German Federal Institute for Risk Assessment

Science Report

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Gelatin as a test simulant for the effectiveness of hunting rifle bullets – investigations into the suitability of gelatin block sizes in comparison with the firing results and the significance of individual procedures

Suitability test of the simulant gelatin in two block sizes for the use of very high hunting rifle bullet energies of >5,000 J as well as testing of a modified method of crack length measurements

Suitability of two gelatin block sizes as ballistic simulant for hunting bullets tested with 2,900 J

Investigation of the influence of casting mold material and storage time on large gelatin blocks as a test simulant for hunting bullets

Dear readers,

which parameters are of decisive importance when testing hunting rifle bullets from the point of view of consumer health protection? The German Federal Institute for Risk Assessment (BfR) has investigated this question and has now come a great deal closer to its goal of increasing food safety by minimizing bullet fragments in game shot by hunters. The development of a method for estimating the possible entry of metallic fragments into the foodstuff "game meat" has been significantly advanced by these investigations.

The effect of a bullet, e. g. the formation of fragments when fired, can be simulated and thus evaluated in test simulants such as gelatin and ballistic soap. However, this is only possible if the test parameters of the simulant used are precisely described and the results are reproducible. Only then are the results reliable and comparable. In close scientific cooperation with national and international experts, the BfR initiated three research projects, the results of which are presented in this volume. On the basis of a procedure that has been tried and tested for many years in Germany for testing police bullets, which is carried out with gelatin blocks, it was first necessary to investigate whether the relatively small block size used in this procedure is also suitable for the much higher energy input of hunting rifle bullets. Result: The smaller blocks used for testing police bullets are not suitable for testing the effectiveness of high-energy hunting bullets. However, gelatin blocks with a larger block size are suitable. It was also compared whether different process steps such as the material of the molds, the cooling time of the gelatin and the storage time of the test blocks have a significant influence on the test results of the bullet. It was found that the use of different mold materials had no influence on the bombardment results. Further results show that due to the larger block size, a longer cooling time is required prior to bomardment and the shelf life of the larger blocks is extended prior to shelling. The bombardment can therefore take place within a maximum period of four days after reaching the required core temperature.

The conditions are now in place to test a method for testing hunting rifle bullets as part of an international round robin test on the basis of standardized test parameters in order to scientifically describe the effectiveness of these bullets when firing large gelatine blocks on the basis of qualitative and quantitative parameters.

I wish you an interesting read.

Professor Dr. Dr. Dr. h.c. Andreas Hensel

German Federal Institute for Risk Assessment

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Gelatine als Prüfsimulanz für die Wirksamkeit von Jagdbüchsengeschossen – Untersuchungen der Eignung von Gelatineblockgrößen im Vergleich der Beschussergebnisse und die Bedeutung einzelner Verfahrensschritte

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Investigation of the influence of casting mold material and storage time on large gelatin blocks as a test simulant for hunting bullets

Suitability test of the simulant gelatin in two block sizes for the use of very high hunting rifle bullet energies of > 5000 J as well as testing of a modified method of crack length measurements

Suitability of two gelatin block sizes as ballistic simulant for hunting bullets tested with 2900 J

Liebe Leserinnen und Leser,

welche Parameter sind bei der Prüfung von Jagdbüchsengeschossen aus Sicht des gesundheitlichen Verbraucherschutzes von entscheidender Bedeutung? Dieser Frage ist das BfR nachgegangen und ist jetzt dem Ziel, die Lebensmittelsicherheit durch Minimierung von Geschossrückständen in jagdlich erlegtem Wild zu erhöhen, ein großes Stück nähergekommen. Die Entwicklung eines Verfahrens zur Abschätzung eines möglichen Eintrages von metallischen Fragmenten in das Lebensmittel „Wildbret" wurde durch diese Untersuchungen maßgeblich vorangebracht.

Die Wirkung eines Geschosses, z. B. die Bildung von Fragmenten beim Beschuss, kann in Prüfsimulanzien wie Gelatine und ballistischer Seife simuliert und somit bewertet werden. Dies ist jedoch nur möglich, wenn die Prüfparameter der verwendeten Simulanz genau beschrieben und die Ergebnisse reproduzierbar sind. Nur dann sind die Ergebnisse belastbar und vergleichbar. Das BfR initiierte in engem wissenschaftlichem Austausch mit nationalen und internationalen Fachleuten drei Forschungsvorhaben, deren Ergebnisse in diesem Band vorgestellt werden. Auf der Grundlage eines zur Prüfung von Polizeigeschossen in Deutschland langjährig erprobten Verfahrens, das mit Gelatineblöcken durchgeführt wird, musste zunächst untersucht werden, ob die dabei verwendete relativ kleine Blockgröße auch für den sehr viel höheren Energieeintrag von Jagdbüchsengeschossen geeignet ist. Ergebnis: Die kleineren Blöcke, die zur Prüfung von Polizeigeschossen eingesetzt werden, sind zur Untersuchung der Wirksamkeit von hochenergetischen Jagdgeschossen nicht geeignet. Geeignet sind jedoch Gelatineblöcke mit größerem Blockmaß. Verglichen wurde auch, ob unterschiedliche Verfahrensschritte wie das Material der Gussformen, die Abkühldauer der Gelatine sowie die Lagerdauer der Prüfblöcke die Prüfergebnisse des Beschusses nennenswert beeinflussen. Es zeigte sich, dass die Verwendung der verschiedenen Gussformmaterialien keinen Einfluss auf die Beschussergebnisse haben. Weitere Ergebnisse zeigen, dass aufgrund der größeren Blockgröße eine längere Abkühldauer vor dem Beschuss erforderlich ist und sich die Lagerfähigkeit der größeren Blöcke vor dem Beschuss verlängert. Der Beschuss kann somit innerhalb einer Zeitspanne von maximal vier Tagen nach Erreichen der erforderlichen Kerntemperatur erfolgen.

Es sind nunmehr die Voraussetzungen gegeben, ein Verfahren zur Prüfung von Jagdbüchsengeschossen im Rahmen eines internationalen Ringversuchs auf der Grundlage von standardisierten Prüfparametern zu testen, um die Wirksamkeit dieser Geschosse bei Beschuss großer Gelatineblöcke anhand von qualitativen und quantitativen Parametern wissenschaftlich zu beschreiben.

Ich wünsche Ihnen eine interessante Lektüre.

Professor Dr. Dr. Dr. h.c. Andreas Hensel

BfR
German Federal Institute for Risk Assessment

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14 March 2024

Suitability test of the simulant gelatin in two block sizes for the use of very high hunting rifle bullet energies of >5,000 J as well as testing of a modified method of crack length measurements

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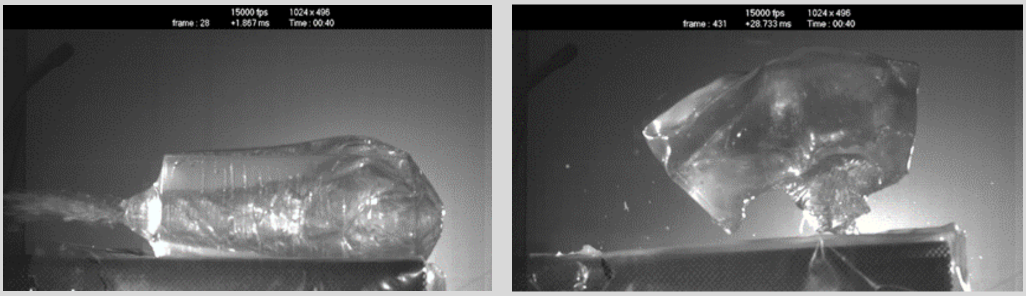
Images of high-speed camera shots during suitability testing of small gelatin blocks at very high hunting rifle bullet energy



Gelatin block: 35 cm x 15 cm x 15 cm / Bullet: RWS – Speed Tip Pro – 16.2 g
Caliber: 338 Lapua Mag. / Target velocity: 800 m/s – Target energy: 5,184 Joule

Content

1 Introduction

In order to make the impact potential of bullets measurable by specific parameters, test simulants such as soap and gelatin are usually shot in block form [1,2,3,4]. Both simulants resemble human or animal tissue in their density and viscosity and are therefore applied in the field of legal medicine and also as test simulants for police bullets and for testing bullet characteristics of hunting rifle bullets. The simulants are internationally recognized and proven. In the European region, 20 % gelatin “is often referred to as “NATO gelatin”” [5] and also 10 % gelatin is used for the production of the blocks, while in the USA 10 % gelatin is mainly used according to the FBI standard [6]. Of particular importance is the way in which the gelatin blocks are manufactured. The temperature during the manufacturing process and during storage until firing is handled differently. According to Fackler [7] the gelatin blocks in the USA are stored and shot at a temperature of 4°C. In Germany, the procedure is often in accordance with the instructions of the Technical Guideline Cartridge 2009, Annex 9 [1], so the gelatin blocks are stored and fired at 15°C. The procedural instructions apply to the production of gelatin blocks (20 % gelatin) measuring 35 cm x 15 cm x 15 cm (L x W x H) and are prescribed for testing police bullets and have been tested for many years. This size of gelatin blocks is also used for the evaluation of bullet characteristics of hunting bullets (Written communication: RUAG GmbH, Kronacher Straße 63, 90765 Fürth/Germany by e-mail dated 14.10.2022).

As part of a research project by the Federal Institute for Food and Agriculture, a draft technical guideline for hunting rifle bullets was developed [8]. In this guideline, essential test criteria for the performance of ballistic tests are derived and their applicability is tested and documented when using test simulants in the form of gelatin blocks and ballistic soap blocks with comparable dimensions (40 cm x 25 cm x 25 cm (L x W x H)). The gelatin blocks were produced according to the Technical Guideline Cartridge [1]. The extent to which the results of the gelatin block shots correlate with those of the soap block shots could not be conclusively answered, since too few shot data were available [8]. The question of reproducibility and comparability of the shooting results obtained using gelatin blocks of different dimensions also remained unanswered.

The German Federal Institute for Risk Assessment (BfR) is addressing these latter issues with the aim of establishing standardized test methods in order to contribute to the establishment of uniform national regulations for the minimization and prevention of harmful lead input into the game meat or, in a broader sense, into the environment in the interest of consumer health protection. The coalition agreement [9] for the 19th legislative period already sought an amendment to the existing Federal Hunting Act that would, among other things, provide for certification of hunting ammunition with optimal killing effect while minimizing lead [10]. To this end, test procedure steps for the behavior of hunting rifle bullets in test simulants (gelatin or ballistic soap) are to be defined and required procedures standardized, which will serve both as a basis for BfR research approaches to demonstrate lead minimization in hunting rifle bullets and to answer questions about fragmentation of hunting rifle bullets across all bullet materials used and particle size distribution in game meat [11].

Years of experience with the Technical Guideline Cartridge [1], which is used for testing police bullets, initially suggested that essential procedures defined therein for a standardized test procedure for hunting rifle bullets should be adopted to a large extent.

These include the production of gelatin blocks (20 % gelatin), the block dimensions: 35 cm x 15 cm x 15 cm (L x W x H), the shooting procedure and the methods for determining the effectiveness of the bullets to be tested. However, since higher bullet energies (8 to 10 times the muzzle energy) are involved in the use of hunting rifle bullets compared to police bullets, a research project was initiated by the BfR in 2019 to investigate the comparability and reproducibility of firing results of the two commonly used gelatin block sizes.

In a two-stage project, the load capacity of the two block sizes was first determined in a first part. With the aim of achieving as significant as possible a difference in the measurable parameters of the two gelatin block sizes when fired at, a bullet (RWS .338 Lapua Magnum SPEED TIP PRO 16.2 g) with a very high energy input of >5,000 J was selected. It is well known that this bullet (in combination with the caliber) tends to be one of the less frequently used hunting rifle bullets by hunters.

As a result of firing at the small block size under these conditions, it was expected that this block size would not withstand the very high energy input of the bullet into the gelatin block and the block would rupture. In contrast, the large block size was expected to withstand the very high energy input of the projectile.

In the second part of the project, a high-energy bullet (energy input of 2,915 J) more frequently used by hunters was selected for comparison: “Evolution”, caliber 30-06 Springfield from RUAG with a mass of 11.9 g and a target velocity of 700 m/s at 100 m which is usual for hunting. The findings obtained will be published in a further paper. The investigations required a slightly modified test setup with the aim of being able to derive the effectiveness of the bullet according to the specifications of the Technical Guideline Cartridge [1]. A meaningful and reliable comparison of shooting results depends, among other things, on the production of qualitatively uniform gelatin blocks, since the energy input of the bullet on its way through the gelatin block causes cracks of different length and shape as parameters to be evaluated. Based on the crack length measurements, a calculation of the effectiveness of the projectile used is possible. A certain disadvantage of the previous method is the necessity of an immediate measurement of the crack lengths directly after the shot at the block, since the gelatin has only a limited shelf life due to its sensitivity to temperature and movement as well as its change in gel strength due to progressive microbiological processes [1]. A follow-up measurement or repeated observation of individual gelatin block slices after weeks therefore does not provide comparable measurement results. For this reason, the BfR additionally wanted to optimize the method. This is based on the previous method [1], but should be supplemented by a standardized, photographic registration of the individual block slice sides with their crack lengths (BfR method). The aim of this method is to provide a location- and time-independent documentation of the crack lengths in the gelatin block slice sides. With the support of national and international users of the modified method, it will be tested and examined with regard to its manageability, statistical significance and suitability by comparing the results of the users with each other and with the existing standard method.

2 Material and methods

2.1 Production and storage of gelatin blocks

Three blocks each in stainless steel molds with two block sizes, 35 cm x 15 cm x 15 cm (L x W x H) as well as 40 cm x 25 cm x 25 cm (L x W x H) (Appendix A 1, Photo 1), were produced and stored in the Beschussamt Ulm according to the instructions in Annex 9 of the Technical Guideline Cartridge [1]. In a detailed recorded time frame, two large gelatin blocks and one small gelatin block were produced on December 9, 2019 and one large block and two small gelatin blocks were produced on December 10, 2019, each between 7:30 am and 10:00 am. The gelatin was mixed, filled into the molds and, after a cooling phase at a temperature of 20°C ± 1°C, removed from the molds, wrapped in PE film (A 1, Photo 2) and stored in a climatic chamber (make: CTS type: CW-40/3 No.: 091131) at 60 % ± 5 % humidity and 15°C ± 1°C (A 1, Photo 3).

2.2 Test setup

2.2.1 Setup of the shooting cabin and shooting channel

The test setup for the shooting experiment at the Beschussamt Ulm (BA Ulm) is shown in Fig. 1.

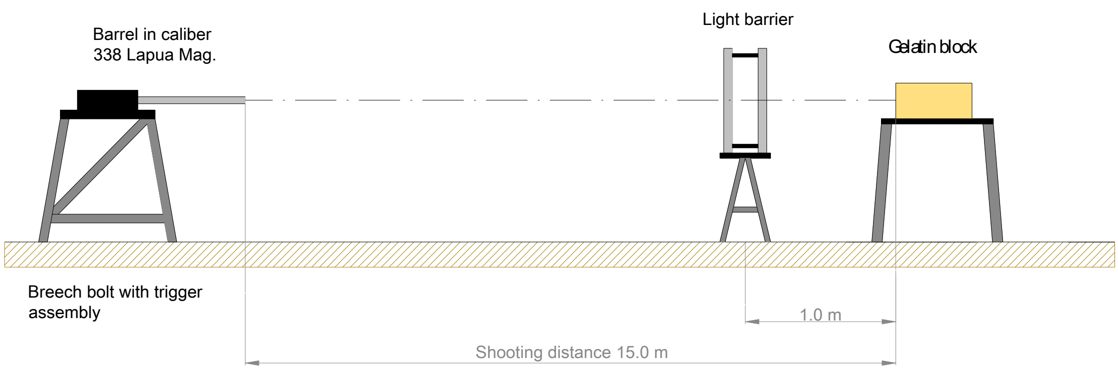


Figure 1: Sketch of the experimental setup for study I (drawing not to scale).

The measuring barrel (barrel length 600 mm, twist length 254 mm) was made available by the Deutsche Versuchs- und Prüf-Anstalt für Jagd- und Sportwaffen e.V. (DEVA), as well as the previously loaded .338 caliber cartridges for a shooting distance of 15 m and bullet target veloctity (v_{Target}): 800 m/s ± 5 m/s. The barrel was clamped in a shooting cabin (A 1, Photo 4) in an electronically controlled shooting system (HPI - EPVAT Receiver Unit 292UR, http://www.ballisticmeasurements.com/epvat-receiver-unit.php) (A 1, Photo 5) and of a laser pointer on the gelatin block to be shot in the middle of the front. A light barrier was set up at a distance of 1 m in front of the front of the gelatin block to check the bullet target velocity. The infrared precision light barrier (Drello Mod.: LS23 with BAL 4043-08 serial number: 1726A0802, measuring base 1000 mm) is located in a transportable and height-adjustable square rod lying in a rail (A 1, Photo 6).

All gelatin blocks were placed on a pedestal made of Regupol plates covered with plastic film. The residual velocity of the bullet after the bullet residue exits the penetrated gelatin block was not measured. The aim of the project was not to calculate the effectiveness of the bullet as described in Technical Guideline Cartridge [1], but primarily to investigate the load capacity of the gelatin block sizes for testing high-energy hunting rifle bullets.

2.2.2 High speed camera and illumination units

To visually capture and better interpret the response of the gelatin blocks to the bombardment, videos were captured using a high-speed camera (Photron Fastcam SA5 (https://photron.com/fastcam-sa-5/)). On the long side of the blocks, the high-speed camera, installed on a tripod, was aligned (A 1, Photo 7) and controlled from a bulletproof observation room via a laptop computer. A large field of view is required to show the movement of the block over as large an area and time span as possible. The shutter speed was therefore set to 1/20,000 s and the frame rate to 15,000 fps. To illuminate the recordings, two lights were positioned at a distance of about 1.5 m from the long sides of the blocks and another (LED light) was positioned half-right from the front side.

2.2.3 Set-up for the standardized acquisitionof crack lengths

2.2.3.1 Cutting devices

The fabricated cutter for the large block size is similar to that described in Technical Guideline Cartridge Annex 9 [1], as shown in Appendix A 1, Photos 8 and 9.

For cutting the small blocks, the cutting machine (Make: OMAS, Food Machinery) was used, as it is used for cutting food, e.g. bread or sausage (A 1, Photo 10).

2.2.3.2 Lighting table

For better visualization of the crack lengths, a lighting table with an opal glass plate was used, which was illuminated from below with two light tubes (type: L65W/25U, Weiss Universal-White) (A 1, Photo 11). For transporting the gelatin block slices of the small blocks, a rolling cart was available due to the greater distance from the cutting table to the lighting table (A 1, Photo 12). The gelatin block slices of the larger blocks were transported on a tray (A 1, Photo 13), since the cutting device was located in the immediate vicinity of the lighting table. Influences due to vibrations and incorrect handling during transport, and thus possible effects on the crack lengths, were to be kept as low as possible.

2.2.3.3 Standardized photography

The tripods for the photo camera (Nikon D4s, lens: Nikon 60 mm), the LED lights and a climbing aid for taking photos from a 90° position above the gelatin block slice were positioned on the long side of the lighting table (A 1, Photo 14). The distance of the camera to the respective gelatin block slice was always the same due to the fixation of the camera to the arm of the tripod (distance: 90 cm). The positioning of the respective gelatin block slice side on the lighting table was ensured by marking with adhesive tape on the opal plate.

2.3 Implementation of the bombardment on 12 December, 2019

A total of six gelatin blocks were shot at. In principle, only one shot was fired at each gelatin block as soon it was transported from the climatic chamber to the shooting channel. The first shots were fired at the smaller block size. After that, shots were fired at the three large gelatin blocks.

Ambient conditions in the shooting channel at the beginning of the bombardments:

- Relative humidity: 55 %.
- Temperature: 21°C.

2.4 Crack length measurements (procedure instructions)

2.4.1 Determination of crack lengths according to Technical Guideline Cartridge, Annex 9 [1]

The measurement method described there [1] and used by the Beschussamt Ulm (BA Ulm) is based on the procedure according to Knappworst and Gawlick [12].

The individual cracks (j) with their lengths (L = length in mm), were measured on each slice (i) of the front side (VS) or the back side (RS) from the center of the shot outward to the crack tip in mm and the values were entered in a prepared form (Appendix A 2) according to the Technical Guideline Cartridge [1]. The crack lengths were always measured by the same member of staff during the measurement period at the BA Ulm in order to minimize sources of error. A second employee transferred the measured values to the prepared form.

In the case of forked cracks, the shorter crack with its own crack length from the fork to the crack tip was recorded.

The following specifications of the Technical Guideline Cartridge [1] have been optimized:

a) Cutting the gelatin block

Immediately after the shot, the small and the large gelatin blocks were cut into 2.5 cm (according to [1]: 2.0 cm) thick slices at 90° to the direction of the shot. The choice of the slice thickness of 2.5 cm was chosen as a compromise between accuracy and cost. The slices were marked with a consecutive number “i = 1 to i = 14 or i = 16” (corresponding to the block sizes), starting with the first slice (i = 1) at which the bullet entered the block, up to the rearmost slice i = 14 for 35 cm long blocks (according to TR) and i = 16 for 40 cm long blocks. Furthermore, each slice has been marked in such a way that the front side facing the weapon (VS) or the rear side facing away from the weapon (RS) can be clearly identified with a marking (label) (A 1, Photo 15).

b) Color marking of the crack lengths

The slices were then placed on the lighting table and the courses of the individual cracks on the front and back (numbered according to index j), which were thus clearly visible through the background lighting, were marked with a moistened copying pencil (Faber Castell water-based varnish) (A 1, Photo 16). Care was taken to blunt the pen tip beforehand by applying pressure to a firm surface so as not to alter the crack lengths during marking. After the crack lengths in blocks 1 and 2 were marked in red on the front and back sides of the gelatin block slices, the crack lengths on the back sides of the slices in block 3 were marked in green in the course of the measurements to better distinguish the colored crack lengths of the front sides from those of the back sides.

A circular template with the following designation was used to measure the crack lengths: Mitutoyo RA1.30 - 201388 (A 1, Photo 17).

2.4.2 Determination of crack lengths with application of the modified method according to the Technical Guideline Cartridge [1] on photo basis (BfR method)

A standardized photograph of each color-marked and labelled gelatin block slice side was taken prior to crack length measurement using the procedure described above (Fig. 2).

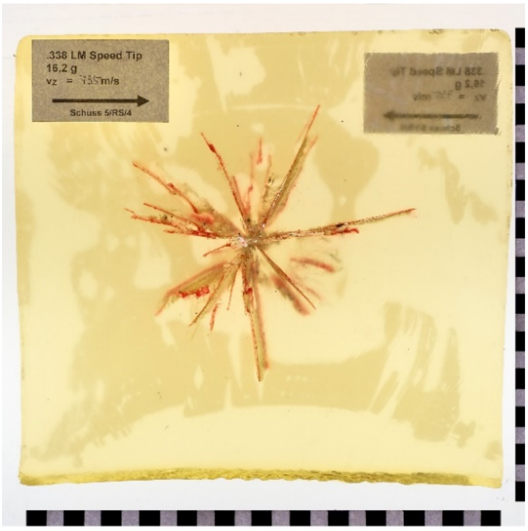


Figure 2: View of the standardized photograph (gelatin block slice).

The label contained the following information: Name of the bullet, caliber specification, measured target velocity (subsequent entry) as well as the shot identifier, the target number (following the shot direction) with specification of the front side (VS) or back side (RS). It is also important to note that each label was marked with an arrow exactly 5 cm long, which served as a scale.

