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A TV demonstration of sound absorption connecting the space shuttle to submarines

Timothy G. Leighton, Jian Jiang and Kyungmin Baik. **Acoustics in 'Engineering Connections'**

In 2009 we were invited to provide an item for the BBC TV program 'Engineering Connections with Richard Hammond', to be broadcast in 2011. Each episode in the series considers a single engineering masterpiece, and examines the host of previous engineering innovations which provided the necessary background for (or nicely illustrate in hindsight) the engineering solutions employed to make the masterpiece work. The enquiry was for a program about the space shuttle. The production team (Darlow Smithson Productions) had heard that acoustic energy generated at launch could, without mitigation, be damaging to the protective tiles on the shuttle, or to instrumentation in, or carried by, the shuttle. We were asked to provide a demonstration on this acoustical aspect of the shuttle (Fig. 1).

Following the filming, it was suggested that the technical aspects of the build be written up for a special 'Education in Acoustics' issue of the Journal of the Acoustical Society of America, and readers are advised to consult that paper for those details. However the current article was suggested to explain the applications of the acoustics contained in that demonstration, those applications being the focus of the TV show. A secondary aim of this article is to describe the process of getting the demonstration to work for the TV show, outlining the constraints and solutions for those wishing to undertake such jobs in future.

The over-riding factor was that, rather than come to film us, the TV company required that we take the demonstration to them as just one item in a packed day of filming. Hence the apparatus would have to be transportable, constructed quickly on site and work first time. This resembles the field work that many practicing acoustic consultants undertake (as opposed to the laboratory experiments of a controlled academic environment), although without the benefit of familiar commercial equipment or prior experience. Because we were a small component of the show, the date depended on the availability of the presenter and others, and so the actual filming date was set at short notice. The budget was small, and covered not much more than the hire of the Ford Galaxy we eventually used to transport the demonstration. Therefore the apparatus had to be constructed from items we already had to hand. A series of telephone conversions with the program's researcher, Rachel Millar, established that an appropriate narrative (with practical demonstration) was feasible.

That narrative had to link the sound suppression system at the shuttle launch with what could feasibly be built from our current apparatus, maintaining the priority that the story, facts and explanations had to be scientifically rigorous and factually correct. Furthermore, the narrative had to be compelling and understandable to an audience of young viewers, whilst of course remaining entirely honest in the extent of the link between the technologies and the explanations of how the science works.

Figure 1

Space shuttle launch

The sound suppression system used at shuttle launch makes use of the effect of the rocket exhaust on a large mass of water. There is a hole in the surface of the launch pad, and below that hole is a "flame trench" which channels the rocket exhaust away in a controlled manner. Following loss of 16 tiles and damage to orbiter components through sound generation during the launch of the first shuttle (STS-1), a sound suppression system was introduced. Just before launch, the flame trench is filled with over 1000 m3 of water (1000 tonnes) in around 40 s (Fig. 2). When the exhaust interacts with this water, there are several potential mechanisms by which the acoustic energy reaching the shuttle itself is reduced. Only one of these mechanisms (sound absorption by water droplets) satisfied the practical criteria, that it: (i) could be safely illustrated to an audience of children; (ii) could be built within the budget, without purchasing specialized equipment; (iii) could be incorporated in a demonstration which could be linked to another engineering innovation in an exciting, comprehensible and truthful narrative; (iv) could be packed away and transported in a family car; and (v) could be reconstructed and operational in around 30 minutes (the timescale required for meeting our filming slot). Illustration of this one mechanism was deemed sufficient, as the other important mechanisms could not satisfy the above criteria. Such mechanisms include the entrainment of the liquid into the flow and its evaporation[1-3].This represented the major compromise, since the reduction of the sound source level of the jet (by decreasing jet transfer through momentum transfer between liquid and gaseous phases, and reduction in jet temperature through partial vaporization of the water)[4,5] was probably more important to mitigating acoustic damage to the shuttle and its component, than was the acoustic absorption that occurs during transmission as a result of the water droplets. If the space shuttle launch was to be the end point of the narrative, the historical engineering innovation which would explain sound absorption by liquid droplets had to be found. In discussion with Rachel Millar, it was agreed to demonstrate the underlying physics of the mechanism we could illustrate (see above) through analogy of the anechoic linings of submarines. The lining was designed in response to the effectiveness of the Allied anti-submarine activities, which the Germans attributed to advances in Allied sonar, but which is likely to have been due to other factors (including the cracking of the Enigma Code). The tile shown in Fig. 3 is from a World War II U-boat. The far side of the tile is smooth, but the side visible in the picture was glued to the hull, trapping air in its circular pores to form bubbles. The technique is acoustically effective, though in early versions the tiles debonded from the hull under pressure cycling.

