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#: ProLas had to leave the consortium due to insolvency.

Start date of project: December 1st, 2009
Duration: 36 months

All active partners of the project PROSYS-Laser contributed to this Final Report.
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1. EXECUTIVE SUMMARY

PROSYS-Laser was dedicated to developing highly innovative passive and active ("smart") laser-protective clothing and curtains for use with hand-held laser processing devices (HLDs) and with automated laser machines. Using such laser-protective clothing and curtains, the skin of the machine operator as well as of any person in the neighbourhood of the laser process shall be protected against accidental laser irradiation. Especially adequate laser-protective clothing is hardly available on the market today.

The major project objectives were:

- to open new markets for high-performance laser-protective clothing and curtains as well as for the testing procedure, especially encouraging participating SMEs to widen their product range and to directly benefit from the project developments and prototypes,
- to sustain the growth of laser technology by providing means for the safe use of innovative technological developments such as hand-held laser devices for material processing and high power lasers with high brightness, to minimise health risks for the operators of HLDs and automated laser machines, and consequently to reduce the number of related accidents,
- to contribute to the standardisation process considering laser-protective clothing and the corresponding testing procedures.

The approach to achieve these objectives was to combine innovative laser technology with high performance textile technology. Key developments were:

- passive functional multi-layer technical textiles, providing a high level of passive laser resistance,
- active functional multi-layer textiles incorporating sensors that detect laser exposure and are, by means of a safety control, able to deactivate the laser beam automatically,
- test methods and testing setups to qualify passive and active functional technical textiles and tailored laser-protective clothing, respectively.

For the planned work, a consortium of 13 European partners, 9 of them being SMEs and 3 of them being research institutions, was founded, representing a goal-oriented combination of the competencies and skills required for a successful project progress and at the same time showing the great relevance of the topic for the SME sector.

Based on the textile systems developed, prototypes for passive and active gloves, jackets and aprons, as well as for active curtains were manufactured, the active systems connected to adequate electronics. In this context, properties such as wear resistance, inflammability and washability, as well as haptics and ergonomic aspects were taken into account. In addition, a specific testing rig was developed, incorporating instrumentation for the automated measurement of optical and thermophysical properties upon defined laser irradiation, in order to evaluate the laser-protective
performance of the new passive and active textile systems. The results of these developments have been used to initiate the standardisation of the laser-protective textile testing procedure, which will later be the basis for the standardisation of the laser-protective clothing and curtains in terms of amendments of existing European standards or of completely new standards.

For the exploitation of the project developments, 14 exploitable results have been defined, for which the partners will conclude contracts in order to achieve a close and successful cooperation after the project end. The market launch of the new passive and active laser-protective clothing and of the active curtains is expected within 2013.
2. PROJECT CONTEXT AND OBJECTIVES

2.1. Technical Background Considering Laser Material Processing

Lasers for material processing are mainly used as part of automated production systems. These laser machines are often closed (class 1 according to EN 60825-1:2007 [1]), however, a class 4 laser is in operation inside the machine. Under standard working conditions, these class 1 systems are safe due to housing and safety interlock circuits that switch off the laser source automatically upon opening the housing. In case of maintenance, service personnel may work under class 4 conditions. Therefore, the safety interlocks have to be bridged. Here, a notable risk of injury by accidental laser irradiation exists. The radiation is able to damage human tissues seriously, depending on the power density on the irradiated surface. This is not only relevant for the protection of the human eyes, for which adequate personal protective equipment (PPE) exists on the market in terms of laser goggles to be able to meet the Maximum Permissible Exposure for the eye ($MPE_{eye}$), but also for the protection of the human skin, for which the Maximum Permissible Exposure ($MPE_{skin}$) can be found in [1,2] as well, however almost no adequate PPE is available.

Hand-held laser processing devices (HLDs) represent a niche application in the field of industrial laser material processing. Such hand-held systems provide a high degree of freedom and thus a significantly higher potential risk considering the exposition to laser radiation. This means that the HLD operator often works under class 4 conditions. In contrast to the typical usage of automated systems, the laser system user is specifically trained and knows about the potential risks of laser radiation. Safety shielding and sensors reduce the risk of injury to a minimum. However, the risk of irradiating the skin either by the direct beam (binocular working station) or the reflected beam remains. Such risks occur as well if persons have to work close to automated “conventional” laser processes which are not housed due to different reasons.

There are two approaches to protect the human skin against the physiological effects of laser irradiation, which are both considered in the following:

- passive protection by means of materials or material combinations that provide a high level of passive laser resistance
- active protection by means of materials incorporating sensors that detect laser exposure and are, by means of a safety control, able to deactivate the laser beam automatically

2.2. Normative Background Considering Laser-Protective Clothing

To protect humans against accidental laser irradiation, comprehensive regulations and standards exist. Based on the European standard EN 60825-1 and on the EU Directive 2006/25/EC [1,2], power density thresholds were defined to allow the allocation of laser systems to different classes as a function of the foreseeable exposure (foreseeable exposure limits – FELs), and to ensure protection of the human eye and skin by taking technical, organisational or personal measures (maximum permissible exposures – $MPE_{eye}$ and $MPE_{skin}$ values). Considering the protection of the operators’
eyes against incident laser radiation, suitable eyewear of different producers exists with protection levels adapted to specific wavelength ranges and power density levels. The usage of such laser goggles is a standard procedure in industry, but also in scientific institutions dealing with laser radiation. This situation is completely different as far as the protection of the human skin is considered. Only a few more or less common recommendations can be found regarding the type of clothing to be worn, e.g. concerning low flammability (see DIN EN ISO 11611 [3] and DIN EN ISO 11612 [4]). However, rules or standards which define the requirements concerning laser-protective clothing (laser PPE, in the following PPE referred to without equipment for eye protection) as well as standardised measurement methods and testing procedures suitable to reproducibly assess laser PPE do not exist. Whenever laser PPE is needed, protective clothing originally produced for other industrial sectors is used, e.g. clothing for welders. There is almost no certified laser PPE available on the market, although the consequences of skin injuries caused by intensive laser radiation are definitely serious: laser radiation emitted in the near-infrared (NIR) range has a rather large depth of penetration into the human tissue and is mainly absorbed in deeper regions at blood vessels or bones. Due to the heat released during the laser-tissue interaction, organic material below the upper skin layers is damaged or even evaporated to a notable extent, what may result in rather serious, painful, and interminable injuries [1,5,6,7,8].

2.3. Accidental Background Considering Laser Injuries

Regarding the turnover of about 7.2 billion Euros (in 2011) for laser sources and laser processing machines worldwide in the field of industrial material processing, the high relevance of laser technology for the whole field of material processing is obvious. Taking into account the whole machine tool market, the worldwide turnover amounted to about 62 billion Euros in 2011. Thus, the market for laser material processing is about one eighth of the machine tool market, what is a remarkable value. One of the global market leaders for lasers and laser systems is TRUMPF GmbH + Co. KG, notable competitors are e.g. Coherent, Inc., ROFIN-SINAR Laser GmbH, IPG Laser GmbH, Newport Corporation, and Laserline GmbH.

For conventional non-laser applications which are more or less dangerous, diverse regulations and standards for the testing and selection of proper PPE already exist since a long time, what is enforcing the prevention of accidents. Consequently, the number of accidents with serious injuries is reduced by the usage of adequate PPE. As already described, such regulations only do not exist concerning the protection of the human skin.