2.4.3 Data sheet for entering the crack lengths and determination of total crack length of the gelatin block

The data sheet for capturing the crack lengths on a photo basis after conversion to scale is shown in Fig. 3, which is similar to the one used in Ulm.

				j: crack length number																					
Slice number i	Penetration depth	Side	Arrow	j=1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	$S_{i.front}$/ $S_{i.back}$	$L_{Total.i}$
1	0,0 cm	front		24,2	22,8	39,1																		86,108	128,41
	2,5 cm	back		16,1	11,1	39	4,23	22	11,6	24	23,3	19,3												170,71	
2	2,5 cm	front		25,3	22,5	27,8	24,5	13,8	40,2	11,1	18,8													184,02	290,83
	5,0 cm	back		55,4	26,4	21,9	47,6	52,1	40,8	19,3	36,6	29,1	68,4											397,64	
3	5,0 cm	front		59,1	71,4	15,3	7,07	61,5	36,5	31,5	50,1	56	14,5	16										418,91	555,73
	7,5 cm	back		34,3	45,9	17,9	27,6	45,2	16,1	78,1	28,2	25,1	29,7	65,1	41,9	66,5	26,8	72,7	71,6					692,55	
4	7,5 cm	front		14,4	31,9	33,6	72,4	12,5	24,7	44,5	44,9	47,1	9,23	69	25,8	23,7	24,8	81,7	61,6	40,3				662,19	660,86
	10,0 cm	back		80,1	88,9	18,1	47,7	72,8	37,2	13,5	52,3	23,3	44,2	34,8	34,1	50	62,5							659,54	
5	10,0 cm	front		64,8	78,6	10,4	30,9	24,8	50,2	30,5	34,9	23	50,4	82,8	22,2	78,5	19,4	21,6						623,07	664,39
	12,5 cm	back		80,9	20,3	81,5	21,1	14	59,3	37	53,6	62	61,1	79,3	21,1	62,7	51,9							705,72	
6	12,5 cm	front		62,7	44,4	86,3	59,1	9,25	58,7	56,9	29,7	19,4	88,9	28,6	115	43,8								702,23	703,98
	15,0 cm	back		49	112	42,4	59,6	15,8	46,4	44,4	50,8	8,75	17,2	44,8	51,9	64,6	21,4	26,1	23,5	11,6	15,8			705,72	
7	15,0 cm	front		50,3	31,9	23,8	66,2	13,1	42,3	22,2	65,4	21,4	64,3	47,5	33,7	8,07	88,7	10,2	20,5	112				721,42	732,09
	17,5 cm	back		88,4	33,5	60,3	32,8	44,8	36,4	20,9	44	84	16,6	60,3	29,1	22,2	48,3	87,4	33,6					742,77	
8	17,5 cm	front		25,8	44,1	8,12	53	26,2	41,9	13,2	76,7	20,4	58,3	15,4	64,6	27,7	16,6	16,4	85,4	29,7				623,22	579,31
	20,0 cm	back		115	67,1	43,3	21,1	12,8	28,4	93	21,1	39,1	34,3	23,2	36,7									535,4	
9	20,0 cm	front		17,5	17	22,3	27,7	39,2	21,3	95,7	42,8	16,5	25,7	57,3	116									499,45	415,91
	22,5 cm	back		68,4	49,3	38,8	95,2	20,2	16,3	44,1														332,36	
10	22,5 cm	front		117	42	13,3	92,7	16,7	34,1															315,42	345,17
	25,0 cm	back		73	24,2	40,1	15,7	75,1	33,4	58,7	20,9	33,8												374,93	
11	25,0 cm	front		47	28,6	34,3	35,1	10,4	13,7	11,7	18,9	58,9	72,9	26,4										358	306,58
	27,5 cm	back		72,3	6,8	22,3	69,9	18,2	57,6	8,09														255,16	
12	27,5 cm	front		74,7	9,57	60,8	17,1	65,7	9	15,5	5,73													258,13	237,19
	30,0 cm	back		67,4	33,4	40,5	52,2	11,9	10,8															216,25	
13	30,0 cm	front		69,4	47,2	24,3	52,5																	193,39	233,68
	32,5 cm	back		52,6	47,3	12,7	14,3	21,9	4,86	14,6	65,6	19,8	5,12	4,68	8,15	2,26								273,97	
14	32,5 cm	front		44,1	52,5	27	32,1	16,2	15,2	21,8	25,4	34,6												268,88	303,81
	35,0 cm	back		42	13,6	17,1	35,2	3,33	10,3	30,7	17,9	44,6	27,5	17,7	12,3	35,5	30,8							338,75	
15	35,0 cm	front		48,2	8,84	15	28,4	34,4	17,3	15,1	36,2	27,2	9,99	16,1	20,6									277,22	231,32
	37,5 cm	back		27,3	16,6	28,9	12,8	26,4	10,7	22,6	8	32,2												185,42	
16	37,5 cm	front		21,6	19,6	16,4	7,39	9,24	31,3	7,13	6,81	16,5	21,5											157,47	115,01
	40,0 cm	back		20,7	15,3	10,5	8,48	17,6																72,554	
BfR	Bundesinstitut für Risikobewertung						Beschussamt Ulm							12.12.2019						L_{Total}					6504

Figure 3: Example of a data sheet for entering the crack lengths on a photo basis (true to scale).

It was sent to the national and international users of the modified method together with further detailed information on how to perform the crack length measurements. The main working steps are described as follows:

Individual cracks (j) with their lengths (L = length in mm), were measured on each slice (i) of the front side (front) or the backside (back) and the values were entered into the prepared form.

First, the crack length sums $S_{i.front}$ (sum of the crack lengths in the front side of the slice i) and $S_{i.back}$ (sum of the crack lengths in the backside of the slice i) were calculated for each individual slice side. To determine the total crack length ($L_{Total.i}$) in slice i (Formula 1), the mean value was formed from the crack length sums $S_{i.front}$ and $S_{i.back}$ [3].

$$L_{Total.i} = \frac{1}{2} * (S_{i.front} + S_{i.back}) \qquad (1)$$

where

$$S_{i.front} = \sum_{j.front} L_{i.j.front} \qquad (2)$$

$$S_{i.back} = \sum_{j.back} L_{i.j.back} \qquad (3)$$

For each block, the total crack length L_{Total} results from the sum of the mean values per slice (Formula 4).

$$L_{Total} = \sum L_{Total.i} \qquad (4)$$

2.4.4 Measurement tools for determining of crack lengths

Thirteen external crack length analyzers measured the crack lengths of each of the 16 slices (front and back) using photos. The measurements performed with different measurement tools (Fig. 4).

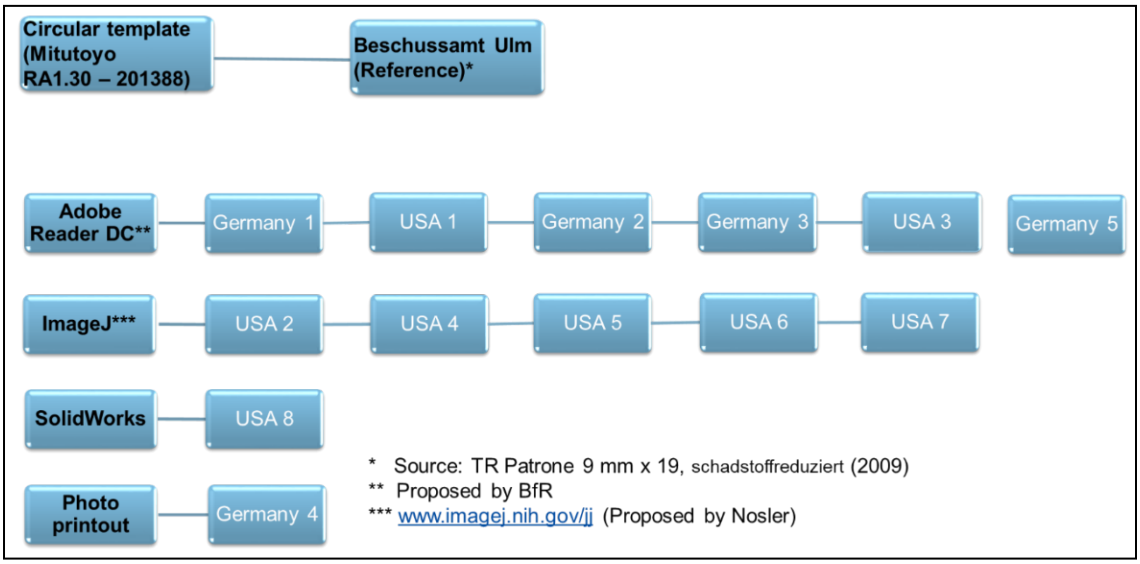


Figure 4: Crack length measurements performed with different measurement tools.

Six crack length analyzers measured the crack lengths based on the photos with measuring tool of Adobe Reader DC (Germany 1, 2, 3, 5, USA 1, 3) and 5 used the software "ImageJ" (USA 2, 4, 5, 6, 7). USA 8 used the Solid Works CAD program, and Germany 4 printed out the photos and then measured them.

2.5 Statistical analyses / Analyses of crack lengths

All statistical evaluations refer to determination of crack lengths with application of the modified method according to the Technical Guideline [1] on photo basis.

A Generalized Additive Model (GAM) was used to assess the effect of the penetration depth of the bullet into the gelatin block on the crack lengths measured with different measurement tools. For this, the GAM with cubic spline was fitted [13] . GAMs provide a suitable design for dealing with non-linear, smooth relationships between response and predictors. In this model, the lognormal distributed response variable is the measured crack length $L_{Total.i}$ [cm] in the slices i. Predictor variables are the non-linear term "penetration depth" of the bullet in the gelatin block as well as different measurement tools as categorical terms. The crack length measurements from the Beschussamt Ulm were used as a reference category for the variable "measurement tool". Thirteen crack length analyzers were included as random variable (Formula 5). GAM was fitted with a log link with the Gaussian family by using the restricted maximum likelihood (REML) algorithm from the "mgcv" package [14]. The Akaike Information Criterion (AIC) was used for model selection where the model with the lowest AIC was selected.

Formula 5 indicates the Generalized Additive Model (GAM) with Gaussian family.

$$L_{Total.i} = \beta_0 + s(\text{penetration depth}, bs = \text{"cr"}, \text{by=Measurement Tool}) + s\,(\text{crack length analyzer}, bs = re) + \text{Measurement Tool} + \varepsilon \quad (5)$$

where

- $L_{Total.i}$ is crack length of slice i as response variable
- β_0 is the intercept term, it denotes the overall mean of the response
- s(penetration depth, by = measurement tool) is a smoother that accounts for the path of the bullet through the block stratified by measurement tool
- s(crack length analyzer) is a random effect smoother for 13 crack length analyzer
- "Measurement tool" is a categorical term with reference category "Beschussamt Ulm" (measurement directly after shooting) and three measurement tools (Adobe Reader DC, ImageJ, Photo printout) at a later time and location-independent
- ε is a Gaussian error term (the unexplained variation)

A prediction model was used to show the crack lengths as dependent on the adjusted penetration depth, which fits the crack lengths of all crack length analyzers. 95 % confidence intervals of the fitted smoother are shown as shaded gray. The goodness of fit of GAM was evaluated on the basis of explained deviation R2 using the R package caret [14]. R2 represents the quadratic correlation between the observed and predicted result values and assess the model quality.

Scatter plots show the relationship between the penetration depth (measured in 2.5 cm steps for each individual slice i) of the bullet into the gelatin block and the crack lengths ($L_{Total.i}$) measured with different measurement tools. The GAM smoothing procedure was applied to fit a smooth curve through points in the scatter plot. This visual representation of the data was done with the R packages "ggplot2" [15].

Paired Wilcoxon exact-rank test from R package “exactRank” [16] was used to compare the total crack lengths L_{Total} of the front and back sides with the crack lengths without considering the back side.

To model the over-dispersed number of cracks per slice depending on crack length analyzer and penetration depth, a GAM was also fitted but with negative binomial family. Formula 6 indicates the Generalized Additive Model (GAM) with negative binomial family.

$$\text{Number of cracks} = \beta_0 + \text{s(penetration depth, bs} = \text{cr)} + \text{crack length analyzer} + \varepsilon \qquad (6)$$

where

- Number of cracks is the response variable
- β_0 is the intercept term, it denotes the overall mean of the response
- s(penetration depth) is a smoother that accounts for the path of the bullet through the gelatin block
- “crack length analyzer” is a categorical term with reference category “Beschussamt Ulm” (Measurement directly after shooting)
- ε is a Gaussian error term (the unexplained variation)

All statistical analyses were two-sided and *p*-values <0.05 were set as the threshold for statistical significance. Statistics were done using R version 4.1.2 [17]).

3 Results and discussion

3.1 First observations

The firing at the gelatin blocks could be observed from a side room secured with an armored glass pane. On the display of the laptop, which controlled the high-speed camera, the bombardment could be followed directly in slow motion from there.

The total of six shots of the six gelatin blocks were documented with the high-speed camera (shot 1 to 3 = small blocks, shot 4 to 6 = large blocks). Two can be viewed at the following video links in Appendix (A 3).

Appendix (A 3), Video 1:
Small gelatin block size_Ulm_shot3_block_3_791,5m-s.mp4

Appendix (A 3), Video 2:
Large gelatin block size_Ulm_shot4_block_1_797,28m-s.mp4

Observations noted directly during firing at the block and shortly thereafter are explained below.

3.1.1 Small block size

The first small gelatin block was subjected to a massive energy input by firing at, which threw the entire block upwards and caused it to roll over backwards so that it came to rest on top of the collecting plate for the bullet residue (A 1, Photo 18). When viewing the high-speed camera images, a stronger lifting of the bullet side compared to the reject side of the block could be observed, combined with a pulsation and twisting of the entire block. The subsequent inspection of the block in the shooting channel showed that when the bullet passed through the gelatin block, the very high energy release along the penetration depth led to longitudinal cracks on the upper side of the gelatin block. However, the external appearance of the gelatin block remained unchanged in its basic shape (A 1, Photo 19). The longitudinal cracks had collapsed and the surface was smooth. The extent to which the pulsing/movements of the block after the shot has passed through influences the crack length formation and is reflected in the energy balance for determining the effectiveness of the bullet cannot be recorded by the crack length measurement method. One possibility would be to assume that these movements/pulsing of all blocks are basically a systemic error, the magnitude of which cannot yet be quantified. The energy required for this is available for each shot. The intensity of these movements/pulsations depends primarily on the kinetic energy of the bullet and the gelatin block mass. The higher the target velocity and lower the gelatin block mass, the more pronounced the movements of the block. If the entire test medium compresses like a spring in several sequences and then pulls apart again, this justifies the assumption that such movements (pulsing) have an influence on the temporary cavity and the crack lengths. However, these are also dependent on other factors such as design, fragmentation and directional stability of the bullet in the test medium [3]. The impact angle of the projectile is always 90° in the tests or 0° in the NATO standard. To reproduce the result of the shooting, two more small blocks were fired at. The observations of block two was almost identical to the first results. Block three showed similar cracks, but the block rolled over and fell to the ground. The landing of the block on the ground may have altered the crack initiation along the shot channel in the block.

3.1.2 Large block size

Shooting at the three large gelatin blocks resulted in unexpectedly strong block vibrations despite the much higher block mass compared to the small blocks. Due to the high energy input, all three blocks lifted several centimeters from the contact surface after the bullet had passed through, with the sides of the bullet entering the blocks lifting more than the sides of the bullet exiting the gelatin blocks. When viewing the high-speed camera images, a pulsation of the gelatin could also be observed, but this was less pronounced compared to the smaller blocks. Only on visual inspection in the shooting chamber could it be seen that the energy release of the projectile along the penetration depth in the first two large blocks fired at, as with the small blocks, resulted in a longitudinal crack in the upper block face. The dark outlines of the shot channel and the collapsed cavern are clearly visible in Appendix (A 1, Photos 20 and 21).

In contrast, the energy release of the bullet was completely absorbed by the third large gelatin block, resulting in cracks that remained within the block.

Due to the light sources directed onto the block for the high-speed camera recordings and the immediately subsequent photographs of the blocks in the shooting channel, a superficial slight “liquefaction” of the gelatin blocks could be observed (A 1, Photos 20 and 21). In order to minimize the effects on the cutting of the blocks as far as possible, the shot blocks were wrapped in PE film after photography, transported on a rolling cart to the climatic chamber and stored at a temperature of 15°C ± 1°C until cutting. There were only one hour between the firing at a block and the cutting of the gelatin block slices, since all six blocks were first bombarded and then cut and the crack length measurements carried out on the same day.

3.2 Crack length measurements

Although the three small blocks did not allow correct crack length measurements due to the visible cutting of the surface, they were also sliced, marked and photographed. Thus, the statements on the crack lengths can be substantiated and possibly evaluated later with other objectives. In blocks 1 and 2 of the large block size, cracks also occurred over the edge of the gelatin block slices. Therefore, the crack lengths were not determined for these two blocks either. Only one large block (shot 6, block 3) withstood the very high energy input of the bullet, with the crack lengths along the shot channel remaining in the block (Photo 22). For this reason, only the crack lengths in block 3 were measured and statistically evaluated for the method comparison.

This result could possibly indicate a limit value with regard to the load capacity of the large blocks as a result of the very high energy input specific to the bullet. However, this could not be statistical verified due to the few bombardment repetitions. The crack length measurement procedure [1] requires the crack lengths to be measured immediately after the shot. Due to the chemical-physical properties of gelatin (in particular its sensitivity to heat and movement) and its time-dependent microbiological changes, it is not possible to store the gelatin block sides for subsequent evaluations. Thus, the previous method is location- and time-bound.

One cause of the different load capacity of the large blocks could be the duration of storage of the gelatin blocks prior to the shooting and the associated temporal differences in the cooling of the large gelatin blocks. The results of the study by Maiden et al. [18] point to possible effects of the storage period and the temperature of the blocks during firing at. Due to the standardized production of the gelatin blocks (point 2.1) on two consecutive days, on which at least one large and one small block were produced and the blocks were stored in the climatic chamber for at least 36 hours at 15°C before the shooting, a direct correlation with the two factors “storage time” and “temperature” cannot be explained.

The crack lengths can also be altered by careless handling and by vibrations when transporting the gelatin block slices from the cutter to the lighting table. However, the manual transports were reduced to a necessary minimum in advance of the planning of the tests by short distances and, in the case of the large blocks, largely minimized by placing the respective slice on a tray for transport.

3.2.1 Comparison of measuring tools for determination of crack lengths

The length of the cracks ($L_{Total.i}$ on the y-axis) along the penetration depth (measured in 2.5 cm steps) of the bullet into the gelatin block (x-axis), depending on different measurement tools used, is shown in Fig. 5.

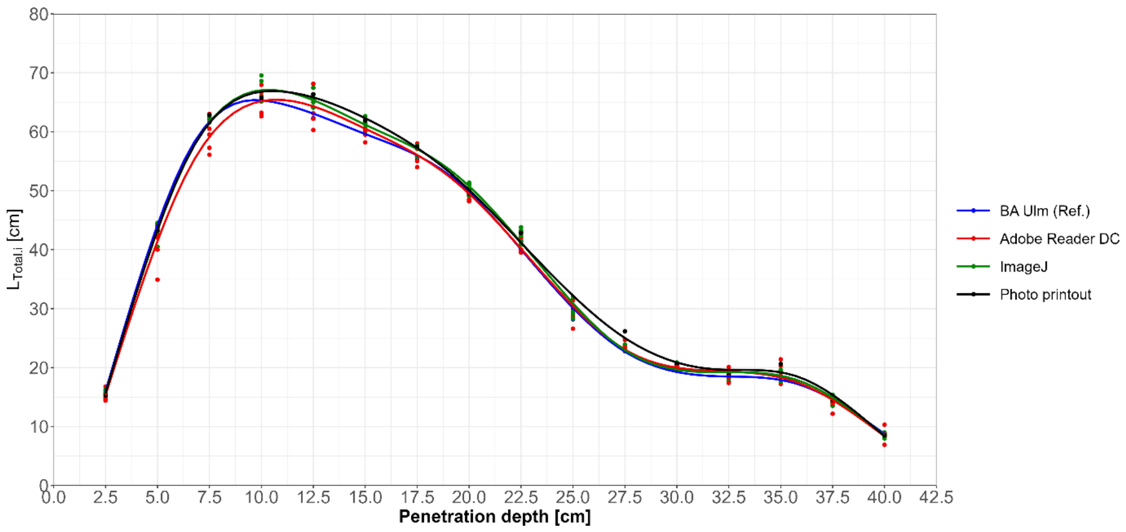


Figure 5: Comparison of measurement tools for determination of crack lengths $L_{Total.i}$ along the penetration depth. Points: observed crack lengths measured with different tools (red: Adobe Reader DC N=6, green points: ImageJ N=5, black points: Photo printout N=1, blue point: Reference method), solid lines: fitted smooth curve through points.

Different colors correspond to the individual measurement tools. Shortly after the bullet reaches the gelatin block (after 2.5 cm), the measured crack length is between 15.4 and 15.7 cm, after which the crack length initially increases and remains constant at a penetration depth of 10 to 12.5 cm (mean value of the longest cracks from both penetration depths: 65.5 cm). Afterwards, the crack length decreases up to a penetration depth of 32.5 cm. Between 35 and 37.5 cm, a slight increase can be observed again. Shortly before the bullet leaves the block (at 40 cm), the crack length is small (between 8.4 and 8.7 cm). This effect of temporary increase in crack length/energy release in the rear region was evident in all three large gelatin blocks. The reason for this could be that the bullet was transverse when passing through the gelatin block and thus led to an expansion of the cracks. As a result of the transversal forming, the stability of the bullet decreases and the bullet starts pendular movement. The uniformity of occurrence of this phenomenon is most likely due to the fact that the target/test velocity of the bullet was maintained with very low tolerance, the gelatin blocks were manufactured according to a proven procedure by experienced staff of the Beschussamt Ulm, and the bullet design allows for reproducible mechanisms of action.

When comparing the crack lengths of shot 6 (block 3) with the generalized additive model (GAM), there were no significant differences between the reference method (direct measurement on gelatin slices – blue line) and the other three photo-based measurement methods (Adobe Reader DC – red line, ImageJ – green line, Photo printout – black line). Depending on the penetration depth of the bullet into the gelatin block, the crack lengths differ significantly ($p<0.001$) from each other (for all measurement tools used). The total crack length L_{Total} at shot 6 was 5.9 m ± 0.14 m (average of 13 measurements with standard deviation).

Note: The measurements with the software Solid Works (USA 8) were not taken into account in the following statistical evaluations, as the scale was changed by the analyzer compared to the specifications and thus a direct comparability with all other measurements is not possible.

3.2.2 Prediction model

A fitted GAM model is shown in Fig. 6, which adapts to all 13 crack lengths ($L_{Total.i}$ of the 13 crack length analyzers) at the respective penetration depth.

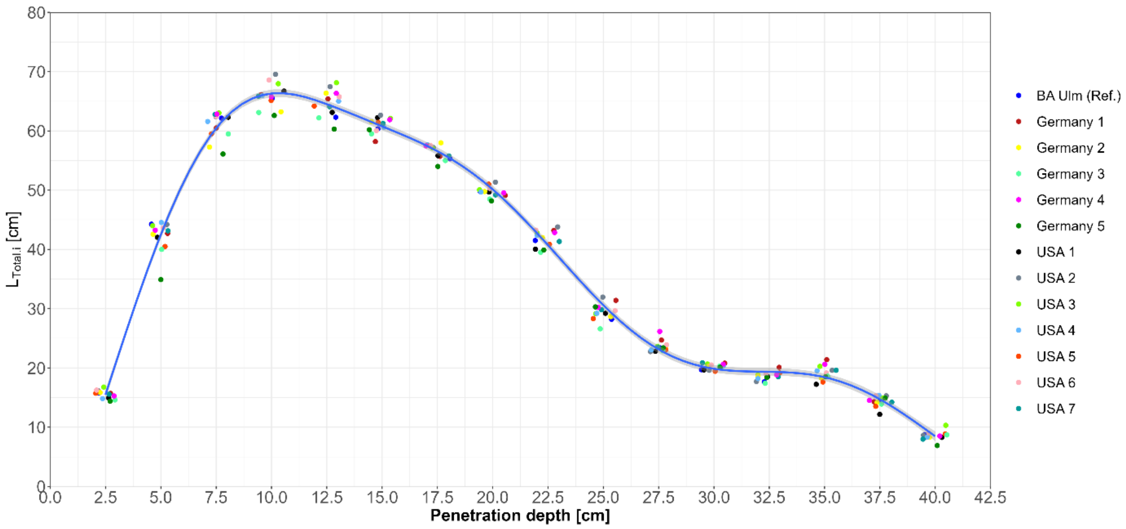


Figure 6: Plot of prediction model for crack length depending on penetration depth. Solid blue line: GAM predicted model with 95 % confidence intervals (grey shaded area). Points: observed crack lengths of individual crack analyzer.

In this model, R^2 was 94 %, which indicates a high quadratic correlation between the observed and the predicted result values. Due to the good fit of the model to the individual measured cracks, it is also possible to predict crack lengths that were not measured at certain penetration depths of the bullet (e.g. at 3 cm penetration depth). In the area of the longest cracks (penetration depth of 10 cm), the variation of crack lengths was largest (Mean: 66.2 cm, Standard deviation: 2.6). The maximum crack length of 69.6 cm was measured by USA 2 at a penetration depth of the bullet at 10 cm. At the same penetration depth, the minimum crack length was 62.6 cm (Germany 5). For comparison: with the reference method, a crack length of 65.5 cm was measured at this penetration depth. Cutting of 2.5 cm slices of gelatin instead of 2.0 cm compared to the Technical Guideline Cartridge [1] is not to be considered disadvantageous, since due to the use of the prediction model by generalized additive models, cracks can also be predicted that were not measured.

3.2.3 Effects of the omission of crack lengths on the back (Si.back) of each slice on the total crack length (L_{Total})

Figure 7 shows the total crack length L_{Total} of the gelatin block when the crack lengths of the front and backsides were measured on each slice (green violin plot) compared to the crack lengths without considering the backside (yellow violin plot).

