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Safety of machinery: three decades of impact testing of machine guards led to significant improvements

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The year 2026 marks three decades of VDW-research on impact testing on machine guard windows and enclosures. The pressure to act was very high in the 1990s due to a significant number of accidents involving machine tools. This urgency led to a pragmatic approach in the initial investigations in order to bring about safe design conventions. This worked well, because all stakeholders contributed effectively. The design recommendations were established in product safety standards for machine tools, to start with, in CEN standards and subsequently in ISO standards. These standard provisions have been tried and tested over a long period of time and they proved to be very successful, because the number of accidents decreased significantly.
However, there was sometimes a lack of scientific professionalism in the early pragmatic approach, for example with regard to the statistical evaluation of the test data. In recent years, this deficit has been overcome by establishing significantly improved testing techniques in the research laboratories, which have also been supplemented with improved models for evaluating the test results: For example, the Recht-Ipson method for determining the so-called "ballistic limit" or the application of a "logistic regression" to derive confidence intervals for the evaluation of results from the interval halving method. The incremental steps to more professional procedures have been documented in great detail every year at ESREL during the last decade by experts from Italy and Germany. However, there have not yet been incorporated in the relevant safety standards.

Keywords: machine tool guard, impact resistance, Recht-Ipson method, logistic regression, proven-in-use.

1. Introduction

This paper provides only an overview of recent findings on possible improvements of impact testing and corresponding design conventions of machine tools. Comparisons between previous pragmatic practices and newer methodological approaches are used to highlight opportunities for upgrading the state of the art. This overview is meant to support the ongoing standardization work in ISO / TC 39 / SC 10 "*Safety of Machine Tools*". In doing so, two different strategies have been established: A. The product safety standards are to be streamlined to be "backward compatible" so that only the dimensioning recommendations remain, which the designer needs as a "recipe" for dimensioning a machine enclosure. B. All supplementary information relevant to obtaining dimensioning recommendations for product safety standards, including both pragmatic contributions and new methodological approaches, should be compiled in an informative ISO Technical Specification. In order to prepare useful proposals, a new standardization group was founded in Germany: DIN NA 122-10-10 AA "Design conventions for guards of machine tools", the author is convenor.

1.1. *Motivation*

In recent years, the working groups of ISO/TC 39/SC 10 have identified a need to update the design requirements for protective guards in the Type C standards for metalworking machine tools. This applies to ISO 23125 (turning), ISO 16089 (grinding), and ISO 16090-1 (milling).
On the one hand, there are new empirical findings on the material properties of, for example, polycarbonate when exposed to new types of cooling lubricants. In addition, the unavoidable variation in material properties is now being addressed statistically, whereas previously it was only treated quasi-scalarly (i.e. no spreading considered).
On the other hand, the risk-reducing effect of separating separating guards is now better understood, as the high importance for operator safety is clear on a probabilistic basis within the framework of the three-stage risk reduction method of the revised Machinery Directive 2006/42/EC. This is because this directive refers to "probabilities of injury" and not just to "hazards as such," as in the previous version. Numerous comments on this topic were collected

for the appendices to the Type C standards, which deal with the dimensioning of separating guards (e. g. a full enclosure as in Fig. 1). It has proven difficult to incorporate these comments into the standards because of the following dilemma:

- On the one hand, backward compatibility of the standard is very important for designers who have referred to the standard in the past and want to continue applying proven design principles.
- On the other hand, testing laboratories repeatedly propose improved testing techniques.

In order to meet the needs of both designers and researchers, the following dual strategy was proposed:

I.) Only a few comments are being collected for improving Annexes A, B, and C of ISO 23125 (or Annexes A and B for ISO 16090-1 and the relevant sections in ISO 16089), so backward compatibility is guaranteed in any case. In particular, improved readability and a plausible explanation of the material characteristics are important.

II.) Most of the suggestions for improvement collected on the design conventions for guards are compiled in a separate document: This is the present draft version of a ISO-TS "*Guards for machine tools - Determination of impact resistance by means of impact tests*" (NWM in DIN, 2025). Detailed proposals for an improved test procedure and subsequent statistical evaluation are also made therein: for example, the Recht-Ipson model. The comparability of results is also important in this context, as it can improve the statistical significance of the results.