A main problem regarding the argumentation for laser PPE is that the number of laser accidents concerning the workers’ skin cannot be specified exactly. Such accidents are often classified as e.g. conventional burnings or accidents caused by faulty machine controls, i.e. they are not allocated to the category of laser accidents at all. Recent information of the German Employers’ Liability Insurance Association [9] indicates a number of about 15 laser accidents in Germany during 6% of the yearly working days. This number includes injuries not only of the skin, but also of the eyes. The extrapolation to one working year yields a number of 250 accidents. However, only notifiable accidents characterised by at least three days of absenteeism from
work, are recorded. The number of unreported cases, i.e. of accidents with less severe injuries and of near-accident cases, is probably much larger. Therefore, the above information of the German Employers’ Liability Insurance Association can only lead to a very rough estimation of the real number of laser accidents concerning the workers’ skin.

Nevertheless, it is assumed for this estimation that one tenth of the total number of recorded laser accidents concerns skin injuries. Furthermore, it is assumed that 75% of all laser accidents are allocated to other categories of accidents, e.g. conventional burnings, accidents by faulty machine controls, etc. Dividing by 10 and multiplying by 4 yields a number of about 100 laser accidents of the skin in Germany per year. Assuming that only 10% of all cases are reported, the number of risk situations would amount to about 1,000 cases per year. This is a really remarkable value, particularly as only the German industry is regarded. Based on a rough research, there are up to 1,000 laser job-shops and comparable companies using laser systems for material processing in Germany. This means that on average, one laser accident concerning the skin will happen per year in each laser company in Germany with high probability.

Apart from the laser wavelength, the hazardous potential of hand-held laser devices or automated non-closed laser machines is strongly dependent on the distance of the potentially irradiated part of the human skin to the processing zone. The reason is that the intensity of focused laser radiation increases with the square of the decreasing distance to the processing zone. A typical situation which occurs to the operators standing next to the processing zone during HLD use, and the corresponding distances from the processing zone to the different parts of the human body are shown in Figure 1. According to this illustration, the most endangered body parts are the hands that operate the HLD.

Figure 1. Left: typical distances between process zone and body parts during hand-held laser-processing (the distance of the body part regarded to the process zone mainly affects the hazardous potential). Right: possible scenario during e.g. maintenance (unintended reflection).
In principle, three types of laser irradiation can be distinguished: irradiation by a diffusely reflected beam, irradiation by a directly reflected beam, and direct irradiation. According to this listing, the safety level required with respect to skin protection increases from left to right in Figure 2.

With respect to the dimensioning of laser PPE and curtains, the worst case has to be taken into account. Mostly, HLDs are equipped with safety systems, e.g. two-hand control buttons or contact pins, which should avoid direct irradiation by a focused laser beam.

![Typical laser irradiation cases and corresponding qualitative safety levels required](image)

Figure 2. Typical laser irradiation cases and corresponding qualitative safety levels required (qualitative consideration).

2.4. Main Project Objectives

The situation described above was the motivation for the work presented in this report. Consequently, the main objective of the PROSYS-Laser project was to combine innovative laser technology with high performance textile technology in order to develop adequate passive and active protective clothing for the protection of the human skin against accidental laser irradiation and of adequate active protective curtains. Here, the passive systems consist of functional multi-layer technical textiles, providing a high level of passive laser resistance. In addition, the active functional multi-layer textiles incorporate sensors that detect laser exposure and are, by means of a safety control, able to deactivate the laser beam automatically. Due to the lack of regulations for testing and qualifying laser-protective textiles used as laser PPE, test methods were defined and validated. Additionally, corresponding testing set-ups were developed. Finally, the gap with respect to standardisation was bridged by the definition of a test procedure and the requirements with respect to laser PPE. The project developments were demonstrated by a set of tailored functional passive and active laser-protective clothing prototypes (gloves, jackets, aprons, trousers) and active curtains as well as by a prototype testing rig, providing the possibility to perform the specified low-power and high-power textile test procedure.
3. MAIN PROJECT RESULTS

3.1. Passive Laser-Protective Systems

Passive laser PPE serves as a kind of screen in order to protect the worker’s skin directly under the clothing against incident laser radiation for as long as possible. However, the user of the laser-protective clothing must be enabled to remove the irradiated body part from the hazard area before a second degree burn occurs. Therefore, the person concerned must be able to perceive the effect of the laser radiation, i.e. the pain caused.

Stoll and Chianta developed mathematical models for the onset of a 2nd degree burn (blister formation) by applying a 95% statistical probability. These models can be used flexibly for different energy types (flame, heat radiation, heat conduction) interacting with the human skin. In Figure 18, the onsets of pain (first stimulus) and of 2nd degree burn (blister formation) are illustrated as a function of the heat flux and the exposure time (tolerance time of the unprotected skin) [10,11], see section 3.5.2.

In this illustration, the reaction time, i.e. the time available to remove the affected body part from the hazard area before a 2nd degree burn occurs, is the time span between the intersections of the calorimetric measuring curve, giving the energy density flowing to the irradiated surface, with the Stoll/Chianta pain threshold curve on the one hand and the 2nd degree burn curve on the other hand. The bigger this time span, the more time has the affected person to react to the exposure. This time span should not be smaller than four seconds according to [12].

This consideration results in the definition of the first main evaluation criterion, the so-called Stoll/Chianta criterion, for the qualification and assessment of the protective functionality of textile single or multi-layer systems to be used as laser PPE or curtain. The second criterion is an almost negligible transmissibility with respect to the laser wavelength used for the investigation, i.e. the transmitted power has to be smaller than the \( \text{MPE}_{\text{skin}} \) value according to [1].

In order to achieve an optimal protective functionality, the textile systems developed consist of one or more functional layers. As example, a 3-layers system is shown schematically in Figure 3. In this construction, the outer layer is intended to reflect the incident radiation as good as possible. This reflection should be diffusive in order to prevent additional hazards for persons who stay near the processing zone.

The function of the middle layer is to dissipate the part of the energy, which is not reflected, but transmitted or absorbed, over a larger surface area. Therefore, the material should have a high scattering ability with respect to the transmitted laser radiation, as well as a high heat conductivity parallel to the surface. Simultaneously, the remaining radiation should be absorbed to a large degree in order to minimise the energy transfer to the inner textile layer, which is adjacent to the skin, and thus to meet the \( \text{MPE}_{\text{skin}} \) value.
Finally, the inner layer is an additional barrier for the energy incorporated into the system. Correspondingly, the heat conductivity should be low. However, it has to be ensured that a small part of the energy can reach the skin in order to cause pain perception and the following movement reaction.

3.2. Active Laser-Protective Systems

In addition to a basic passive protective functionality, active laser-protective systems feature a possibility to deactivate the laser emission immediately in case of accidental irradiation. For this purpose, sensors are integrated into the multi-layer construction, generating an adequate electrical or optical signal upon irradiation, which is processed by a connected control unit.

In general, such sensors may be designed as single-layer or multi-layer sensors. A possible setup is shown schematically in Figure 4. The signal generation can either be based on a reversible or an irreversible effect: an irreversible change is easier to detect, but the sensor has to be repaired or exchanged afterwards.

In the course of the project, two types of sensor systems for active laser PPE as well as for active laser-protective curtains were developed. The functionality of both sensor types is based on irreversible changes of the electrical properties. The first sensor is based on a wire that changes its electrical properties in case of a damage of the sensor structure (see Figure 5, left).

The second sensor variant consists of a multi-layer structure with conductive layers on the outer surfaces. In case of an irradiation, an electrical conduction is generated due to the melting of the layers (see Figure 5, right). These sensors are integrated in the multi-layer structure in such a way that they are protected against mechanical influences as well as against a premature activation by very low (quasi non-dangerous) incident laser powers. Furthermore, the layers below the sensor layer have to provide the PPE user with sufficient protection during the time span between the detection of accidental irradiation and the shutdown of the laser system until a safe condition is reached.
Figure 4. Textile multi-layer system with integrated sensors for active protection against laser radiation, i.e. for automated deactivation of the connected laser system.