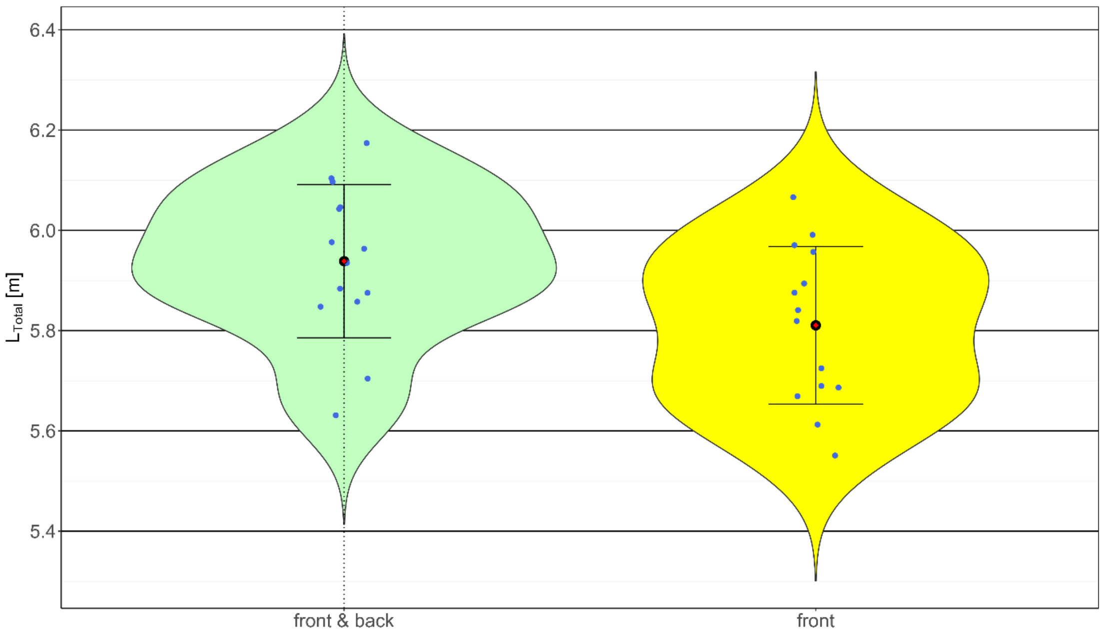


Figure 7: Total crack lengths measured on the front and back (light green) compared to crack lengths that were only measured on the front (yellow). Black error bars representing the standard deviations of the means (black dot), red dots represent the median, blue dots (jittered) represent raw data of individual crack length analyzers, shape of violin plots represent the density distribution.

Omitting the measurement of the crack lengths on the back (Si.back) of each slice has a slight significant ($p<0.04$) influence on the total crack length of block 3 (L_{Total}). By omitting the backside, L_{Total} becomes lower (yellow violin plot). However, a trend can be observed that the backs of the slices no longer need to be measured. This could considerably reduce the time required for the complex measurements. It is possible that the answer to this question also depends on the amount of energy input when the projectile passes through the block. This would have to be further investigated on a larger sample.

3.2.4 Evaluation of the number of cracks depending on crack length analyzers

Frequency of the measured individual crack lengths for each analyzer is shown in Table 1.

Table 1: Frequency of cracks and total crack length depending on crack lengths analyzer

	Number of cracks <6 mm	Number of cracks ≧6 mm	Total number of cracks	Total crack length L_{Total} [m]
Reference	0	323	**323**	**5.9**
Germany 1	6	327	**333**	**6.0**
USA 1	1	294	**295**	**5.8**
USA 2	1	313	**314**	**6.1**
USA 3	45	416	**461*** **	**6.2**
Germany 2	7	334	**341**	**5.9**
USA 4	3	336	**339**	**6.1**
USA 5	7	364	**371**	**6.0**
USA 6	20	436	**456*** **	**5.9**
USA 7	8	338	**346**	**6.0**
Germany 3	3	317	**320**	**5.7**
Germany 4	3	327	**330**	**6.0**
Germany 5	1	300	**301**	**5.6**

*** p<0.001 (generalized additive model fitted with negative binomial family, R^2 = 93 %)

On average, 348 cracks were measured in this gelatin block (average of 13 crack length measurements). USA 3 and USA 6 measured significant (p<0.001) more cracks in the gelatin block with 461 and 456 cracks, respectively, compared to the reference (323 cracks). Both external analyzers measured more frequently small cracks less than 6 mm (USA 3: 45 cracks, USA 6: 20 cracks). With the reference method, only cracks from 6 mm were measured whereas all external analyzers also measured cracks from 1.9 mm (depending on the analyzer). Differences in the number of cracks are due to the fact that some crack length analyzer measured differently than described in the BfR specifications. Some crack length analyzers did not record small crack lengths. For each slice, the individual cracks of the front and back side were added. To determine the total crack length per slice, the mean value was calculated from the sum of the crack lengths from both sides. Thus, the deviating measurement of the cracks does not affect the determination of the total crack length. In summary, the comparison with the indication of the total crack length assumes a kind of "control function", which shows that regardless of the number of individual crack lengths, the summed total crack length is almost the same for all analyzers. Significant differences in the number of cracks recorded for this block were only found in two of a total of twelve crack length analyzers compared to the reference "BA Ulm".

3.2.5 Relationship between crack length ($L_{Total.i}$) and number of cracks per slice

To find out whether it is useful to measure each small crack, the crack length per slice ($L_{Total.i}$) was plotted against the number of cracks using loess smoothing. Fig. 8 shows that $L_{Total.i}$ remains constant from about 27 cracks (black dashed line).

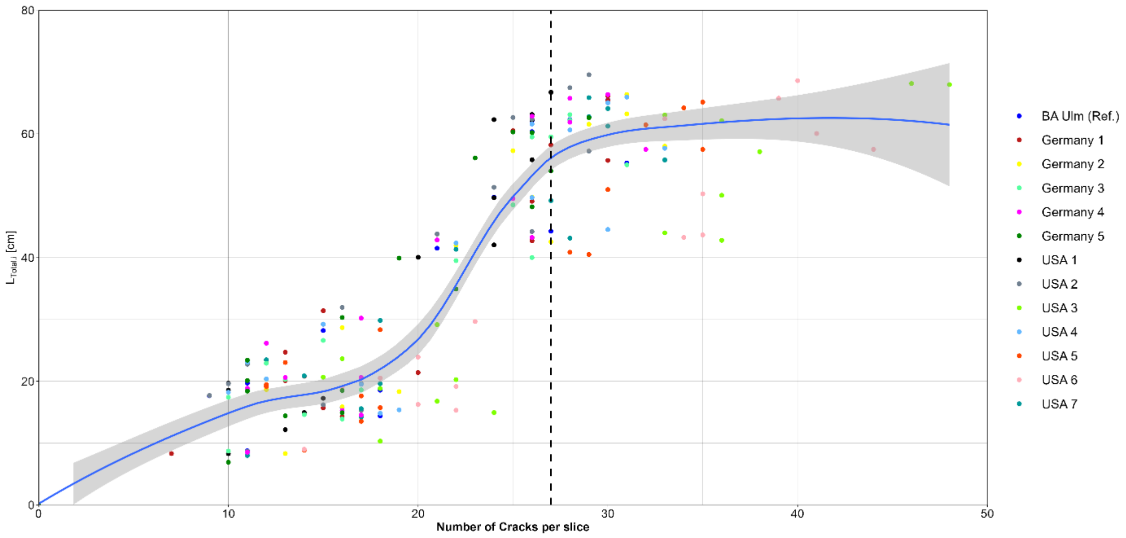


Figure 8: Relationship between crack length ($L_{Total.i}$) and number of cracks per slice. Single points denote the raw data of individual crack length analyzers, Solid blue line: predicted smoothed crack lengths on gelatin slices with 95 % confidence intervals of the fitted smoother.

4 Summary

The results of the research project show that the two gelatin block sizes commonly used for testing bullet characteristics of hunting rifle bullets have differences in load capacity that affect the reproducibility of the results. When the target energy of the bullet is very high (>5,000 J), the differences in the responses of the two block sizes become apparent. If the small block size is used in combination with a very high energy of the bullet, there is a considerable uncertainty regarding the reproducibility of the results based on the crack length measurement method of the Technical Guideline Cartridge [1]. For this reason, the smaller blocks were not suitable for an evaluation of the crack lengths to determine the effectiveness of the bullet according to the specifications of this Technical Guideline [1]. Since only one large block out of a total of three blocks withstood the bombardment, the gelatin block slices from this block could be evaluated using the crack length method. Therefore, at least the tendency shows that even large gelatin blocks (40 cm x 25 cm x 25 cm) are only conditionally suitable for an energy input in the range >5,000 J to achieve reproducible results with a manageable number of bombardment repetitions.

The investigations to test a modified method for measuring the crack lengths of gelatin block slices have shown that the modified photo-based method (BfR method) based on the Technical Guideline Cartridge, Annex 9 [1] is suitable and has clear advantages over the previous method [1]. With the modified method, comparative investigations can be carried out for the first time at any location, staggered over time and with different measurement tools. A disadvantage of this method is the time-consuming, standardized photographing of each pane side of the block. The methods of crack length measurement with the tools “Adobe Acrobat Reader” and “ImageJ” proved to be particularly suitable.

From a purely statistical point of view, the exclusion of small cracks (<6 mm) from the summation and averaging has only a minor influence on the final result of the total crack lengths. For this reason, very short cracks (<6 mm) could be excluded from the measurement, depending on the requirements.

Compared to the specifications described [1], the gelatin block slice thickness to be evaluated in the study was changed with respect to the crack lengths and increased from 2.0 cm to 2.5 cm. The statistical prediction model (GAM) can also predict cracks that were not measured. Therefore, the change in slice thickness does not affect the statistical significance of the crack length measurements.

During the comparison of the measured crack length results, a trend was observed showing that the back sides of the gelatin block slices would not need to be measured. This would need to be further investigated on a larger sample.

A minor uncertainty currently results from the first-time application of the procedure for crack length measurement according to the modified photo-based method (BfR method), since the procedure has so far only been tested on one block. The procedure and the processes should be reviewed in the further study.

Finally, it is recommended to verify the block size for the 20 % ballistic gelatin simulant to be used for the planned testing of the behavior of hunting rifle bullets with very high bullet energies.

5 References

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6 List of Figures

7 List of tables

8 Appendix

A 1 Photos

A 2 Data sheet – Example large blocks: Registration crack length measurements

A 3 Videos – Two Highspeed-camera-recordings: Firing at a small and a large gelatin block size

Appendix (A 1)

Supplementary material – A 1 Photos

Photo 1: Finished gelatin blocks

Photo 2: In black PE foil wrapped gelatin block

Photo 3: Climatic chamber temperature and humidity

Photo 4: Shooting cabin with shooting channel

Photo 5: Shooting channel

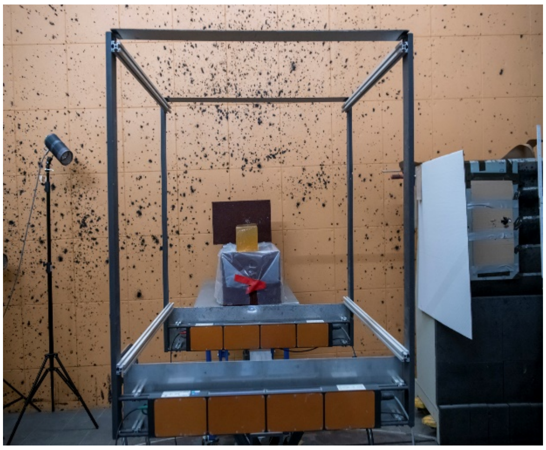


Photo 6: Test setup (view of the block from the the shooting cabin

Photo 7: High speed camera and lighting

Photo 8: Cutting device large gelatin blocks

Photo 9: Cutting device large gelatin blocks

Photo 10: Cutting machine for small gelatin blocks

Photo 11: Lighting table with opal plate (before setup)

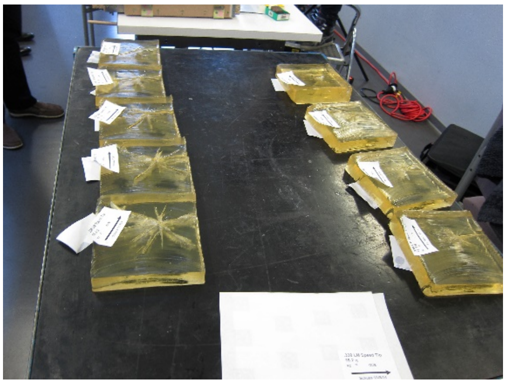


Photo 12: Transport of small gelatin block slices with the rolling cart

Photo 13: Tray for transporting large gelatin block slices

Photo 14: Photographer setting up the tripod and the camera

Photo 15: Gelatin block slice with label


Photo 16: Marking of the crack lengths on the front side

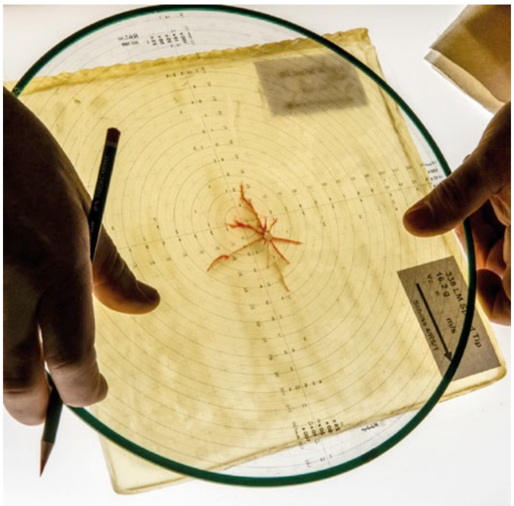


Photo 17: Measuring the crack length

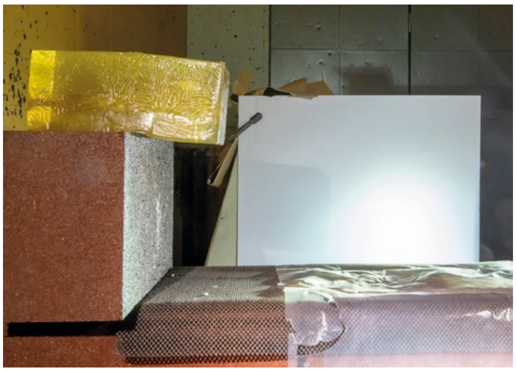


Photo 18: Small block after the shot


Photo 19: Close up: Small block after the shot

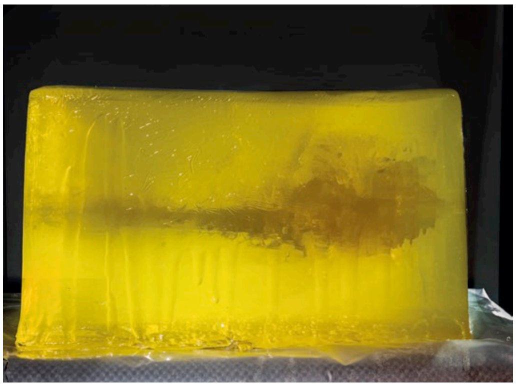


Photo 20: Large block 1 after the shot

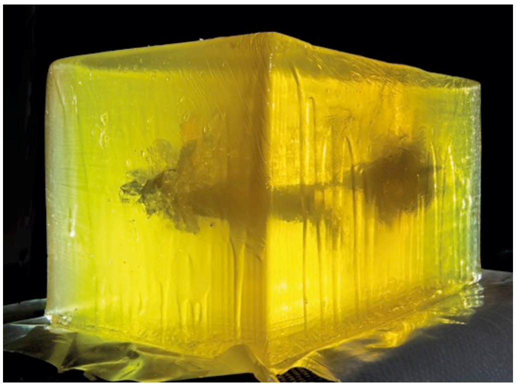


Photo 21: Large block 2 after the shot

Photo 22: Large block 3 after the shot

Appendix (A 2)

Data sheet – Example large blocks: Registration crack length measurements

				j: crack length number																			
Slice number i	Penetration depth	Side	Arrow	j=1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0,0 cm	front																					
	2,5 cm	back																					
2	2,5 cm	front																					
	5,0 cm	back																					
3	5,0 cm	front																					
	7,5 cm	back																					
4	7,5 cm	front																					
	10,0 cm	back																					
5	10,0 cm	front																					
	12,5 cm	back																					
6	12,5 cm	front																					
	15,0 cm	back																					
7	15,0 cm	front																					
	17,5 cm	back																					
8	17,5 cm	front																					
	20,0 cm	back																					
9	20,0 cm	front																					
	22,5 cm	back																					
10	22,5 cm	front																					
	25,0 cm	back																					
11	25,0 cm	front																					
	27,5 cm	back																					
12	27,5 cm	front																					
	30,0 cm	back																					
13	30,0 cm	front																					
	32,5 cm	back																					
14	32,5 cm	front																					
	35,0 cm	back																					
15	35,0 cm	front																					
	37,5 cm	back																					
16	37,5 cm	front																					
	40,0 cm	back																					
BfR	Bundesinstitut für Risikobewertung																						

Appendix (A 3) – Videos

Two Highspeed-camera-recordings: Firing at a small and a large gelatin block size

<u>Video 1: Small gelatin block size_Ulm_shot3_block_3_791,5m-s.mp4</u>

Small gelatin block
size_Ulm_shot3_bloc

<u>Video 2: Large gelatin block size_Ulm_shot4_block_1_797,28m-s.mp4</u>

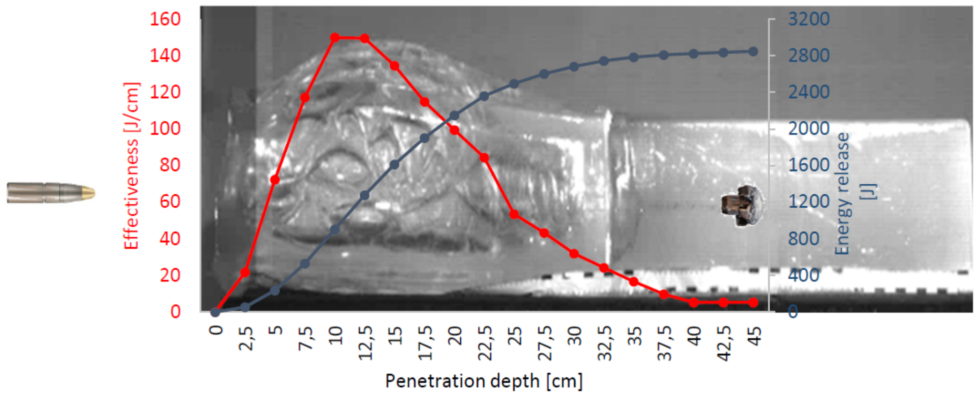
Large gelatin block
size_Ulm shot4_bloc

Science Report

14 March 2024

Suitability of two gelatin block sizes as ballistic simulant for hunting bullets tested with 2,900 J

Authors: Annett Martin, Ellen Ulbig, Ingo Rottenberger, Helmut A. Schafft, Monika Lahrssen-Wiederholt



Content

1 Introduction

Aim of the amendment of the Federal Hunting Act was to formulate new requirements for the proof of a reliable killing effect as well as a minimization and avoidance of the harmful lead input into the game or the environment. Therefore, the German Federal Institute for Risk Assessment (BfR) performed several studies to assess the safety of game meat due to the entry of metal fragments when using leaded and lead-free ammunition [1,2]. The background to these investigations is that hunting game can lead to unwanted metal fragments in the game/game meat.

In this context test procedure steps for determining the behavior of all hunting bullets in test simulants (gelatin or ballistic soap) are to be defined and standardized. Criteria for a killing effect do not yet exist [3].

Simulants such as gelatin or ballistic soap are already used to test the behavior of bullets. Simulants are materials that show similar behavior (e.g., elasticity, energy absorption capacity, resistance, etc.) to body tissue when they are shot at. The material must have (approximately) the same density. For example, soap and gelatin have a very similar density p to muscle (p=1.06 g/cm^3) [4]. Tissue consists of different tissue types where the effects of shooting at game cannot be simulated for each individual tissue type. Therefore, an attempt is made to evaluate the energy transfer from the bullet to the game via a homogeneous medium such as manufactured gelatin with appropriate density. With gelatin, the effects on human and animal tissue can be reproduced within certain limits [5,6]. The behavior of the bullet in the gelatin block can be described physically. When a bullet penetrates gelatin, it is slowed down and the kinetic energy is converted into work in the gelatin mass. This accelerates the gelatin and moves it vertically to the path of the bullet, forming a temporary cavity that is visible for a few milliseconds. This cavity collapses due to the elastic property of the gelatin. The bullet penetrating the gelatin transfers kinetic energy and causes radial cracks corresponding to the temporary cavity. Cracks remain in the gelatin blocks, while the temporary cavity collapses after a few milliseconds and disappears after the shot. The crack length is therefore a function of the kinetic energy spent in the gelatin block [5]. The more cracks, the higher the energy release of the bullet to the gelatin block. Bullet penetration depth depends on the available target energy and the bullet design. A path-related energy release is referred to as effectiveness in ballistics. Energy transfer along the shot channel can be very different.

There are various methods for measuring crack lengths, such as the total crack length method [4,7]. In addition to the total crack length method, other methods have been tested, such as the polygon method [5,8] or the measurement of the two largest cracks per slice according to Fackler's wound profile [9]. Schyma and Madea [8] measured only the longest cracks per slice. In contrast to these crack length determinations, the advantage of crack length analysis using computed tomography (CT) software is emphasized [10], since here the gelatin does not need to be sliced as in the conventional methods. In another study, the correlation between the temporary cavity recorded with high-speed video (HSV) and cracks in gelatin slices [11] was investigated. Since in practice the cracks are poorly contrasted, methods for contrast enhancement were searched [5]. These methods were tested when shooting at gelatin blocks (10 %) with a bullet energy of approximately of 500 J.

Background and aim of the study

The BfR initiated an international expert panel to continue working on issues related to the establishment of a test method for hunting bullets [3]. Due to the controversial discussions among users of test simulants, the BfR commissioned practical experiments to investigate the suitability of gelatin as a test simulant for hunting bullets in a two-stage research project. In the first part of the research project [12], a high-energy hunting bullet (>5,000 J) was used to test the load capacity of two different block sizes (15 cm x 15 cm x 35 cm and 25cm x 25 cm x 40 cm (width x height x length)). It was found that the smaller block size was not suitable for bullet testing and the larger block size was only marginally suitable. In the present study (second part of the research project), a frequently used hunting bullet (target energy of 2,900 J) was used to also test the load capacity of the two gelatin block sizes for a hunting-relevant distance (100 m). The idea was to adopt the procedures to be used for testing police bullets according to "TR Patrone 9 mm x 19, schadstoffreduziert" (abbreviation "TR Patrone 9 mm x 19") [13], also for testing hunting bullets. This should include the use of the small gelatin block size (20 % gelatin) as a test simulant. Since, in addition to the use of the small block size for the testing of certain properties of hunting bullets, gelatin blocks with a large size are also used as a test simulant, the central question is to what extent the gelatin block size affects the shooting results and their reproducibility. In the previous study [12], a method developed by the BfR was applied to measure the crack lengths, which supplements the previous crack length method [7] with photographic records and is thus independent of location and time. In the current study, the application of the modified method was to be further refined and statistically validated by a larger data base. Due to the time-consuming crack length measurements, it should be tested whether it is possible to decrease these times by measuring fewer cracks. Based on the number of cracks measured by eleven analyzers, it was to verify that the instructions for measuring cracks were followed.

By placing two gelatin blocks in a row per shot, the bullets remained stuck in the gelatin block so that the entire kinetic energy of the bullet could be absorbed, and thus along the penetration depth the energy release curve ("effectiveness") could be calculated using the "TR Patrone 9 mm x 19"[13]. This is in contrast to the first study where the bullet escaped after penetrating the block.

2 Material and Methods

2.1 Production of gelatin blocks

The production of the gelatin blocks with two different sizes (small: 15 cm x 15 cm x 35 cm, large: 25 cm x 25 cm x 40 cm) was taken over by the Beschussamt Ulm (BA Ulm) as an institution certified for all police forces of the federal states for testing police bullets according to "TR Patrone 9 mm x 19"[13]. It is described in detail in the first study [12], so that a detailed description can be omitted here.

Small gelatin blocks were conditioned for at least 18 hours in a climatic cabinet (Manufacture: CTS type: CW-40/3 No.: 091131) at 60 % ± 5 % humidity and 15°C ± 1°C and stored until the respective shot. This procedure is described in the "TR Patrone 9 mm x 19" and was also adopted for the large block size. However, since there was still no knowledge about the cooling process of large gelatin blocks, the cooling time was extended to more than 36 hours in order to achieve through-cooling to the core.

2.2 Experimental setup for shooting the gelatin blocks

Figure 1 depicts the experimental setup for performing the shots. A measurement run of a run length of 600 mm and a twist length of 254 mm was used to carry out the shots in the shooting channel. Labored cartridges (RWS .30-06 Springfield, bullet: Evolution, bullet mass: 11.9 g / 184 grains, leaded deformation bullet) were provided for the shooting distance of 15 m and a target velocity of 700 m/s ± 10 m/s. The run was clamped in an electronically controlled shooting facility (HPI - EPVAT Receiver Unit 292UR) in a shooting facility and aligned by means of a laser pointer to the gelatin block to be shot at the center of the front. In front of the shooting table, the infrared precision light barrier (Drello Mod.: LS23 with BAL 4043-08 serial number 1726A0802, measuring base 1000 mm) was set up, which recorded the impact velocity of the bullet at a distance of 1.0 m in front of the front of the block.

