

Comparison of copper and tungsten carbide calibration spheres

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The properties of calibration spheres made from electrical-grade copper, denoted Cu, and tungsten carbide with 6% cobalt binder, denoted WC, are examined theoretically. Effects of variations in material, medium, and equipment parameters are determined for spheres intended to calibrate 38-kHz echo sounders when a target strength of order -41.5 dB is required. The derived 30.4-mm-diam Cu sphere and selected 38.1-mm-diam WC ball bearing show different dependences on the varied parameters. Changes in the material and equipment parameters within wide ranges will not upset a precision calibration with expected ± 0.1 -dB accuracy. Adjustment of the calibration value of backscattering cross section with changing temperature is generally necessary for elastic spheres. This is the case for the present WC sphere, but not for the Cu sphere by virtue of its optimization with respect to temperature. Greater hardness is found to be insufficient for choosing between the two; the particular application must be considered. Pragmatic criteria for sphere selection are discussed.

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INTRODUCTION

Interest in the use of solid metal spheres as calibration or reference targets has increased significantly since their dismissal for presumably large-system calibrations by Wallace *et al.*¹ Dragonette *et al.*² have used tungsten carbide spheres for gauging backscattering measurements in the laboratory. Similar spheres have been examined in Scotland for possible application to echo sounder calibrations.³ Copper has also received much attention.³⁻⁶ Spheres machined from electrical-grade copper are being used to calibrate fisheries echo sounders in Norway and elsewhere.⁷ There have also been applications of solid metal spheres in nonlinear acoustics.^{8,9}

Purely theoretical considerations have favored the so-called "group II" materials of Anson and Chivers' classification.¹⁰ This is somewhat misleading, for while they are generally hard and dense, they are also among the most expensive and hazardous, not to mention least machinable of materials.^{11,12} Some examples are beryllium, boron, sintered diamond, iridium, niobium, osmium, platinum, rhenium, ruthenium, and tungsten carbide.¹³ "Group III" materials, in contrast, while less hard and possessing more complicated radiation functions and backscattering cross sections than the group II materials, are generally much easier to fabricate. Copper belongs to this class, as do aluminum, nickel, monel metal, stainless steel, and zinc.¹³

The present study deals with pragmatic considerations in the choice of material for fabrication into spheres designed for use in hydroacoustic calibrations. The object materials, copper and tungsten carbide, are convenient both for their immediate and potential applications and for their representation of acoustically dissimilar materials according to Anson and Chivers' admittedly somewhat arbitrary classification.¹⁰ Since both materials have been used successfully for

precision calibration, as has fused silica,¹⁴ which is also a group III material like copper, secondary aims of the study are to emphasize the futility of selecting materials solely on the basis of their hardness and to discourage misuse of the rigid-sphere approximation in the calculation of scattering properties.

I. SPHERE SELECTION

Selection of a sphere for calibrating any given acoustic instrument generally involves selection of the material and determination or selection of the diameter. This is now discussed both for copper and for tungsten carbide. As a practical example, the derived spheres are to be suitable for calibrating the 38-kHz echo sounders commonly used in fish stock estimation. The calibrations are to be performed at short ranges, but in the farfield of the transducer. Furthermore, the target strength is to be roughly equal to that of a ping-pong ball; namely, about -41.5 dB.¹⁵

A. Copper

This noble metal has many virtues.^{4,7} It is cheap, corrosion resistant, easy to machine, readily available in a high state of purity, and hard when cold-worked and unannealed.¹⁶

With respect to the elasticity, which with the density determines the scattering response for a given immersion medium, the elemental composition of commercial electrical-grade copper is important. The effect of trace element content should be negligible.¹⁷⁻²⁰ The two commercial electrical-grade forms of copper, the oxygen-free (OF) and the electrolytic tough-pitch (ETP), may be expected to have very similar elastic properties.²¹

Another property of copper which is advantageous to its elasticity, hence choice, is its cubic structure. Texturing is

unlikely to influence this, which may explain the evident constancy of the rigidity modulus of commercial electrical-grade coppers.^{18,22-27} This appears to be very near 47 GPa, which corresponds to a Poisson's ratio of 0.350, assuming a Lamé parameter λ of 110 GPa, or a density of 8950 kg/m³ and longitudinal sound speed of 4770 m/s.

The constancy in elasticity of OF and ETP coppers allows the acoustic characteristics of such spheres to be calculated reliably. The fact of copper being a group III material and having a frequency-sensitive backscattering cross section and radiation force function is thus no drawback to its choice.¹³ Indeed, this feature may be exploited to obtain high, or low, values of backscattering cross section or radiation force function for a sphere size which could not be achieved with the harder, more acoustically constant group II materials.