Finally, this dimensioning of the “passive” protection as part of the active system is decisive for the high protection level of the whole system, meeting the two above-mentioned main evaluation criteria. However, weight and thickness of the textile construction are of particular importance for the usage of laser PPE with respect to wearing comfort and ergonomics (see section 3.3).

Figure 5. Schemes of the active sensor constructions no. 1 and no. 2, including the definition of the respective measurement signal thresholds upon laser irradiation for the evaluation by the sensor electronics.

To ensure a high degree of movement freedom and comfort for the PPE user, the electrical connection to the laser source is realised as a wireless connection.
Therefore, the sensors embedded into the textile structure are connected to a sensor unit (emitter, Figure 6, left) which is linked to the safety unit (receiver, Figure 6, right) via Bluetooth. The safety unit is hardwired to the interlock of the laser source. This system can be used for active laser PPE, but also for curtains. The principle described here has been tested successfully for different sensor variants and a large range of laser powers. Figure 7 shows as a scheme of the intended use of such active laser PPE and curtains to protect the operator as well as the persons which also stay in the hazard area.

Figure 6. Sensor unit (left), safety unit (right).

Figure 7. Principle of the automated deactivation of a hand-held laser device, caused by accidental laser irradiation.

In order to provide maximal system reliability, a high robustness of the wireless communication has to be ensured. The specifications of this system have been defined in terms of system architecture, sensor block diagrams, and safety units, as well as the definition of the safety protocol layer. Software programming and adaptation with respect to the specific requirements of the active concept regarded
have been performed. The system is configured in such a way that the safety control does not release the laser radiation unless a control signal is received from the sensor unit, confirming the proper sensor function. If the sensors are hit by laser radiation of a sufficiently high intensity, the electrical properties are changed significantly which is detected by the sending unit and submitted to the safety control. Thus, the laser can be switched off or the radiation can be blocked immediately.

3.3. Evaluation and Assessment of Potential Laser-Protective Systems

Two main criteria for the qualification of laser PPE were identified (see above): the MZB\text{skin} value and the so-called Stoll/Chianta criterion have to be met. As secondary evaluation criteria, the results of the visual observation and assessment of the samples upon laser irradiation can be considered, e.g. showing the changes of the material structure in terms of hole formation, shrinkage, etc. An afterburning time of more than 2 seconds is not allowed according to [13]. Furthermore, the textile multi-layer systems should be washable or cleanable without suffering a significant change of the specific optical and thermophysical properties in order to be useable as protective clothing against laser radiation successfully. In addition, the textile material combination should have a sufficient high temperature resistance. For the systematic and reproducible qualification of the laser-relevant properties mentioned, a specific testing setup was designed, which combines several optical and thermal measurement methods (see section 3.8). In particular, diffusive and specular remittance and transmittance of the material combination considered may be investigated for the laser wavelength and the heat transfer through the multi-layer construction can be determined as a function of the irradiation parameters.

The experiments performed in the course of the project showed that using specific textiles with adequate coatings, passive systems can be manufactured which provide sufficient protection against incident laser radiation with an average power density of up to 900 kW/m² for at least four seconds. This exceeds the protective ability, provided by systems actually available on the market, by about one order of magnitude. In general, the protective ability increases with the mass per unit area of the textile layers used, however this is in contrast to the ergonomic requirements of the protective clothing. Here, a compromise has to be found between the protection level and the wearing comfort. Regarding the developments done so far, the mass per unit area is still up to 1,000 g/m². In terms of ergonomic aspects, a mass per unit area of less than 600 g/m² is desirable according to the project partners’ experience. However, it is noticed that single-layer systems with a mass per area e.g. of about 300 g/m² provide a protection level of 120 kW/m². By adding an adequate coating, the protection level can be increased by a factor of about 2.5.

Regarding active laser PPE systems, it could be shown that upon laser irradiation of sufficiently high-power density, adequate designs of the sensors described above are able to generate signals suitable to achieve a shutdown of the laser system within less than 100 ms, using the wireless connection. Based on these results, laser-protective clothing can be manufactured ensuring protection against laser power densities of up to more than 20 MW/m² by fast laser deactivation. This means that the pure passive protection level explained above is further exceeded by a factor of
25. During the irradiation time, a sufficiently high passive protection has to be guaranteed, i.e. the 2\textsuperscript{nd} degree burn threshold must not be exceeded. Theoretically, this combined passive protection may be less than the protection of pure passive systems, because the reaction time of the active systems is much smaller than the native reaction time of the PPE user. In case the laser can be activated without coupling to the active laser PPE or curtain by non-authorised bridging of the safety control, it is helpful to have a high passive protection level in order to tackle potential misusage of the laser PPE.

3.4. Prototypes of Passive and Active Laser PPE and Curtains

Corresponding to the large number of possible applications and to the resulting manifold requirements with respect to laser PPE and curtains, several PPE and curtain variants have been realised and different textile-layer combinations and multi-layer thicknesses have been implemented up to the project end in order to be able to choose adequate PPE and curtains for the relevant laser sources with their different powers and for the resulting \textit{FEL} values.

First, several design studies were performed. As examples, Figure 8 shows design solutions for passive and active jackets and trousers.

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\caption{Passive system}
\end{minipage}
\begin{minipage}[c]{0.45\textwidth}
\includegraphics[width=\textwidth]{active.png}
\caption{Active system}
\end{minipage}
\end{figure}
\end{center}

Figure 8. Design for passive and active laser-protective clothing (here: jacket and trousers).

After intensive discussions between designers, PPE manufacturers, and end-users, the following prototypes were manufactured in order to demonstrate the functionalities and the limits with respect to the practical handling. For each prototype, different design solutions were realised and tested. Furthermore, additional applications such as pockets, air-ventilation, sleeve fasteners, etc. were investigated, thus always taking into account protection as well as comfort aspects.
Several passive laser PPE prototypes were manufactured. Figure 9 shows some examples:

- passive aprons
- passive jacket
- passive gloves
- passive trousers

The prototypes consist of single and multi-layer protective textiles. Partly, uncoated materials were used as outer layer. In case of the gloves, a higher sensitivity and improved haptics can be reached in this way, providing a sufficiently high protection level in the area which cannot be irradiated. Also for applications with lower laser powers, the coating can be omitted to achieve a higher comfort and breathability of the textile.

Figure 9. Examples of passive laser PPE (top left: jacket, top middle: apron, top right: jacket and trousers, bottom: 2 types of gloves) developed in the course of PROSYS-Laser.
For the demonstration of the functionality of the active laser-protective systems, several active PPE and curtain prototypes were manufactured using both active sensor types described in section 3.2. Figure 10 shows some examples:

- active curtains
- active aprons
- active jacket
- active gloves

In all cases, the active prototypes consist of a textile multi-layer system with the sensor elements embedded. The coating of the outer layer is rather important to reduce the energy input into the material as much as possible. The gloves prototype shown in Figure 10 also contains uncoated material in the inner hand in order to provide improved haptics. This design should only be used in case of impossible irradiation of this area.

Figure 10. Examples of active laser-protective prototypes.
Top: apron (meander sensor). Bottom left: gloves (meander sensor or foil/foil sensor). Bottom right: curtain (meander sensor).
In order to provide the user of the laser-protective clothing with a high degree of ergonomics and wearing comfort, practical tests were performed with the prototypes developed and manufactured in the course of selected industrial applications of hand-held laser processing devices and portal systems. Based on the results obtained, the protective systems were optimised with respect to their functional design.

For the exemplary application of a hand-held material processing using a high-power laser system with an emitted power of up to 5 kW as well as for laser cleaning applications, field tests have been performed using the protective clothing and curtain prototypes that have been manufactured in the course of the project. Figure 11 shows exemplary scenarios during which the wearing properties of the PPE in terms of jacket, gloves, apron, and trousers have been evaluated.