Bubbles are well-known to absorb sound extremely effectively, and so the demonstration was designed to show absorption of bubbles in water (linking to the submarine lining), and absorption of water droplets in fog (linking to the shuttle launch). Two vertical PMMA (PerspexTM) tubes were to be placed side by side, one filled with water and the other with air (seen on location in the background of Fig. 3). Each tube had a sound source at the bottom and a sound sensor (a microphone in the air column, and a hydrophone in the water column) at the top. The same signal was to be used to drive each source (the actual acoustic signal emitted by each source being

Figure 2

The photograph shows the testing of the system to fill the flame trench with over 1000 m^3 (1000 tonnes) of water in around 40 s, shown here covering the mobile launcher platform on Launch Pad 39A (photo courtesy of NASA/KSC).

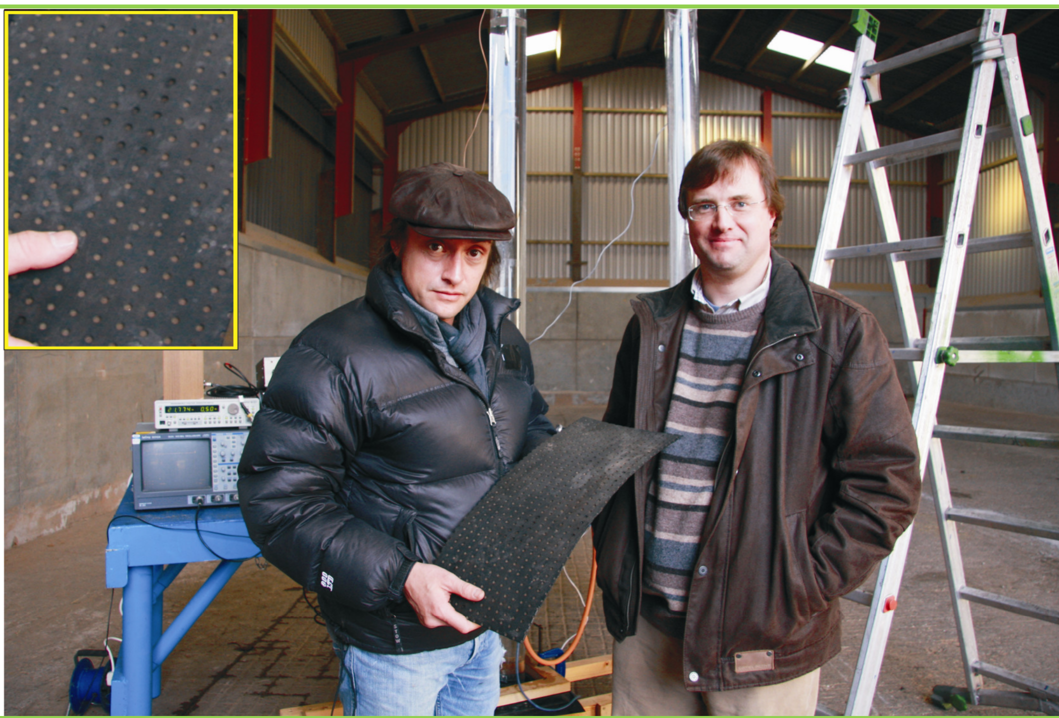

Figure 3

One of the authors (T.G.L.) and TV presenter Richard Hammond with a piece of anechoic tiling from a WWII German U boat (details in inset).

Slightly different because of the response of the source and amplifier), and travel up the tube to be monitored by the microphone/hydrophone (coupling between the fluid and the walls, and reflections in the pipe, changing its form [6,7]). The introduction of bubbles into the water column would then attenuate the sound more than would the introduction of fog into the air column (because the bubbles provide at least one extra potent mechanism for sound absorption). This effect would be detected by the microphone/hydrophone, and then explained to the audience to link the space shuttle to the submarine in a way which makes the underlying physics clear. The apparatus is shown under construction on location in Fig. 4.