The diameter of the copper sphere is determined in accordance with the optimization scheme developed in Ref. 4. The backscattering cross section is to vary as little as possible over the temperature range from 0° to 30 °C in sea water of salinity 35 ppt. Given that the target strength must be about -41.5 dB, the optimal diameter is found to be 30.40 mm. Machining a sphere of this size can be accomplished quite easily with a tolerance of 0.1%, which earlier investigations have shown to be adequate.^{4,7}

B. Tungsten carbide

Tungsten carbide with 6% cobalt added as a binder was chosen as a promising material. It is extremely hard—tungsten carbide is 9.5 on the Mohs hardness scale—and it is commercially available in the form of precision ball bearings. Only discrete sizes can be procured easily, but others can be obtained through the usual sintering process. Off-the-shelf ball bearings are available in convenient sizes for the purpose of calibrating the acoustic equipment used in fisheries research, where frequencies are typically in the range from 30 to 150 kHz.

Tungsten carbide is a group II material. The frequency dependence of its form function follows that of the ideally hard sphere up to a wavenumber-radius product of about six.¹³

The diameter of the sphere is chosen from the standard range of ball bearing sizes to obtain the target strength nearest to -41.5 dB. The selected diameter is thus 38.1 mm, i.e., 1.5 in., and the diameter tolerance is better than 0.01%.

II. METHOD

The objects of the comparison are a 30.40-mm-diam sphere made from electrical-grade copper, denoted Cu 30.4, and a 38.1-mm-diam sphere formed of tungsten carbide with 6% cobalt binder, denoted WC 38.1. Since these are intended for use in the calibration of 38-kHz echo sounders, the operationally defined backscattering cross section σ is the natural quantity for comparison.⁴ This is related to the incident signal spectrum S , the backscattering form function F , and the frequency response function H by the well-known formula:

$$\sigma = 4\pi \int_0^\infty |SFH|^2 d\omega / \int_0^\infty |SH|^2 d\omega, \quad (1)$$

where ω is the frequency. S , F , and H are normally explicit functions of ω .

In the computation below, S is the spectrum of a pulsed sinusoid, and H is the receiver response function of the Simrad EK-400/38 echo sounder.⁴ F depends on the characteristics of both the sphere and the medium, in addition to the frequency.²⁸ For the chosen homogeneous elastic materials, the relevant properties of the sphere are the radius a , the density ρ_1 , the longitudinal sound speed c_1 , and the transverse sound speed c_2 . The medium properties are expressed through the density ρ and the sound speed c . The nominal values of these quantities are given in Table I.

Variation of these parameters is the basis of the comparison, for discovery of an instability or other severe dependence of σ would suggest that the sphere is unsuitable for use in precision calibration. In order to render the comparison as realistic as possible, the ranges of variation are chosen in accordance with the following principles.

Ideally, the material parameters would be varied over percentage ranges corresponding to the larger of the observed parameter ranges of the two materials. However, knowledge of the particular tungsten carbide in WC 38.1 is extremely limited, and generic tungsten carbides span too wide a range of densities and elasticities to be meaningful for the intended comparisons.^{29,30} More is known about variations in copper, and the parameter ranges are therefore derived from the literature on high-purity polycrystalline coppers.⁶ These are shown in Table II.

The medium parameters ρ and c both depend on the temperature τ and the salinity. The intended application is marine, so the salinity is chosen to be 35 ppt. Temperature variations from 0° to 30 °C are considered, as in earlier studies.^{4,7} The medium density and the sound speed are determined by the hydrographic parameters in the usual manner.^{31,32}

Since the echo sounder may have to be calibrated in an untuned condition and might be used with different pulse durations, these parameters are varied over the ranges shown in Table II. The variation of the sphere diameter is redundant insofar as the scattering is a function of the wavenumber-radius product. Thus the same proportional change in frequency or diameter should produce the same change in form function. The examined 0.20-mm range in diameter

TABLE I. Parameters and their nominal values for the two spheres, immersion medium, and equipment.

Type	Name	Symbol	Units	Sphere	
				Cu 30.4	WC 38.1
Sphere	Diameter	$2a$	mm	30.4	38.1
Sphere	Density	ρ_1	g/cm ³	8.947	14.900
Sphere	Longitudinal sound speed	c_1	km/s	4.760	6.864
Sphere	Transverse sound speed	c_2	km/s	2.2885	4.1612
Medium	Density	ρ	g/cm ³	1.027	
Medium	Sound speed	c	km/s	1.490	
Equipment	Center frequency	f	kHz	38.0	
Equipment	Pulse duration	T	ms	1.00	

TABLE II. Ranges of parameter variations.

