

# Evaluation of a newly constructed Shooting Range with regard to Acoustic Safety

Christian Kleinhenrich, Philipp Bechtel, Karl-Wilhelm Hirsch  
*Cervus Consult GmbH, kleinhenrich@cervus.de*

## Abstract

In 2022, the extension „Acoustic Safety“ [1, 2] to the German Armed Forces construction guideline came into effect. Based on modern measurement methods and appropriate assessment criteria, this initiative aims to reduce noise exposure for personnel during shooting through structural measures. The primary objective is the minimization of additional sound reflections, which occur particularly in indoor shooting ranges.

This paper describes the stepwise application of the methodology, from the operator’s requirements and the identification of suitable surface materials to the completion of the facility. Furthermore, the evaluation results based on reflection and shooting measurements are presented.

## Basics - Acoustic Safety

The aim of the procedure is to compare the hearing exposure in a new facility with that of a known one.

### Determination of the Quality Number

The quality number ( $Q_S$ ) is a parameter used to determine the allowable number of shots in a shooting range. It indicates the percentage adjustment of the maximum shots needed to maintain equivalent hearing load conditions compared to a reference facility.

$$Q_S = \frac{N_S}{N_A} \quad (1)$$

Here,  $N_A$  is the maximum number of shots at a reference range, and  $N_S$  is the maximum at a relevant shooter position in the range under study. The reference is typically an open range with inclined side walls. The quality number can be obtained either through prediction or measurement, with both  $N_S$  and  $N_A$  derived from calculated or measured sound pressure time histories using the AHAH model[3].

**Table 1:** Classification of the load classes.

Class	Quality Number	Relative number of shots
A	$0,9 \leq Q_S$	90 %
B	$0,7 \leq Q_S < 0,9$	70 %
C	$0,5 \leq Q_S < 0,7$	50 %
D	$0,3 \leq Q_S < 0,5$	30 %
E	$0,1 \leq Q_S < 0,3$	10 %
F	$0 \leq Q_S < 0,1$	0 %

## Load Classes

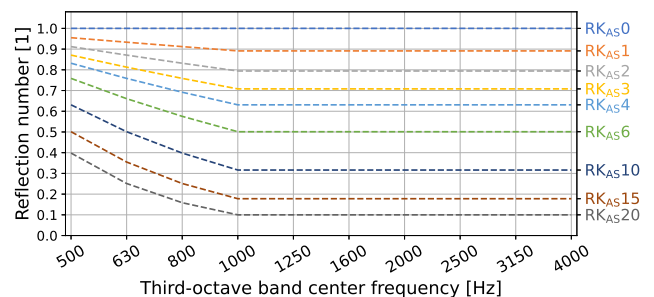
According to Table 1, the quality number  $Q_S$  is categorized into load classes. The table lists the relative number of shots for each class from A to F.

## Reflective Properties

Accurate consideration of reflections within a facility is a fundamental prerequisite for the procedure presented here. Absorption coefficients measured in reverberation chambers provide insufficient data for evaluating surface materials in shooting noise mitigation[4]. The applicable standard was DIN EN 1793-5:2018-12, which is commonly used in road construction. Purpose-driven simplifications allowed smaller sample sizes, and near-field holography methods[5] are also permitted.

## Reflection Classes

After determining the angle- and frequency-dependent reflection properties, the wall and ceiling systems are classified into the so-called reflection classes according to Figure 1. To meet a specific reflection class, the values for each third-octave-band between 500 Hz and 4 kHz must remain below the corresponding horizontal curves in Figure 1. For instance, to satisfy reflection class  $RK_{AS6}$ , a wall system must have a reflection coefficient of at least 0.5 in the frequency range from 1 kHz to 4 kHz. Below 1 kHz, the requirements are slightly lower, as this frequency range is less critical in terms of hearing hazard.



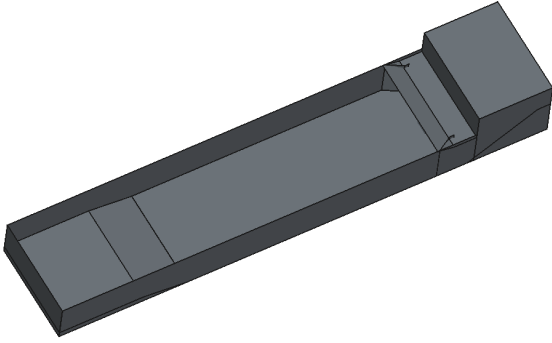
**Figure 1:** Third-octave specific reflection values of the reflection classes.