Details on how the apparatus is constructed, and the signals designed, can be found in reference [1]. Practical details range from the mundane to the subtle. For example, the air-filled tube needed to be sealed at the base (Fig. 4(b)), and fitted with an exhaust pipe to allow displaced clean air to vent from the base of the pipe, so allowing the fog to fall to the base of the pipe and completely fill it. At the other extreme, the choice of signal had to be selected such that it would be audible to the audience when no bubbles or fog were added, but be dramatically attenuated when fog and bubbles were added. This proved challenging, since there was not great flexibility in the bubble and droplet populations that could be generated with the simple apparatus to hand. A relatively high frequency audio signal was required, which was sufficiently characteristic for the audience to latch onto it above the background noise. An upwards linear chirp sweep from 10 kHz to 20 kHz was chosen since it was sufficiently high to produce attenuation that could be heard by the listeners, but not so high as to be difficult for a wide age range of listeners to hear. The chirp is repeated every second to facilitate the audience in hearing the changes due to addition of bubbles/droplets. Rather than try to enable the audience/viewer to hear the sound emitted directly by each tube, it was most convenient to let them listen to the output of the microphone/hydrophone (which for the TV show was fed directly to the sound channel, but for live audiences can be transmitted by loudspeaker or, if feedback is a problem, by headphones).

Having found a signal which can be heard by the audience in fog-free and bubble-free conditions but which is dramatically attenuated by the fogs we could easily make (Fig. 4(c)), the objective was to ensure that we could make a bubble population which would also dramatically attenuate the signal. This bubble population would need to one that could easily be injected into the water pipe using a standard portable compressor and hypodermic needle. The difficulty here was that this required bubbles which are smaller than those produced by simple injection [1] Simply reducing the bore of the hypodermic needle does not produce smaller bubbles: although a small bubble might initially be released from the needle, it does not rise sufficiently rapidly under buoyancy to prevent it coalescing with the next bubble that is growing at the needle tip (Fig. 5). The result is that the only bubble that can rise away from the needle swiftly enough to avoid any more coalescence is one that has already grown large through such coalescence [1]. The solution was to place the vibrator from a mobile phone on the needle outside the pipe at such a position as to produce maximum displacement at the needle tip. This removed the successor bubble growing at the tip away from the location of the newly released bubble, and enabled sufficiently small bubbles to be generated (for details, see the reference list [1,9] and the video at the associated web page [10]). As stated above, the low budget required that the demonstration be adapted from existing equipment. The two-tube apparatus for

Figure 4

(a) The apparatus is reassembled having been to a barn for filming for a TV show. The build has sufficient simple components that supervised children can learn through assisting set it up (the photograph shows J.J. and T.G.L.'s children). (b) Detail of the mounting of the loud speaker in the air-filled tube, when sponge is rolled about the loudspeaker cables and squeezed into the pipe base to seal it. (c) Fog made by pouring hot water into dry ice. The plastic jugs used here are not safe for repeat usage as the thermal cycling shatters them.).

