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Statistical distribution of protection times of passive laser safety barriers – normal distribution or is there a better description?

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Abstract

Recent developments in laser material processing technology, like the rapid increase of maximum output power, the remarkable improvement of the beam quality, and the availability of deflection optics, have put a focus on laser safety technology. Moreover, the development of new application fields, such as processing of CFRP, has led to a higher demand for laser technology, and an increased need for suitable safety technology. The protective exposure limit (PEL) according to IEC 60825-4 is currently calculated based on the assumption that protection times are normally distributed. This approach is criticised for generating too low protection times and for not reflecting the reality. Thus, the question arises whether there is a better way to describe the distribution of protection times for a more accurate calculation of the PEL. The aim of this work was to take the first step to answer this question by executing protection time tests, using steel plates and a fibre laser, and to determine the statistical distribution. In the following, random based protection time calculations were executed by the aid of the resulting distributions. This normative procedure was opposed to an alternative method, and the results were compared. It could be demonstrated, that both approaches lead to similar results for the examined case.

"Keywords: laser safety; protection of employees; health and safety; IEC 60835-4"

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1. Introduction

1.1. Evolution in laser technology puts focus on laser safety technology

In the past few years, the area of laser material processing has been strongly influenced by a rapid development of system technology. With the exponential increase in commercially available output power in conjunction with an increase in beam brilliance and the use of six-axis industrial robots, new applications were enabled (Kroth, 2008). By the additional deployment of deflection optics highly flexible systems could be created. An example of the success of this evolution is remote laser welding in car body production (Erdoes et al., 2013, Zaeh et al., 2010). The safety technologies are challenged by the possibility to guide tremendous intensities in the blink of an eye at distances in the range of several meters in every direction of the environment, (Goebel, 2015). Older laser systems most commonly were designed with short processing distances, fixed beam directions, low output powers and a high beam divergence. Thus, the enclosure was overdimensioned. This approach cannot be used economically in modern systems. For this reason, the design of passive laser safety barriers has come into the focus of research. An important aspect in designing safety housings is the statistical distribution of the time to failure of safety barrier-samples, which is the subject of investigation in this work.

1.2. Calculation of protection time – normal distribution or not?

As safety devices represent non-value-adding costs of production facilities, a conflict of aims between adequate safety and minimum cost arises when designing safety units. Thus, the testing and the subsequent calculation of the protection time of laser safety barriers is important. In the standard IEC 60825-4, 2011 a normal distribution of the time to failure is assumed and the protection time is defined as:

$$t_{P\ 60825-4} = 0.7(\mu - 3\sigma) \qquad (1)$$

$t_{P\ 60825-4}$: Protection time according to IEC 60825-4
μ: Expectation value of the normal distribution, calculated based on a minimum of the time to failure of six samples
σ: Expectation value of the normal distribution, calculated based on a minimum of the time to failure of six samples

This calculation sometimes results in negative values of the protection time. Although this case is excluded by definition, critics often use this fact as an evidence that the standard needs to be improved (Gomolka, 2013). The calculation procedure is based on experience and theoretical considerations. It is criticized, that systematic experiments are not used for the calculation procedure.

The German Social Accident Insurance (DGUV) proposes an alternative method of calculation. This method also relies on experience. The protection time is calculated by executing ten tests, the shortest time to failure is determined and multiplied with a safety factor of 0.7 (DGUV, 2014).:

$$t_{P\ DGUV} = 0.7 * t_{min} \quad (2)$$

$t_{P\ DGUV}$: Protection time according to DGUV PL-Info 007
t_{min}: Minimum time to failure based on ten samples

1.3. Objective of this study

As shown above, the statistical distribution of the protection times of passive laser safety barriers plays a major role for an economic and safe design of laser material processing units and their safety facilities. Thus, the objective of this study is to examine this distribution. Based on experiments, the protection times were determined by using the above mentioned procedures and compared to each other.

2. Experimental setup

2.1. Determination of the statistical distribution

For the experiments, an Ytterbium multi-mode fibre laser “IPG YLR-8000” with a maximum laser power of 8 kW and a processing fibre with a core diameter of 200 µm was used. The processing head was a HIGHYAG BIMO laser optics. A collimating module with a magnification of 1.4 and a focusing module with a magnification of 1.5 and a focal length of 300 mm were used. This resulted in a theoretical focus diameter of 420 µm. The laser beam was measured using a PRIMES focus monitor. A Rayleigh length of 5.2 mm at a power level of 3 kW and a Rayleigh length of 5.7 mm at power levels of 5 and 7 kW was measured. Using the described equipment, steel sheets (1.0241) with a thickness of 1.5 mm and a zinc-magnesium coating on both sides were irradiated at laser power levels of 3 kW, 5 kW, or 7 kW. Since the time to failure depends not only on the intensity, but also on their components power and focal spot diameter (Lugauer et al., 2014), the spot diameter d was adjusted to 60 mm for 3 kW and to 80 mm for 5 kW and 7 kW by defocusing (see Tab. 1). The necessary distance was calculated by Eq. 3 (Steen, 2003).