The use of reflection classes allows for preliminary studies using realistic reflection values. In addition, these classes can be used to establish product-neutral acoustic requirements for surface systems.

## Preliminary Studies

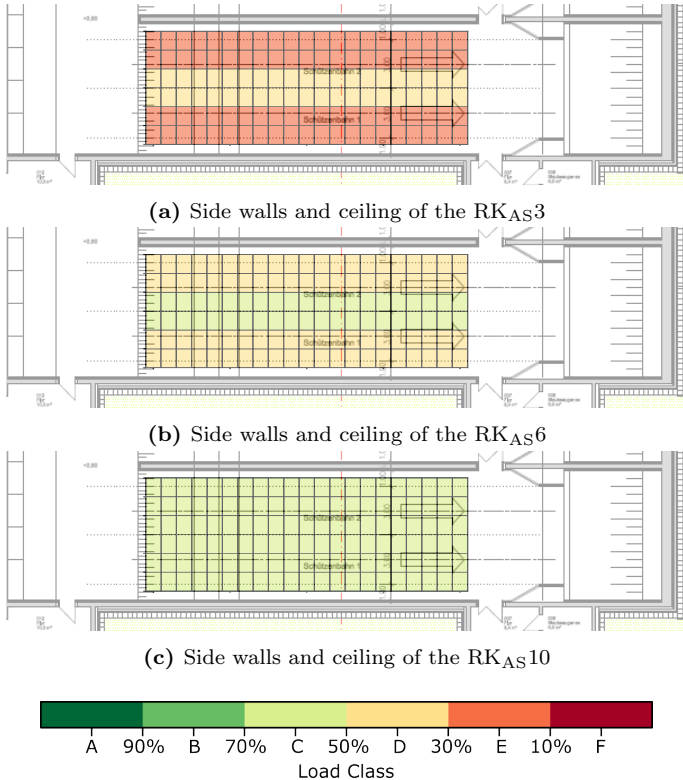
This section outlines the planning phase of an indoor shooting range. After the German Armed Forces identified the need for a new facility, the design focused on its intended use, with acoustic considerations initially secondary. Preliminary wall and ceiling systems with a maximum depth of 200 mm were selected to provide re-

coil protection and basic acoustic performance. Once the interior dimensions - approximately 32 m long, 8 m wide, and 3 m high - were set, preliminary studies on suitable surface systems began.



**Figure 2:** CAD model of the indoor shooting range

Unlike the final model shown in Figure 2, a simplified room geometry was assumed for these preliminary studies. The rear ramp was ignored, and the sloped bullet trap was replaced with a highly absorbent vertical panel. Broadband reflection classes were then applied to all surfaces. For example, the floor was set to  $RK_{AS0}$  and remained unchanged due to structural constraints. The side walls and ceiling, on the other hand, were the only surfaces that could be varied.



**Figure 3:** Personnel load charts from the preliminary studies as plan view projections. Rifle as weapon class and  $P_{B,2}$  as assessment point

Exemplary personnel load maps for three scenarios in which different reflection classes were applied to the side walls and ceiling are shown in Figure 3. Relative shot

numbers ranged from 10%–30% for  $RK_{AS3}$ , 30%–50% for  $RK_{AS6}$ , and 50% for  $RK_{AS10}$ . This demonstrating a clear link between surface reflection class and hearing load. Based on the installation depth and the available systems<sup>1</sup>, the operator set  $RK_{AS6}$  as the minimum requirement and  $RK_{AS10}$  as the ideal value. Consequently, the relative shot counts in the finished shooting range are 30%–50%.

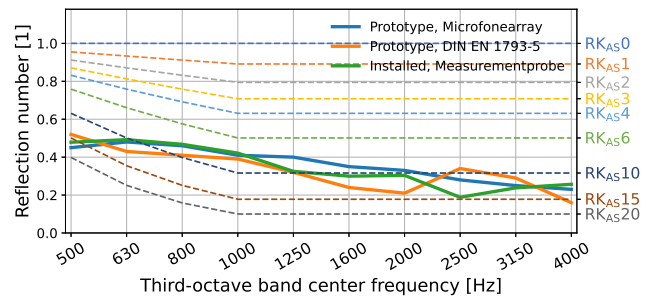
## Competitive Dialogue

Based on these requirements, a competitive dialogue started in 2021. In this legally compliant procedure, the client and manufacturers jointly developed a product. After the first phase, only one manufacturer remained, and it began developing a system that met the requirements of  $RK_{AS6}$ .