Figure 11. Field tests: pulsed laser welding with manual wire feed (top left), HLD usage (top right). Typical application scenarios: 3D robot system (bottom left), HLD usage (bottom middle), mobile laser cleaning (bottom right).

Apart from laser PPE, active laser-protective curtains have been manufactured and equipped with the same wireless communication unit as the active laser PPE. In the
field of laser PPE, it has to be verified depending on the realised variant which active sensor is most suitable. For the realisation as laser-protective curtain, both sensor types presented in this report may be used in principle and have already been tested successfully.

A major objective of future development work will be the reduction of the mass per area of the multi-layer systems to improve the everyday suitability of the protective clothing. For this purpose, feedback of industrial users with respect to ergonomics and comfort, experienced during practical tests, shall be taken into account.

3.5. Detailed Description of Testing Methods

In the following, the most relevant testing methods used for the qualification of textile-based laser PPE and curtain system are described. This will be the basis for the initiation of a testing standard.

The experimental investigations are divided into low-signal measurements, which do not damage the material or change the optical or thermophysical properties, and high-power tests, which are destructive due to the high laser powers used, in order to show the material behaviour under realistic conditions and including time-dependent changes.

3.5.1. Optical Qualification

In order to gather basic information about the optical properties of protective systems with respect to laser radiation of different wavelengths, the protective systems can be investigated by low-signal test methods in a first step. Commercial spectrometers and specific mathematical models to calculate the important criteria can be used to determine the low-level transmittance and reflectance of the protective systems. Taking into account the dependence on the irradiation time, values for the maximum permissible exposure of the skin regarding direct laser irradiation ($MPE_{\text{skin}}$) according to DIN EN 60825-1:2001 are shown in Figure 12 for different laser wavelengths (near infrared lasers, CO$_2$ lasers). Below these exposure limits, no damage is expected, and hence neither protective clothing nor gloves are required.

Part of the project work was the definition of a testing procedure, regarding among others the optical properties, which shall serve as basis for the testing standard. Relevant testing methods for the optical qualification of protective systems against laser radiation, made from technical textiles and natural fabrics, are:

- **classic RTA (Reflectance, Transmittance, Absorbance) measurements** to determine spectrometric information
- **BRDF and BTDF (Bidirectional Reflectance/Transmittance Distribution Functions) measurements** for single wavelengths with higher power limit compared to RTA measurements
- **comparison of transmittance values with $MPE_{\text{skin}}$**
Reflectance, transmittance, and absorbance (RTA) are the most important evaluation criteria for the low-signal measuring setup. If the protective system shows high transmittance values because of its optical properties, $MPE_{skin}$ can be exceeded easily for relatively low laser powers. This may cause thermal damages of the skin (second degree burn) even within the reflex time, i.e. before or while the affected body part is drawn back. The foreseeable exposure limits ($FELs$) have to be assessed at the outside of the protective system. Dependent on the spectral transmittance of the textile system, it can be determined whether $MPE_{skin}$ is exceeded at the bottom side or if it is generally possible to avoid skin damages within the reflex time.

3.5.1.1. Spectrometer with Integrator Unit (RTA Test Method)

In the course of the project, a customary spectrometer (PerkinElmer Lambda 900, Figure 13) was used to determine the general optical properties of the textile fabrics. Generally, this instrument provides a wavelength range from 280 to 2500 nm. This range includes the emission wavelengths of lots of industrial laser systems, such as near-infrared (NIR) lasers, near-ultraviolet (UV) lasers, and lasers emitting in the visible range (VIS). Here, the wavelength of CO$_2$ lasers (10.6 µm) is not included.

In the wavelength range between 280 and 2500 nm, a photometric integrator (so-called Ulbricht sphere) with a barium sulphate coating (BaSO$_4$) is used for the integration. The integrating sphere is an optical component consisting of a hollow cavity with its interior coated for highly diffuse reflectance (i.e. white), having relatively small holes required as entrance and exit ports. The shape of the cavity is commonly spherical. Its relevant property is a uniform scattering or diffusing effect. An integrating sphere may be considered as a diffuser that preserves power but destroys spatial information.
In relation to the power or energy density, the transmittance can be used to theoretically calculate the maximum exposure density at the outer surface, i.e. the $FEL$, of a laser beam for which the $MPE_{\text{skin}}$ value will not yet be exceeded (Equation 1).

$$MPE_{\text{skin}} \geq \frac{FEL \ [kW / m^2] \cdot \text{transmittance}_{\text{protective clothing}} \ [%]}{100}$$  \hspace{1cm} (Eq. 1)

Figure 14 shows the spectral characteristics of a passive, coated PPE textile investigated with the spectrometric system using the integrating sphere. This allows assessing the effects of different laser systems in a wide wavelength range with respect to the protective properties.

Figure 14. Spectral behaviour of a coated laser PPE garment.
3.5.1.2. BRDF, BTDF Test Method

The previously described method of reflectance, transmittance, and absorbance (RTA) measurement, using spectrometer and integrating sphere, does not cover the measurement of another important feature of laser-textile interaction (from a laser safety point of view): the spatial distribution of reflectance and transmittance.

The character of reflectance may vary from ideally diffusive (radiation is scattered into all directions evenly, independent of the incident angle, so-called Lambertian scattering) to ideally specular (mirror-like behaviour of reflectance). This feature, called specularity, may be determined by measuring the angular reflectance distribution for various incident angles. It is important to measure specularity for laser PPE and curtains, because in case of high total powers of the reflected radiation, it has to be guaranteed that the reflected beam is much less dangerous than the incident one, i.e. the character of reflectance of the protective textile system should be as diffusive as possible.

The character of transmitted radiation may vary from ideally directional (textile does not change direction and divergence of incident beam) to omnidirectional (back side of the textile behaves like omnidirectional source of radiation). This feature, called transmission directionality, is not as relevant as specularity with respect to safety, as PPE textiles are supposed to be located closely to the skin, however, an omnidirectional character of the transmitted part of the radiation (low directionality) could be considered as safer.

According to the so-called Bidirectional Reflectance Distribution Function (BRDF) (see e.g. [14]), which is a mathematical formalism commonly used in radiometry and computer graphics (for realistic and physically correct illustration of surfaces), a specific test method for the simplified measurement of the distribution of reflected and transmitted radiation was realised in the course of the project (Figure 15).

![Figure 15. Examples of reflectance and transmittance distributions for a highly diffusive sample (left) and a highly specular one (right). Each curve represents the cross-section of the distribution in the plane of the incident light. The colours denote incident angles from 0 (blue) to 45 degrees (green).](image)
The BRDF is a four-dimensional function that defines how light is reflected from a given surface. The arguments of this function are incoming light direction and outgoing direction (each defined with respect to the surface normal). The result of the function is the angular density of radiation reflected in a given outgoing direction, expressed as a factor of the incident radiation. Calculating the BRDF function for a given textile for all outgoing directions (full hemisphere) will give the full angular distribution of reflected radiation for a given incident angle (assuming that there is only one direction of incident light, as in case of laser irradiation). The character of reflectance may then be determined by analysis of the shape of this distribution. The integral of the BRDF over the entire hemisphere is equal to the total reflectance of the surface for a given incident angle.

Analogically, a similar formalism for transmittance exists: the Bidirectional Transmittance Distribution Function (BTDF). It represents the angular distribution of radiation transmitted through a sample (which allows determining the transmission directionality). Its integral over the entire hemisphere gives the total transmittance of the surface for a given incident angle of the laser radiation.

