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A record "longest echo" within the Inchindown oil despository (L)

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In 2013, Guinness World Records awarded tank number 1 at the Inchindown oil despository, Ross-shire, Scotland, the record for the "longest echo" at 75 s. Guinness World Records calls it the longest echo because that was the name of the record that was broken, however, the correct name for the phenomenon measured is reverberation. This Letter has been written to document this unique acoustic space where the reverberation time is 112 s at 125 Hz, to detail the methodology for those who wish to attempt to break the record, and to discuss why the tank is so uniquely reverberant.
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[MV] Pages: 1602–1604

I. THE TANKS

The six oil storage tanks at Inchindown were dug into a hillside north of Invergordon in Ross-shire, Scotland amid concerns about the strengthening of Germany's armed forces during the 1930s.[1] As shown in Fig. 1, each tank is a long single space, concrete-lined and with an arched roof. The walls to the tanks are 45 cm thick. Completed in 1941, the five largest tanks each contained 25.5×10^6 liters of shipping oil. The tanks were 237 m long by 9 m wide by 13.5 m high. Entrance to a tank is gained through one of four 2.5 m long pipes, each 45 cm in diameter, which was the way of entering the spaces to carry out maintenance. The tanks were decommissioned in 2002.

II. METHOD

The measurements were carried out according to ISO 3382-2 2009.[2] Measurements took place in tank number 1 on Sunday, 3 June 2012 between 11 and 12 a.m. The measurements were carried out as part of research for two popular science books.[3,4] Before these measurements, the world record had been held by the Hamilton Mausoleum near Glasgow with a time of 15 s.

The Guinness record guidelines stated, "This record is for the longest time taken for the reflections of an impulse sound to decay 60 dB below the sound pressure level of the initial impulse sound." As is well established in architectural acoustics, a more reliable value with lower experimental error can be obtained from the measured impulse response using backward integration to give a reverberation time equivalent to the decay from a steady-state excitation.[5] Another deviation from the record guidelines agreed with Guinness was to follow normal practice and to measure the decay rate from the Schroeder curve between −5 and −35 dB.

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The impulse response measurement method used a starting pistol firing 9 mm revolver blanks (clause 3.4 from ISO 3382). Two 1/2 inch microphones were used [Bruel and Kjaer (Nærum, Denmark) 4165 condenser microphone connected to Bruel and Kjaer 2669 preamp]. These were connected to a Norsonics (Lierskogen, Norway) 336 front end power supply and pre-amplifier. The outputs from the Norsonics 336 s were recorded on a Roland (Shizuoka, Japan) R44 sound recorder at a sampling frequency of 44.1 kHz with a 24 bit precision uncompressed. Level indicators on the Norsonics 336 and Roland R44 were monitored to check that neither overloaded during measurement.

Six source-microphone combinations were measured giving an engineering precision according to Table I in ISO 3382,[2] giving a more accurate estimation of the reverberation time than the single measurement requested in the record guidelines. Source and microphone positions could not follow from the normal use of the room, as required by ISO 3382, because the tanks were designed to be full of oil. Consequently, the following protocol was adopted. The two microphones were placed roughly a third of the way from the rear wall of the tank, ~5 m apart, roughly 2 m and 3 m,

FIG. 1. (Color online) Playing the saxophone in tank number 1 at Inchindown. Photo by Alessana Hall, Lion Television.

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TABLE I. Average T_{30} and T_{20} for six source-receiver positions along with 95% confidence limits.

Center frequency (Hz)	63	125	250	500	1000	2000	4000
T_{20} (s)	163 ± 4	112.2 ± 0.8	68.8 ± 0.1	42.6 ± 0.2	28.3 ± 0.1	17.6 ± 0.2	7.70 ± 0.07
T_{30} (s)	—	112 ± 1	70.4 ± 0.3	43.2 ± 0.2	28.8 ± 0.2	17.8 ± 0.1	7.89 ± 0.07

respectively, from the center line running along the length of the room. The microphones were ~1.5 m and ~2 m above the ground. Three source positions were measured, starting roughly a third of the way from the entrance pipes and ending about half way into the room. Source positions were away from the center line of the room. All sources and receivers were at least 1 m from any surface. The large distances, lack of lighting and inhospitable conditions in the tank meant that precise positions of the source and receiver were not measured. The minimum source-receiver was far in excess of that required by Eq. (1) of ISO 3382-2. The Guinness record guidelines stated that, "The SPL meter must be located within 2.5 metres of the source of the impulse sound" but this contradicts the requirements in ISO 3382-2 and so was ignored.

