 15, with all the particles deposited into the scintillator or rhodium.

The current assembly of the detectors is shown in figure 18. This assembly is too sensitive to background counts to provide useful data at this time and improvements in the assembly are proceeding. With modifications, the concept could potentially be used in other applications, such as radiation monitoring at high altitudes or in space environments. This detector development effort was successfully leveraged in radiation detector development for the application of dosimeters on surface suits for lunar EVA (ref. 37).

Energy Harvesting Concept

The common goal of energy harvesting devices is to generate electricity from the environment. In the case of energy harvesting from sonoluminescence, the environment has point locations of extremely hot bubbles. The most direct method of energy harvesting of such localized heating is by thermoelectric conversion to electricity.

Thermoelectric voltage generation uses the Seebeck effect, which is the generation of a potential difference between two ends of a conductor or semiconductor that are at different temperatures. The effect involves the movement of charge carriers from the hot end of the conductor, where the carrier density is forced lower, to the cold end, where the carrier density is allowed to be greater. The electric field due to the new distribution of charge carriers leads to a thermoelectric voltage. The voltage

generation per degree difference is referred to as the Seebeck coefficient. To complete the electrical circuit a different conductor is used with its own Seebeck coefficient, making the net thermoelectric voltage generated the difference of the two with a corresponding relative Seebeck coefficient. The simplest example of this effect is a thermocouple used for temperature measurement (ref. 38).

If the thermoelectric voltage generated is high and the losses due to the thermal conduction and electrical resistance of the conductors are low, then the voltage generated by such a device can be used to generate power. This the form of power generation used on deep space probes (such as the Vikings, Voyagers and Galileo missions) where solar power, fuel cells and batteries are not practical. As their name indicates, the heat source for radioisotope thermoelectric generators (RTG's) on spacecraft is a radioactive pellet heating a ceramic block, and the cold side is the darkness of space.

To take advantage of the high temperature robustness of ceramics and the miniature non-intrusiveness of thin films, GRC is investigating thin film ceramic thermocouples for high temperature environments. Initial results revealed a chromium silicide film with a Seebeck coefficient to be similar to that of bulk materials used thermoelectric generators (ref. 38). These results suggest that ceramic thin films can be tailored for thermoelectric energy harvesting applications.

A schematic of the energy harvesting concept is shown in fig. 19. A 6-mm-diameter thermopile, originally used for fabrication of heat flux sensors (shown in fig. 20), will be used in fabricating devices for the initial test of a thermoelectric generator for sonoluminescence. The thermoelectric elements will be made of high temperature ceramics, covered with electrical insulation for use in the liquid. The inner junction will be covered with a high temperature insulator embedded with a palladium catalyst based on the indications of high temperature generation seen in figures 14 and 15.

The output of the generator can be estimated using the properties of the chromium silicide film (ref. 38). A thermoelectric voltage of 200 mV per junction results assuming sonoluminescent bubbles react on the inner junctions of the thermopile with a 2000 °C temperature difference from the surrounding liquid. The thermopile resistance should be about 200 Ω per junction, giving 0.2 mW of power per junction. About half of the generated power is expected be lost to the resistance of the thermopile. Thus, a 40-pair thermopile as shown in figure 20 should generate 4 mW of power under sonoluminescence. As this 28 mm² generator is a fraction of the MBSL area seen in figure 13, an array of generators can conceivably output enough electrical power to match the acoustic power input to the system. Clearly, the improvement of the Seebeck coefficient, thermal resistance or electrical conductivity is needed for the high-performance thermoelectric generators needed to allow practical applications for energy harvesting of sonoluminescence.

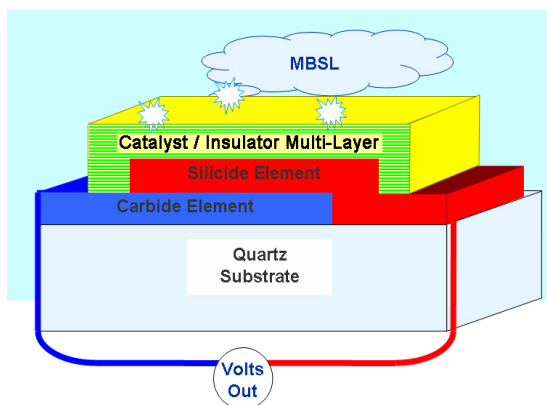


Figure 19.—Cross-section concept of a high temperature thermopile for energy harvesting sonoluminescence.

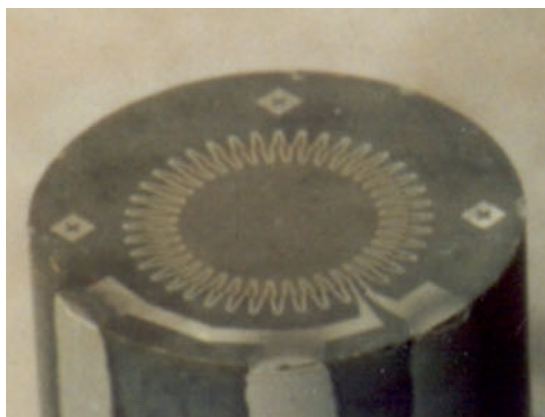


Figure 20.—A 6-mm-diameter thermopile for initial test of ceramic thin-film thermoelectric device.

Conclusions

Instrumentation techniques were explored at GRC to measure optical, radiation, and thermal properties of the phenomena of sonoluminescence, the light generated using acoustic cavitation. The objective of the effort was to investigate claims and theories of power generation based on sonoluminescence, particularly from fusion reactions in the glowing bubbles. The approach was to determine whether there is any difference in the emission from bubbles in light water and heavy water, then from bubbles in other solvents, eventually to formulate conclusions of sonoluminescence-based power generation concepts utilizing the data from the experiments.

A resonating test cell and a Sonicator test cell were built to generate sonoluminescence. Multi-bubble sonoluminescence in the tests cells were imaged with low-light cameras in a variety of containers. Indications of high temperature generation were observed in palladium chromium films when exposed to sonoluminescence in heavy water but not in light water. No indication of high temperature generation was observed in platinum films exposed to sonoluminescence in heavy or light water, though the platinum film is estimated to require about the same amount of energy to be modified as the palladium chromium film.

Localized bright sonoluminescence was generated in glycerin saturated with water, allowing future spectroscopic and other optical investigations. A design was presented for in situ radiation monitoring of the sonoluminescence, with plans for future improvements. A concept for harvesting the effects seen in this study as electricity was presented, however there is clear need for improving the thermoelectric properties of the thin films for practical energy harvesting.

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14. ABSTRACT Instrumentation techniques are being developed at NASA Glenn Research Center to measure optical, radiation, and thermal properties of the phenomena of sonoluminescence, the light generated using acoustic cavitation. Initial efforts have been directed to the generation of the effect and the imaging of the glow in water and solvents. Several images have been produced of the effect showing the location within containers, without the additions of light enhancers to the liquid. Evidence of high energy generation in the modification of thin films from sonoluminescence in heavy water was seen that was not seen in light water. Bright, localized sonoluminescence was generated using glycerin for possible applications to energy harvesting. Issues to be resolved for an energy harvesting concept will be addressed.					
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