The measurement of full BRDF and BTDF of a textile sample is quite complicated from the mechanical point of view. It requires a mechanism with at least 3 degrees of freedom (2 for rotating the sensor with respect to the sample, 1 for rotating the sample with respect to the light source), or 4 degrees of freedom when material anisotropy is considered. Such measurements are performed using a device called gonioreflectometer. This mechanism combined with other equipment required for PPE testing would make the whole setup rather complex. Therefore, a simplified method of BRDF/BTDF measurement was developed in the course of the project. Figure 16 shows the conceptual design of the goniometer arm and the corresponding optical setup.

Figure 16. Conceptual design of testing setup.
This method is based on the assumption that reflectance and transmittance distribution of textiles (and other materials as well) can be described approximately by a certain model of reflectance or transmittance, respectively. Such a model is represented by a mathematical formula: a function which uses incident and outgoing direction (expressed as unit vectors) and is dependent on several parameters. These parameters completely describe the reflectance or transmittance properties. If they are known for the given material, the complete angular distribution of reflectance or transmittance may be reconstructed.

3.5.1.3. Transmittance Measurement during High-Power Laser Tests

In addition to the low-power measurement, a high-power measurement is required as part of the testing procedure in order to analyse the material behaviour under realistic conditions. In comparison to the low-power tests, the material properties can change during the high-power laser irradiation, eventually until its damage leading to hole formation and direct irradiation of the sensor (representing the skin). Considering the optical properties, the material transmittance as a function of irradiation time has to be measured in order to investigate the time until $MPE_{\text{skin}}$ is exceeded. Therefore, a power-meter with a high sensitivity in the low-power area (to measure the $MPE_{\text{skin}}$ value correctly) and a high time resolution has to be used behind the textile samples. A laser shutdown (automatic shutdown in case of too high laser transmittance or manual shutdown upon hole formation) is foreseen in order to protect the sensor.

3.5.2. Thermal Qualification

For the thermal qualification of textile samples considered as laser PPE materials, a calorimetric system is used (Figure 17). The specification of this system is based on the standardised copper calorimeter intended for arc fault testing according to EN 61482-1-2 [15]. However, it has to be noticed that the experimental setup must be attuned to the laser parameters considered (in particular the spot diameter) by adjustment of the geometry. This means a smaller measuring surface and a larger thickness.

![Figure 17. Schematic drawing of the calorimeter used.](image)

The surface of the calorimeter is coated with a thin black layer with an emissivity $\varepsilon > 0.9$ (such as temperature-resistant spray paint) and has to be kept free of deposits due to material decomposition. The total energy per area $Q$ introduced into the system (exposure energy) is given by the following Equation 2:
\[ Q = K \cdot \frac{\text{weight}_{\text{copper}} \cdot c_p}{\text{surface area}} \cdot \Delta T = F \cdot \Delta T \quad \text{with} \quad F = K \cdot \frac{\text{weight}_{\text{copper}} \cdot c_p}{\text{surface area}} \quad (\text{Eq. 2}) \]

Here, \( c_p \) is the specific heat capacity of the copper, and \( \Delta T \) denotes the measured temperature increase in [K]. \( K \) is a dimensionless correction factor to take into account that the heat transfer to the calorimeter is not ideal and the absorbance of the coated surface is \(< 1\) in reality, as \( \varepsilon < 1 \) as well.

The measuring system is designed to log the temperature values output provided by the calorimeter as a function of time during the complete exposure time span. The Stoll/Chianta 2\(^{nd}\) degree burn values and pain threshold values are determined for the respective measurement times of the test in order to calculate the time difference available for the operator’s reaction.

Approximately, the Stoll/Chianta 2\(^{nd}\) degree burn values and pain threshold values can be calculated as a function of time using the two following formulas in order to be able to determine the exceedance of the pain threshold or the limit of second-degree burn, respectively (see Figure 18).

Approximate formula of the Stoll/Chianta measuring curve (Equation 3a):

\[
\text{exposure energy}_{\text{Stoll/Chianta}} \left( \text{J/cm}^2 \right) = 5.0204 \cdot (t/s)^{0.2901} \quad (\text{Eq. 3a})
\]

Approximate formula of the pain threshold curve (Equation 3b):

\[
\text{exposure energy}_{\text{threshold of pain}} \left( \text{J/cm}^2 \right) = 2.685 \cdot (t/s)^{0.25416} \quad (\text{Eq. 3b})
\]

Figure 18. Exemplary result of the thermal qualification of a textile sample (here: single layer) using a calorimeter (laser power 46 W, spot diameter 15 mm, wavelength 940 nm).
For the laser exposure density that just does not result in a time difference smaller than the minimum reaction time of four seconds, five individual measurements have to be carried out in order to be able to determine mean value and standard deviation of the reaction time subsequently. A measurement example is shown in Figure 18.

3.5.3. Visual Assessment

Within the scope of the opto-thermophysical testing of the protective systems under realistic exposure conditions, a visual assessment and evaluation must be done. This includes the test conditions and requirements shown in Table 1. As a consequence of the manufacturing or finishing processes, flames may form during the real exposure test because of sublimating finishing agents. This burning is characterised by a flame which will form in front of or at the surface of the textile fabric material. Such behaviour does not result in disqualification of the material in terms of suitability as laser-protective textile fabric, but a separate risk analysis with regard to its application is required.

Table 1. Visual test criteria for the assessment of the laser-protective properties of the textile samples investigated (the textile systems are not suitable for laser PPE if one the described observations is made).

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>piercing</td>
<td>a full-length hole in the specimen of not less than 5 mm in any direction</td>
</tr>
<tr>
<td>melting through at the inner side</td>
<td>softening and / or melting at the inside of the specimen, depending on the material</td>
</tr>
<tr>
<td>dripping flames</td>
<td>burning material peeling away and falling down from the specimen</td>
</tr>
<tr>
<td>after-burn time &gt; 2 seconds</td>
<td>independent thermal combustion of the specimen after the laser has been deactivated</td>
</tr>
</tbody>
</table>

For selected material combinations, afterburning tests were performed and showed in most cases the general suitability with respect to the flammability properties required.

3.6. Proposal for Complete Testing Procedure considering Laser PPE and Curtains

In the following, a basic testing procedure is described which allows performing the low-signal as well as the high-power measurements to investigate the laser protection performance of textile systems to be used as laser PPE or curtains, using the testing rig and the experimental methods specifically developed in the course of the project (see sections 3.5 and 3.8). Apart from the optical characterisation, this procedure includes the measurement of the heat flux due to the laser irradiation and the observation of the burning behaviour (camera-based visual inspection). The RTA measurements are performed separately to the tests with the testing rig and prior to the following tests in order to get an overview about the optical material
properties. Furthermore, the investigation of burning (flame) and abrasion has to be performed separately using standardised test methods. Thus, these operations have not been implemented into the following procedure.