Initial acoustic tests measured individual materials with a near-field holography-based microphone array[5] to determine vertical reflection factors for  $1\text{ m}^2$  samples. Materials were combined into layered systems, re-measured, and a preferred system selected. A  $3.6\text{ m} \times 2.4\text{ m}$  prototype was then built and tested with both the microphone array and DIN EN 1793-5. Reflection values are shown in Figure 4. Once the system met  $RK_{AS6}$  and all other range-specific tests, the competitive dialogue concluded in summer 2022.

## Acceptance Measurements

By the end of 2024, the acoustic surface systems were installed and measured using a near-field holography-based measurementprobe, a further development of the microphone array. The results, shown in Figure 4 as the “Installed, Measurementprobe” confirm that the system meets  $RK_{AS6}$ . Comparison with the prototype measurements and across methods shows strong agreement.



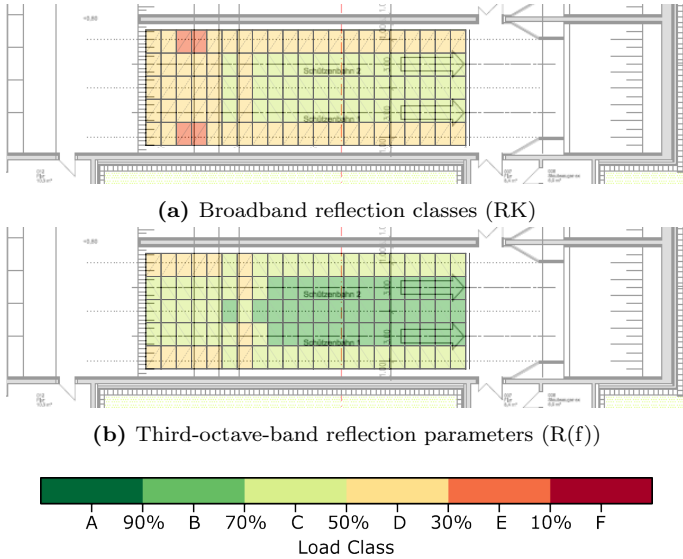
**Figure 4:** Reflection coefficients measured on the prototype and in the finished facility

In addition to the acceptance measurements, the reflection properties of the rear wall, composed entirely of ventilation grilles, and the acoustic impact of the ceiling-mounted lights were evaluated.

Using these and other on-site measured third-octave-band reflection values, the predicted personnel load maps

<sup>1</sup>In 2021, commercially available systems meeting other requirements reached at most  $RK_{AS3}$ .

<sup>2</sup>Over the years, the default source model weapon class has been changed from the rifle class to the pistol class.



**Figure 5:** Personnel load maps with broadband reflection classes and third-octave-band-dependent parameters as plan view projections. Pistol<sup>2</sup> as weapon class and  $P_{B,2}$  as assessment point

from the preliminary calculations were refined. The CAD model in Figure 2 was now simulated in full detail, including the rear ramp, sloped bullet trap, and doors.

Beyond reflection parameters, other simulation variables - such as the source model or muzzle height - can also be adjusted and each producing its own personal load map. This study considers two variants, shown in Figure 5, differing only in surface reflection properties: broadband versus third-octave-band parameters. The evaluation of these variants is presented in the section *Evaluation*, compared with shooting signal measurements in Figure 7.

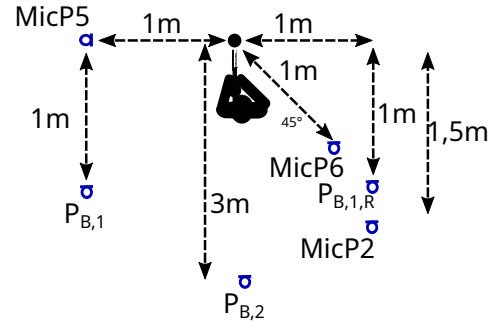
### Shooting Signal Measurements

By November 2025, the facility was fully completed and ready for shooting measurements. These tests aimed to verify that the previously calculated quality numbers and relative shot counts were actually achieved.

The Acoustic Safety procedure specifies fixed shooter and microphone positions. For the indoor range, six relevant shooter positions<sup>3</sup> were considered. In addition to the two primary microphone positions ( $P_{B,1}$  and  $P_{B,2}$  four additional measurement points were included. See Figure 6.