Parameter	Range of variation
ρ_1	$\pm 1\%$
c_1	$\pm 5\%$
c_2	$\pm 3\%$
τ	$[0, 30]^\circ\text{C}$
f	$\pm 0.5\text{ kHz}$
T	$\pm 0.5\text{ ms}$
$2a$	$\pm 0.1\text{ mm}$

variation is much larger than the manufacturing tolerance, but it is relatively small compared to the variation in the center frequency.

III. RESULTS AND DISCUSSION

The effects of varying the material parameters from the nominal values are shown in Fig. 1. In each case, the effects for the tungsten carbide sphere are observed to be much less than the corresponding ones for the copper sphere. This is a consequence of tungsten carbide being much harder, in an acoustic sense, than copper at frequencies near 38 kHz. In no case are the variations large, although the examined parameter ranges are considerable. In the worst case, that of the copper sphere Cu 30.4 when the transverse sound speed is varied, the maximum change from the nominal target strength is $\pm 0.1\text{ dB}$. Thus, even if the transverse sound speed were poorly known, use of the nominal target strength should allow a calibration to be performed with an accuracy of $\pm 0.1\text{ dB}$.

The temperature variation results in larger changes in the backscattering cross section. These are seen from Fig. 2 to be greater for the tungsten carbide sphere than for the copper sphere. Of course, the diameter of the copper sphere was calculated to minimize the temperature dependence. The diameter of the tungsten carbide sphere was merely selected from the limited range available in off-the-shelf items. Were the tungsten carbide sphere to be optimized in the manner of the copper sphere, then costly or nonstandard fabrication by machining or sintering would be necessary.

The precision of a marine calibration with the copper sphere will not be significantly affected by the weak temperature dependence of the target strength. The same is not true of the tungsten carbide sphere, for its target strength varies by 0.3 dB over the investigated temperature range. Since the temperature range from 0° to 5°C contributes 0.2 dB to this variation, however, a single value of target strength can be found which will ensure a precision calibration over the range from 5° to 30°C . The temperature during a calibration

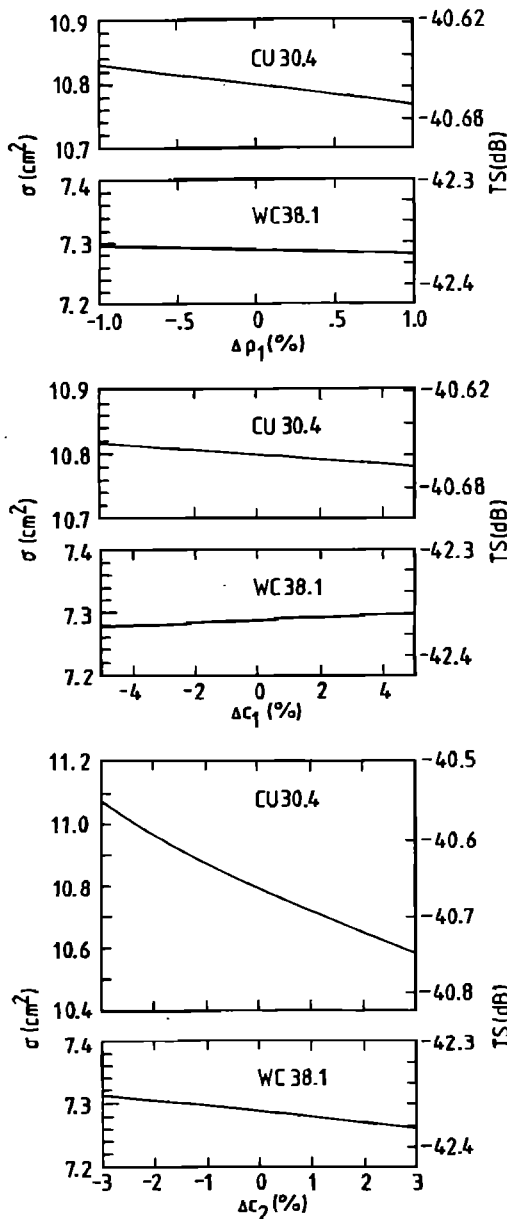


FIG. 1. Effects of material parameter variations on the backscattering cross sections σ of two calibration spheres. ρ_1 is the density, c_1 the longitudinal sound speed, and c_2 the transverse sound speed. Nominal values of these and other parameters are given in Table I. TS denotes the target strength, defined as $10 \log \sigma / (4\pi)$, where σ is given in mks units.