- Conditioning of the test samples (preparation of at least 10 samples per test method to provide enough samples also for statistical evaluation)
- Measurement of the laser intensity profile and first calibration of the measurement system (calorimeter and power meter)
- BRDF measurement, evaluation of remittance and transmittance as well as of the degree of specularity, using certain laser wavelengths up to a laser energy of 1 W; comparison to the determined RTA values
- Calorimetric tests (4 seconds limit pain/burning according to the Stoll/Chianta criterion) in several test steps (increasing laser energy to determine the maximum safety level)
- Statistical monitoring based on 5 tests with identical parameters just below the safety limit
- Calibration of the measurement system to check the reference values
- Thermographic inspection up to a defined power level
- Transmittance test by high-power radiation, statistical monitoring based on 5 tests with identical parameters just below the safety limit (comparison of $MPE_{skin}$ with the measured $FEL$) as a function of time
- In case of exceedance of the $MPE_{skin}$ value (Test 4), the laser energy has to be decreased until the transmitted energy is below the $MPE_{skin}$ value. The safety level pre-defined in Test 2 has to be adjusted accordingly for safety reasons so that both criteria (Stoll/Chianta criterion and $MPE_{skin}$ threshold) are fulfilled.
- Active system: check of the shutdown ability of the system
- Visual inspection of irradiated samples as a function of time (hole burning etc.) in combination with Test 2 or 3 or 4, 4a
- Documentation of the test results

3.7. Proposal of Safety Levels for Laser PPE

If special clothing is foreseen for the use as laser PPE in a defined laser application, a certain safety level has to be met. For the classification and suitability assessment of the clothing in terms of skin protection against laser radiation, the laser parameters to be applied under realistic conditions and the corresponding $FEL$ values have to be taken into account. The testing rig developed in the course of the project with respect to realistic exposure conditions is in principle designed for the investigation of pulsed irradiation and of cw (continuous wave) or quasi-cw irradiation (corresponding to laser pulse widths of more than 250 ms). In the course of the project, only tests with respect to cw mode have been performed (see section 3.8).
Using cw lasers such as diode lasers, Nd:YAG lasers, and CO₂ lasers (quasi-cw operation), a power density range from 20 to 1500 kW/m² at reasonable stages should be taken into account for the assessment of the passive laser-protection performance. It is noticed that CO₂ laser radiation was not taken into account in the course of PROSYS-Laser.

Based on test results and knowledge about textile behaviour, the safety levels with regard to laser-protective clothing listed in Table 2 are proposed. These safety levels are based on typical irradiation scenarios for two different spot diameters (1.0 mm and 11.3 mm, the latter giving and irradiated area of 1 cm² for circular spots). The consideration of the large diameter value is in contrast to the conditions which are e.g. defined in [16]. However, in typical application scenarios where high-power HLDs for welding or cutting, there is almost no risk that a body part is irradiated in focus under specified normal operation conditions.

Currently, the safety levels required for gloves used in or near the focus distance of a pulsed or cw high-power laser system cannot be met in combination with an adequate handling ability (e.g. feeding of filler wire for welding operations, typically with diameters in the range of 0.3 mm). Therefore, alternative safety concepts have to be investigated. In principle, active laser PPE solutions should have the potential to allow hand-guided operation in or near a high-power laser focus, providing sufficient protection of the skin.

For a basic understanding, textiles of typical daily clothing are listed in Table 2 to give an impression with respect to the degree of protection against laser radiation.

Table 2. Proposed safety levels for passive laser-protective clothing (cw mode).

<table>
<thead>
<tr>
<th>No.</th>
<th>Average intensity</th>
<th>Adjusted power (1.0 mm spot)</th>
<th>Adjusted power (11.3 mm spot)</th>
<th>Example for conventional clothes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>up to 20 kW/m²</td>
<td>0.02 W</td>
<td>2 W</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>up to 40 kW/m²</td>
<td>0.03 W</td>
<td>4 W</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>up to 60 kW/m²</td>
<td>0.05 W</td>
<td>6 W</td>
<td>T-shirt (cotton) *</td>
</tr>
<tr>
<td>4</td>
<td>up to 80 kW/m²</td>
<td>0.06 W</td>
<td>8 W</td>
<td>blue jeans *</td>
</tr>
<tr>
<td>5</td>
<td>up to 100 kW/m²</td>
<td>0.08 W</td>
<td>10 W</td>
<td>boiler suit standard work gloves *</td>
</tr>
<tr>
<td>6</td>
<td>up to 150 kW/m²</td>
<td>0.12 W</td>
<td>15 W</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>up to 200 kW/m²</td>
<td>0.16 W</td>
<td>20 W</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>up to 300 kW/m²</td>
<td>0.24 W</td>
<td>30 W</td>
<td>welder’s gloves *</td>
</tr>
<tr>
<td>9</td>
<td>up to 400 kW/m²</td>
<td>0.31 W</td>
<td>40 W</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>up to 600 kW/m²</td>
<td>0.47 W</td>
<td>60 W</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>up to 800 kW/m²</td>
<td>0.63 W</td>
<td>80 W</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>up to 1000 kW/m²</td>
<td>0.79 W</td>
<td>100 W</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>up to 1500 kW/m²</td>
<td>1.18 W</td>
<td>150 W</td>
<td></td>
</tr>
</tbody>
</table>

Attention: * significant afterburning, † significant shrinking
3.8. Testing Rig Design

To enable the practical realisation of the testing procedure presented in section 3.6, three testing rigs (see Figure 19) were built up. The following measurements can be performed using the testing methods described above:

- BRDF / BTDF measurement using goniometer arm
- Thermal measurement of transmitted energy using calorimeter
- Visual observation using visual CCD camera
- Thermographic inspection of heat flux using thermo camera
- Measurement of transmitted laser power using power-meter
- Measurement of shutdown time of active systems

The functionality of these rigs is in principle identical. However, the equipment implemented differs according to the tests to be performed and to the facility environment where the rig is placed. One rig is mostly foreseen for low-power testing. The second one is equipped particularly for high-power testing and the third one is used as a reference system. Thus, such a testing rig provides the mechanical potential to perform the described low-power and high-power tests on technical textile systems in terms of a semi-automated procedure.

Figure 19. Two of three testing rigs, both providing full testing functionality with respect to laser-protective textile systems.

To ensure the comparability of the three systems, a simplified round-robin test was performed for the statistical coverage of the presented testing procedure in order to prepare the implementation of a laser PPE testing standard. The structure of the testing rig is open which allows the installation of other measurement equipment, and the computer-aided testing procedures can be updated for the different tests. Thus, the testing rig is not only dedicated to Notified Bodies for the
certification of textiles. It can also be used as a regular research tool for research institutions and PPE manufacturers involved into laser PPE development. The testing as well as sensing equipment is enclosed in the safe housing of the testing rig. In order to ensure the protection of the operator against laser radiation, the state of the housing is controlled by safety switches on the doors. Of course, an emergency stop button to switch off the laser is implemented. Furthermore, a beam trap is installed to antagonise undesired penetration of laser radiation through the investigated sample. A ventilation system protects the inner space against smoke and a camera is installed to monitor the internal space.

The internal space is divided into four sections:

- laser-head holder including positioning adjustment, exhaust tube, cross-jet for protection of optics
- optical measurements section for optical characterisation of textile surfaces with adequate sensors, goniometer arm, power-meter, and textile sample holder with 3 observation windows
- thermal measurement section for thermal textile characterisation with calorimeter and IR camera,
- auxiliary section for laser-beam trap and electronic processors placing

Below, pictures of the different parts of the testing set-up are shown (Figure 20).

![Figure 20](image)

*Figure 20. Internal and external views on laser-head holder, control panel, measurement tableau, calorimeter including cooling, goniometer arm.*
All functions of the system are controlled from outside the rig, i.e. from outside the hazard area. The fully automated, computer-aided testing routines are carried out using a dedicated processing unit and a LabVIEW-based software. The data gathering is fully automated as well.

As shown in Figure 21 (top), each measurement sequence can be assembled and adjusted specifically. The test series to be performed are split into two steps according to the testing procedure proposed in section 3.6.

Step 1 deals with the optical characterisation of the textile samples using low-power laser radiation of a specific wavelength. The textile surface is analysed with respect to specularity, and the reflection, transmission and absorption coefficients (R, T, A) are determined. This step is more dedicated to research focusing on laser-PPE textile architecture development. The measurement results are assessed as positive if the threshold values prospected for the RTA coefficients and the specularity are met in terms of high diffusive remission and low absorption of the incident radiation, which assures satisfying the conditions of the Stoll/Chianta criterion.