1.2. *Background of impact testing*

The latest product safety standards (Type C) for machine tools, such as ISO 16089 (grinding machines), ISO 16090-1 (milling machines), and ISO 23125 (lathes), follow the three-step method of risk reduction as explained in the risk management standard ISO 12100. Step 1 is always the inherent safety of the machine design. Step 2 follows with the use of additional safety measures, and Step 3 focuses on instructional safety, such as the operating instructions (including warning signs on the machine) and operator training.

Very effective risk reduction can be achieved if the working area of the machine is completely enclosed (this is part of step 2 of ISO 12100, see Fig. 1). Machine enclosures prevent access to hazardous areas and protect against the ejection of parts during machining, such as chips, tool and workpiece splinters, and cutting fluids. Viewing windows as part of machine tool enclosures allow the operator to observe the machining process, usually without having to open the safety doors. This means that automatic machining processes can run with (almost) no risk to the operator from parts released from the working area, a desirable goal! However, operator access to the work area is sometimes necessary for manual interventions, e.g., for adjustments in the work area, for changing workpieces, or for troubleshooting or maintenance. In this case, careful instructions are necessary so that the operator can fully control the situation and protect themselves from the corresponding hazards by paying the necessary attention to the uncertainties in the work area and behaving with appropriate caution.

1.3. *When is the resistance sufficient?*

The uncontrolled ejection of a workpiece, a tool, or parts thereof can cause potentially weak guards on machine tools, such they were penetrated by ejected parts, with serious consequences for the operator. For this reason, experimental tests have been carried out in Germany, Italy, and Japan over the last three decades to define specific requirements for separating guards that provide sufficient penetration resistance, expressed as joules of impact resistance, see the basic concepts of Ising (1997), Bold (1999) and Mewes et al. (2005). As a result, a unique global database for metalworking machine tools was created, and machine-specific design regulations were summarized in CEN and ISO product safety standards.

In order to support designers with practical specifications, various protective materials have been compiled in dimensioning tables, in which the impact energy is assigned to the necessary thickness of the selected material. The typical dispersion of experimentally determined material properties is neglected by specifying quasi-scalar values for the sake of simplification. In addition, formulas for estimating the worst-case projectile energy are provided, taking into account machine-specific boundary conditions, such as rotational speeds. Here, too, the impression is given that determining the impact resistance is an "exact science" (i.e., a quasi-deterministic approach without addressing statistical variations).

However, a quasi-deterministic interpretation of the results from impact tests ignores several significant influences on the results of the impact tests. For example, current standards do not yet take into account the fact that the empirically determined impact resistance always exhibits considerable statistical variation, even with an exact test setup, and even more so when results from different laboratories are compared.

Results from the IWF laboratory in Berlin have shown that there is a significant difference between a) a quasi-deterministic and b) a statistical interpretation of scattered test results, see Uhlmann et al. (2017). Consequently, a probabilistic review of existing design guidelines is necessary. Since backward compatibility of existing design methods is of great importance to manufacturers, at least the following two questions arise:

A) How can the existing database be interpreted probabilistically?

B) How can the current impact test and evaluation procedure be improved in order to obtain a more realistic understanding of the determined impact resistance?

Perhaps the commonly known “safety factor” could be a suitable solution, e. g., based on confidence intervals of test data with sufficient sample sizes.

1.4. *Reducing accidents*

When it comes to the high level of safety of European machine tools, the “secret to our success” in reducing accident figures in Germany can be explained by safety measures of existing safety standards. The risk-reducing effect of movable and fixed guards on the machine's full enclosure plays an important role here, see Fig. 1. In the event of a dangerous failure in the working area, the impact resistance of the guards is able to prevent or at least significantly minimize harmful consequences such as injuries to the operator. The protective principle of machine enclosures has a long and successful history in standardization and in the operational practice of automatic manufacturing. Fig. 1 shows the typical state of the art of a full enclosure for a lathe. Test methods for the dimensioning of fixed and movable guards and the corresponding design conventions were an important step toward improving machine enclosures in the 1980s and early 1990s. Consequently, in the late 1990s and early 2000s, there was a significant decline in workplace accidents caused by parts being released inside the working area of machine tools, see Coenen et al. 1994 and Rostek et al 1999.

Figure 1. Full enclosure of an automatic vertical lathe in accordance with EN ISO 23125 (source: INDEX).

This is a remarkable result, which is linked to the systematic improvement in the impact resistance of machine enclosures (with safety doors and viewing windows).

However, the design conventions for dimensioning safety doors and vision panels (i. e. windows) are based on assumptions that are only representative of certain release scenarios (e.g., tool parts and workpiece chucks), while other types of releases are conceivable.