Table 1. Overview of test parameters

Configuration	Laser output power (in kW)	Beam diameter (in mm)	Distance from the focal plane (in mm)
1	3	60	644.2
2	5	80	930.6
3	7	80	930.6

$$d(z) = 2 \cdot \mathrm{w}_0 \sqrt{1 + \frac{\mathrm{z}^2}{{\mathrm{z}_\mathrm{r}}^2}} \quad (3)$$

d: Spot diameter
w_0: Beam waist radius

z: Distance from the focal plane
z_r: Rayleigh length

A measuring device was placed behind the steel sheet sample to determine the duration until the laser beam pierces the sample. The test setup is illustrated in Fig.1.

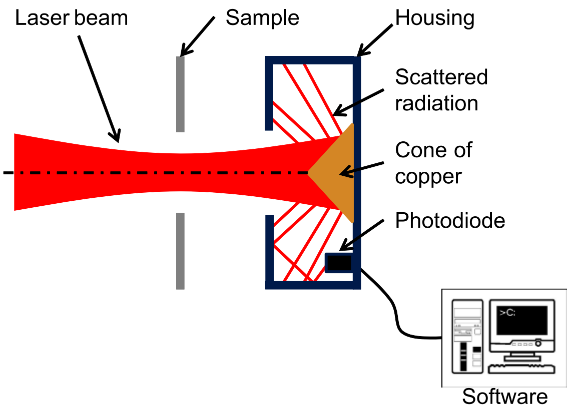

Fig. 1: Schematic assembly of the measurement unit

At the moment of the failure of the sample, the measuring device is irradiated. The transmitted radiation is detected inside the housing by an OSRAM OPTO SEMICONDUCTORS infrared-sensitive photodiode BPW 34 F with a spectral sensitivity of about 0.33 A/W at a wavelength of 1070 nm. To avoid a direct exposure of the photodiode, the laser radiation is scattered by a copper cone. The photodiode is connected in reverse direction to a PC using an AD-converter. A software visualizes and records the signal of the diode and stops the measurement in the case that radiation is detected. The output value is the time from the beginning of the laser process until the failure of the steel sheet. The emission signal of the laser in form of a potential-free contact was used to trigger the measurement.

2.2. Analysis of the suitability of the different calculation approaches

The experimental setup described in section 2.1. was used to investigate the suitability of the different calculation approaches mentioned in chapter 1.2. Therefore, either six or ten values of the time to failure were chosen randomly by a computer programme from each configuration. The protection time according to IEC 60825-4 or DGUV was calculated subsequently. The protection time was calculated based on the statistical distributions of the above mentioned experiments and the procedure was repeated 1000 times to simulate the behavior of the results, caused by different initial values. Subsequently the results of the simulation were compared to each other and to the minimal empirical value of the configuration.

3. Results and discussion

3.1. Statistical distribution of the time to failure

The test results of the three different configurations are shown in Fig 2 to 4. Every distribution is based on 150 single measurements. The time resolution was 0.1 s.

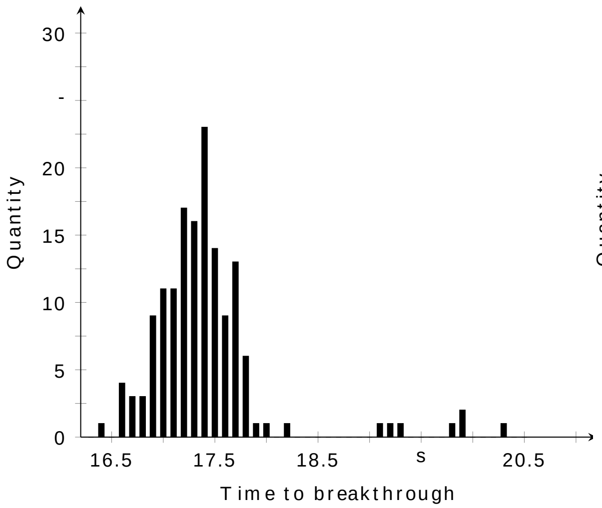

Fig. 2: Statistic distribution of 150 samples irradiated with a laser power of 3 kW and a beam diameter of 60 mm