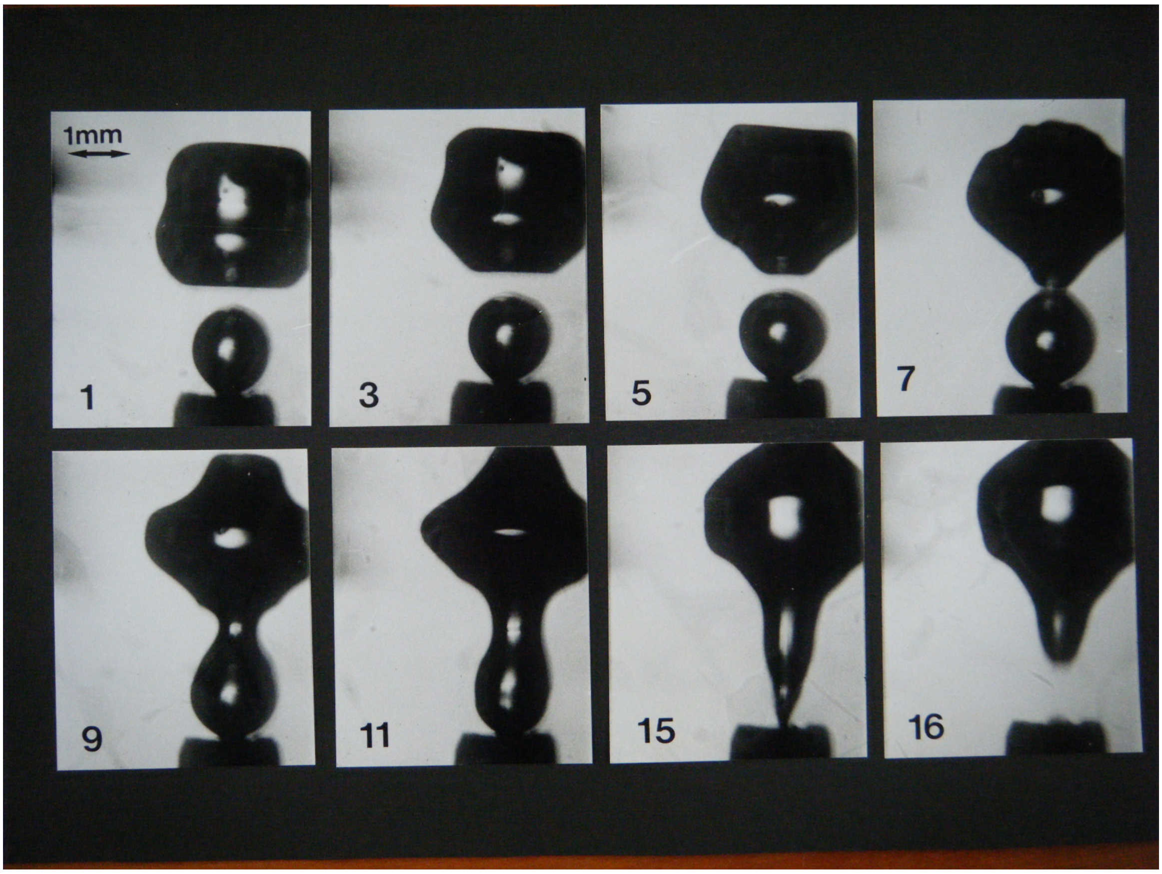

Figure 5

Selected frames (filmed such that frames with consecutive numbers would have interframe times of 0.22 ms) as air bubbles are injected into water (at a glass flow rate of 0.2 ml/s) through a metal nozzle of external diameter 1.6 mm with a bore of 0.5 mm. Frame 1 shows a newly-released bubble above its successor which is growing at the nozzle tip. The growth rate of the success is sufficiently great, and the rise speed of the newly-released bubble sufficiently slow, for the two to merge in frame 7, such that the resulting bubble is released in frame 16: if it is not sufficiently large to rise sufficiently fast, it too may merge with the next successor bubble. From reference [9].

this experiment was readily available as it had been built for previous projects on developing sensors to measure bubble populations in pipes. These two projects (for potteries and the neutron generation industry) nicely illustrate further applications linked to the acoustic absorption of bubbles demonstrated for the TV show. The first of these previous projects been to build sensors that could be clamped onto the outside of pipes in potteries to measure the bubble population within the pipe (Fig. 6)[10]: when liquid ceramic 'slip' is pumped from settling tanks into molds, any bubbles in the slip will expand when the product is fired in the kiln, producing defects and holes in the resulting pottery product (Fig. 7). This is extremely wasteful as the problem is currently not discovered until after firing, meaning that many hours of production can have been wasted. Moreover the undetected bubbles generate defective product which cannot be recycled into new slip. Ultrasonic sensors were developed for the industry to detect such bubbles in the pipeline before they reached the mold [11]. This system was then adapted for a second project (using the two vertical tubes re-enlisted for this TV demo) to provide bubble detectors for the $1.4 billion Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory, Tennessee, the most powerful pulsed spallation neutron source in the world (Fig. 8). In this facility, a 331 m long linear accelerator (linac) accelerates beam pulses of H- ions to almost 90% of the speed of light. These ions are stripped of their electrons upon entering a pulse accumulator ring that combines 1000 linac pulses into much larger pulses of protons. These proton pulses – shorter than a micro-second – are ejected from the ring at 60 Hz towards the neutron generating spallationg target. The produced neutrons emanate out of the target into a reflector / moderator assembly than serves to collect as many neutrons as possible and cool them to energy levels of greatest utility to the suite two dozen research instruments. Neutron instrument capabilities are largely constrained by the neutron flux that can be sent to samples to be studied. In a spallation source, higher flux can be achieved by increasing proton beam power on the target.