A Regupol plate support was used as a base for the gelatin blocks on the shooting table. For each shot, two gelatin blocks of the same size were positioned with their front sides lying closely together. After all preparatory work was completed, test shots were taken to adjust the point of impact and to fine-tune with the high-speed camera. However, no gelatin blocks were used in the process.

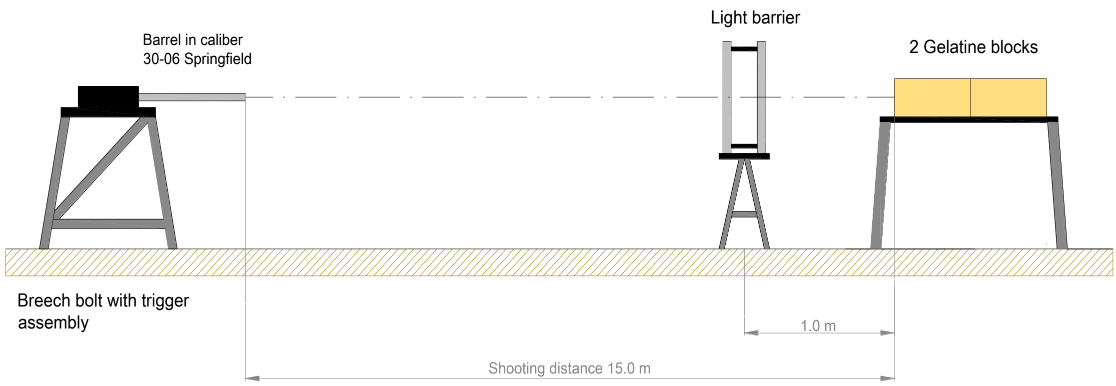


Figure 1: Experimental setup (drawing not to scale).

During the first three days of the firing tests, the shots were recorded using a high-speed camera. The high-speed camera set up next to the firing table was set to a shutter speed of 1/49,000 sec with a frame rate of 15,000fps. Although the camera recorded the entire length of the two blocks behind each other, the focus, also for illuminance, was on the first block in specific. This allowed the shutter speed to be reduced slightly and the motion blur to be reduced somewhat compared to the images taken during the Part I pilot study. The illumination was provided by two luminaires at a distance of approx. 1.5 m from the firing table and an additional luminaire (LED) in a semi-right position next to the front of the firing table. A staff member controlled the high-speed camera from a bulletproof monitoring room via a laptop computer.

2.3 Preliminary work for the measurement of crack lengths

As previously described in the publication of our results on the research project [12], a lighting table was also used this time for crack length evaluation. As cutting device for the large blocks the same was used as described in the first publication [12]. Based on the handling experience gained in the first test series, it was optimized in terms of manageability. To make it easier to remove the gelatin block slices from the bottom and back, and to make it easier to pull the cutting wire through to the bottom, flat, narrow wooden strips were stuck to the contact surface. Thereby, the cutting edge between the vertically narrow, parallel metal guide pins was left free (Figure 2).

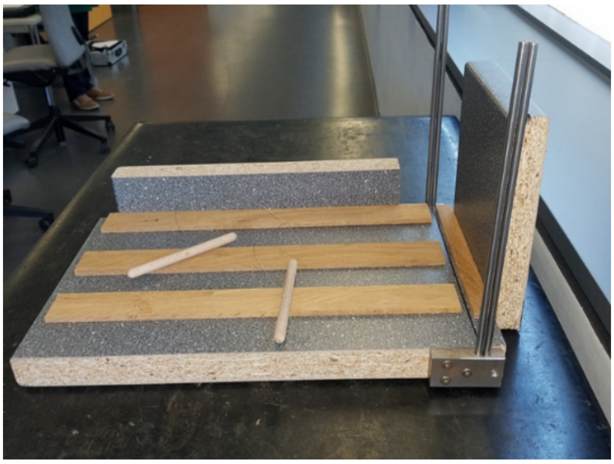


Figure 2: Cutting system.

For the small block size, the cutting machine was used as described in the Part I publication [12]. The gelatin block slice sides of the small blocks were marked with a colored pencil and labeled. To measure the crack lengths, they were moved to the lighting table with a trolley. To simplify photography, BfR separately set up a repro column next to the lighting table (Figure 3), which was attached to a transparent illumination plate. The illumination plate could optionally be covered with an edge template for the small or the large block size. This ensured the exact positioning of the gelatin block side on the illumination table. The camera was permanently installed on the rear side of the upright column in the specified and marked positions, so that photographs could always be taken at the same distance from the gelatin block side. Triggering was done via release cable. Photographs were taken with photo camera Nikon D4s, lens: Nikon 60 mm. Distances of the photo lens to the gelatin block slice were 89.5 cm and 58.5 cm for the large and small gelatin block slice sides, respectively.

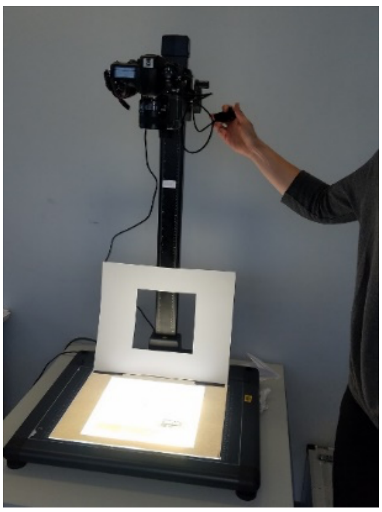


Figure 3: Repro column with lighting panel.

2.4 Crack length measurements with standard method (Beschussamt Ulm)

The experimental procedure of crack lengths measurement in the BA (on site measurement) was previously described elsewhere [12]. Two consecutive blocks, each 40 cm long (Figure 1), were shot once with the RWS Evolution 11.9 g hunting bullet, caliber .30-06. The crack length measurements from BA Ulm were taken as a reference method for the evaluation of the crack lengths.

2.5 Measurement of the bullet residual body

After the cracks on the last slice (end position of the bullet) were measured by BA Ulm, the largest piece of the bullet (bullet residual body) was removed from the last slice. Any gelatin that may still be adhering on the residual body can be dissolved in a warm water bath and was dried under a hair dryer. Subsequently, the rest mass and rest diameter of the cleaned bullet was measured (Annex 8.1, Table 1). For this purpose, a calibrated scale (Kern PRJ 1200-3N, Ser. No.: W 55170 max. 1220 g, d = 1 mg) was used as well as a caliper gauge (PM 2004, analog). The bullet residual body was measured at the location of the largest diameter.

2.6 Crack length measurements with modified method according BfR – participants and measurement tools

For the determination of the crack lengths by the external analyzers (munitions manufacturers, associations, government agencies etc., anonymized in Figure 4), the photos with the crack lengths on each slice as well as data sheets (Figure 5) for input the crack lengths were sent via Dropbox. Instructions for measuring the cracks were also sent at the same time.

Eleven crack length analyzers measured the crack lengths on the photos (Figure 4). The photos show the crack lengths of six shots on twelve large gelatin blocks (always two blocks in a row per shot) and six small blocks (also two blocks in a row per shot). Depending on the analyzers, the crack lengths were measured using different measurement tools (Figure 4). Four crack length analyzers measured the crack lengths based on the photos with Adobe Reader DC (Germany 1 to Germany 4) and six using the ImageJ software (USA 1 to USA 6). USA 1, 2 and 3 measured only crack lengths of shot 1 to shot 3, whereas USA 4 to USA 6 measured the crack lengths from shot 4 to shot 6. One crack length analyzer printed out the photos and then measured them (Germany 5). Therefore, nine crack length measurements were taken per shot (including BA Ulm as reference).

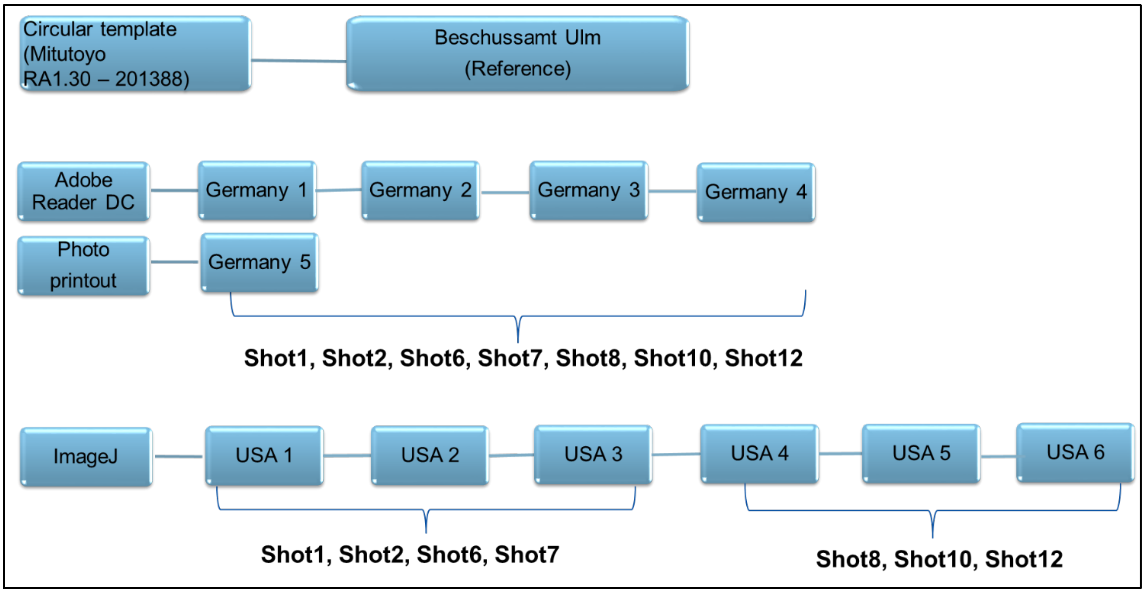


Figure 4: Participants and used tools for crack length measurement.

Each analyzer entered the crack lengths per slice i (front and back) in a data sheet (Figure 5).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE
1	Block 12	Penetration					j: crack length number																							Si.front/	
2	Slice number i	depth	Site	Arrow	j=1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Si.back	LTotal.i
3	1	0,0 cm	VS		7,2																									7,2	62,2
4		2,5 cm	RS		21	6,2	6	5,9	7,1	13	5,9	6,3	8,3	9,1	11	17														117,1	
5	2	2,5 cm	VS		34	3,9	9,6	12	23	23	21	4,1	21	6,4	12	13														183,5	247,4
6		5,0 cm	RS		29	34	26	11	26	6	20	24	9,7	17	13	20	19	10	40	7,7										311,3	
7	3	5,0 cm	VS		30	24	24	22	14	21	15	20	29	24	12	20	2,4	15	48	17										336,5	426,5
8		7,5 cm	RS		47	35	22	24	58	10	26	22	28	6,2	30	36	22	13	38	43	37	19								516,5	
9	4	7,5 cm	VS		23	29	21	4,8	31	39	8,4	26	35	16	4,7	37	11	19	28	9,2	1,5	59	51	46						498,5	476,5
10		10,0 cm	RS		59	40	63	9,5	9,8	36	12	20	38	16	14	7,2	7,2	17	37	34	28	8,9								454,5	
11	5	10,0 cm	VS		32	32	26	2,8	23	9,7	22	20	46	48	21	43	12	2,8	47	63										447,8	463,2
12		12,5 cm	RS		30	5,6	34	17	68	43	26	51	23	19	34	24	37	29	25	12										478,5	
13	6	12,5 cm	VS		40	8,1	12	4,5	13	11	15	48	36	13	17	44	22	40	29	5,4	67	32	9,5	27						494,5	501,1
14		15,0 cm	RS		40	12	51	26	36	8,4	9,6	60	25	25	17	11	14	6,4	27	33	5	48	19	3,6	30					507,7	
15	7	15,0 cm	VS		17	2,2	32	54	33	3,2	23	28	9,1	30	8,2	8,4	39	27	7,3	25	14	25	22	26	34	35				501,2	460,5
16		17,5 cm	RS		55	28	21	9,1	45	42	51	31	47	23	13	3,4	13	14	23											419,7	
17	8	17,5 cm	VS		21	16	7,5	11	49	37	18	30	42	43	15	30	4,1	20	23	24	55									443,8	396,5
18		20,0 cm	RS		14	14	25	10	25	27	18	20	2,1	65	23	16	23	9,7	22	16	18									349,1	
19	9	20,0 cm	VS		7,2	17	11	4,9	9,4	22	31	7,6	58	11	13	21	20	2	23	16	19	30	6,4							330,1	331,4
20		22,5 cm	RS		20	24	25	12	10	49	60	25	36	18	39	15														332,6	
21	10	22,5 cm	VS		20	17	2,3	27	15	34	32	17	32	25	7,4	16	11	12	11	2,8	16	17								312,9	240,9
22		25,0 cm	RS		19	2	11	8,7	2,8	11	6,3	11	11	27	14	22	20	4,4												168,9	
23	11	25,0 cm	VS		20	11	23	7,6	17	15	20	11	20																	144,2	149,6
24		27,5 cm	RS		19	6,5	6,8	8,4	25	20	9,4	13	4,8	19	13	12														155	
25	12	27,5 cm	VS		25	31	16	18	27	14	15																			146	113,3
26		30,0 cm	RS		24	9,9	30	17																						80,5	
27	13	30,0 cm	VS		17	32	8,8	19																						77,2	77,2
28		32,5 cm	RS		25	15	23	15																						77,1	
29	14	32,5 cm	VS		16	22	9,1	7,3	17																					70,2	55,8
30		35,0 cm	RS		18	13	10																							41,3	
31	15	35,0 cm	VS		14	7,8	9,6	5,5																						36,7	38,1
32		37,5 cm	RS		12	9,7	9,6	8,4																						39,5	
33	16	37,5 cm	VS		7,2	7,8	7,3	7,9																						30,2	23,0
34		40,0 cm	RS		3,2	4,8	7,8																							15,8	
35	17	40,0 cm	VS		8,7	1																								9,7	9,6
36		42,5 cm	RS		5,3	3	1,2																							9,5	
37	18	42,5 cm	VS		6,4																									6,4	6,6
38		45,0 cm	RS		5,6	1,2																								6,8	
39	19	45,0 cm	VS		2,2	2,5																								4,7	7,65
40		47,5 cm	RS		4,3	6,3																								10,6	
41	20	47,5 cm	VS																											0	0
42		50,0 cm	RS																											0	
43	21	50,0 cm	VS																											0	0
44		52,5 cm	RS																											0	
45	BfR																				LTotal										4087
46		Bundesinstitut für Risikobewertung						Beschussamt Ulm																							

Figure 5: Data sheet for entering the crack lengths (after conversion to scale) on a photo basis. VS=front, RS=back.

2.7 Calculation of crack lengths and effectiveness

When the gelatin blocks withstood the bombardment and the energy of the bullet leads to cracks within the gelatin block, an energy release profile (E_{rel}) can be derived by measuring the cracks formed [13]. Since the calculation of the crack lengths for each slice ($L_{Total.i}$) and for each block (L_{Total}) has already been described elsewhere [12], only the calculation of the effectiveness is described here.

The effectiveness W_i in formula (1) is defined as energy release ($E_{rel.i}$) over a certain distance (for slice i with thickness s = 2.5 cm) and is derived in formulas (2) to (5).

$$W_i = \frac{E_{rel.i}}{s} = \frac{E_{kin}}{s * L_{Total}} * L_{Total.i} \quad (1)$$

where

$$E_{rel.i} = \frac{E_{kin}}{L_{Total}} \cdot L_{Total.i} \quad (2)$$

$$E_{kin} = E_{kinTarget} - E_{kinRest} \quad (3)$$

$$E_{kinTarget} = \frac{m}{2} v_{Target}^2 \quad (4)$$

$$E_{kinRest} = \frac{m_{Rest}}{2} v_{Rest}^2 = 0 \quad (5)$$

- L_{Total} = Crack length of the respective block (Figure 5)
- $L_{Total.i}$ = Crack length of the respective slice per block (Figure 5)
- E_{kin} = Kinetic energy of the bullet in J
- $E_{kinTarget}$ = Kinetic energy of the bullet when hitting the block in J
- $E_{kinRest}$ = Kinetic residual energy of the bullet
- v_{Rest} = Residual velocity of the bullet = 0, because the bullet got stuck
- v_{Target} = Target velocity of the bullet in m/s
- m = Bullet mass in g
- m_{Rest} = Residual mass of the bullet
- $E_{rel.Total}$ in formula (6) is the total energy output of the bullet to the gelatin block

$$E_{rel.Total} = E_{kinTarget} - (E_{kinRest}) = \sum E_{rel.i} \quad (6)$$

2.8 Statistical analyses

For each shot on gelatin blocks (only those that withstood the bombardment), a generalized additive mixed model (GAM) [14] was used to evaluate the influence of the used crack length measurement tool on the crack lengths of the respective gelatin block along the penetration depth of the bullet. The penetration depth (measured in 2.5 cm increments for each individual slice i) of the bullet through the gelatin block was included in the model as a smoothed nonlinear spline. Nine crack length analyzers were included in the six models as random variables. One reason for creating six models (one model per shot) is that not all analyzers measured the cracks in all gelatin blocks.

Formula (7) represents the generalized additive model (GAM) with Gaussian family (for six shots).

$$L_{Total.i} = \beta_0 + s(\text{penetration depth}, bs = \text{"cr"}, k{=}5) + s(\text{analyzer}, bs = re) + \text{measurementTool} + \varepsilon \qquad (7)$$

whereby

- $L_{Total.i}$ is the crack length of slice i as response variable
- β_0 is the intercept term, it denotes the overall mean of the response
- s(penetration depth) is a smoother that accounts for the path of the bullet through the block
- k denotes the degree of smoothing
- s(analyzer) is a random effect smoother for the nine crack length analyzers
- “Measurement tool” is a categorical term with reference category “Beschussamt Ulm” (measurement directly after shooting) and two measurement tools (AdobeReader DC, ImageJ, Photo printout) at a later time and location-independent
- ε is a Gaussian error term (the unexplained variation)

In a second GAM model we included only measurement tools as fixed effects (and the nonlinear spline) in the model if the random variable was significant in the mixed model. To measure the goodness of fit for both models the Akaike information criteria (AIC) was used to obtain the most suitable model. For all GAM models a two-tailed p value of <0.05 was considered statistically significant.

Scatter plots show the course of crack lengths ($L_{Total.i}$) as a function of the respective penetration depth (measured in 2.5 cm increments) of the bullet through the gelatin block using different measurement tools. A GAM smoothing procedure was applied to fit a smooth curve through the points in the scatter plot. The same plot type was used to show the crack lengths in relation to the number of cracks measured on each slice.

Paired Wilcoxon exact-rank test from R package “exactRankTests” [15] was used to compare the total crack lengths L_{Total} of the front and back sides with the crack lengths without considering the back side.

Statistical evaluations and graphs were performed with the statistical software R version 4.1.1 [16].

3 Results and discussion

3.1 Description of the bullet behavior

The gelatin blocks were shot once with the hunting bullet RWS Evolution 11.9 g, Caliber .30-06 Springfield. An overview of the 12 shots on small and large gelatin blocks gives Table 1 in the annex 8.1.

The target velocity level of the charge with this bullet was 700 m/s (± 10 m/s tolerance level). This velocity ranged between 688 (shot 8) and 706 m/s (shot 9, Table 1, Annex 8.1). Only at shot 8 (688 m/s) was the speed slightly below the tolerance level. The difference in muzzle velocities was 18 m/s over the entire experiment and from 13 m/s for the large blocks only.

The end position of the remaining bullet is always over 40 cm (Annex 8.1, Table 1). This means that all bullets entered the 2^{nd} block and got stuck there. Often wider for the smaller blocks than for the large blocks.

When shot at the first gelatin block (shot 1: large block size), the bullet recorded a mass loss of about 0.4 g, which corresponds to about 3.5 %. In comparison, the mass of the bullet at shot 11 (small block size) was reduced from 11.9 g to 9.9 g, which corresponds to approx. 16.8 % (Table 1 in Annex 8.1 and Figure 6). The large and small blocks were almost all separated into two clusters based on the target speed and mass loss. Only shot 7 (shot on a large gelatin block) was included in the group of small blocks and one small block (shot 3) in large blocks.

When comparing the residual bullet masses when shooting at large and small gelatin blocks, the bullets shot at small gelatin blocks emitted more material to the test simulant than the bullets fired at the large blocks at approximately the same target velocity. The reason for that could possibly be related to the manufacturing process of the gelatin blocks. A larger body takes longer to cool down and cure. But there were always nearly two days (42 hours or more) between production and shooting of the blocks. The gelatin is cooled in a climatic cabinet after it has been mixed. It could be possible that by not cooling the large blocks completely, the density in the middle of these blocks is slightly smaller and this caused a changed behavior during deformation. Since the deviations were not clearly attributable to this possible cause, further investigations will follow. The results, which also take into account the cooling time of the large blocks, will be published in a further paper.

The aspect of how long the block lies on the plate and was exposed to the light sources is also important.

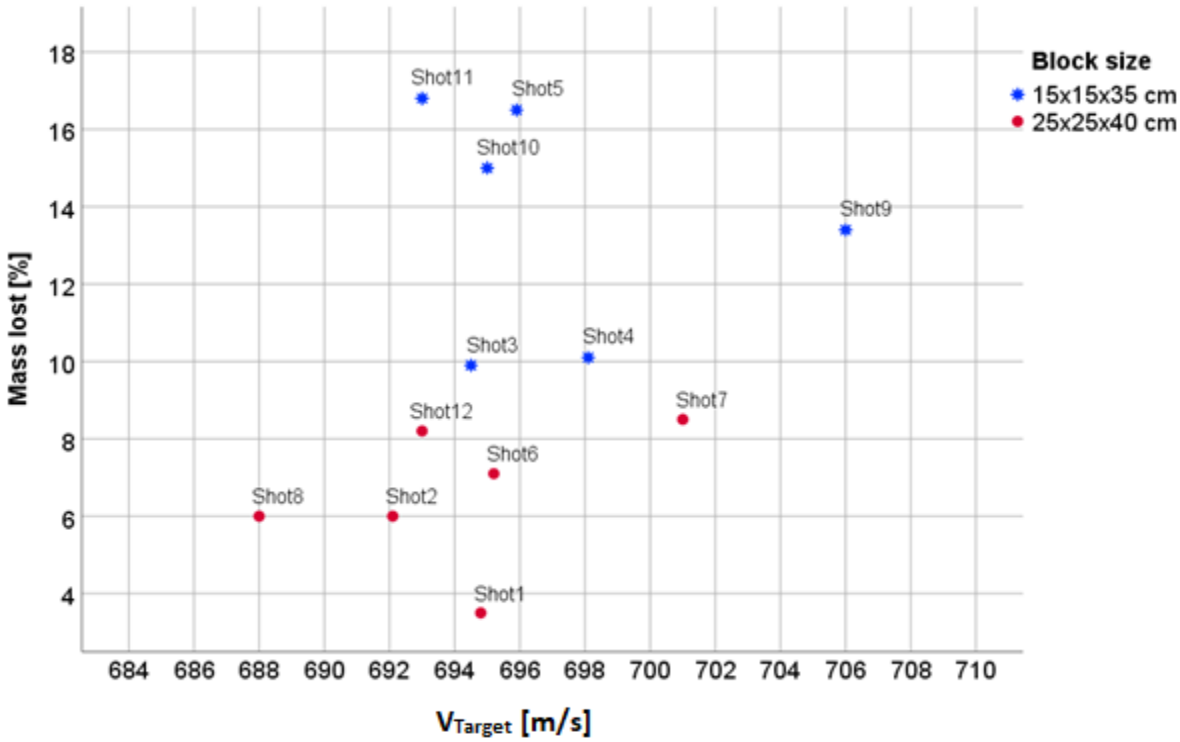


Figure 6: Mass loss of the bullet [%] depending on target velocity V_{Target} [m/s].

3.2 Crack length measurement

The shootings took place in BA Ulm, which also included testing the load capacity of the block sizes. All crack length measurements were carried out using the technical guideline as described in [13].

3.2.1 Testing the loading capacity of two gelatin block sizes

There was a basic requirement for the analysis of crack lengths. If cracks in the gelatin block go outside at any point as the bullet penetrates, the total energy release not reflected in crack lengths, so this is inherently erroneous. Therefore, these blocks were not analyzed. All twelve large blocks (per shot two blocks in row) but only one of six small blocks could withstand the energy of the bullets (cracks did not go outside). In five small blocks cracks emerged on the outer sides of the blocks. The crack lengths could not be determined for these five blocks. The result of the small block (shot 10) is a single event. This result was rather random.