The above-mentioned ISO-TS “*Guards…”* identifies opportunities for improvement, e.g., a database of typical material properties and an explanation of the design rules in the Type C standards (ISO 23125, ISO 16089, ISO 16090-1).

2. Risk reduction with separating guards

According to ISO 12100, risk reduction should be considered as a reduction in the probability of injury. The reason for this is easy to understand in the case of machine tools, for example because serious hazards are always conceivable with metalworking lathes due to the rotating workpiece. When securing the workpiece, it is therefore only possible to reduce the probability of injury, but not the severity. The risk reduction process according to the three-step method of ISO 12100 can be intuitively represented in the Farmer diagram (see Figure 2) before going into the details of the safety measures. This becomes significant in the context of the numerous probabilistic requirements for functional safety (performance level), for example with regard to safe tool clamping. With metalworking lathes, the severity level “fatal injuries” is always possible (reasons: large masses, high kinetic energy, etc.).

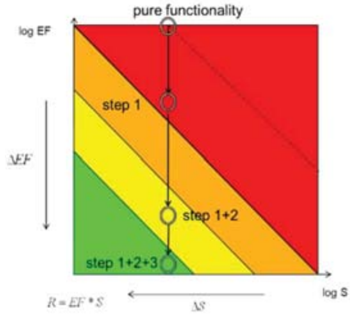


Figure 2: Farmer diagram and risk reduction acc. to 3-step method of **ISO 12100** (source: Neudörfer).

Starting point: Pure machine functionality
Step 1: Inherently safe design
Step 2: Additional safety measures (e.g., safety doors with locking and interlocking devices)
Step 3: Operating instructions and training
(S: Severity of injury, EF: Expected frequency of injury, R: Risk variable as a combination of EF and S; both variables are shown on a logarithmic scale)

It is therefore crucial to reduce the probabilities as far as reasonably practicable (ALARP) through an effective combination of manufacturer and user responsibility and appropriate measures on both sides (design and operational). In this way, the initial risk in the red zone (unacceptable risk) can be reduced to an acceptable risk in the green zone. The combination of "safe design" and "operational safety" is illustrated by combining the measures for the three-step method of risk reduction for guards (with windows) in Figure 3.

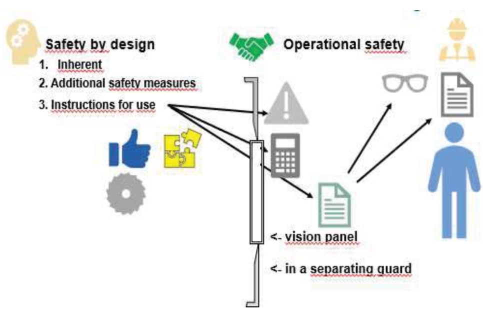


Figure 3: Combination of manufacturer and user responsibility (source: VDW).

2.1. *Reference to reduced accident data*

Most recently, the magazine "BGHM-Aktuell" reported in its 04/2023 issue on the declining accident figures in the combined wood and metal industries (quote): "*In 2022, the number of workplace accidents fell again compared to the previous year – by 5.4 percent. This is a positive development, especially given that the pandemic-related restrictions were gradually lifted in 2022 and more people were back at work in companies.*"

2.2. *Overall numbers and subsets*

Unfortunately, combining the accident figures for metal (i.e., machine tools) with those for wood (i.e., woodworking machines) provides an unclear picture of the situation for metalworking machine tools (which is what the VDW stands for), especially since the commuting accidents included in the figures increase the number of reportable accidents. In addition, the "hand tools" on machine tools, which are also recorded, do not appear. For this reason, the subset for machine tools was separated from the total figures at the VDW (with the help of the DGUV) until 2015, after which responsibility was transferred from Munich to Berlin. Since then, there has been no continuation of the good cooperation.
Figure 4 shows an overview of reportable accidents involving machine tools from 1993 to 2003 (grey curve) and 2004 to 2015 (blue curve). Because the follow-up data up to 2022 is currently only available in summary form for all types of "stationary machines," these have been added as a black curve.
The DGUV's total figures for the category "stationary machines" (black curve) also include accidents involving other stationary machines and not just metalworking machine tools. This is why the curve for the period 2010 to 2015 shows significantly higher values than the blue curve for the same period. However, the significant downward trend in both the blue and black curves for these years is interesting.