In traditional spallation neutron sources, a typical target material would be a high density solid (e.g., lead or tungsten) cooled by water. Cooling is necessary as the proton beam volumetrically deposits thermal energy with each pulse. While higher proton power will increase total neutrons produced in a solid target, the commensurate need for greater cooling water volume fraction limits the desired payoff in neutron flux. Liquid metal targets side step this limitation since circulation of the metal through a heat exchanger removes the beam energy without dilution of neutron flux.

Mercury (atomic number Z= 80; melting point = -38.83°C) was selected for the SNS because of its attractive spallation neutron production and room temperature liquid state. It is circulated through a stainless steel target vessel where the

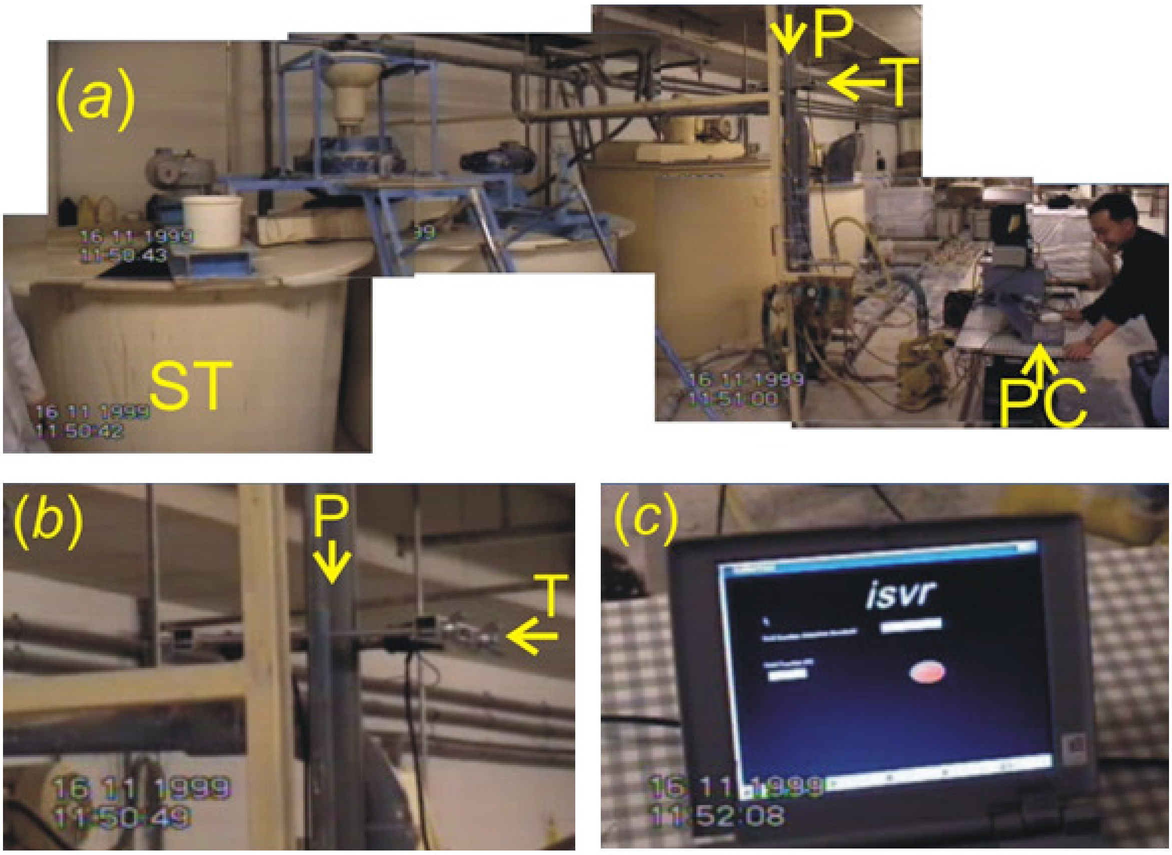

Figure 6

Frames from a video sequence filmed at the Bridgewater Pottery (Stoke-on-Trent, UK) during testing of the prototype (16 November 1999). (a) Slip flows from the settling tank (ST) through the pipelines. The transducers (T) are attached outside one particular downpipe (P). The output of the receiver transducer is monitored by student Geun Tae Yim on a PC. (b) Detail of the pipe and transducers. (c) The 'light' on the PC has switched from green to red following the addition to bubbles to the flow. The Bridgewater tests were the first in the development of the prototype (the device was subsequently tested at 6 other potteries around Europe). In later trials the PC was replaced by a stand-alone unit. From reference [11].