Only two people were present in the tank as required by ISO 3382-2. The space was virtually empty, although odd bits of equipment still remain in parts as can be seen in Fig. 1. This metal equipment was used to warm the shipping oil. They were negligible compared to the large volume of the room. The floor was largely covered in puddles of water and oil. Thin deposits of oil coated the walls.

The Guinness record guidance states, "Background noise before the attempt must be less than 60 dB. Any spurious sounds make null and void the particular attempt." Being deep inside a hill in a tank made from 45 cm thick concrete, the only sound in the room was that created by the experimenters. Care was taken to ensure no unwanted noises were made during the decay measurement. As is normal practice, the measured decays were checked during processing to ensure that the background noise level was sufficiently low.

Analysis was carried out as follows. Each impulse response was trimmed to exclude the pre-record before the impulsive sound had arrived at the microphone, and to exclude any interfering noise after the decay had stopped (e.g., operator moving to turn off recorder). The impulse response was filtered into octave bands from 63 Hz to 4000 Hz. For each filtered impulse response, the Schroeder decay curve was calculated by backward integration. The −5 dB and −35 dB points of the Schroeder decay curve were located and a least-squares best fit line computed from the decay curve between those two points. The octave band reverberation time, T_{30}, is calculated from the gradient of the best fit line.

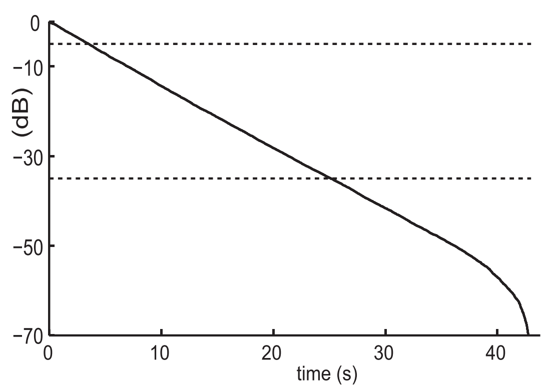

FIG. 2. Schroeder curve for a measurement in the 500 Hz octave band. The dashed lines indicate the limits for the reverberation time calculation.

III. RESULTS

Figure 2 shows an example Schroeder curve for one measurement in the 500 Hz octave band. A visual inspection comparing the measured decay to the best fit line shows that all plots are linear, the space was diffuse, and so techniques to deal with curvature as outlined in ISO 3382 are unnecessary. One measurement position at 125 Hz shows a moderate curvature at the end due to truncation of the measurement. This has a negligible effect on the resultant reverberation time estimations.

There was insufficient signal-to-noise ratio to allow a full T_{30} to be estimated at 63 Hz, but a reasonable estimate of T_{20} could be made. Table I shows the average reverberation times, and a graph is shown in Fig. 3.

Because the reverberation time varies considerably with frequency, the analysis above has been carried out in octave bands, as is standard practice in acoustics. Guinness World Records, however, requested a single broadband decay time. This is problematic because the broadband reverberation time depends on the frequency response of the source rather than being solely a property of the room. The lead author suggested that the longest reverberation time within an octave band should be used for the record, as this is scientifically more defendable, but Guinness World Records insisted on a single broadband value.

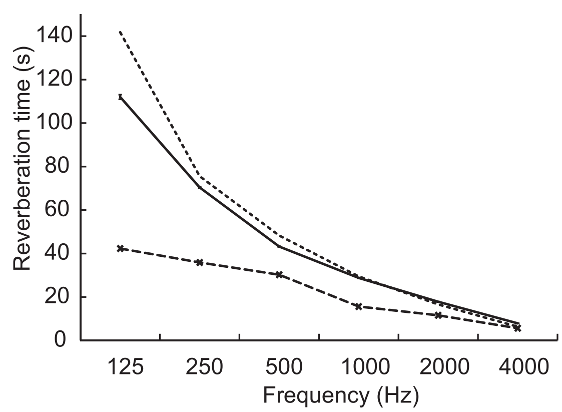

FIG. 3. (—) Average measured reverberation times with error bars indicating 95% confidence limits, (- - - -) predicted reverberation time for the tank, and (···) estimation for longest possible reverberation time if the tank had completely rigid walls.