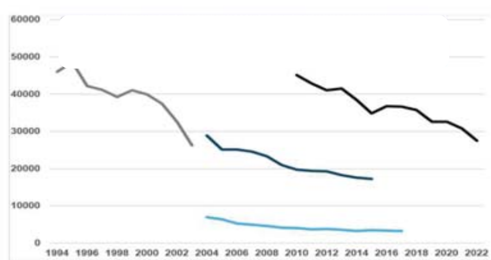


Figure 4: Reportable accidents involving machine tools from 1993 to 2022 (sources: HVBG and DGUV)

2.3. *Longterm development*

The periods from 1994 to 2003 and 2004 to 2015 show a downward trend, albeit to varying degrees. The two curves are not connected because the statistical framework changed in 2004 with the introduction of European occupational accident statistics. A comparison of the two five-year periods a) 1999 to 2003 (grey curve) and b) 2004 to 2008 (blue curve) shows that the relative decrease is higher in a) (45%) than in b) (34%), (i.e., comparison assuming almost identical numbers of machine tools). In addition to the change in the statistical basis of the DGUV, the more pronounced decrease in a) is probably also related to the introduction of the EC Machinery Directive in 1996. This is because the first product safety standards for machine tools in Europe (CEN standards) were completed in the period up to around 2003 in order to interpret the Machinery Directive for machine tools. After that, this success story continued, but less significantly.

2.4. *Subset of ejected parts*

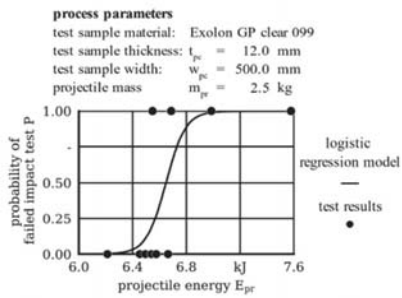
In the new committee NA 122 – 10 – 10, senior safety expert Olaf Mewes (DGUV) repeatedly described the beginnings of impact testing technology in St. Augustin (similar to the laboratory at the Technical University of Berlin) and how it led to an evident success in reducing the number of accidents in the 1990s, i.e., from approximately 2,000 reportable accidents per year caused by ejected parts, the number was reduced to approximately 300 accidents per year (some of which were caused by defeating safeguards). See also Coenen et al. 1994 and Rostek et al. 1999.

3. More profound evaluation of test data

New models and better statistics are available.

3.1. *Logistic regression*

This method was proposed by Uhlmann, Bergstroem, Landi, et al. (2023). The theoretical details are explained in detail in their ESREL-paper. Here, only one example result is presented in Figure 5, based on ballistics tests with a 2.5 kg projectile on a 12 mm polycarbonate sample. The reader is invited to consider the partially contradictory test results in the range from 6.4 kJ to 6.8 kJ, where the impact test was passed 5 times and failed 2 times. The appeal of this new evaluation technique lies in the fact that the partially contradictory test results (see Fig. 6) can be used to derive a mean value and a standard deviation in a reproducible manner. Bergstroem (2023) also shows how the corresponding confidence intervals can be determined from this, see table below Fig. 5.



Parameter of logistic regression model	value
Mean $\bar{x}$ in kJ	6.6
STD s in kJ	$7.3 \cdot 10^{-3}$

Figure 5: Experimental impact test and logistic regression model, with MEAN and STD.

3.2. *Regression with Gaussian distribution*

Back in 2017, Uhlmann, Landi, Moedden, Meister, et al. proposed a method for deriving a Gaussian normal distribution for the expected impact resistance (i.e., with mean value and standard deviation) from the series of test results (pass/fail). This method is more complex than logistic regression because a histogram is required to derive an empirical density function. For a sufficiently large sample size, the results correspond to those of logistic regression. However, the latter requires a smaller sample size and also delivers more reproducible results. From the distribution function (CDF) in Fig. 5 and 7, empirical density functions (PDF) of the Gaussian bell-curve type can be obtained by differentiation with respect to energy: mean value and standard deviation can be derived then, as well as confidence intervals, see Uhlmann, Bergstroem et al (2017), Moedden et al (2022).

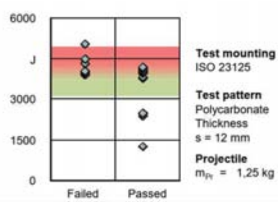


Figure 6: Failed and passed tests with 1,25 kg projectile and 12 mm PC, source: Landi et al. (2017).