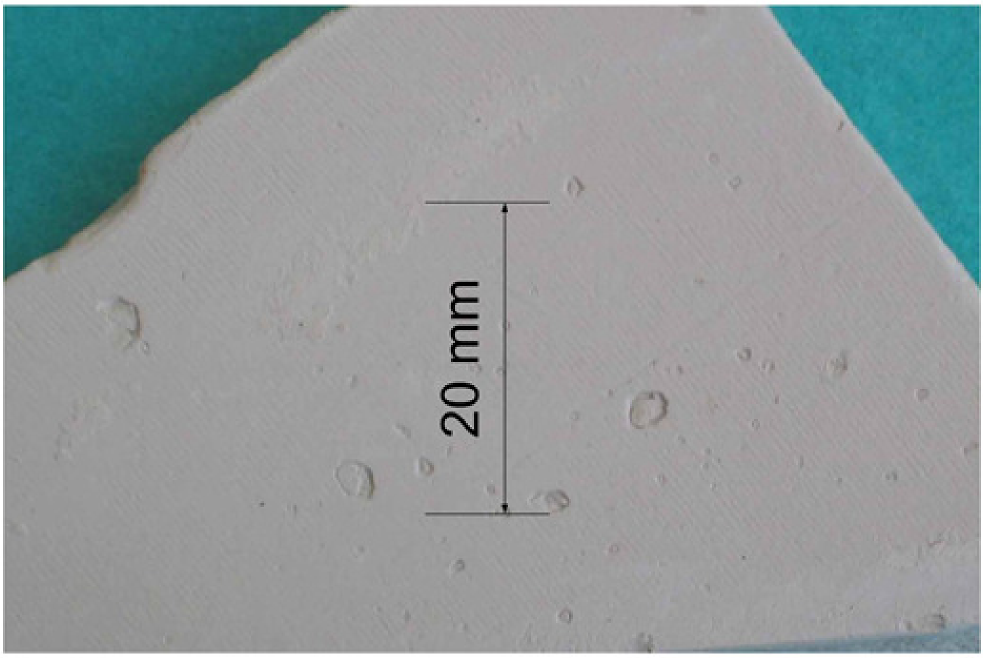

Figure 7

Photograph of a sample of defective ceramic, showing 'pinholes'.

Figure 8

Schematic of the Spallation Neutron Source at Oak Ridge National Laboratory, Tennessee. The hydrogen ions for the linear accelerator are generated in the 'front end' building at the top left of the picture, and are accelerated down the linear accelerator (shown in red) to the ring, where protons are accumulated. During repeated circulation of the ring, more protons are added to 'pain out' the complete 9-inch diameter proton beam. When this is complete (which occurs 60 times per second), the proton pulse is released into the 'target' building, the centre of which houses the sarcophagus in which the actual mercury target is housed. A possible future target building is shown in ghost outline.

proton beam is directed and the spallation reaction occurs. A process system circulates some 20 tonnes of mercury that can accommodate 2 MW of proton beam power on target. The target vessel is designed as a replaceable component because radiation damage eventually embrittles the steel. Another problem – recognized at a late time in facility construction – is cavitation damage of the steel vessel that is due to intense pressure pulses caused by the micro-second beam pulses. On this timescale the heated mercury is inertially confined such that tremendous pressure (up to 40 MPa) results. During the time subsequent to the pulse, this pressure interacts with the vessel whereupon rarefaction waves cause significant tensile pressure – tensile pressure that leads to mercury cavitation.

Cavitation bubble collapse near the vessel wall has been observed to erode an interior SNS target vessel wall. Failure of a mercury vessel outer wall – while not a credited containment boundary – would require immediate change of the target which has consequences for the neutron science user program and cost (procurement and waste disposition). The erosion rate is apparently strongly dependent on beam power.

As SNS operations mature there is a risk that this cavitation phenomenon will limit a target's useful life more severely than radiation damage thus prohibiting the facility from achieving ultimate performance goals. One solution under development at SNS is to introduce non-condensable gas bubbles into the bulk of the mercury that can absorb the pressure pulse and attenuate cavitation formation. In this way, it is envisaged that cavitation bubble activity on the vessel walls is low energy, and erosion there is reduced. Using the two-tube rig, such sensors were developed and fitted to an SNS test facility to assess small gas bubble populations generated in the mercury flow (Fig. 9).