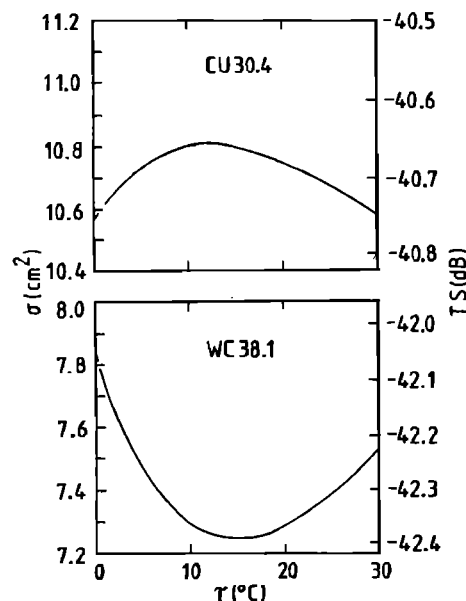


FIG. 2. Effects of temperature (τ) variation on the backscattering cross sections of two calibration spheres when they are immersed in sea water of nominal salinity 35 ppt.

could be measured, of course, and the target strength value adjusted, if necessary.

Variations in the equipment parameters are seen from Fig. 3 to produce similar effects on the backscattering cross sections of both spheres. As in the case of the material parameters, the computed changes in target strength are small enough not to upset a precision calibration. The same conclusion applies to the diameter variations, whose effects, as noted above, are similar to those of frequency.

It is noted that the copper sphere is a stronger acoustic target than the physically larger tungsten carbide sphere. The nominal target strengths are -40.7 and -42.4 dB, respectively. This illustrates the greater flexibility afforded by group III materials like copper, compared to those of group II, such as tungsten carbide. In the case of the harder, group II materials, which might *a priori* be considered more desirable for calibration applications, the range of variation

in backscattering cross section is smaller than that of materials in group III. The elasticity of these less hard materials may be exploited in a manner not possible with comparably sized specimens of harder materials.

IV. CONCLUSIONS

The effects of variations in material and equipment parameters are generally small for both the copper and tungsten carbide spheres. The greater hardness of the tungsten carbide sphere results in the target strength having an extremely weak dependence on the material parameters. However, this confers no particular advantage with respect to variations in the equipment parameters, for which the two spheres show comparable effects.

Temperature has a greater effect than the other considered parameters, especially in the case of the tungsten carbide sphere below 5°C . Insofar as the temperature can be measured or otherwise determined in a calibration exercise, corrections to the nominal target strength may be computed in order to preserve the 0.1-dB precision.

Both copper and tungsten carbide are excellent materials for precision calibration spheres. Such considerations as cost, the need for a particular target strength, and acoustic robustness, among others, must dictate the choice between these in any particular application. It is evident that hardness is not the only, or even the most important, property to be considered in selecting a reference target for the calibration of acoustic systems.

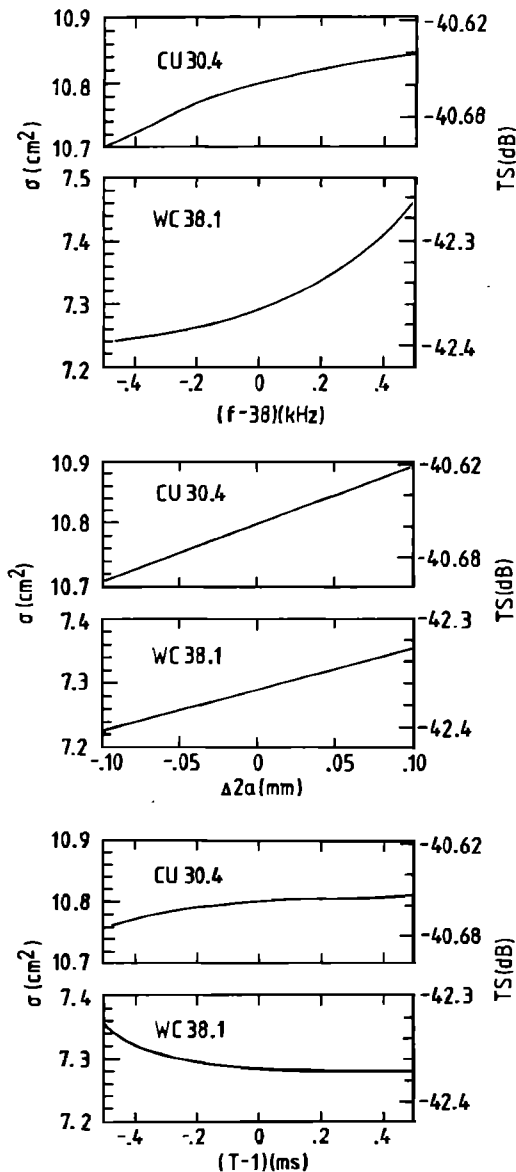


FIG. 3. Effects of variations in the equipment parameters and the diameter $2a$ on the backscattering cross sections σ of two calibration spheres. f is the center frequency and T is the duration of the transmit pulse.

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