Table 2 (Annex 8.2) and Figure 12 (Annex 8.3) shows the total crack length L_{Total} [m] for six shots on large gelatin blocks per crack length analyzer. The crack lengths of the large gelatine blocks were always measured by nine crack length analyzers (including BA Ulm).

The lowest values for total crack length L_{Total} were measured at shot 2 and shot 6 with 3.8 m, the highest with 4.4 m at shot 1 and 7 (Results from Reference – BA Ulm).

3.2.2 Comparison of photo-based crack length measurement tools (modified method) with direct measurement (Reference – BA Ulm)

Figure 7 shows the course of the crack lengths $L_{Total.i}$ as a function of the penetration depth of the bullet, separated according to the measuring tool for all shots on six large blocks. For each shot, two blocks were always positioned one behind the other, each with a length of 40 cm. The cracks were measured on both sides of each gelatin block slice, with a slice thickness of 2.5 cm. Different colors correspond to the crack length measurement methods (with Reference BA Ulm, dark blue line and points). At each penetration depth, nine crack lengths (3x ImageJ, 4x Adobe, 1x BA Ulm, 1x Photo printout) were measured per shot. Shortly after the bullet reaches the gelatin block (after 2.5 cm penetration depth), the measured crack length is between 5 and 20 cm, depending on the respective measurement tool, and then initially increases. Longest cracks were measured during the 1st shot at a penetration depth of 10 to 12.5 cm (Annex 8.1). In this range, the largest variations of crack lengths between the analyzers were found (from 40 cm for shots 6 and 12 to 67 cm for shot 1, respectively). Meaning a deviation of 27 cm. The penetration depths at which crack lengths were still be measured vary depending on the shot and range from 42.5 cm (shots 6 & 7) to 50 cm (shots 8 & 12).

When comparing the crack lengths $L_{Total.i}$ [cm] for each of five shots (shot 1, 6, 7, 8, 12) on large blocks with GAM (one model per shot, results are listed in Tables 3–8 in Annex 8.3), there were no significant differences between the reference method (blue line) and the three crack lengths methods on photo basis ($p>0.05$). Most significant for $L_{Total.i}$ was the nonlinear term penetration depth in the models ($p<0.001$), with the longest cracks measured at a penetration depth of about 12.5 cm. The individual crack length analyzers, included in the models as random variables, had an effect on crack lengths only for shot 2 and shot 7. However, this effect did not affect the fixed effect in the model (measurement tool). The standard errors of fixed factor of the mixed model (shot 2: AIC=732, shot 7: AIC=665) did not differ from those of the fixed effects model (shot 2: AIC=741, shot 7: AIC=670), and thus neither do the p-values. For shot 2, significantly ($p=0.027$) longer cracks were measured using the “Photo printout” method compared to the reference method. However, it should be noted that this method was only used by one crack length analyzer and did not comply with the specifications.

The course of the crack lengths per target at shot 12 is unusual. After a clear increase, the crack lengths reach a first plateau at a bullet penetration depth of 7.5 cm and then reach a maximum at a bullet penetration depth of 15 cm. Due to the bullet design (bonded deformation bullet) and the bullet core material composed of lead, it would have been expected that after the penetration of the bullet into the simulant, the crack lengths would rapidly reach a maximum and then decrease in the further course, because they depend on the available bullet energy (resp. velocity) and the momentary cross-sectional area of the bullet. Since the bullet energy decreases with increasing penetration depth, this behavior can only be explained by a change in the position of the bullet. However, this is contradicted by the bullet design. Deformation projectiles usually achieve a relatively directionally stable movement in simulants due to mushrooming and the resulting shoulder stabilization.

Our results show that the photo-based method is suitable for large gelatin blocks. On-site measurement of crack lengths did not provide significantly different results than the later measurements on the computer. Deviations in individual crack length measurements depended on the analyzer and his experience. Crack lengths at the end of the shot channel were difficult to measure because the gelatin was very destroyed in this area. However, due to the very small cracks, this had only a minor influence on the total crack length of the respective block.

The applied crack length method according to Knappworst and Gawlick [7] has been tried and tested for decades and was also applied by the Beschussamt Ulm. However, it has the disadvantage that the evaluation must be made immediately after the shot (location- and time-dependent). The gelatin cannot be stored for later evaluation due to its consistency. This is where the modified evaluation procedure of the BfR applies. It offers the possibility that an evaluation can be carried out at a later time, at different locations, by a large number of interested persons and with different measurement tools. The software “Adobe Acrobat Reader” and “ImageJ” have proven to be particularly suitable for measuring crack lengths based on the photos.

In a new study, the measurement of the total crack length was classified as less reproducible [11]. However, the difference with our study is that in this study, shortguns were used to shoot at 10 % gelatin and the energy input was less than 500 J.

Nonetheless, the main disadvantage is that the crack length measurement procedures are very time consuming.

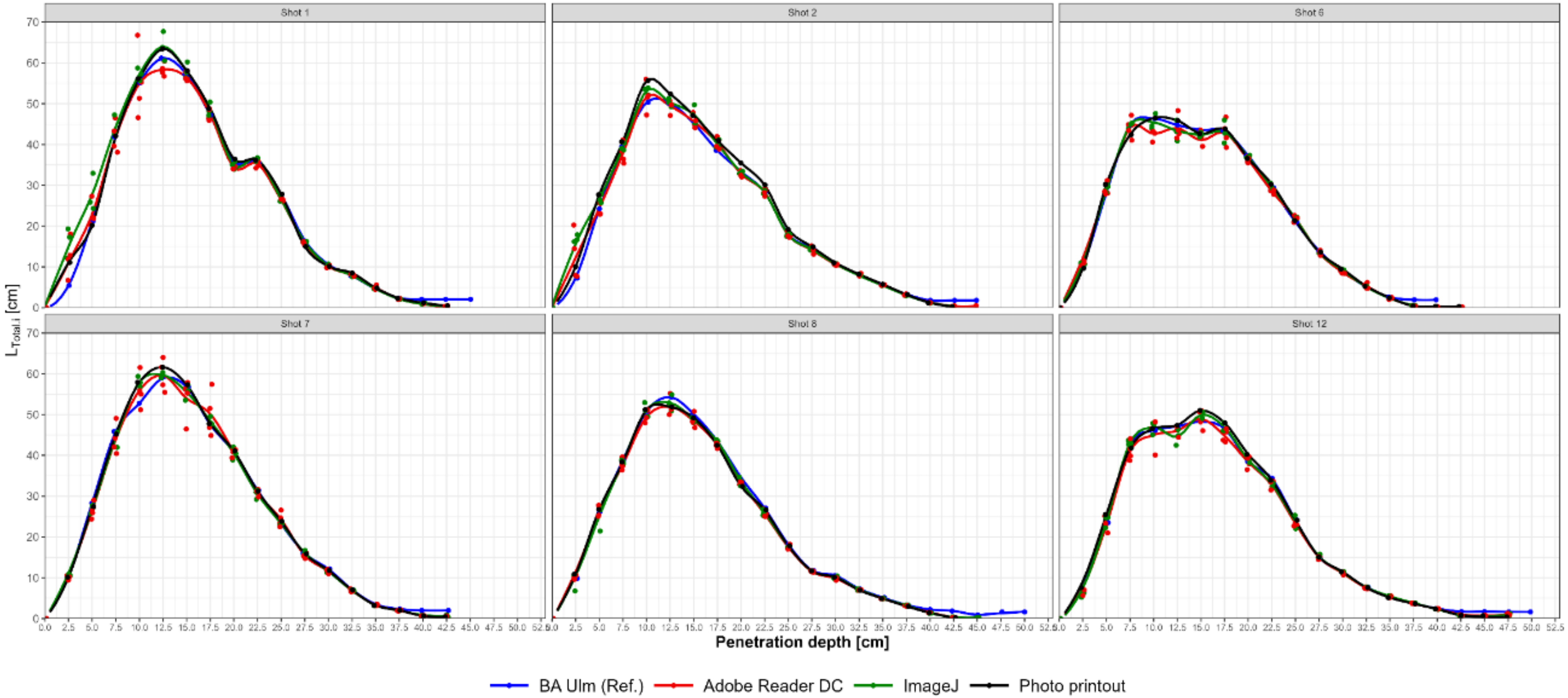


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Figure 7: Method comparison for the determination of crack lengths per shot. Solid lines denote smoothed crack lengths along penetration depth. Points denote the observed crack lengths of individual crack analyzer.

3.2.3 Effects of the omission of crack lengths on the back ($S_{i.back}$) of each slice on the total crack length (L_{Total})

The question should be investigated whether the length of the cracks on the back needs to be measured. Hypothesis: For example, the crack lengths on the back of slice 1 should have the same length as the front of slice 2 (corresponding to slice 2 back vs. slice 3 front and so on). Figure 8 shows the results of the total crack lengths L_{Total} when measuring the front and back sides and when omitting the back side. When cracks are measured on both sides of the gelatin slices, the total crack lengths are between 3.76 m (shot 6) and 4.4 m (shot 1). Omitting the crack lengths on the back side of each slice had no significant effect on the total crack length (for all 6 shots on large gelatin blocks). With this bullet, the crack length measurements on the back of the gelatin block slices can be omitted. No generally valid statements can be made about this. In the case of the bullet used in the previous study [12], omitting the crack length measurement on the back resulted in the total crack length becoming smaller. Omitting the crack length measurement on the back possibly depends on the velocity and bullet type. An important positive effect is the time saved by omitting the measurements on the back side. Therefore, further observations should be made.

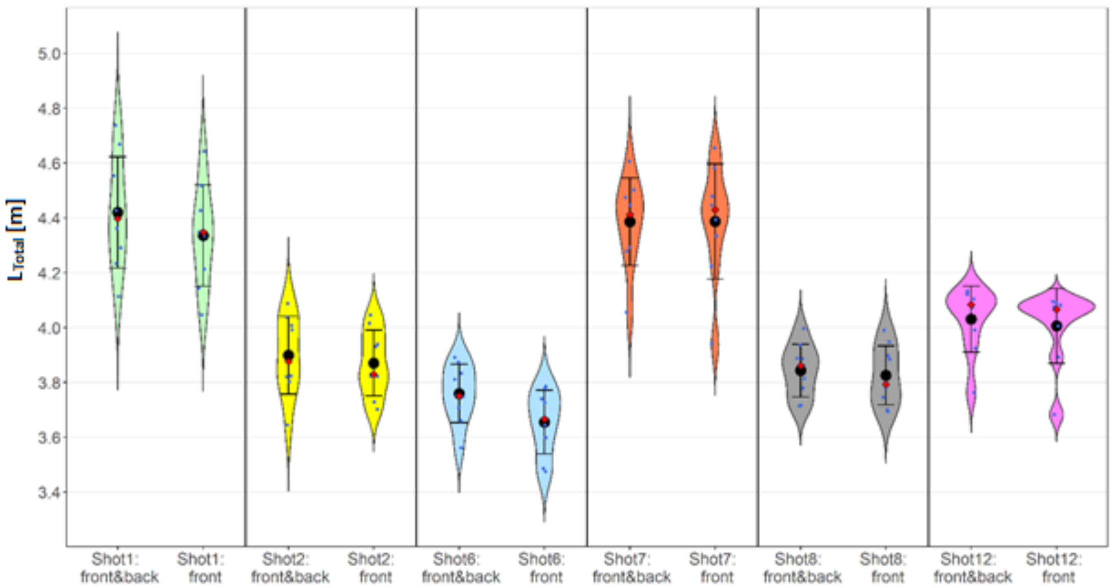

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Figure 8: Total crack lengths of front and back side compared to total crack lengths on front side. Black error bars representing the standard deviations of the means (black dot), red dots represent the median, blue dots (jittered) represent raw data of individual crack length analyzers, shape of violin plots represent the density distribution.

3.2.4 Number of cracks

To find out whether it is useful to measure each small crack, the crack length per slice ($L_{Total.i}$) was plotted against the number of cracks using GAM smoothing (to show a trend in the data). $L_{Total.i}$ remains constant from about 30 cracks (dashed line, Figure 9, shot 12). Compared to the first study, many more participants adhered to the specifications for crack length measurements. However, it was also pointed out again. Therefore, differences in the number of cracks are only due to the fact that a single participant (USA 6) measured differently than described in the BfR specification. However, this had no influence on the determination of the total crack lengths. The high number of cracks occurred because very small cracks (minimum 1 mm) were also measured on single slices. Especially at the beginning of the bullet penetration through the gelatin block and at the end, very small cracks frequently occurred. These small cracks have only a minor effect on the determination of the total crack lengths in the gelatin block. Cracks smaller than the caliber (here 7.62 mm) could be ignored. In the reference measurement (BA Ulm), at the beginning of the bullet penetration (after 2.5 cm), often only the caliber was given if the cracks were very small. One conclusion from this is that the instructions for measuring cracks need to be further specified.

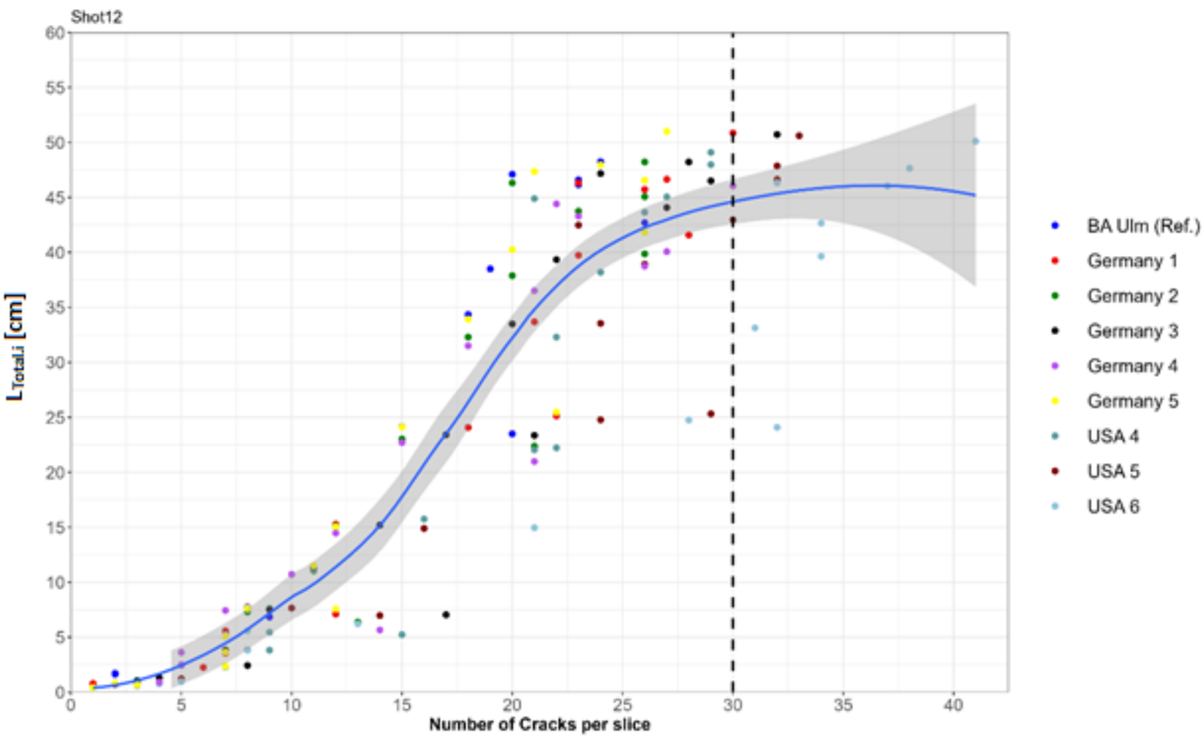

Figure 9: Relationship between number of cracks and crack length. Solid lines denotes the smoothed crack length along penetration depth with 95% confidence intervals (shaded area). Points denotes the observed crack lengths of individual crack analyzer.

3.3 Considerations of the physical effectiveness of the bullet

It has been shown that the measurement of energy release along penetration depth of the bullet through the gelatin block is possible in conjunction with the crack length methods, but is only valid for the large block size in this energy level. Due to the two large gelatin blocks lying one behind the other per shot, plug-in shots were expected, so that the energy release of the bullet along the path (“effectiveness”) was calculated according to “TR Patrone 9 mm x 19” [13].

Figure 10 shows the course of the energy release of the bullet on six large gelatin blocks per 2.5 cm penetration depth (effectiveness). At each penetration depth, 54 points of effectiveness (9 analyzers x 6 shots) were calculated. Per shot, a fitting curve (solid line) passes through these points. The course of effectiveness is similar up to the penetration depth of the bullet of 7.5 cm, which is indicative of uniform energy delivery. It is obvious that the largest variations between shots on six large gelatin blocks occur in the area of maximum effectiveness, i.e. after 10 to 15 cm penetration depth of the bullet. In the descending range (penetration depth from 17.5 cm), the effectiveness curves of the individual shots differ more strongly than in the ascending range.

For shot 1 (smoothed blue line of crack length along penetration depth and blue points (observed crack lengths)), the maximum effectiveness was reached after 12.5 cm (except Germany 1) and ranged between 152 and 165 J/cm (depending on crack length analyzer, single data points in Figure 10). At 22.5 cm penetration depth, there was a slight increase in energy release. For shot 6 (smoothed green line with single data points), the maximum effectiveness had a wider range and was between 7.5 and 17.5 cm. However, the maximum effectiveness was overall less than with the first two shots (range 135–143 J/cm depending on crack length analyzer). The highest effectiveness maximum was measured at shot 7 (smoothed violet line with single data points) and was 166 J/cm while the lowest efficacy maximum was measured at shot 12 with 134 J/cm (smoothed black line). Which corresponds to a difference of 32 J/cm. Given the wide range of results, the manufacturer would have to assume the lower value of the maximum effectiveness in the interest of reliable killing of the game. This means that the maximum operating range of his bullet would be lower. Results of energy release (E_{rel}) and maximum effectiveness (W_{max}) per crack length analyzer and per shot are listed in Table 2 (Annex 8.2).

Our results show that the physical effectiveness of a bullet could be simulated in the test medium gelatin, but is subject to uncertainties. Uncertainties also include the large variation of the maximum effectiveness under almost identical test conditions. This inevitably leads to the fact that a large number of large gelatin blocks must be shot in order to obtain meaningful results. In addition, the longer expression of the maximum effectiveness over the penetration depth (shot 6 and shot 12) was observed with two gelatin block shots. However, the cause of this could not yet be clearly determined. Another uncertainty is that the violent movements and the pulsing of the blocks after the shot cannot be recorded in the energy balance. Due to the extreme inherent motions, especially with the small blocks (recorded with the high-speed camera, see video), part of the kinetic energy of the bullet is transformed into other forms of energy. Thus, it is not available for the formation of cracks in the gelatin. When the block jumps up, there is an elastic movement of the block in the flight phase. Together with the impact of the block on the base, this very likely has an influence on crack formation. Due to the larger inertia of the large gelatin blocks, their motion is also considerably smaller compared to the small blocks. Since these motions occur in all shot gelatin blocks, it would be possible to classify them as systematically occurring biases, the magnitude of which depends on the particular energy input. These uncertainties possibly lead to an increase of the variation within a series of measurements and thus to the necessity of a large number of shots for statistical validation.

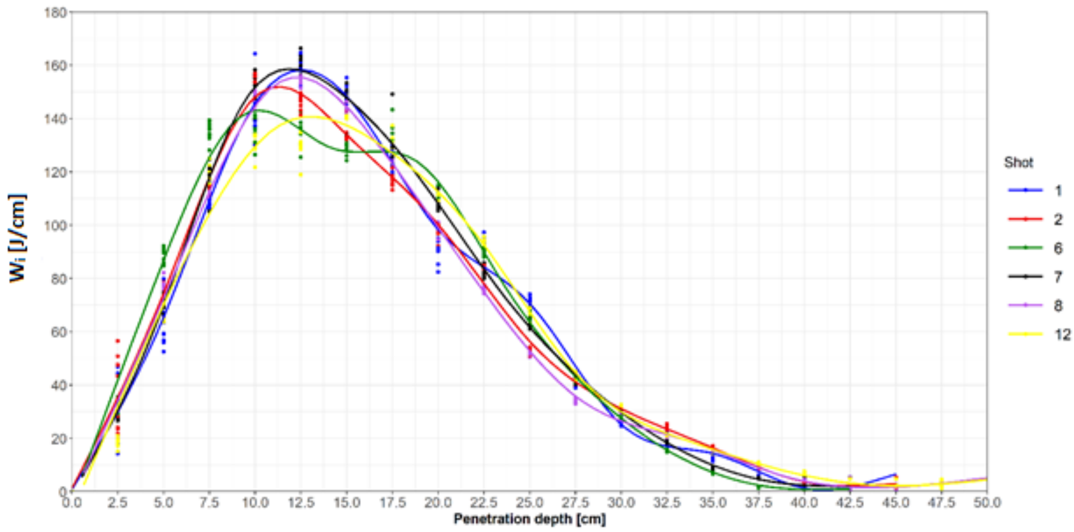

Figure 10: Effectiveness [J/cm] of the bullet from six shots on large gelatin blocks. Solid lines denote smoothed effectiveness along penetration depth. Points denote the observed effectiveness of individual crack analyzer.

Figure 11 shows the values for the bullet effectiveness (J/cm) on the primary y-axis and the cumulated energy release in J on the secondary y-axis along the length of penetration in centimeters (x-axis) for each shot on six large gelatin blocks (results from BA Ulm). As expected, the bullet with the highest impact velocity on target (701 m/s) released the highest energy at shot 7 (dark blue line) with 2,924 J. In contrast, the bullet with the lowest target velocity (688 m/s) on target at shot 8 released the lowest energy (red line) with 2,816 J (Figure 11). The difference in target velocities was 13 m/s for the shots on large gelatin blocks. These represent excellent values for a cartridge load. The deviations at the maximum effectiveness are not due to the low velocity tolerance. It is possible that due to progressive bullet deformations (after 7.5 cm penetration depth of the bullet), different angles of attack are achieved, which then lead to a changed energy output.

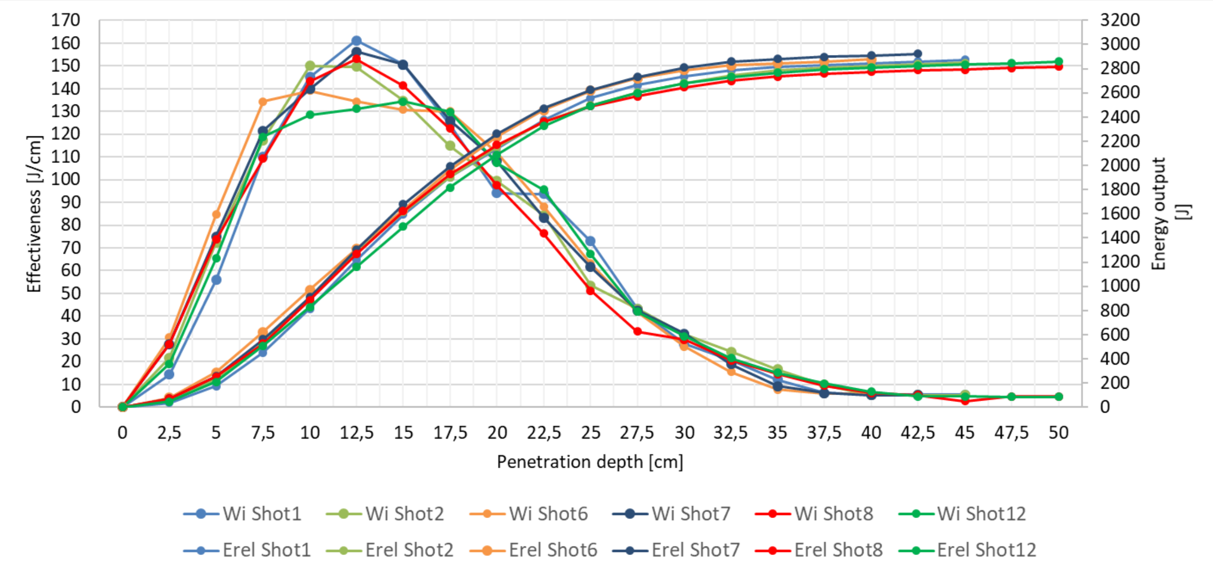

Figure 11: Bullet effectiveness (J/cm) on the primary y-axis and the cumulated energy output in J on the secondary y-axis along the length of penetration depth in centimeters (x-axis) for shot on six large gelatin blocks. (Solid lines: smoothed crack length along penetration depth with 95 % confidence intervals (shaded area) of the fitted smoother, Points: observed crack lengths of individual crack analyzer).

4 Summary

By further investigation, the suitability of the two gelatin block sizes was to be tested by shooting a hunting bullet (2,900 J) at a simulated distance of 100 m. The size of the gelatin blocks has an influence on whether an analysis regarding "effectiveness" of hunting bullets (2,900 J) is possible. In the experiments, five out of six small gelatin blocks (15 cm x 15 cm x 35 cm) tore over the edge. A measurement of crack lengths could therefore not be carried out. The small block size does not withstand the energy output of the bullet. The large block size (25 cm x 25 cm x 40 cm) withstands the energy release of the bullet and measurement by crack length method [11] is possible.