In summary, a real-world contract to exploit the absorption of acoustic waves by bubbles (at SNS) therefore produced the two-pipe apparatus which was readily adapted for the TV demonstration. The equipment was dismantled and driven to the Herefordshire on 19 February 2010 .It was a snowy evening, and the equipment was unloaded from the car into the hotel room for the night. This was an important precaution for field work with such experimental equipment required to

Figure 9

T.G.L and Mark Wendel of ORNL fit bubble detectors to the mercury-filled steel pipelines of the ORNL SNS test loop. The large khaki pump in the foreground is a candidate bubble generator for the neutron source.

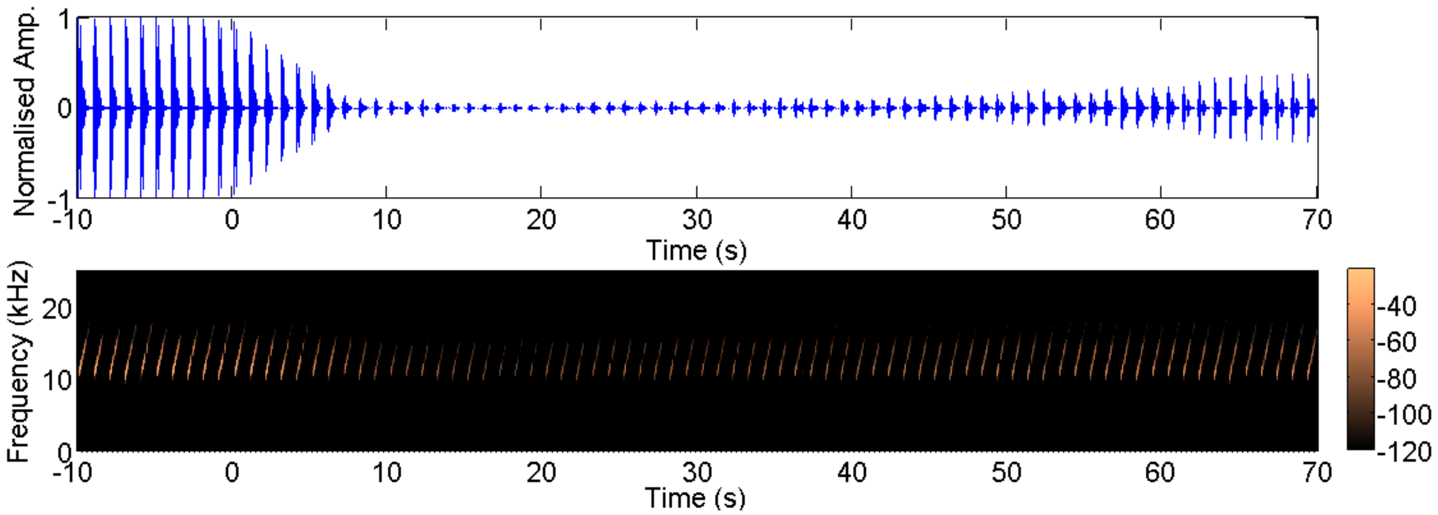

Figure 10

The upper plot shows the time history of the signal from the microphone which is at the top of the air-filled tube. The lower plot shows the corresponding time-frequency representation of the same data (shown on a common time base), in which the chirp can be seen as a line rising to the right, repeated every second. The fog is added to a previously clear tube at time t=0. It fills the tube in under 10 s, attenuating the chirp. After 90 s the fog has substantially dissipated, and the received amplitude of the chirp has partially recorded. For clarity of presentation, the time series data have been normalised to zero mean and a maximum positive voltage equal to 1, which carries through to the time-frequency plot of this time series. The colour scale shows dB sound pressure level relative to 20 µPa rms *A recording of these data can be found at the website[10].*