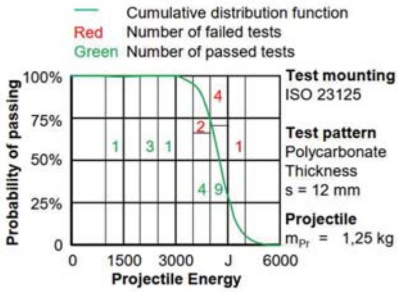


Figure 7: Cumulative distribution function for the probability of a 12 mm PC sheet to pass an impact test for resistance class B at different energy levels, source: Meister et al. (2017).

3.3. *Enhanced impact testing*

At the IWF of the Technical University of Berlin, the impact testing laboratory, which has been in operation for around three decades, has recently been significantly upgraded so that the model-based method developed by Recht and Ipson can be applied, see Uhlmann, Bergstroem et al (2024 and 2025). This provides a useful addition to the interval halving method previously used for testing material samples. Figure 8 shows a schematic diagram of the impact testing laboratory. For the test, air is suddenly released from the pressure vessel, accelerating a projectile toward the PC viewing window. Before the projectile hits the viewing window, it passes through a light barrier that determines the initial projectile velocity $v_{pr,i}$ before impact. In addition, the light barrier sends a trigger signal that starts recording on the high-speed cameras. The rear high-speed camera records the projectile's movement after it has perforated the PC viewing screen, thereby determining the post-perforation velocity $v_{pr,p}$ after the viewing screen has been penetrated. Using the determined projectile velocities v_{pr} before and after penetration, the so-called ballistic limit velocity (BLV) v_{bl} can be derived as a measure of the impact resistance Y using a regression approach. Figure 9 shows an example of the evaluation of a series of impact tests.

3.4 *Confidence interval of Recht-Ipson data*

The standard practice for determining confidence intervals is explained in detail in the VDW's guide for research partners, “Statistical Toolbox for Investigations in Machine Safety”, see Voigt (2022). For the Recht and Ipson method, the common methods of statistics can be applied, too.

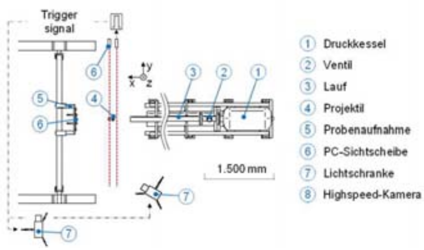


Figure 8: Details of the impact test laboratory of IWF at TU Berlin (top view), source: Bergstroem (2025).

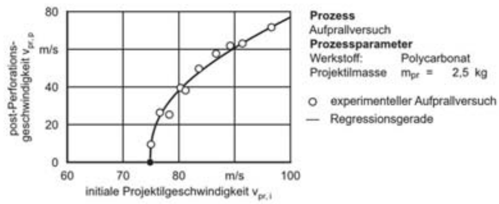


Figure 9: Example of the evaluation of a series of impact tests, source: Bergstroem et al. (2024, 2025).

4. Phenomenological evidence dispels hypothetical fears

If the determined value for the impact resistance of a material sample (e.g., 6 mm PC) is close to the modal value (equal to the mean value) of the (symmetric) distribution function, the value is only 50% reliable. This raises the question of a “safety factor,” also in the sense of whether a “safety factor” is not already implicitly present, see Uhlmann, et al (2017).

4.1. *Thesis on the 100 g standard projectile according to ISO 16090-1*

With the statistical evaluation of the numerous results from decades of bullet impact tests with the 0.1 kg standard projectile on common materials with different material thicknesses, the design conventions that have existed for more than 20 years in accordance with ISO 16090-1 (previously EN 12417) have been repeatedly examined and applied constructively. Because there have been no complaints to date, the standard specifications of ISO 16090-1 can be considered to be proven in use (an exception are the 4 mm PC results, which have been removed from the standard). The question of an additional “safety factor” in the implementation of the standard recommendations does not arise because this “safety factor” is implicitly included in the standard recommendations, for example, by assuming the failure hypothesis with the 100 g projectile in the safe range.