The modified method for crack length measurement has proven successful and could be confirmed by a larger number of shots. It offers the possibility to measure the cracks independent of location and time. Deviations in crack length measurements using the modified method compared to the direct method (BA Ulm) are due to the fact that not all participants had experience with the method. The specifications for measuring the cracks were largely adhered to this time.

The trend from the first study that the backs of the slices no longer need to be measured has solidified in this study with a larger number of shots. At least for this bullet and at the target velocity of 700 m/s, the backs of the slices would no longer need to be measured.

The course of energy release along the penetration depth (physical effectiveness) was determined from the crack lengths in the gelatin and the kinetic energy of the bullet in front of the target (calculated from target velocity and bullet mass). Due to the placement of two gelatin blocks one behind the other, the bullet remained stuck for all shots. Therefore, it was not necessary to measure the residual speed. This allowed the energy profile of the bullet to be calculated along its penetration depth through the large blocks.

Despite the similar curve progressions of the effectiveness, the results showed larger deviations between the six shots and the individual crack lengths analyzers at the maximum effectiveness. Since the differences in the maximum effectiveness did not depend on the target speed, the storage conditions (temperature and storage time) of the gelatin blocks could possibly be a cause. This could reduce the reproducibility of the results. Hence, further investigations are planned in this context. The basis for an international round robin test is thus to be expanded.

5 References

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6 List of Figures

7 List of Tables

8 Appendix

8.1 Bullet data

Table 1: Overview of the 12 shots on small and large gelatin blocks. Bullet (RWS Evolution 11.9 g, Caliber .30-06 (Bullet diameter: 7.62 mm)

Shot	Room temperature °C/Humidity%	*V_{Target} [m/s]	End position of the remaining bullet [cm]	Rest diameter d_{Rest} [mm]	Rest bullet mass m_{rest} [g] (Loss of mass %)
1 (25x25x40 cm)	21.6/ 56.4	694.8	45	20.7	11.48 (3.5)
2 (25x25x40 cm)	21.6/ 56.4	692.1	45	17.9	11.18 (6.0)
3 (15x15x35 cm)	21.7/ 52.0	694.5	45	17.9	10.72 (9.9)
4 (15x15x35 cm)	21.7/ 52.0	698.1	46.5	18.5	10.70 (10.1)
5 (15x15x35 cm)	21.4/ 51.0	695.9	45	16.8	9.93 (16.5)
6 (25x25x40 cm)	21.8/ 50.9	695.2	41	19.5	11.05 (7.1)
7 (25x25x40 cm)	21.5/ 54.1	701	44	20.0	10.89 (8.5)
8 (25x25x40 cm)	21.7/ 56.9	688	44.5	18.7	11.18 (6.0)
9 (15x15x35 cm)	22.0/ 58.0	706	50	16.1	10.31 (13.4)
10 (15x15x35 cm)	22.3/ 59.3	695	51	16.4	10.12 (15.0)
11 (15x15x35 cm)	21.6/54.7	693	47.5	17.5	9.9 (16.8)
12 (25x25x40 cm)	21.6/54.7	693	45	17.2	10.92 (8.2)

8.2 Summary of results per shot on large gelatin blocks

Table 2: Results of crack length measurements (L) and derived energy release (E_{rel}) and maximum effectiveness (W_{max}). The results are listed per crack length analyzer and per shot.

Crack length analyzer	Shot (block size)	Number of cracks	L_{Total} [m]	E_{Target} [J]	$E_{rel.Total}$ [J]	W_{max} (J/cm)
Ulm (Reference)	1 (25x25x40 cm)	265	4.4	2872.3	2872.2	161
Ulm	2 (25x25x40 cm)	234	3.8	2850.1	2849.7	150
Ulm	6 (25x25x40 cm)	212	3.8	2875.7	2875.4	139
Ulm	7 (25x25x40 cm)	280	4.4	2923.8	2923.5	156
Ulm	8 (25x25x40 cm)	249	4.0	2816.4	2816.5	153
Ulm	12 (25x25x40 cm)	255	4.1	2857.5	2857.6	134
Germany 1	1 (25x25x40 cm)	291	4.7	2872.3	2872.4	164
Germany 1	2 (25x25x40 cm)	263	4.1	2850.1	2850.1	156
Germany 1	6 (25x25x40 cm)	240	3.9	2875.7	2875.8	143
Germany 1	7 (25x25x40 cm)	319	4.6	2923.8	2924.1	156
Germany 1	8 (25x25x40 cm)	262	3.9	2816.4	2816.2	158
Germany 1	12 (25x25x40 cm)	282	4.1	2857.5	2857.8	143
Germany 2	1 (25x25x40 cm)	275	4.2	2872.3	2872.3	159
Germany 2	2 (25x25x40 cm)	246	3.8	2850.1	2850.1	154

Crack length analyzer	Shot (block size)	Number of cracks	L_{Total} [m]	E_{Target} [J]	$E_{rel.Total}$ [J]	W_{max} (J/cm)
Germany 2	6 (25x25x40 cm)	232	3.7	2875.7	2875.7	143
Germany 2	7 (25x25x40 cm)	301	4.3	2923.8	2923.9	156
Germany 2	8 (25x25x40 cm)	252	3.8	2816.4	2816.4	153
Germany 2	12 (25x25x40 cm)	268	3.9	2857.5	2857.7	140
Germany 3	1 (25x25x40 cm)	271	4.3	2872.3	2872.5	152
Germany 3	2 (25x25x40 cm)	262	3.8	2850.1	2849.7	156
Germany 3	6 (25x25x40 cm)	250	3.7	2875.7	2875.3	137
Germany 3	7 (25x25x40 cm)	305	4.5	2923.8	2923.6	166
Germany 3	8 (25x25x40 cm)	250	3.8	2816.4	2816.3	148
Germany 3	12 (25x25x40 cm)	303	4.1	2857.5	2857.3	141
Germany 4	1 (25x25x40 cm)	296	4.1	2872.3	2872.2	161
Germany 4	2 (25x25x40 cm)	278	3.6	2850.1	2849.9	148
Germany 4	6 (25x25x40 cm)	247	3.6	2875.7	2875.8	134
Germany 4	7 (25x25x40 cm)	314	4.1	2923.8	2923.8	160
Germany 4	8 (25x25x40 cm)	263	3.7	2816.4	2816.5	155
Germany 4	12 (25x25x40 cm)	272	3.8	2857.5	2857.3	140
USA 1	1 (25x25x40 cm)	284	4.4	2872.3	2872.4	158
USA 1	2 (25x25x40 cm)	251	3.9	2850.1	2849.8	153
USA 1	6 (25x25x40 cm)	228	3.7	2875.7	2875.4	137
USA 1	7 (25x25x40 cm)	319	4.4	2923.8	2924.0	160
USA 2	1 (25x25x40 cm)	259	4.6	2872.3	2872.3	161
USA 2	2 (25x25x40 cm)	239	4.0	2850.1	2849.8	152
USA 2	6 (25x25x40 cm)	225	3.9	2875.7	2875.8	141
USA 2	7 (25x25x40 cm)	276	4.5	2923.8	2924.0	155
USA 3	1 (25x25x40 cm)	263	4.7	2872.3	2872.6	164
USA 3	2 (25x25x40 cm)	231	4.0	2850.1	2849.8	154
USA 3	6 (25x25x40 cm)	213	3.7	2875.7	2875.3	139
USA 3	7 (25x25x40 cm)	273	4.3	2923.8	2923.9	163
USA 4	8 (25x25x40 cm)	239	3.7	2816.4	2816.6	154
USA 4	12 (25x25x40 cm)	307	4.0	2857.5	2857.1	141
USA 5	8 (25x25x40 cm)	358	3.9	2816.4	2816.5	153
USA 5	12 (25x25x40 cm)	336	4.1	2857.5	2857.3	142
USA 6	8 (25x25x40 cm)	376	4.0	2816.4	2816.2	156
USA 6	12 (25x25x40 cm)	395	4.1	2857.5	2857.2	140
Germany 5	1 (25x25x40 cm)	277	4.4	2872.3	2872.60	165
Germany 5	2 (25x25x40 cm)	247	4.0	2850.1	2850.0	157
Germany 5	6 (25x25x40 cm)	236	3.8	2875.7	2875.50	140
Germany 5	7 (25x25x40 cm)	292	4.4	2923.8	2923.60	162
Germany 5	8 (25x25x40 cm)	242	3.9	2816.4	2816.70	151
Germany 5	12 (25x25x40 cm)	269	4.1	2857.5	2857.80	141

8.3 Results of GAM models

Table 3: Results of GAM models for Shot 1.

Predictor	Estimate	Std. Error	t value	p
Measurement tool				
Adobe Reader	0.3162	1.0671	0.296	0.767
ImageJ	1.5970	1.0586	1.509	0.134
Photo printout	1.4858	1.5345	0.968	0.335
Approximate significance of smooth terms				
		edf	**F value**	**p**
s(penetration depth)		3.9925	1194.412	<0.001
s(crack length analyzers, random effect)		0.6129	1.583	0.11

Table 4: Results of GAM models for Shot 2.

Predictor	Estimate	Std. Error	t value	p
Measurement tool				
Adobe Reader	0.7570	0.7931	0.954	0.3415
ImageJ	1.2473	0.7738	1.612	0.1092
Photo printout	2.6065	1.1634	2.240	0.027
Approximate significance of smooth terms				
		edf	**F value**	**p**
s(penetration depth)		3.9949	1640.643	<0.001
s(crack length analyzers, random effect)		0.7849	3.649	0.0327

Table 5: Results of GAM models for Shot 6.

Predictor	Estimate	Std. Error	t value	P
Measurement tool				
Adobe Reader	-0.1080	0.9801	-0.110	0.912
ImageJ	0.1150	0.9693	0.119	0.906
Photo printout	1.0679	1.3994	0.763	0.447
Approximate significance of smooth terms				
		edf	**F value**	**p**
s(penetration depth)		3.9868		<0.001
s(crack length analyzers, random effect)		0.6649		0.0864

Table 6: Results of GAM models for Shot 7.

Predictor	Estimate	Std. Error	t value	p
Measurement tool				
Adobe Reader	0.5176	0.6512	0.795	0.4280
ImageJ	0.4394	0.6277	0.700	0.4850
Photo printout	1.7914	0.9568	1.872	0.0632
Approximate significance of smooth terms				
		edf	**F value**	**p**
s(penetration depth)		3.9977	3741.0	<0.001
s(crack length analyzers, random effect)		0.8611	6.2	0.00815

Table 7: Results of GAM models for Shot 8.

Predictor	Estimate	Std. Error	t value	p
Measurement tool				
Adobe Reader	0.6774	1.7420	0.389	0.698
ImageJ	0.7001	1.7749	0.394	0.694
Photo printout	0.9515	2.2292	0.427	0.670
Approximate significance of smooth terms				
		edf	**F value**	**p**
s(penetration depth)		2.992	331.8	<0.001
s(crack length analyzers, random effect)		0.00008	0	0.779

Table 8: Results of GAM models for Shot 12.

Predictor	Estimate	Std. Error	t value	p
Measurement tool				
Adobe Reader	-0.6780	0.6523	-1.039	0.300
ImageJ	-0.2542	0.6714	-0.379	0.705
Photo printout	0.1620	0.8269	0.196	0.845
Approximate significance of smooth terms				
		edf	**F value**	**p**
s(penetration depth)		3.996	2054	<0.001
s(crack length analyzers, random effect)		0.0000969	0	0.467

8.4 Effect of penetration depth on crack length

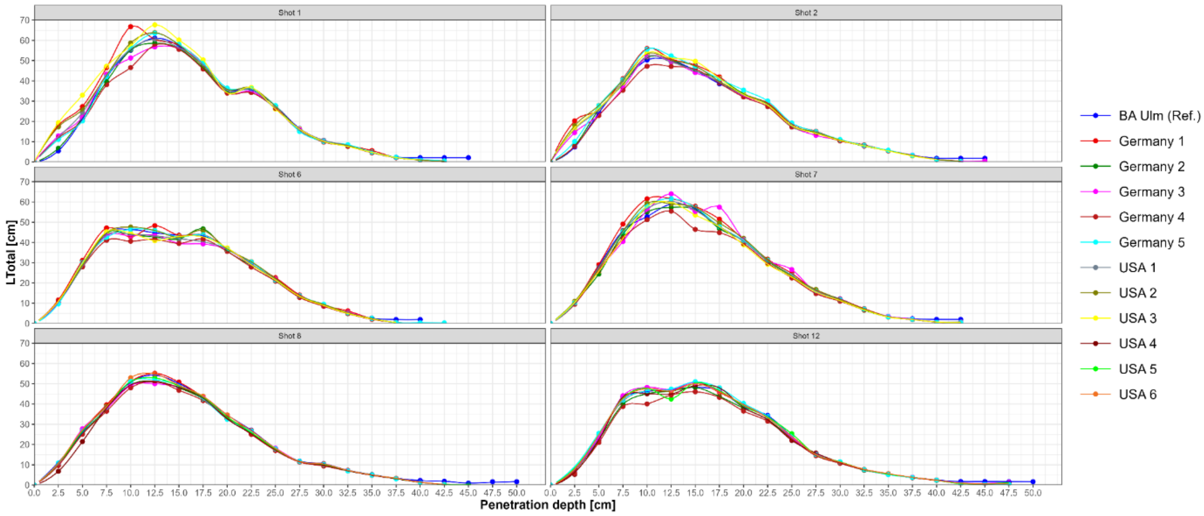


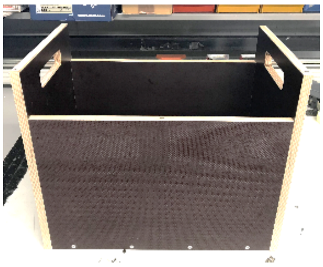
Figure 12: Effect of penetration depth on crack length for 12 crack analyzers (9 per shot). Smoothed curves of crack length sum along penetration depth of projectile (Solid lines: smoothed crack length along penetration depth. Points: observed crack lengths of individual crack analyzer).

German Federal Institute for Risk Assessment

14 March 2024

Investigation of the influence of casting mold material and storage time on large gelatin blocks as a test simulant for hunting bullets

Authors: Ingo Rottenberger, Annett Martin, Ellen Ulbig, Johann Höcherl


Content

1 Introduction

The process of killing when shooting at huntable game cannot be simulated. Experimental firing at ballistic simulants (e.g. soap, gelatin) can only make the effects of the firing visible and show the energy transfer of the projectile to the simulant. Scientific expert discussions with international participation took place at the Federal Institute for Risk Assessment (BfR) to describe a reliable killing effect of hunting projectile [1]. In this context, criteria for describing the effective potential of projectiles in test simulants were developed. The consistent quality of the bombardment medium (e.g. 20 % gelatin or ballistic soap) is an essential prerequisite for such investigations. The production and storage of the test simulant gelatin is described for the testing of police bullets in the Technical Guideline "Patrone 9 mm x 19, schadstoffreduziert" of the Police Technical Institute (PTI) of the German Police University (DHPol), as of September 2009 (in short: TR Patrone 9 mm x 19) [2] for gelatin blocks with the dimensions 15 cm x 15 cm x 35 cm. Recent studies [3,4] show that this small block size is poorly suited for testing with much higher energy hunting bullets (>5,000 J [3] and 2,900 J [4]) and that gelatin blocks measuring 25 cm x 25 cm x 40 cm with lower bombardment repetitions produce reproducible results in crack length measurements. In the course of the evaluation of test shots, questions arose as to the extent to which the cooling time of large gelatin blocks (25 cm x 25 cm x 40 cm) after their manufacture, the detaching by heating from the metallic mold, the use of different gelatin mold materials and the storage time of the gelatin blocks could have an effect on the results of the crack length measurements.

Using large gelatin blocks, the influence of the cooling time in different casting mold materials until a core temperature of 15°C is reached, the influence of different gelatin casting mold materials (metal, wood, plastic) and the storage time (two, four and seven days) on the reproducibility of crack length measurements when using the crack length method according to Gawlick and Knappworst [5] was therefore investigated. For comparison with the specifications from the "TR Patrone 9 mm x 19" [2], a small block was also produced and its temperature profile during cooling determined in parallel.

Based on the "TR Patrone 9 mm x 19" [2], the effectiveness (energy release per centimeter of penetration) of the projectiles used has been determined.

Based on further observations in previous experimental shootings [2,3], the influence of the block underlay on the direction of the longest cracks in the gelatin, the need to measure crack lengths on the front and back of the gelatin block slices, and the detection of cracks longer than 75 mm were included in the studies.

2 Material and Methods

2.1 Preparation and performance of experiments

2.1.1 Core temperature measurement and cooling time

Three large and one small gelatin blocks were produced in November 2021 in compliance with "TR Patrone 9 mm x 19" [2] by the Beschussamt Ulm. For the large gelatin blocks (25 cm x 25 cm x 40 cm), a mold made of stainless steel (referred to as metal in the further course), wood and plastic was used in each case, and for the small gelatin block (15 cm x 15 cm x 35 cm), a metal mold made of stainless steel from the Beschussamt Ulm. The temperature measurements were made with the digital meat thermometer "Turata" (range of application: -50°C to 300°C with a tolerance ± 0.1°C).

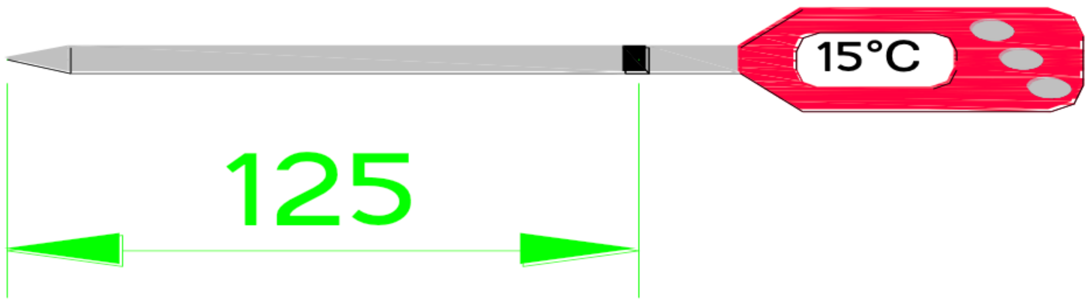


Figure 1: Thermometer "Turata" with marked measuring depth of 125 mm for the large gelatin block

The measuring depth in the small gelatin block is 75 mm due to its smaller cross-section. A comparison carried out with a reference thermometer resulted in a deviation of 0.4°C to -0.3°C for the desired measuring range of 12°C to 50°C depending on the respective based temperature. These tolerances are extremely low for a standard meat thermometer.

Due to the fact that the processes are always the same, the temperature recording began immediately after the pouring at 2:00 p.m. The next measurement took place two hours later at 4:00 p.m. On the next and all subsequent days, temperature measurements were taken during regular working hours at four-hour intervals at 8:00 a.m., 12:00 a.m. and 4:00 p.m. The timing of the measurements is shown in full in Appendix B. All measurements were carried out in the Beschussamt Ulm.

The temperature to be maintained throughout the cooling (climate chamber) was 15°C ± 1°C and the humidity was 60 %. The measurements each started in the middle of the block. The thermometer was inserted into the gelatin to the marked depth, the reading was read and transferred to an Excel spreadsheet with one decimal place (see Appendix B). Only one measurement per block was carried out at the specified times.

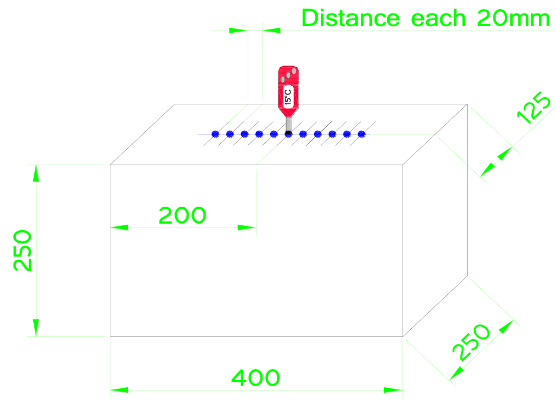


Figure 2: Order of measurements on the gelatin block.

The cooling time added up in the data sheet (see appendix B). The next measurement was carried out alternately to the right/left of the centre towards the outer end faces (see Fig. 2), so that a new measuring point with undamaged gelatin was always available. Upon reaching 20°C in the centre of the block, the blocks were removed from the mold and further cooled until the core temperature reached 15°C. The series of measurements was ended when 15°C was detected again in the middle of the respective puncture level. The procedure has been retained for all gelatin blocks regardless of size and mold material.

2.1.2 Gelatin casting mold materials

During the technical discussions held at the BfR [1], the assumption was made that the subsequent heating to release the gelatin block from the metal mold [2] could have an influence on the crack length formation during bombardment in direct comparison with a wooden or plastic mold, since these do not have to be briefly heated again to remove the gelatin.

Three molds for each of the large blocks of gelatin made of three different materials (metal, wood, plastic) were available for the experiment.

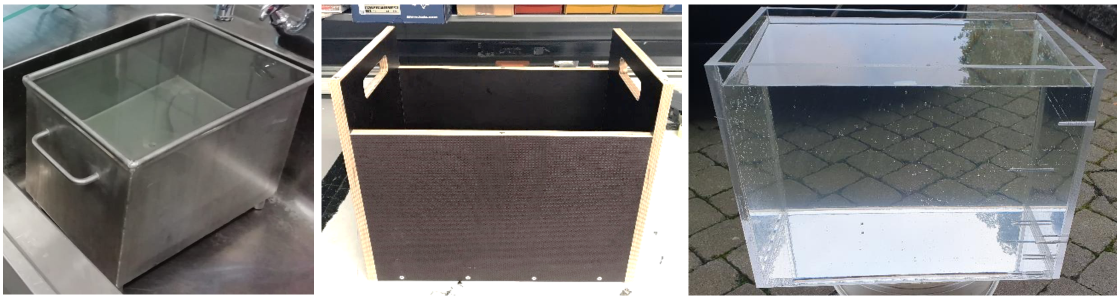


Figure 3: From left to right: metal mold[1], wood mold[2], plastic mold[3].

Three large blocks of gelatin (gelatin batch no.: 073830) were cast for each casting mold material, in compliance with the specifications from the “TR Patrone 9 mm x 19” [2] and a schedule developed by the Beschussamt Ulm, cooled (tempered) and prepared for shooting (see Appendix C). The storage period after reaching the core temperature of 15°C was two days for all casting mold materials.

2.1.3 Storage period

Since gelatin is made from biological materials, it is subject to microbiological processes that lead to changes in the material properties over longer periods of storage. To ensure that the test conditions are the same, it is important to know how long cast gelatin blocks can be stored without this having an impact on the formation of crack lengths when bombardment.

For this series of tests, a total of 6 large gelatin blocks were cast, cooled, and prepared for shooting exclusively in the large metal molds in compliance with the specifications from the “TR Patrone 9 mm x 19” [2] and a sequence plan developed by the Beschussamt Ulm (see Appendix C). Since three large gelatin blocks had already been stored in the metallic mold for a period of 2 days after the core temperature of 15°C had been reached in the “casting mold materials” experiment and then shot, these results could also be used for the experiment on the storage period of two days (L2). Therefore that only three blocks each had to be produced for a 4-day (L4) and a 7-day storage period (L7). Thus, by ensuring the core temperature of 15°C, the storage period was the only variable in the experiment. Three shots each were fired per bearing duration of 4 days (L4) and 7 days (L7). Nine blocks/shots (including L2) were thus available for later evaluation for this part of the experiment

2.1.4 Bombardment preparations

In preparation for bombardment the gelatin blocks, the existing 30-06 Springfield calibre measuring barrel was clamped into an electronically controlled firing unit (HPI-EPVAT Receiver Unit 292UR) and centered on the face of the gelatin block using a laser pointer. A

[1] Metal mold from Beschussamt Ulm
[2] Wooden mold provided by company OMI Mellrichstadt
[3] Plastic mold made of Plexiglas, manufactured by Ingo Rottenberger, BfR

first, permanently installed pair of photoelectric sensors “Drello - LS 30 I” was located at a distance of 3.0 m from the mouth of the barrel. Another transportable pair of photoelectric sensors “Drello 19 i 3” recorded the target velocity 1.0 m in front of the target, and a third pair of photoelectric sensors (LS 260 from Mehl with BMC 31 receiver) was set up directly behind the gelatin block to be fired at to determine the exit velocity of the projectile.

The ammunition was produced by the Beschussamt Ulm. A 165 grains (10.7g) Barnes TTSX bullet was used, which was have to have a velocity of 700 m/s ± 10 m/s at a distance of 1.0 m in front of the gelatin block.

A Regupol sheet with a thickness of 43 mm was used as a base for the gelatin blocks. The experimental setup is shown in Figure 4.

The top of the gelatin blocks was marked with a white continuous line in the direction of shooting.