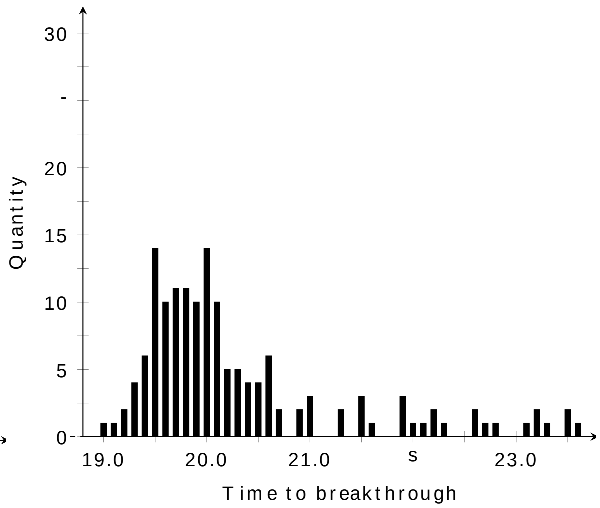

Fig. 3: Statistic distribution of 150 samples irradiated with a laser power of 5 kW and a beam diameter of 80 mm

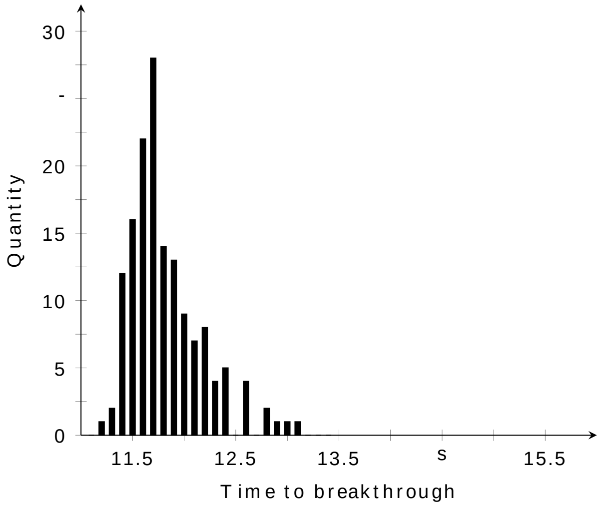

Fig. 4: Statistic distribution of 150 samples irradiated with a laser power of 7 kW and a beam diameter of 80 mm

The essential characteristics of all three distributions are similar. Outliers are located right to the global maximum. Neglecting the outliers, a normal distribution can be seen in good approximation. Including the outliers, an asymmetric function could be a better model.

3.2. Suitability of calculation procedure

The results of the simulation are shown in Appendix A. Fig. 5 summarizes the key results, the lowest occurring time to failure within each configuration, the average protection time calculated according to IEC and DGUV, and the corresponding standard deviation is shown.

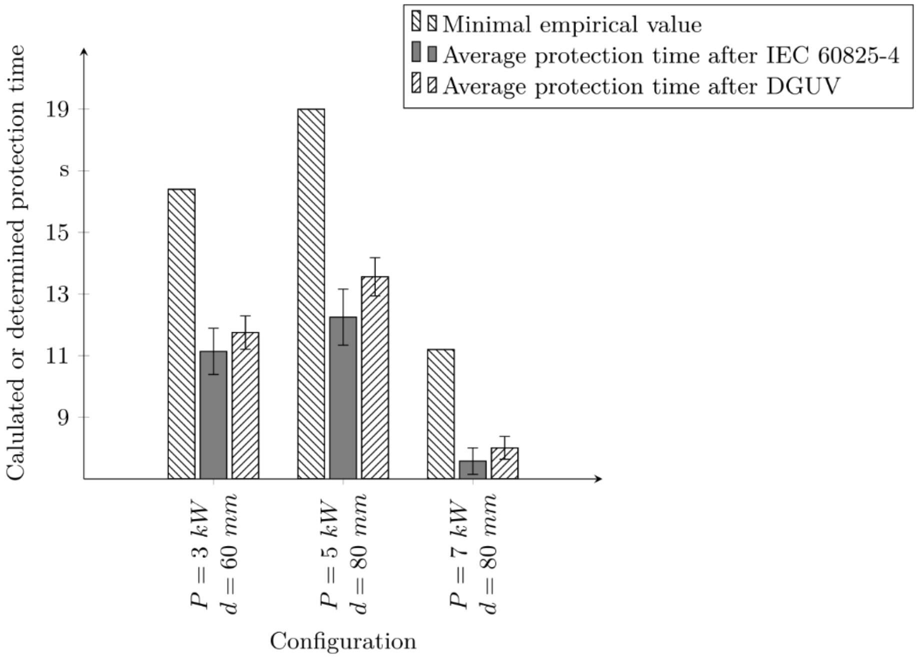

Fig. 5: Schematic assembly of the measurement unit

All calculated protection times are significantly below the smallest empirically determined value (cf. Fig. 5). Thus, it can be assumed that both methods result in a calculation of secure protection times. Within the standard deviation, the values of the average protection time differ insignificantly between both calculation procedures.