Figure 21: Adjustment window for measurement sequences (top), example of BRDF measurement result in terms of a polar diagram (bottom).
Step 2 deals with the thermal validation of the textile samples using high-power laser radiation of the same wavelength as in step 1. The measurement results are assessed as positive if the time span between reaching the pain perception threshold and the threshold of 2nd degree burn is 4 seconds at minimum, i.e. if the Stoll/Chianta criterion is met. At the same time, the radiation energy density transmitted to the skin has to be smaller than the prospected $MPE_{skin}$ threshold.

Considering the optical characterisation, a polar diagram is derived and displayed based on the data acquisition for the BRDF (see Figure 21, bottom). Additionally, the values of R, T, and A are calculated.

As example for the calorimetric test using high-power laser radiation, the Stoll/Chianta measurement is displayed in a diagram, including the curve predicted for the heat absorption by the skin (corresponding to the heat absorbed by the calorimeter plate). The program automatically calculates the time span between pain perception and 2nd degree burn (Figure 22).

![Diagram](image)

**Figure 22.** Reporting example: result of calorimetric high-power test with respect to the Stoll/Chianta criterion. For the parameters considered, the criterion is met (calorimetric measurement represented by the blue line).
4. POTENTIAL IMPACT

4.1. Standardisation Process

A major aim of the project was the initiation of the standardisation process with respect to laser PPE and the corresponding test methods and procedures. Therefore, the following actions have been taken:

- monitoring of current standardisation in the area of work, to ensure that the developments will meet existing standards
- transfer of the project results to standardising committees
- development of a strategy plan to establish new requirements for laser PPE and proposal of basic documents for the standardisation procedure

In the end, the standardisation process based on the laser PPE and curtains developed during the PROSYS-Laser project as well as on the laser-protection testing procedure, together with well-organised dissemination activities, should help to promote the successful exploitation of the project results, especially considering the involved SMEs.

A thorough study of the regulatory framework has been performed in 2 parts. Part 1 of this study focussed on existing regulations with respect to laser devices and laser safety, whereas part 2 intended to analyse the PPE legislation. A lot of standards were found concerning devices, standards in the field of eye protection (goggles and screens), a standard related to surgical drapes and patient-protective covers. However, no standards were identified in the field of skin protection against laser radiation apart from the definition of the $MPE_{\text{skin}}$, as mentioned above.

To summarise the research, standards and directives for PPE that are important for the development of personal protective clothing against laser radiation are:

- EU Directive "PPE" No. 89/686/EEC
- EU Directive "Medical devices" No. 93/42/EEC
- EN ISO 11611 "Protective clothing for use in welding and allied processes"
- EN ISO 11612 "Protective clothing – Clothing to protect against heat and flame"
- EN 407 "Protective gloves against thermal risks (heat and/or fire)"

The CEN path was followed to initiate the standardisation process and to start establishing a new European standard, covering both clothing and gloves for skin protection against laser radiation. Figure 23 shows the organisational structure of CEN. The TC 162 is the technical committee contacted by the consortium.

According to the information of international standardisation experts, at least 5 European countries have to support the initiation of the standardisation process, otherwise the subject is rejected. It has turned out that information about the number
of skin injuries due to accidental laser irradiation (see section 2.3) is essential to convince the members of the standardisation committees of the importance to establish the intended standard.

After an EN test method has been developed and proven to have acceptable realism and reproducibility, it is envisaged that it will either be added to the performance specification EN ISO 11612 “Clothing to protect against heat and flame” or be the main test method in a new performance standard specific with respect to laser PPE.

In the course of the project, it turned out that the generation of a New Work Item Proposal (NWIP) with respect to the testing standard is too complex to be completed before the project end. In general, the submission of an NWIP to the appropriate CEN committee (here CEN/TC 162) is a critical issue: after this submission, a fixed time duration of only 36 months is running during which the standardisation procedure has to be completed. Thus, the relevant documents have to be prepared very well and extensive experimental data for test validation have to be available before submission. Instead of a completed NWIP, a comprehensive information letter has been used to contact the different standardisation committees and working groups, in particular CEN/TC 162 Working Group 2 (162/2), in order to receive a decision about the support of the progress of the intended standardisation activities. The information letter is based on an in-house standard of the project partner Sächsisches Textilforschungsinstitut e.V. (STFI) concerning a test certificate “additional requirements on the testing of laser resistance of protective clothing” as well as on tests results and the testing rig developed during the project. It includes the proposed test procedure to evaluate the laser-protection performance of textile systems, described in section 3.6, and also summarises the accidental and technical background, thus showing the need for a new test standard.

The lack of a completed NWIP does not prevent the standardisation process to go on, as the decision of 162/2 to follow up this topic has been taken at its meeting in December 2012, based on the comprehensive information letter. PROSYS-Laser
experts have been invited to join the DIN mirror committee to 162/2, which will then nominate the members of the German delegation to 162/2 with the major role being to run a specific Project Group on the test method development. Furthermore, a new working group (CEN-CENELEC BT Working Group (BT WG 8)) has been created with the objective to develop a work program in response to the programming mandate M/509 – Mandate on protective textiles and personal protective clothing and equipment.

The generation of the NWIP documents is actually in progress. They will be finalised several months after the project end at the earliest, i.e. after having collected the feedback of all standardization instances involved. This process of standardisation will probably take some years to be completed and requires significant funding, perhaps via the new mandate of the European Commission to CEN, CENELEC, and ETSI.

4.2. Market Analysis and Socio-Economic Impact

Personal protective clothing does not mean the same to all people. As in most discussions concerning technical products, the subject has to be defined first. While all clothing is protective to some degree, the consortium’s concern is not with routine needs, such as clothing for warmth, rainwear, or routine work. The focus is put on more sophisticated needs, i.e. protection in situations where hazards exist that pose considerable risks of injury or damage to the persons working in and around the hazard area. In some cases, such as clean rooms, not only the personal protection, but also the protection of products used or manufactured has to be considered. Thus, the general PPE definition involves garments or textile-related products worn, that prevent persons (or products) from coming into contact with, that protects from, and/or reduces the risk of exposure to hostile elements or environments.

PPE manufacturing requires a lot of material, since around 10% of all clothing and technical textiles are concerned – approximately four million tons worldwide. Plastics are also important materials for PPE manufacturing, regarding in particular head protection although this is not quantified. The PPE sector is an important market for polyester, polyamide, polyethylene and other polymers derived from fossil resources. More technical demands also lead to the addition of materials such as aramides, flour based membranes and finishes (e.g. Gore-Tex®), or phosphates, again, all derived from fossil sources. Maintenance of PPE deepens its carbon footprint. Most energy and water use with respect to PPE is connected to washing it. Extending the PPE lifetime can be enabled by a better tracking and tracing of PPE. This could be done by adding tracers to PPE, RFID tags or “end-of-life” or “end-of-service” indicators. The University of Wuppertal has, by the research of Professor Helmus [17], obtained a breakthrough in applying RFID tags in footwear, helmets, and PPE clothing. This helps to monitor incidents and to trace the usage and maintenance of PPE. Making materials stain-repellant has an important impact on reducing maintenance frequency and intensity. However, more efficient maintenance can be obtained by alternative business models, in which design, manufacturing management, and maintenance are contracted out as one package.
4.2.1. Laser Market

The development of HLDs, which represent the starting point of the PROSYS-Laser developments, has made significant progress during the last 10 years, although no specific regulations or safety and health standards with respect to skin protection exist to protect employees against harsh laser environment as explained before. Consequently, the PPE selling is limited in the short to medium term, but the novel PPE systems have a huge potential in the long term.