Prior to the start of the experiments, a shot was fired at a cardboard box (in place of the gelatin block) without a gelatin block to determine the point of impact (POI). Due to a deviation between the point aimed at with the laser and the POI of the projectile, a correction was then made so that after another test shot the target point matched the POI. After that, the cardboard box was removed and the gelatin block coming from the refrigerator was placed in the shooting position. A block of soap behind the pair of exit light barriers served as a bullet catch in order to be able to record the residual bullet mass.

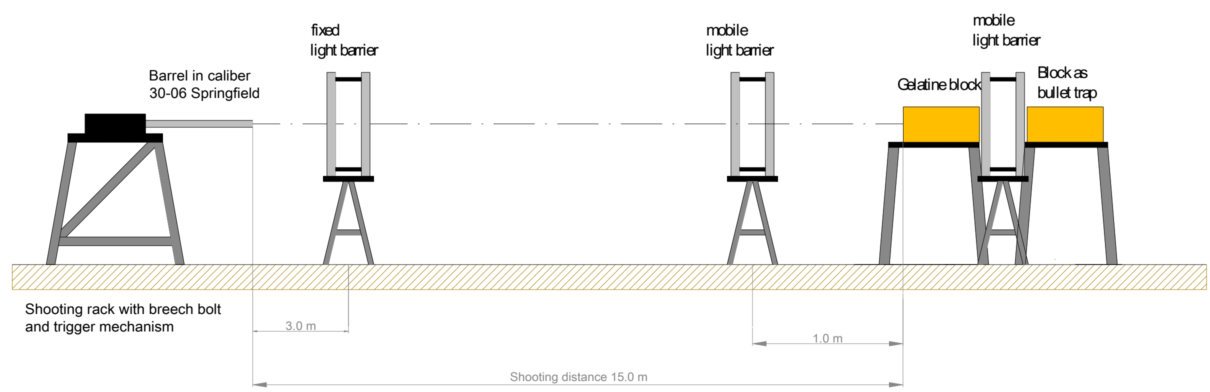


Figure 4: Test setup for gelatin bombardment using different casting mold materials and storage times.

The entire technical structure, the cartridge load used and the process before, during and after shooting were identical for the test parts “Casting mold material” and “Storage time”.

2.1.5 Bombardment of the gelatin blocks

The bombardment of the large blocks of gelatin took place in an indoor shooting range (ISR) of the Ulm bombardment office under airconditioned conditions. After the specified cooling time of 42 hours and the additional storage of two days, the gelatin blocks were removed from the cooling and shot upon immediately.

The bombardment took place exactly in the middle of one front side of the gelatin block. Immediately after the shot was fired at the block, the target velocity of the bullet, the exit velocity of the bullet rest, the air temperature, the humidity and the total penetration depth of the bullet (gelatin block plus block behind it as bullet trap) recorded in a data sheet in the ISR (see Appendix D). The next step was to measure the crack lengths.

2.2 Test evaluation

2.2.1 Crack length measurement

The measurement of the crack lengths for the tests "Casting mold materials" and "Storage time" was carried out immediately after the bombardment by two employees of the Ulm bombardment office according to the crack length method [2,5]. However, as already described in earlier tests [3,4], the disc thickness was increased to 2.5 cm instead of the usual 2.0 cm according to the "TR Patrone 9 mm x 19" [2]. The crack length measurement results were recorded in data sheets from the bombardment office, with the same employee to minimize errors always being responsible for the measurement and another for the entry in the data sheets.

2.2.2 Statistic

First, Tukey's post-hoc-tests (for all pairwise comparisons) were performed using the mctp-function from the R-package nparcomp [6] to determine if the molding materials used (wood, plastic, metal) had a significant effect on the length of the cracks when stored for two days (univariate analysis). A plot shows the relative contrast effects (differences) between pairwise comparisons with 95 % confidence intervals. The same analysis was applied to a possible relationship between crack length and storage time of the gelatin blocks in the steel mold.

Two generalized additive models (GAMs) were used as multivariate analysis to evaluate the influence of the three gelatin casting molds (when the storage period was two days) and the storage period (when the steel casting mold was used) of the gelatin blocks on the crack lengths of the gelatin block along the penetration depth of the bullet. For this purpose, the respective GAM with cubic spline was adapted [7]. The generalized additive models (GAM) can be used to model the nonlinear progression of crack lengths along the penetration depth of the projectile. In both models, the lognormally distributed dependent variable is the measured crack length $L_{Total.i}$ [cm] in the slice i. The penetration depth (measured in 2.5 cm increments for each individual slice i) of the bullet through the gelatin block was included in the model as a nonlinear term. Three shot repetitions were included in the model as random variables. Both models (Formula 1 and Formula 2) were adjusted for the covariates target velocity and room temperature and humidity on the day of bombardment. In the first model, the predictor variable chosen was the mold used (wood, plastic, steel) as a categorical term with the reference category "steel mold". In the second model, the storage duration (two, four and seven days) of the gelatin blocks was used as a categorical variable with the reference category "7 days storage duration". The GAM models (Formula 1 and Formula 2) were fitted with a logarithmic link with the Gaussian family using the restricted maximum likelihood (REML) algorithm from the package "mgcv" [7]. The Akaike

Information Criterion (AIC) was used for model selection and the model with the lowest AIC was selected.

$$\log(\mathrm{L}_{\mathrm{Total.i}}) = \beta_0 + \mathrm{s(penetration\ depth, bs = cr, k = 5) + s(shot, bs = re)} \\ + \mathrm{castina\ form} + \mathrm{V}_{\mathrm{Target}} + \mathrm{room\ temperature + humidity} + \varepsilon \tag{1}$$

$$\log(\mathrm{L}_{\mathrm{Total.i}}) = \beta_0 + \mathrm{s(penetration\ depth, bs = cr, k = 5) + s(shot, bs = re)} \\ + \mathrm{storage\ form} + \mathrm{V}_{\mathrm{Target}} + \mathrm{room\ temperature + humidity} + \varepsilon \tag{2}$$

Whereby

- $L_{Total.i}$ is crack length of slice i as response variable
- β_0 is the intercept term, it denotes the overall mean of the response
- s(penetration depth, bs = measurement tool) is a smoother that accounts for the path of the bullet through the block stratified by measurement tool
- K denotes the degree of smoothing
- s(shot) is a random effect smoother for three shot repetitions
- casting form (wood, plastic, steel) is a categorical term with reference category "steel"
- storage period (2, 4, 7 days) is a categorical term with reference category "7 days"
- v_{Target} (Target velocity of the projectile in m/s)
- ε is a Gaussian error term (the unexplained variation)

Scatter plots show the crack lengths ($L_{Total.i}$) in the slices that occurred at each penetration depth (measured in 2.5-cm increments) of the bullet through the gelatin block (x-axis). The diagrams were shown as a function of the casting mold material as well as the storage time. The GAM smoothing procedure was applied to put a smooth curve through the points in the scatter plot. This visual representation of the data was done using the R-package "ggplot2" [8].

The paired Wilcoxon exact rank test from the R package "exactRankTests" [9] was used to compare the total crack lengths L_{Total} of the front and back faces with the crack lengths without considering the back face. All statistical analyses were two-sided, and p-values <0.05 were set as the threshold for statistical significance. Statistics were generated using R-version 4.1.1 [10].

3 Results and discussion

3.1 Core temperature measurement and cooling time

In the small gelatin block, the prescribed core temperature of 15°C could be measured after 18 hours. This corresponds to the requirements in the “TR Patrone 9 mm x 19” [2]. For all large blocks, the core temperature of 15°C was observed after 42 hours of cooling at an ambient temperature of 15°C, regardless of the gelatin casting mold material used.

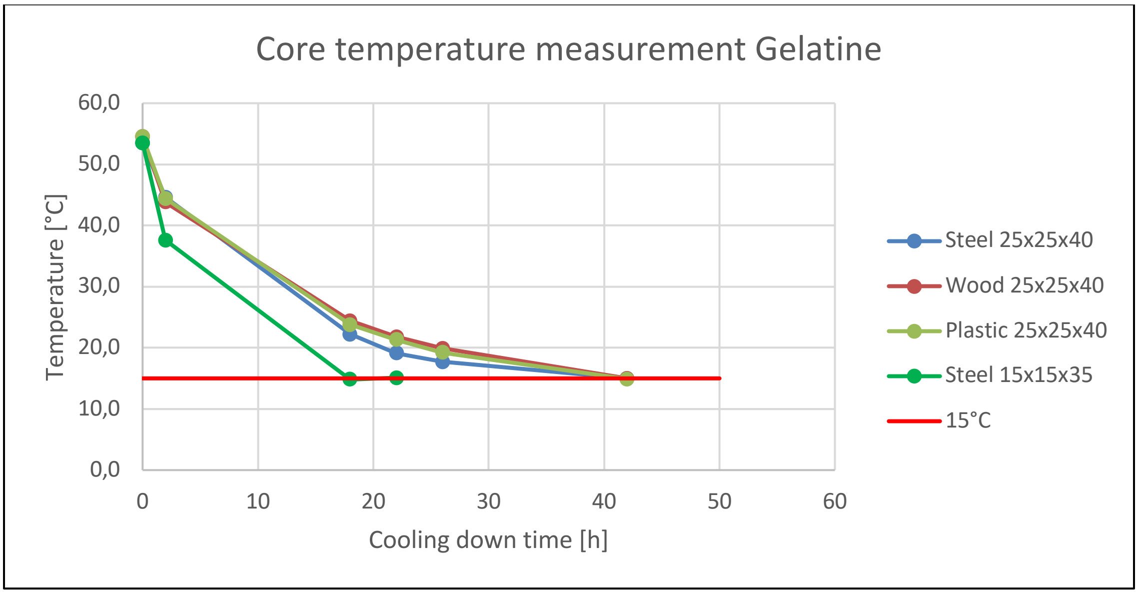


Figure 5: Results of the core temperature measurements.

The cooling function (according to Newto’s cooling law) normally has an exponential course. Within the conducted investigation, removing the gelatin block from the mold at temperatures around 20°C changes the cooling process of the block. Due to the significant increase in the heat-emitting surface, the cooling down constant also changes.

For this reason, and because there were 16 hours between the measurement on the previous day (at 16:00 – cooling time: 26 hours) and the measurement the next morning (08:00 – cooling time: 42 hours), it was not possible to determine an exact time when the standard temperature of 15°C was reached (Fig. 5). This had no disadvantage for the experimental procedure, since regardless of the casting mold material used (metal, wood, plastic), all large gelatin blocks had reached a core temperature of 15°C at the start of work. According to “TR Patrone 9 mm x 19” [2], bombardment would be possible at this time.

These results (cooling time of 42 hours) formed the basis for further planning of the experiments on the gelatin casting mold materials and the storage time. They ensured that, also with regard to the core temperature, the same conditions always existed for all large gelatin blocks prior to shots.

3.2 Gelatin casting mold materials – bombardment results

After bombarding the blocks, the target and exit velocities of the projectile (see Fig. 6) as well as temperature and air humidity (see Appendix D) were immediately entered in the data sheets. The shooted block was cut into 2.5 cm slices perpendicular to the direction of shot, and the crack lengths were recorded according to “TR Patrone 9 mm x 19” by staff of the Beschussamt Ulm. In parallel, the bullet remains have been recovered in the soap block behind. The bullet residual mass and the largest diameter of the mushrooming could be determined on them. The determined residual velocity and the residual mass are the basis for a consideration of the energy output course of the projectile along its path (effectiveness in J/cm).

Risslängenauswertung im Zielmedium "Gelatine" für Energieprüfung Datum: 25.03.2022 Beschussamt Ulm

Prüfer: **Frank** Barnes TTSX #30368

Prüfer: **Hörmann** **Schuss 1** **Kunststoff** **Konditionierung:** **2 Tage** V_3 = 719 m/s

"Risslängen in mm" **Block** groß V_{14}(m/s) 707 E (J) 2674,2 m (g) 10,7 E tiefe 75 cm G rest= 10,65 g Def. = 12,4 mm

Scheibe	1		2		3		4		5		6		7		8		9	
Schnitttiefe	0 cm	2,5 cm		5 cm		7,5 cm		10 cm		12,5 cm		15 cm		17,5 cm		20 cm		22,5 cm
Seite	VS	RS	VS	RS	VS	RS	VS	RS	VS	RS	VS	RS	VS	RS	VS	RS	VS	RS
1	5	14	15	35	11	43	31	13	39	57	30	15	50	44	45	17	52	48
2	5	5	7	22	24	15	33	30	30	34	55	16	17	23	37	59	22	34
3	4	16	12	27	17	16	28	6	54	21	50	21	10	42	30	19	18	20
4		7	7	17	24	28	48	13	46	54	24	41	9	49	8	43	96	47
5				34	12	16	42	6	35	50	22	11	61	12	20	92	36	14
6				11	35	11	15	51	31	45	48	30	49	16	15	10	20	59
7				8	30	35	27	22	23	11	46	25	8	91	34	13	50	11
8				28	25	16	32	11	40	22	28	38	17	22	90	50	14	11
9				16	23	12	17	18	52	35	45	35	9	20	49	8		34
10				12	37	42	20	42	22	47	37	59	26	7	30	21		23
11						15	16	33	24	46	48	12	62	19	10			20
12						28	17	29	44	32	54	35	35	43	41			55
13						32	40	15	34	28	58	22	60	11	29			16
14						34	37	29	15	55	25	61	8	25				12
15						29		44		24	17	41	35	48				
16								15		28		15	8					
17								30				11	47					
18								33				5	15					
19								40				23	41					
20												61	20					
21																		
22																		
23																		
Summe	14	42	41	210	238	372	403	480	489	589	587	577	587	472	438	332	308	404

Figure 6: Data sheet of the Beschussamt Ulm with results of crack length measurements using the example of the plastic casting mold – shot 1 and a storage period of 2 days.

For statistical analysis, the data (9 data sets) were combined in an evaluation scheme. In it, both the crack length per target (individually for front and back) and the total crack length per block for all shots have been recorded. This also allows later calculation of the effectiveness according to “TR Patrone 9 mm x 19” [2].

First, in the univariate analysis, Tukey’s test was used to determine the differences in crack lengths when the casting molds were compared pairwise. These differed only slightly from each other ($p>0.05$, Fig. 7). The confidence intervals overlap.

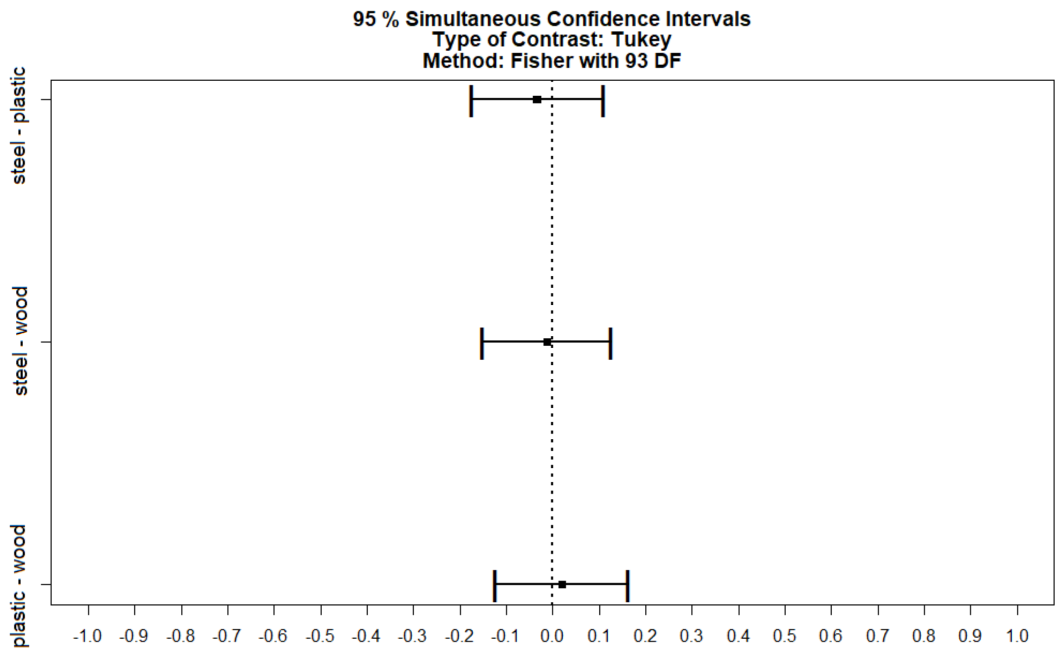


Figure 7: Pairwise comparison of crack lengths according to Tukey using different casting molds. Black dots: Estimators for the relative contrast effects (differences) with confidence intervals (error bars) for the effects.

Figure 8 shows the crack lengths (y-axis) in the 16 slices of the 40 cm gelatin block using different molds (2 days storage period). Cracks were always measured per gelatin block slice ($L_{Total.i}$) in 2.5-cm increments and represent the penetration depth of the bullet through the gelatin block (x-axis).

Shortly after the bullet reaches the gelatin block (after 2.5 cm penetration), the measured crack length ($L_{Total.i}$) is between 3 cm and 8 cm and then initially increases. The largest deviations are in the area of the longest cracks between 10 cm and 17.5 cm penetration depth of the projectile. The maximum crack length ($L_{Total.i}$) of 58 cm was reached, when shooting at the 1st gelatin block cast in the plastic mold (yellow line) (at 15 cm penetration depth). The smallest maximum crack length of 45 cm was achieved when shot the 3rd gelatin block, which was cast in the metal mold (gray line, after 12.5 cm).

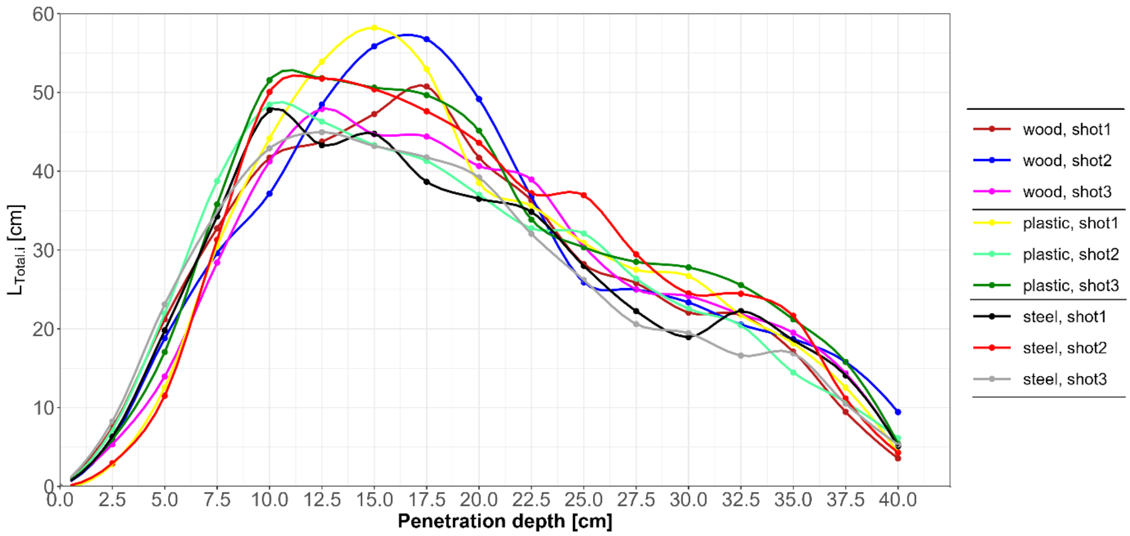


Figure 8: Course of crack lengths ($L_{Total.i}$) as a function of bullet penetration depth, subdivided by casting mold and shot repetition. Dots: observed crack lengths of the slices ($L_{Total.i}$) in gelatin blocks cast in different molds; solid lines: fitted smooth curve through the dots (GAM).

The generalized additive model showed that there is no difference when different casting mold materials are applied with respect to crack lengths in large gelatin blocks. The penetration depth (nonlinear term in the model) had a significant effect ($p<0.001$) on the crack length in the gelatin blocks for all three casting mold materials. The covariates target velocity (in the covered area), room temperature and humidity on the bombardment day had no influence on the crack lengths.

3.3 Storage period – bombardment results

The results of Tukey's posthoc test show that all pairwise comparisons of storage time in the metal form have no effect on crack length. The deviation from zero is small and the confidence intervals overlap (Fig. 9).

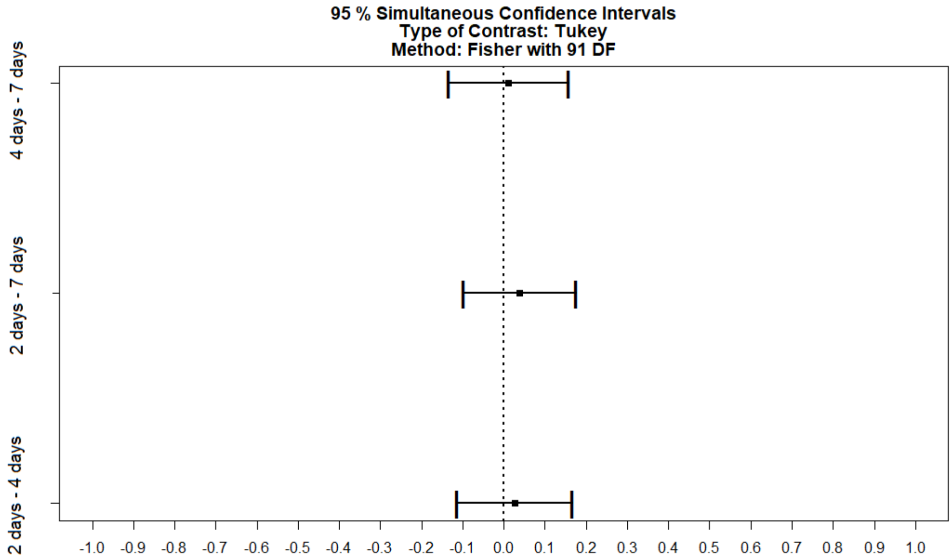


Figure 9: Pairwise comparison of crack lengths according to Tukey at different bearing durations (2 days, 4 days, 7 days). Black dots: Estimators for the relative contrast effects (differences) with confidence intervals (error bars) for the effects.

The crack length curves for different storage times of the gelatin blocks in the metal mold are shown in Figure 10. At a storage time of 4 and 7 days, the progressions of the crack lengths through the block are very similar. At 2 days, the crack lengths are lower in the area of the maximum crack lengths.

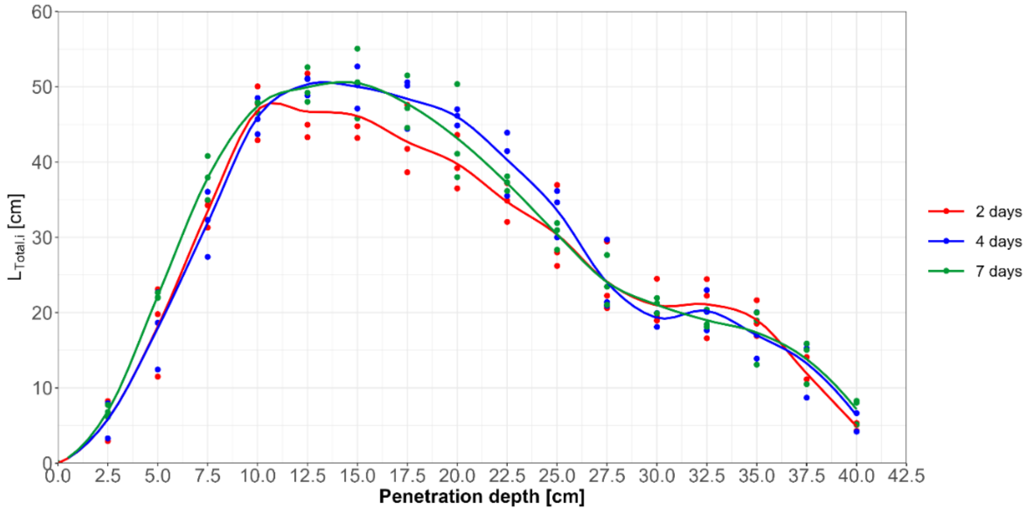


Figure 10: Course of crack lengths ($L_{Total.i}$) as a function of bullet penetration depth subdivided by storage time. Dots: observed crack lengths in the slices of gelatin blocks ($L_{Total.i}$) stored in metal molds for different lengths of time; solid lines: fitted smooth curve through the dots (GAM).

When comparing the crack lengths in the whole gelatin block with the generalized additive model (GAM), there were no significant differences in terms of crack lengths between the storage period of 7 days compared to 2 and 4 days. Only one trend was found: after 7 days of storage, the cracks are slightly longer ($p = 0.07$) than compared to 2 days of storage. On the basis of this database, the bombard is without statistical abnormalities up to a storage period of the gelatin blocks of four days.

The covariates target speed, room temperature and humidity on the bombardment day had no influence on the crack lengths. The penetration depth (nonlinear term in the model) had a significant influence ($p<0.001$) on the crack length in the gelatin blocks for all three storage durations.