4. Conclusion and future work

The determined statistical distributions of the time to failure lead to the conclusion that a better model than the normal distribution could exist. Known statistical distributions should be compared with the empirical results to find a better mathematical model for the distribution. The appropriate tools for this purpose are goodness of fit tests like the Kolmogorov-Smirnov test or the Chi-square test (cf. Huber-Carol et al., 2002). It should also be noted that the show distributions only apply to the case investigated within this study. In particular, it is expected that the use of materials with a different failure mechanism (e.g. sublimation vs. melting) results in significantly different distributions. Therefore, larger series of experiments should be carried out with different materials.

The simulation of protection times shows that both examined procedures lead to a safe identification of the protection time for the experimental setup of this study. While the IEC calculation yields more conservative values, the approach according to DGUV leads to values which are closer to the lowest empirical value. Due to the small difference of the values, both calculation methods must be considered to be almost equivalent. However, this may be different for other test parameters. Therefore further distributions should be tested, and the correct method of calculation must be determined for any other material.

Acknowledgements

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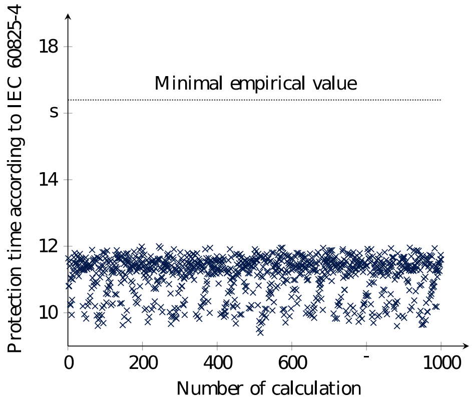
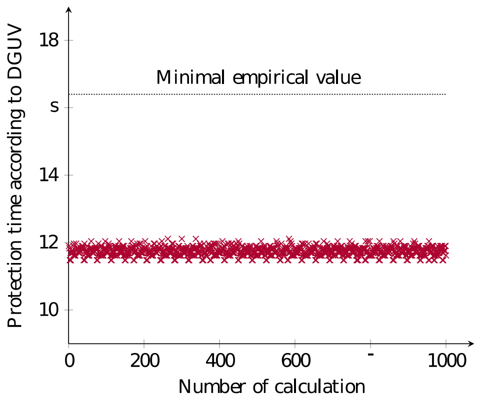
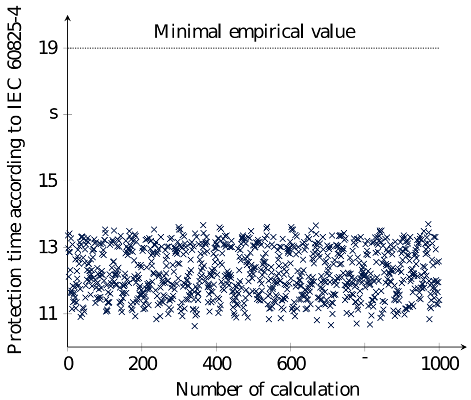
Appendix A. Simulation of protection time determinations according to IEC and DGUV

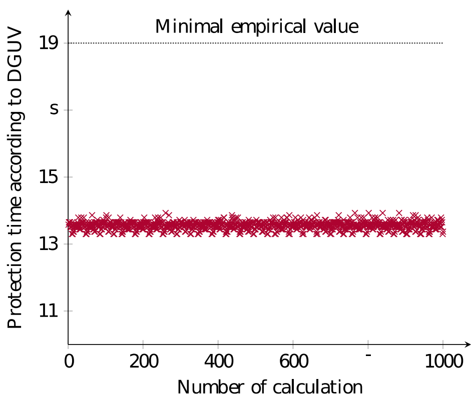
Configuration 1 (Laser output power 3 kW, beam diameter 60 mm):
Protection time according to IEC 60825-4 (left) and DGUV (right)





Configuration 2 (Laser output power 5 kW, beam diameter 80 mm) :
Protection time according to IEC 60825-4 (left) and DGUV (right)





Configuration 3 (Laser output power 7 kW, beam diameter 80 mm) :
Protection time according to IEC 60825-4 (left) and DGUV (right)