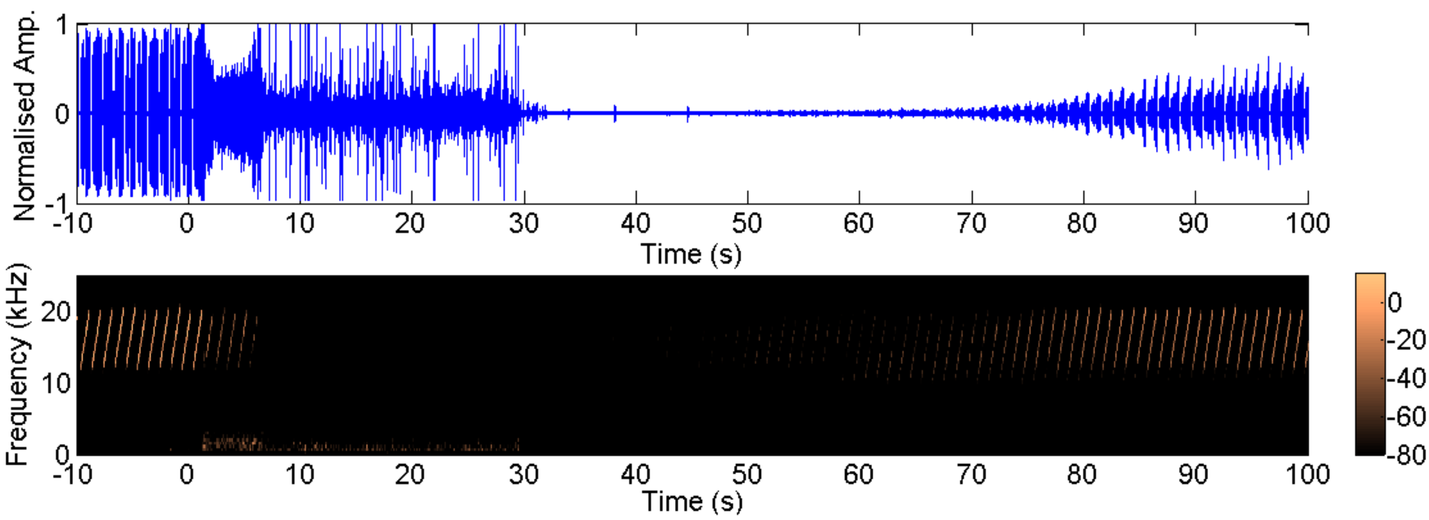

Figure 12

The upper plot shows the time history of the signal from the hydrophone which is at the top of the water-filled tube. The lower plot shows the corresponding time-frequency representation of the same data (shown on a common time base), in which the chirp can be seen as a line rising to the right, repeated every second. The bubbles are added to the previously bubble-free water at time t=0. The addition of bubbles generates audio frequency injection noise, which is clearly visible in the time-frequency plot. More detailed analysis of these data shows that modes of the tube are excited, which rise in frequency as the rising cloud of bubbles effectively shortens the acoustically-active length of the pipe in which the hydrophone sits (see ref. [1] for details). The chirp is significantly attenuated in under 10 s as bubbles fill the tube, although injection noise continues for the 30 s during which gas injection is maintained. The chirp slowly returns as bubbles rise out of the tube, although the small bubbles which remain after 2 minutes still generate significant attenuation. For clarity of presentation, the time series data have been normalised to zero mean and a maximum positive voltage equal to 1, which carries through to the time-frequency plot of this time series. The colour scale shows dB sound pressure level relative to 1 μPa rms *A recording of these data can be found at the website[10].*

perform first time: had not been taken, the demonstration might have failed the next morning because of condensation on electrical terminals kept overnight in the car. The location for filming was a barn, and we requested in advance that electrical power, a table to support the rig, dry ice and hot water be provided (it would not have been safe for us to transport dry ice in the car for such a prolonged drive). With these in place, it took only 30 minutes to assemble the rig, and the filming was done in one continuous shoot. Such preparations and precautions are vital: there is a perception in parts of the media that academics are unreliable in generating demonstrations outside their laboratories, because such 'field' demonstrations do not work when filming begins. With such perceptions it is small wonder if TV companies risk little funding on academics, which can create a vicious circle of low-cost field demonstrations which then fail, supporting the perception. Planning can offset the limited ability to purchase bespoke solutions for field demonstrations.

Data are shown in Figs. 10 and 11, and sound files of the effect of adding bubbles and fog are available at the website [10]. Compared to the case when fog is added to air (Fig. 10), the addition of bubbles to water (Fig. 11) both attenuates the chirp more (because of additional absorption mechanisms [1] and contributes lower frequency sounds of bubble injection (addition of the fog generates no equivalent signal). A secondary acoustical effect demonstrated by this bubble injection is that, as the first bolus of bubbles rise up the tube, they effectively create an 'underwater organ pipe' which produces a note of rising pitch [1], clearly audible in the sound files [10]. Construction details for the rig, results, and explanations suitable for a young audience, can be found in reference [1].

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