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There are no standard methods for "averaging" reverberation times across frequency. The Guinness World Record guidance said to use an "SPL meter" and measure the time an impulse took to decay by 60 dB via the meter. Using a method that most closely matched this guidance, the reverberation time was calculated from the broadband impulse response with no frequency weighting. First, a third-order high pass Butterworth filter with a -3 dB point at 20 Hz was applied to the impulse responses to remove energy outside the audio frequency range. The Schroeder plot was calculated via backward integration (because the reverberation time varies a great deal across frequency, the decay was very non-linear). A least squares best fit line was calculated between the -5 and -35 dB points on the Schroeder curve, and the reverberation time calculated from the gradient of the line. Averaging all six measurement positions gives a broadband value of (75 ± 2) s.

IV. PREDICTIONS

Figure 3 shows the reverberation times predicted using Eyring-Norris formulation.[6] Unfortunately, the temperature and humidity were not measured and so air absorption[7] can only be estimated assuming 10 °C and 90% relative humidity. Working from Fig. 1, the arch was estimated to have a radius of 4.78 m and the distance from the floor to the start of the arch is 10.32 m. This gave a room volume of 26 100 m^3 and surface area 8957 m^2. The surfaces were assumed to have the absorption coefficient of smooth, painted concrete.[6]

At 4000 Hz, the highest frequency measured, the agreement is best between prediction and measurement because the reverberation time is dominated by the effects of air absorption. The predicted reverberation time is, however, 33% too small. At low frequency, the predicted reverberation time is about a third of what was measured. The measured absorption of sound provided by the walls is far smaller than indicated by the absorption coefficients given for concrete in the literature. For example, at 125 Hz, the absorption coefficient for smooth, painted concrete is often quoted as 0.01. In contrast, the reverberation time in Inchindown implies an absorption coefficient in this octave band of $\sim$0.003. It is assumed that the very low wall absorption is due to the thick concrete walls that are bonded onto the bedrock. The tanks were made by first tunneling out the space. Then shuttering was placed 45 cm in front of the sandstone and the concrete poured between the shuttering and the bedrock. In addition, pores in the walls were sealed to make the tank water tight.

The dotted line in Fig. 3 shows a prediction for the longest possible reverberation time that could have been measured if the walls were completed impervious to sound. It combines the absorption due to air with the inevitable viscous and thermal absorption at the boundaries of a completely rigid surface.[8] (This estimation makes allowance for the non-flat frequency response of the gun shot by calculating the absorption coefficient for a hundred frequencies across each octave band, and then averaging these results having first weighted them for the sound power produced by the gun.) This confirms that for many frequencies the oil tank is close to the limit of what could have been achieved. At the two highest frequencies, the measured results exceed this estimated longest possible reverberation time. This happens because of uncertainty about some of the values needed in the calculation, such as the exact geometry of the tank and the environmental conditions. There is also a small service hatch at the top of the tank at one end that may have allowed sound to access a work area. This might have acted as an additional coupled volume and so increased the reverberation.

V. CONCLUSIONS

This paper has examined the acoustic properties of the oil storage depository at Inchindown, Scotland. Tank number 1 holds the Guinness World Record for the "longest echo" at 75 s. At high frequency, the reverberation time is mainly limited by air absorption. Measurements indicate that the extraordinary reverberation time of 112 s at 125 Hz arises because the construction has unusually low absorption coefficients because the oil tanks were made to withstand heavy bombing.

[1]The Royal Commission on the Ancient and Historical Monuments of Scotland, Site Record for Inchindown, available at: http://canmore.rcahms.gov.uk/en/site/173294/details/inchindown+royal+navy+fuel+tanks/ (Last viewed 1/6/2014).

[2]ISO 3382-2:2009, Acoustics—Measurement of room acoustic parameters, Part 2: Reverberation time in ordinary rooms (International Organization for Standardization, Geneva, Switzerland, 2009).

[3]T. J. Cox, *Sonic Wonderland: A Scientific Odyssey of Sound* (Bodley Head, London, 2014), pp. 53–57.

[4]T. J. Cox, *The Sound Book: The Science of the Sonic Wonders of the World* (W. W. Norton and Company, New York, 2014), pp. 53–57.

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[7]ISO 9613-1:1993, Acoustics—Attenuation of sound during propagation outdoors, Part 1: Calculation of the absorption of sound by the atmosphere (International Organization for Standardization, Geneva, Switzerland, 1993).

[8]K. Walther, "The upper limits for the reverberation time of reverberation chambers for acoustic and electromagnetic waves," J. Acoust. Soc. Am. **33**, 127–136 (1961).

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