4.2. *Thesis on resistance classes of ISO 23125*

Because (for instance) resistance class B2 (with a 1.25 kg standard projectile according to ISO 23125) on 12 mm polycarbonate for almost three decades with a impact resistance of at least 2480 joules in ballistic tests, this is an relatively high reliable value. (Preconditions: A quality polycarbonate, which meets the minimum requirements for vision panels, e. g. when manufacturing polycarbonate, care must be taken to ensure that the polymer chains reach a sufficient length. This is crucial for the elastic deformation of the polycarbonate. In addition, the polycarbonate must be extruded with as little stress as possible). The question of a “safety factor” does not arise here at all. Statistical evaluation of the numerous results from decades of ballistic testing with the 1.25 kg standard projectile on common materials with different thicknesses has resulted in a tried-and-tested state of the art.

5. Ageing of Polycarbonate

In the VDW project “KSS-PC,” impact tests were carried out on aged PC viewing panels at the IWF laboratory in Berlin, see Uhlmann, Bergstroem et al. (2025). Aging curves were derived for various cooling lubricant compositions: The decrease in BLV v_{bl} over the service life t_u in hours is shown in Figure 10, which is based exclusively on the actual exposure time t_{exp} in the cooling lubricant.

5.1. *Average of all sorts of polycarbonate*

In approximately 30 years of testing in laboratories in St. Augustin and Berlin, a wealth of test results on the impact resistance of polycarbonate has been collected. In practical terms, this means that a very large population of individual test results is available, which could be used to statistically evaluate the material behaviour in impact events and make good predictions with reference to the confidence intervals of the results. The (estimated) empirical density function of 12 mm (good quality) PC to be tested with the 1,25 kg is shown separately in Fig. A.1, see Annex A.

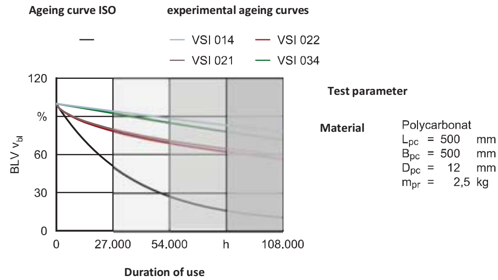


Figure 10: Comparison of the current aging curve with the aging curves derived in the project, source: IWF.

Remark: The grey filters indicate that the extrapolation curves are increasingly questionable beyond 27.000 hours (i. e. about 3 years).

5. Summary and Outlook

Three decades of impact testing of machine guards led to considerable improvements. One of the lessons learned is, for a complex safety issue such as the impact resistance of separating guards on machine tools, we need both experts and practitioners: practitioners bring indispensable experience, while theorists provide the necessary depth to approach coordination within the expert group in a well-founded manner. Good solutions arise when both come together – especially in safety engineering. Material behaviour is always subject to variation and can only be reliably determined through empirical investigations and statistical methods.

In addition, accident data relating to ejected parts (which is already low but stagnating) could potentially be reduced further if impact test data were evaluated more thoroughly, i.e. using models and standard statistical methods.

Acknowledgement

We would like to thank Olaf Mewes (DGUV), Germany's most experienced impact testing expert, who often provided us with useful advice during 30 years of cooperation. Many thanks also to our partners in Italy, Fabio Pera (inail) and Luca Landi (University of Perugia), who contributed very useful suggestions, such as the application of the RI method (used in military technology) and the logistic regression. And special thanks to Nils Bergström, who introduced the proposed methods in Germany, and he modernized the test laboratory in Berlin accordingly. Gratitude also to Christian Neumeister (NWM in DIN), who carefully collected the German proposals in DIN NA 122-10-10 such that they can be presented in a new working group of ISO / TC 39 / SC10, probably in late 2026.

Appendix A. Empirical density function

In February 2026 in Berlin, DGUV, IWF and VDW agreed upon collecting representative test results, such that the hypothetically estimated histogram in Figure A.1 (i. e. Monte Carlo simulation to obtain 500 random values, sorted into a histogram with 20 classes, most values fall into the class from 4200 to 4300 joules) should be confirmed with evidence. The spreading of the bell curve in Figure A.1 (i. e. worst case assumed) may be much smaller with real data.

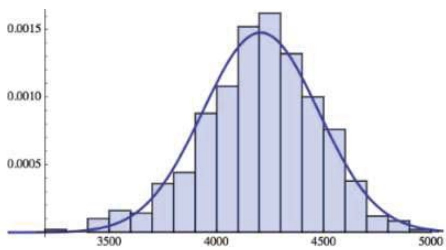


Figure A.1: Histogram and empirical density function (hypothetical estimate, 12 mm PC), source: VDW.

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