The US and European markets account for more than half of the global market of industrial protective clothing. Growth in Asia will be driven by new manufacturing and construction projects underway in the Middle East and Asia, particularly India, China, and Vietnam. Apart from being the world’s most populous countries, China and India have large numbers of unprotected industrial workers, offering untapped potential for future growth. With Asian countries becoming the hub of global manufacturing operations, the need for workers’ protection products will even get stronger.

Considering the laser market, the largest regional share has Europe (20%), followed by China (16%), the USA (15%), and Japan (7%). Between 1999 and 2011, the global laser market for material processing systems shows an average annual growth of 7.3%, while the growth between 2010 and 2011 is 28%. In 2011, the global laser systems market reached 7.2 billion USD. Consequently, the demand for laser protection is expected to increase strongly, especially in Europe and China.

4.2.2. Product Development

For an internal market survey, a product questionnaire and end-user interviews were prepared and distributed among the project partners in order to better define plans and actions for each partner involved in the exploitation process.

Two Exploitation Strategy Seminars (ESSs), offered by the European Commission, were organised. From these seminars, a list of exploitable results providing detailed descriptions, several documents with respect to risk analysis, opportunities and partner relationships, as well as tables for the definition of exploitation claims were generated. The ESS results helped to define an enhanced exploitation strategy and to set up contracts that open up the way to collaborative exploitation by the project partners after the project end.

For the developed products, the following market aspects have been considered:

- manufacturing
- comfort
- maintenance
- costs
Manufacturing Aspects
Fabricas, weave and functional layers (e.g. membranes) will be manufactured automatically using machines, respectively. Also the cut will be carried out automatically. These tasks will be done with machinery that is available to the project partners. In contrast, sewing of laser PPE will be carried out predominantly manually. This applies to both passive and active protective systems. The contacting or connection of active systems to the wiring and the signal processing unit (e.g. Programmable Logic Controller – PLC) will be also done manually. This work will be carried out by European companies.

Comfort Aspects
Laser PPE must provide comfort comparable to conventional workwear (e.g. wear, fit, breathability). Furthermore, laser PPE must meet all demands, required in standards for workwear. It will be provided in different sizes, as unisex models. Special emphasis has to be put on gloves and their tactility, since HLD control panels must be operated during PPE usage. With regard to protection against laser radiation originating from high-power lasers, comfort restrictions will be minimised by advantageously reinforcing only those parts of the clothing (e.g. by patches), for which the risk of unintended exposure is exceedingly high.

Maintenance Aspects
Considering maintenance procedures, passive and active systems must be distinguished strictly.

Passive systems (one-piece without patches) are controlled by visual inspection (e.g. after machine-wash or dry-cleaning, respectively). In case of damages, the user manual (e.g. according to German PPE-usage regulation) gives advice to repair or to dispose the laser PPE. Maintenance of laser-resistant clothing should be similar to comparable workwear (e.g. for welders). Generally, active systems are designed to automatically test themselves (they are “safety-related parts of control systems” – SRP/CS). After dry-cleaning of clothes and/or re-attaching of patches equipped with active systems, a visual and operating test is carried out.

Costs
The PPE market of standard protective clothing and gloves is characterised by a strong competition. Even suppliers from abroad put the market under pressure, and there is a strong price competition considering sophisticated standard PPE as well. However, this issue is different considering a new development, in this case new PPE providing protection against laser radiation. Such protective solutions enter a lot of work situations, in which no certified clothing has been available before. Thus, there is no market price level that could be used for a comparison. This offers a very favourable situation considering the definition of prices during the first years of the market introduction of the developments. The initial prices of laser PPE are not comparable to prices of conventional PPE. Thus, the prices offered during the first years are based on the novelty factor. This means:
a) There is no directly comparable competition product.
b) In this case, possible competitors would be “latecomers” from the marketing point of view.
c) The new laser PPE is based on scientific development and testing processes, but on assumptions with respect to hazards.
d) By offering the solution-based PPE to the so-called early adopters in industry, the price may be relatively high due to receipt of a technical-solution system, but not only of a single PPE.
e) It is economically well known that the price strategy for high-tech products in the first years of the life cycle is a “skimming profits” strategy which is inevitable. This shall lead to a return of costs and revenues used to cover the high costs for development, market opening, and specific marketing process.

4.3. Dissemination Activities

To promote the PROSYS-Laser project and its developments and to get a high visibility in the research and PPE sector, various dissemination activities were done such as publications in magazines and journals, trade fair booths, presentations on conferences, etc.

In detail, the project results were published in the following magazines/journals:
- Advances in Science and Technology – Smart and Interactive Textiles [18]
- Technische Textilien / Technical Textiles [19]
- sicher ist sicher – Arbeitsschutz aktuell [20,21]

In addition, contributions were submitted to the following journals and conferences:
- Journal of Laser Applications (JLA)
- SPIE journal "Applications of Lasers"
- Lasers in Manufacturing (LiM) 2013, to be published in Physics Procedia

On quite a lot of fairs and conferences, the project was presented by flyer distribution or poster and prototype shows on booths of single partners. Important examples are Euroblech 2012, PPE Conference 2011, A+A 2011 PPE, Occupational Safety and Health, Stainless Steel World 2011, LASYS (fair for laser material processing) 2012, and Industrial Technologies Conference 2012. Furthermore, a project website (http://www.prosyslaser.eu), including basic project-related information, was created.
Presentations were held at several conferences and workshops:

- PPE Conference 2011 (Belgium)
- Scandinavian Laser Safety Conference (SLSC) 2011 (Sweden)
- 7th Annual Public Conference EURATEX (ETP) 2012 (Belgium)
- CIMTEC 2012 (Italy)
- 6. Auswärtsseminar der AG „Optische Technologien“ 2012 (Germany)
- Nano-Biotechnology PL 2012 (Poland)
- Dornbirn Man-Made Fibres Congress 2012 (Austria)
- Workshop "Aktiver Laserschutz - aktive Schutzkonzepte und -systeme für den sicheren Lasereinsatz" 2012 (Germany)
- Aachen Dresden textile conference 2012 (Germany)

Furthermore, the trademark “PROSYS-laser” has been filed in terms of a word as well as a figurative mark (Figure 24).

![PROSYS-Laser logo](image)

Figure 24: PROSYS-Laser logo, protected as a figurative trademark.
4.4. Conclusions

As described, PROSYS-Laser mainly targeted passive and active laser-protective clothing for use with HLDs. The major technical objective was to provide adequate PPE and curtain prototypes, which significantly reduce the risk of occupational injuries, and in turn to increase the employees’ safety. Finally, this will produce a social win situation, with the preservation of production capabilities and reduced medical costs. A positive image of the innovative HLD technology will be created, which is accepted by the industry as well as by the employees. This development, together with the standardisation of laser PPE and corresponding testing procedures, will support the growth of the overall laser market and therefore also increase the productivity in Europe.

Regarding the HLD market, the project is expected to increase the use of HLDs by more than 50% within a few years after the project end, which would probably lead to a break-through for the technology and its large-scale industrial utilisation. For European textile industry, it is highly important to develop innovative products in order to keep their leadership. Intelligent, knowledge-based materials, developments, and processes need highly qualified personnel. This keeps the industry in Europe. Thus, especially active laser PPE and curtain solutions will strengthen the market position of European SMEs in the world. The knowledge is expected to be transferred to other fields of laser application aside from HLDs, such as protection by active curtains during work with automated laser machines or use of lasers in laboratories. Active PPE solutions will impact not only the laser processing area. Using smart PPE systems, it will be possible to connect and shut down any potentially dangerous tool in a short time span, thus minimising injuries. An example is the work with electrical arcs. By further development and transfer of these active solutions (textile system, sensor principle, signal transmission) to other PPE applications, it will be possible to gain leadership in the active PPE market. Thus, the project contributes to the Lead Market Initiative for Europe [22] in a reliable way.
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