Each shooter used a pistol (P), a submachine gun (MP), and two rifles (G1 & G2) of different calibers. At each shooter position, ten shots per weapon were fired and recorded. The same weapons were measured on an open range as a free-field reference at the same points. Hearing loads were calculated from these signals using the AHAH model, and the quality numbers were then determined for each shooter, microphone position, and weapon.

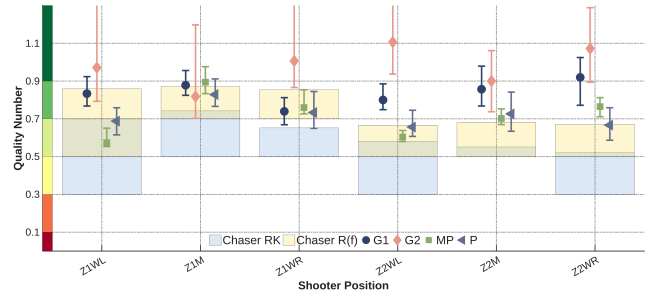
<sup>3</sup>For a front and rear zone each on the left, in the center, and on the right.



**Figure 6:** Sketch of the measurement points used for each shooter's position

## Evaluation

This section compares the measured quality numbers with the predicted values. An example for measurement point  $P_{B,1}$  across all shooter positions is shown in Figure 7.



**Figure 7:** Comparison of quality number based on measured and predicted values at  $P_{B,1}$  across all shooter positions

The abbreviations Z1 and Z2 indicate the front and rear zones, while WL, WR, and M refer to positions near the left wall, right wall, and center of the range, respectively. Quality numbers from the broadband (Chaser RK) and third-octave-band (Chaser R(f)) predictions are shown as rectangles. The top edge represents the highest predicted value and the bottom edge corresponds to the achieved load class from Table 1. Markers indicate the respective weapons, and the 20th and 80th percentiles define the upper and lower bounds of the spread bars.

For evaluation, each position and weapon is classified as critical overestimation  $\ominus$ , accurate prediction  $\checkmark$ , or conservative overprotection  $\delta$ . Table 2 shows an example for shooter position Z1WL according to Figure 7.




**Table 2:** Illustrative evaluation of the forecasting models for  $P_{B,1}$  and Z1WL

Weapon	G1	G2	MP	P
Chaser RK	$\delta$	$\delta$	$\checkmark$	$\checkmark$
Chaser R(f)	$\checkmark$	$\delta$	$\checkmark$	$\checkmark$

With six microphone and shooter positions, each weapon yields 36 data points, allowing an objective assessment of the prediction quality. An example for rifle G1 is shown in Table 3.

Using the broadband reflection model, no critical overestimations occur, but 86 % of cases show overprotection, making this model highly conservative. With third-octave-band reflection parameters, overprotection drops to 50 %, with only 8 % critical overestimation.

**Table 3:** Example assignment for the G1 rifle in the indoor shooting range

Model			
Chaser RK	0 (0%)	5 (14%)	31 (86%)
Chaser R(f)	3 (8%)	15 (42%)	18 (50%)

The allowable number of critical overestimations was set at 10 %. This accounts for the dynamic nature of modern shooting training, where both shooters and instructors are constantly moving. Moreover, hearing load is assessed cumulatively over many shots, so evaluating a single critical case is insufficient. In addition, the prediction models and load maps are also conservatively designed.

Considering the 10 % threshold, the third-octave-band reflection model is acceptable for the pistol P and rifles G1 and G2, making the exposure map in Figure 5b relevant. For the submachine gun MP, 11 % of cases exceed the critical threshold with the third-octave-band model, but none with the broadband model. Thus, the exposure map in Figure 5a applies for the MP.

## Conclusion

The outlined procedure - from needs assessment through product development to the completed range - provides a acoustically relevant evaluation metric at every stage. Predicted quality numbers initially defined realistic target shot counts, which in turn set the minimum acoustic requirements for surface systems and enabled a product-neutral procurement, here conducted via a competitive dialogue. Reflection values were measured in-situ on prototypes and the final installation to monitor and verify compliance. Acceptance was finalized through shooting signal measurements, confirming that the required relative shot counts were achieved.

Despite the Acoustic Safety procedure, prediction calculations retain some uncertainty, currently accounted for by allowing 10 % critical deviations. Optimization of source models [6, 7] could further improve prediction accuracy and reduce deviations.

## Acknowledgments

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## References

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