3.4 Energy and efficiency considerations

The residual energy of the bullet after exiting the gelatin block could only be calculated for 12 of the total 15 shots, because for three shots the light barrier for the exit velocity was apparently not triggered by the residual bullet (Appendix D). A bullet was deflected due to decreasing stabilization such that it entered the wall lining of the shooting channel. It could not be found.

On average, the residual energy of the projectiles, according to the formula: $E=m/2*v^2$, after passing through the large gelatin block 221 J. Considering the target energy, which averaged 2,631 J for these shots, an average of 2,410 J was delivered to the test simulant. This means that 90.8 % of the available energy was converted in the 40 cm gelatin block.

Since neither storage period nor casting mold material showed significant differences with regard to the expression of the crack lengths, all available shot (12 of 15 – see first paragraph under point 3.4) were subjected to a effectiveness analysis. The results are shown in Figure 11.

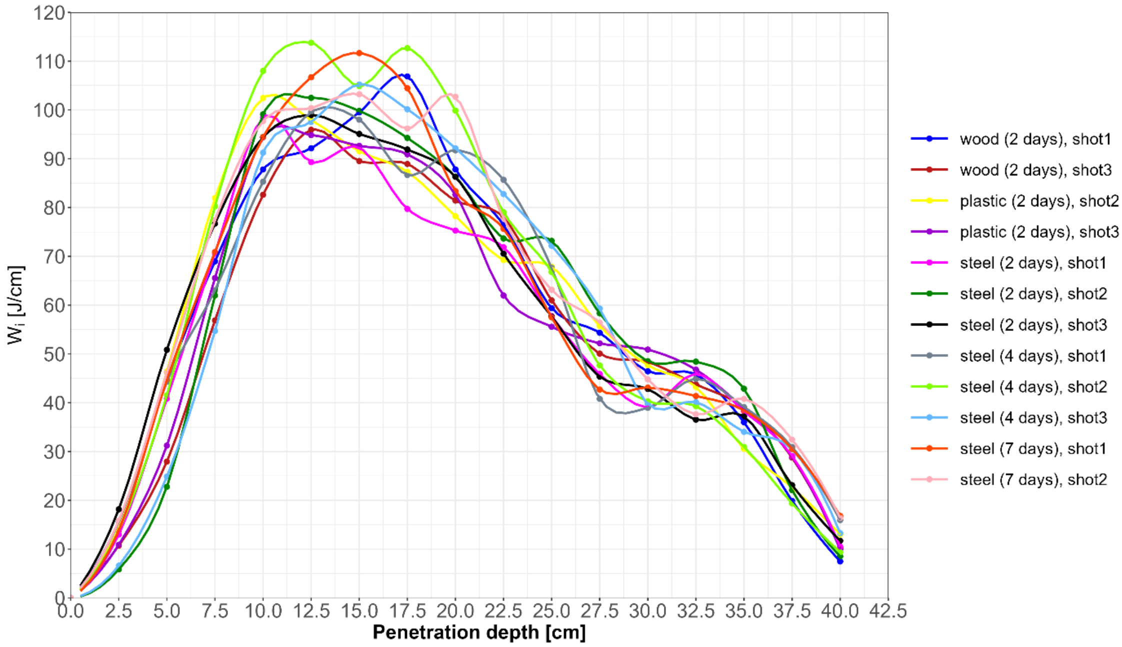


Figure 11: Effectiveness [J/cm] of the bullet for 12 shots on large gelatin blocks, subdivided by casting mold material, storage time and shot repetition (S1–S3).

The maximum effectiveness of 113.8 J/cm is reached after 12.5 cm when shot the 2nd block (metal, 4 days). In contrast, when shooting the 3rd block (plastic, 2 days), only a max. effectiveness of 94.8 J/cm is achieved (penetration depth 12.5 cm).

The energy output as a function of penetration depth (effectiveness) reveals greater deviations within the series of measurements in the test simulant gelatin, particularly noticeable after a penetration depth already after 5 cm. At the maximum, they range from 94.8 J/cm to 113.8 J/cm. These are fluctuations of about 17 %.

If the method were to be used to determine a maximum use distance of a projectile, the lower value would have to be chosen for its calculation for animal welfare reasons (sufficient killing effect). This confirms the statements in Martin et al [4] in an application to determine maximum operational ranges of hunting bullets.

The partly wave-like expression of the efficacy maximum cannot be sufficient explained at present. Several approaches to this are being considered. Thus, it is possible that the inflow conditions of the bullet in the block change when the bullet commutes. The energy output reaches the highest value when the longitudinal axis of the deformed projectile moves exactly perpendicular to the cross-sectional area of the block. With a slight inclination, the resistance is reduced so that, as a consequence, the energy transfer to the test simulant also decreases. For projectiles with a corresponding angle of attack, this changes periodically. Since the wave-like expression could not be observed in all shots, an inhomogeneity within that of the gelatin was also included in the considerations. However, based on the experience of the staff of the Beschussamt Ulm with the production of gelatin blocks, always the same procedures, long cooling of the blocks (42 hours) and storage for at least two days before bombardment, this is to be regarded as rather unlikely.

Due to the scatter, a sample in the amount of at least 5 shots is required for a representative determination of the maximum effectiveness of the bullet, if the accuracy is specified at 5 % and the safety probability at 95 %.

In the case of solid copper bullets, the deformation process begins only at a bullet velocity in the range of 560 m/s to 580 m/s. Although the specified tolerance of ±10 m/s for the target velocity (700 m/s) was small for the tests, it is evident from the data that the maximum effectiveness of the projectile increases with increasing velocity in this velocity range (Figure 12).

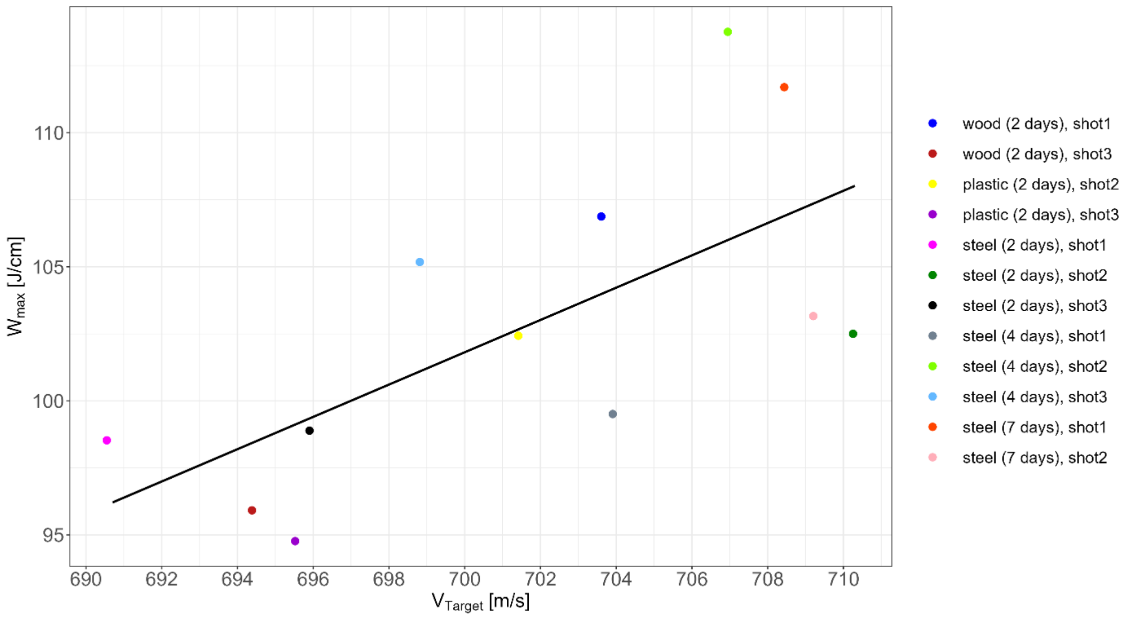


Figure 12: Relationship between target velocity (v_{Target}) and maximum bullet effectiveness (W_{max}) using different casting mold materials and three different bearing durations and shot repetitions (S1–S3) [y = 0.6x-320, R^2=0.44].

3.5 Additional results

3.5.1 Influence of the block underlay on the direction of the longest cracks

During the technical discussions and in Martin et al. [1,4], the question was raised to what extent the underlay used for the gelatin blocks can have an influence on the crack formation in the direction of the bearing surface. Therefore, as part of this study, a continuous white line was applied longitudinally to the top of each gelatin block prior to the start of tests. After cutting the individual block slices, it was now possible to check whether the longest cracks were in the direction of the bearing surface (opposite to the marked surface). Evaluation of 104 photographs of gelatin block disc sides did not reveal a preference for any particular direction. Throughout the course of the test, cracks were unevenly spaced in all directions in the gelatin, with a trend to up, as shown in Figure 13.

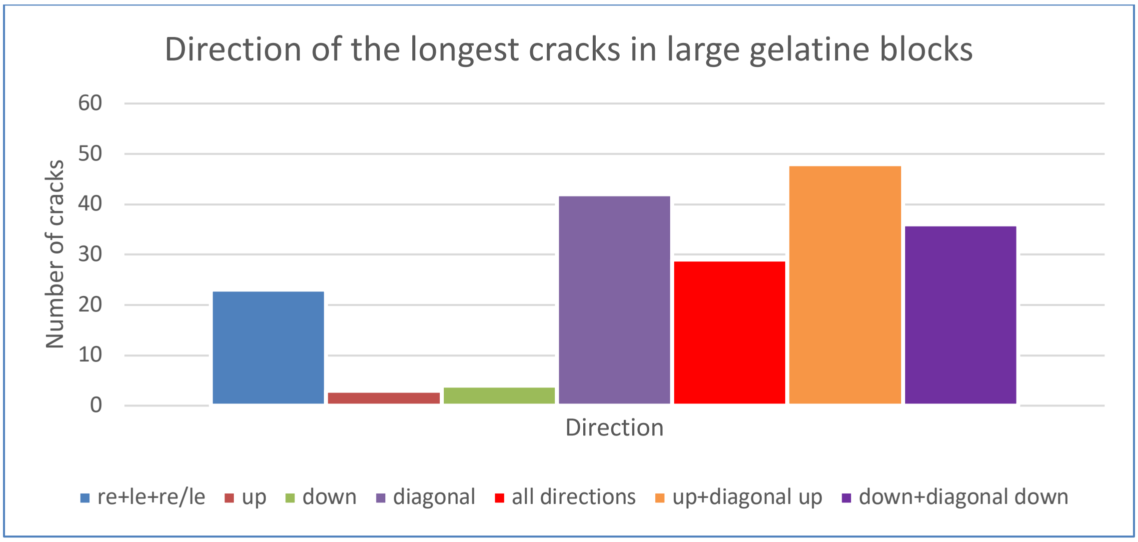


Figure 13: In “up + diagonal up” are all longest cracks summarized against the top and in “down + diagonal down” are all longest cracks summarized towards the block underlay. The arrangement of the longest cracks is random and without preference towards in direction the block underlay.

3.5.2 Evaluation of the front and back side compared to the evaluation of the front side only

Measuring the crack lengths of gelatin blocks by hand is very time-consuming. Already during the firing tests on gelatin blocks with hunting rifle bullets (target energy: 2,900 J [4]), the question of reducing the measuring time while maintaining the accuracy within the measurement by measuring only the front side of the gelatin block discs instead of the front and back side as before has been investigated. In the following diagram (Fig. 14), the total crack lengths of both variants are compared for different casting mold materials, bearing durations and per measurement repetition. The paired Wilcoxon test ($p = 0.201$) shows that there is almost no difference between total crack lengths when measuring front and back compared to measuring only front. Thus, the results of the Martin et al. study [4] are confirmed.

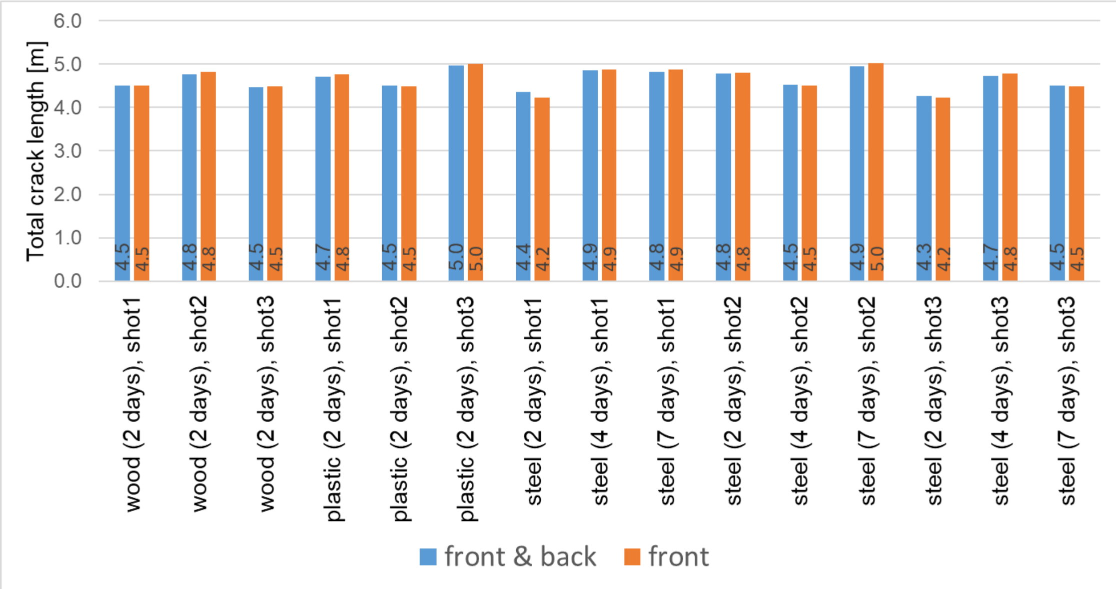


Figure 14: Total crack lengths in the gelatin block when measured on the front and back of the targets (VS_RS, blue bars) compared to the total crack length when measured only on the front side (VS, orange bars). The results are shown as a function of the casting mold material, storage time and shot repetition (S1–S3).

3.5.3 Crack lengths over 75 mm

From the data sheets it was possible to determine the cracks whose length was more than 75 mm. A large number of these cracks were significantly longer. Some reached a total length of up to 115 mm. This length could only be measured before the entry in the data sheets, since in the evaluation procedure itself the length of the cracks up to the respective forks are recorded and from there on the length of the turnoffs. Thus, in these cases, only smaller individual lengths are recorded in the data sheets.

A total of 50 cracks >75 mm in length were recorded in all 15 blocks (25 cm x 25 cm x 40 cm) shooted. This results in an average of more than 3 cracks over 75 mm per shooted block. When the small gelatin block (edge length 150 mm) was bombarded in the center, these would have cracked beyond the edge. An evaluation of the small gelatin block size according to crack length methods [5] would therefore be error-prone from the outset for a target energy of approx. 2,600 J and cannot be recommended. However, according to Schyma [11], a small uncertainty in the transfer of data from large blocks to small blocks are the elasticity and inertia of the different block size of gelatin.

4 Summary

Conducting experimental shots on 20 % gelatin and large blocks (40 cm x 25 cm x 25 cm) showed that complete cooling of the large blocks at a room temperature of 15°C is safely achieved after 42 hours. The use of different casting mold materials (metal, wood, plastic) does not affect the crack lengths in large gelatin blocks.

The storage period at 15°C of up to seven days also has no significant influence on the formation of the crack lengths. Only a tendency towards longer cracks can be observed in the comparison of two days to seven days of storage.

During the tests, no influence of the block underlay (Regupol) on the cracking in the direction towards the bearing surface (bottom) could be detected.

Determination of the effectiveness of the bullet showed that when large blocks of gelatin (20 % gelatin) were used, there was a large variation (17 %) in the range of maximum effectiveness. The partly wavelike expression of the maximum cannot be adequately explained at present.

The comparison of the evaluation of the crack length measurement results of the front and back side to the evaluation of only the front side of a gelatin block disc did not show any significant difference. Therefore, the evaluation of the front side is considered sufficient.

For target energies in the range of 2,600 J, small gelatin blocks (15 cm x 15 cm x 35 cm) should not be used because crack lengths greater than 75 mm were observed when large blocks were used.

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6 List of Figures

7 Appendix

Appendix A: Analysis report gelatin

GELITA
Improving Quality of Life

ANALYSENBERICHT

GELITA AG - Uferstr. 7 - 69412 Eberbach - Deutschland
Hergestellt in Deutschland DE BW 03004 EG
Ihr Ansprechpartner: Simone Augustin, Tel. +49 (0)6271/84-2524, Fax +49 (0)6271/84-4524, E-Mail: simone.augustin@gelita.com

Kunde: **REGIERUNGSPRÄSIDIUM TÜBINGEN Landesbetrieb Eich- und Beschusswesen BW, Stuttgart, Deutscl**
Bestellzeichen: **Ihre Bestellung vom 23.07.2021**
Auftrag: **274484** Produktionsdatum: 14.05.2020
Lot: **073830** Mindestens haltbar bis: 14.05.2025

GELITA® BALLISTIC 3
Gelatine

Eigenschaft	Testmethode	Sollwerte	Resultate	
Gallertfestigkeit	AOAC	255 - 265	264	g Bloom
Viskosität	6,67 % ; 60 °C	3,40 - 4,60	3,91	mPa*s
pH	6,67 % ; 60 °C	4,70 - 5,70	5,24	
Transmission 620 nm	6,67 % ; 620 nm	>= 93,00	96,42	%
Transmission 450 nm	6,67 % ; 450 nm	>= 83,00	89,20	%
Leitfähigkeit	1,00 % ; 30 °C	<= 300	191	µS/cm
Feuchte	>= 16 h ; 105 °C	9,0 - 13,0	10,8	%
Gesamtzahl aerober Keime	Ph. Eur. / USP-NF	< 1000	< 10	KbE/g
Salmonellen	ISO 6579	0	negativ	/25g

Dieses Produkt hat unter den üblichen Lagerbedingungen im Originalbehälter eine Mindesthaltbarkeit von 5 Jahren. Bei Raumtemperatur, trocken und geruchfrei lagern. Packungen erst kurz vor Verbrauch öffnen.

Dieses Zertifikat wurde elektronisch erstellt und ist ohne Unterschrift gültig.
gezeichnet: Christoph Simon am 23.07.2021

Produktfreigabe

Verkauf:	Christoph Simon	23.07.2021
Materialwirtschaft:	Michael Magenheimer	23.07.2021

STDANA-1-21.12.2015/ASW260-2020021100/AUG/274484/23.07.2021 10:46:52

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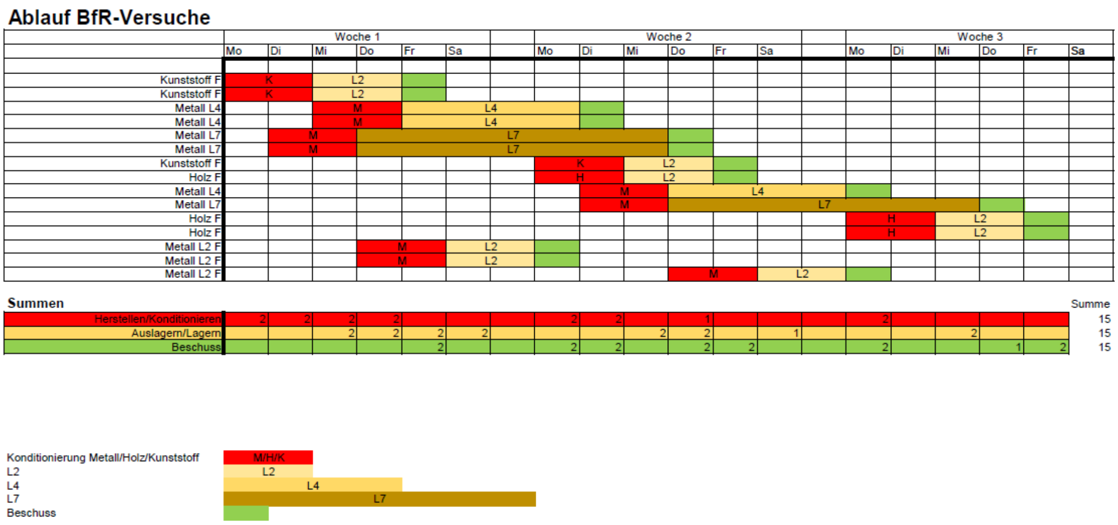
Appendix B: Data sheet cooling down time

Auswertung Kerntemperaturmessung

Tag	Uhrzeit	Abkühldauer [h]	Stahl [°C]	Holz [°C]	Kunststoff [°C]	Block 15cm x 15cm x 35cm [°C]	Bemerkungen
15.11.2021	14:00	0	53,5			53,5	Blöcke gegossen
15.11.2021	16:00	2	44,6			37,6	
16.11.2021	08:00	18	22,2			14,8	Gelatine aus Form 15 x 15 x 35 entnommen
16.11.2021	12:00	22	19,1		Messung beendet	15,1	Gelatine aus Form 25 x 25 x 40 entnommen
16.11.2021	16:00	26	17,7				
17.11.2021	08:00	42	15,0				Messung beendet
22.11.2021	14:00	0		54,5	54,5		Blöcke gegossen
22.11.2021	16:00	2		43,8	44,4		
23.11.2021	08:00	18		24,4	23,8		
23.11.2021	12:00	22		21,8	21,3		
23.11.2021	16:00	26		19,9	19,2		Blöcke aus Formen genommen
24.11.2021	08:00	42		15,0	14,9		Messungen beendet

Appendix C: Production-, storage- and bombard planning of the BA Ulm



Appendix D: Results data sheet BfR

Vorversuche 2+3 - Gelatine

Geschoss: Barnes TTSX 11,7 g (165 grains) Kaliber: 30-06 Springf. Nr.: #30368

$v_{Ziel\ nom.}$ 700 m/s $v_{Tol.}$: ±10 m/s

		Umgebungsbedingungen		Geschoss							
Beschusstag	Beschuss-Nr.	Temperatur [°C}	Luftfeuchtigkeit [%]	m_{Ziel} [g]	v_{Ziel} [m/s]	E_{Ziel} [J]	Eindringtiefe [cm]	$Ø_{maxRest}$	m_{Rest} [g]	v_{Rest} [m/s]	E_{Rest} [J]
25.03.2022	Kunststoff F - 1	20,5	21,5	10,69	708	2677	75	12,4	10,65	-	-
	Kunststoff F - 2	20,5	22,2	10,69	701	2629	77	12.0	10,47	219	251
28.03.2022	Metall L2 F - 1	20,0	26,1	10,69	691	2550	75	12,3	10,63	240	305
	Metall L2 F - 2	20,2	26,7	10,69	710	2697	64	12,1	10,63	248	326
29.03.2022	Metall L4 - 1	20,6	23,7	10,69	704	2648	75	12,4	10,64	228	277
	Metall L4 - 2	20,8	25,8	10,69	707	2670	55	13,1	10,61	169	151
31.03.2022	Metall L7 - 1	21,3	35,4	10,69	708	2682	64,5	12,7	10,63	213	242
	Metall L7 - 2	21,4	35,6	10,69	709	2690	65	11,7	10,29	180	167
01.04.2022	Kunststoff F - 3	21,2	28,3	10,69	696	2585	67,5	12,4	10,62	244	315
	Holz F - 1	21,2	29,0	10,69	704	2648	77	12,1	10,64	227	274
04.04.2022	Metall L4 - 3	21,0	18,1	10,69	699	2611	70	12,2	10,63	217	250
	Metall L2 F - 3	21,1	19,1	10,69	696	2589	63	12,4	10,46	217	246
07.04.2022	Metall L7 - 3	21,4	33,3	10,69	699	2615	>40	-	-	94	-
08.04.2022	Holz F - 2	21,5	29,1	10,69	705	2655	70	12,7	10,65	81	35
	Holz F - 3	21,3	31,1	10,69	694	2577	53	12,3	10,63	254	344

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Science Report 1
Suitability test of the simulant gelatin in two block sizes for the use of very high hunting rifle bullet energies of >5,000 J as well as testing of a modified method of crack length measurements

BfR-Autor/innen: Ellen Ulbig, Annett Martin, Ingo Rottenberger, Sara Graetz, Helmut Schafft, Monika Lahrssen-Wiederholt
Anzahl Tabellen: 1
Anzahl Abbildungen: 8
Anzahl Seiten: 31

Science Report 2
Suitability of two gelatin block sizes as ballistic simulant for hunting bullets tested with 2900 J

BfR-Autor/innen: Annett Martin, Ellen Ulbig, Ingo Rottenberger, Helmut A. Schafft, Monika Lahrssen-Wiederholt
Anzahl Tabellen: 8
Anzahl Abbildungen: 12
Anzahl Seiten: 30

Science Report 3
Investigation of the influence of casting mold material and storage time on large gelatin blocks as a test simulant for hunting bullets

BfR-Autor/innen: Ingo Rottenberger, Annett Martin, Ellen Ulbig, Johann Höcherl
Anzahl Tabellen: 0
Anzahl Abbildungen: 14
Anzahl Seiten: 24

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