The threat of (high energy) laser against military combat clothing

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Abstract. The High Energy Laser (HEL) is becoming a technologically mature weapon system. Although high energy lasers are not intended to be used as a direct threat to dismounted personnel, incidental exposure to radiation from high energy lasers will be an increasing (indirect) threat. In the past few years TNO performed research on laser-material interaction, to investigate the effects of lasers against different targets in terms of lethality. Parallel to this, work has been done on laser reflections from targets and hazard-risk analyses related to the use of high energy lasers in the field. It was shown that reflections of targets irradiated with high energy lasers show a highly dynamic and irregular intensity distribution in both temporal and spatial manner. A dismounted combat soldier may also be exposed to these laser reflections. Due to the relative novelty of this threat, the influence or effect of indirect exposure of clothing and equipment to a high energy laser was unknown, e.g., the occurrence of melting, smouldering or ignition of the fabric materials. This paper discusses the experiments performed within TNO's high energy laser facility (L30) on a range of single and multi-layered samples taken from military combat clothing and personal equipment (vests and/or helmets). The intensities used during the experiments were calculated from laser safety scenarios and reflected intensities from typical targets determined from earlier test series. These were then translated into the possible reflective intensities that could reach the dismounted combat soldier in the same scenarios. In this paper the experimental set-up and selected results in terms of effect and transmitted heat will be shown and discussed.

1. INTRODUCTION

High energy laser weapons will increasingly be used, for example as a counter drone system, by both own troops and opponents. Accidental exposure to radiation from high energy lasers is an increasing (indirect) threat for the dismounted combat soldier. It has been shown that laser reflections from targets show a highly dynamic and irregular intensity distribution in both a temporal and spatial manner [1, 2]. The reflections when engaging a potential target show a highly dynamic pattern that varies in magnitude and direction and depends on bulk material, material surface condition, phase state of the material (solid or liquid) and geometry. The dismounted combat soldier may be (inadvertently) exposed to these laser reflections. The focus of this paper is on the experimental investigation of the influence or effect when exposing military clothing and equipment to these laser reflections.

Using relevant reflection intensities from typical target engagement scenarios, experiments were performed within TNO's high energy laser facility on a range of single and multi-layered samples taken from military combat clothing and personal equipment. The data on heat flux obtained from the experiments are compared to existing thermal thresholds doses [3, 4]. The goal of the study was to gain insights into the effects of exposed military clothing to laser reflections (at typical reflection intensities), as well as the associated potential risks for the dismounted soldier.

1.1 Laser safety

The principal approach to protect personnel or bystanders from laser exposure is to define a space in which the direct, reflected and scattered radiation from the laser exceeds the Maximum Permissible Exposure (MPE). The MPE is a non-damage threshold for eye and skin damage due to laser radiation (at a given wavelength and duration). This zone is known as the Nominal Hazard Zone (NHZ) and controlling access to this NHZ promotes safety, see Figure 1, left [5]. This NHZ is translated into a NOHD (Nominal Ocular Hazard Distance), which is a linear distance. Deterministic approaches to calculate these areas exist for purely specular (worst-case) and purely diffuse (best-case) reflections, see Figure 1, right.

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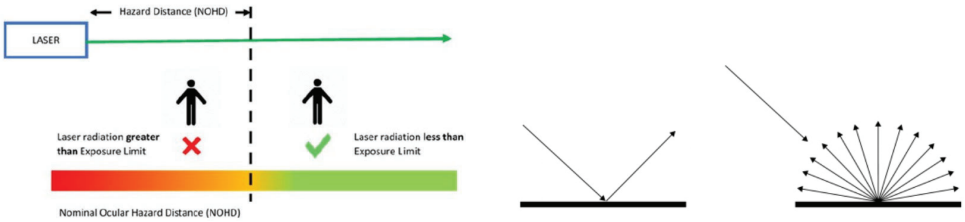

Figure 1. Nominal Ocular Hazard Distance schematically explained [5] (left). Specular and diffuse reflections (right).

Conservative approaches in respect to laser safety assume a worst-case scenario: the reflection is perfectly specular and the laser beam properties are conserved. In reality, the experimental results suggest that reflections generally are a mix of specular and diffuse components, and that the reflection process increases the beam divergence (see Figure 2 for some experimental examples) [6]. This implies that the safe stand-off distance (NOHD) for observers is somewhere between the values found for purely specular and those for diffuse reflection. This is also the approach taken to determine the intensities used during the experiments.

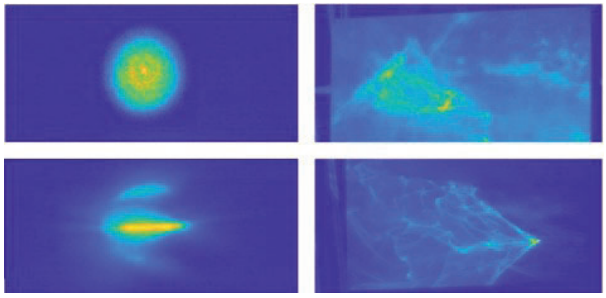

Figure 2. Reflection patterns of glass (top-left panel), machined steel (bottom-left), and curved steel (top-right and bottom-right). Scales and intensities are not comparable. The shape of the reflection screen itself is visible in the images on the right [6].

1.2 Scenario description

The focus is on reflections from targets engaged by a high power laser beam, irradiating personnel present in the vicinity as an incidental or collateral effect. The potential exposure will depend on the intended target, atmospheric conditions, laser specifications as well as on circumstantial aspects such as range, direction, orientation, doctrine and protection. Ideally, all relevant aspects are accounted for as they determine the relevant exposures applied in the experiments. To determine laser power and intensity levels to which samples will be exposed during the experiments, two scenarios and vignettes were created.

Scenario 1 (“drone”) involves a HEL system trying to engage and intercept an approaching drone. A recon team crosses an open field ahead of their unit as suddenly a hostile armed drone appears at a low altitude (~7 m. The drone moves at 5 km/h towards the recon team posing a lethal threat. A support unit at the rear (~1 km) targets the drone with a laser. The drone is hit and destroyed, but reflections of the laser beam reach the recon team members. Scenario 2 (“155 mm”) involves a HEL system trying to eliminate a 155 mm artillery shell before it hits the ground. A platoon attempts to cross an open field when it comes under artillery fire using 155 mm shells. The shell, aimed near the platoon, is detected on radar and engaged with a laser nearby (~1 km). The shell is hit and destroyed but reflections of the laser reach the recon team members.

Table 1 highlights the most important input parameters for the experiments discussed in this paper. The reflection intensities are estimated from previous TNO laser material experiments performed on 3 mm ABS (Acrylonitrile Butadiene Styrene) material and inert 155 mm artillery shells where the reflection data was gathered. This data was then used to extrapolate relevant reflection intensities for the laser, at target and observer positions defined in the scenarios. The performed laser

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hazard assessment assumes worst case numbers, e.g., the target is considered to be close to personnel and the peak reflection intensities are taken from the earlier experiments.

Table 1. Scenario data for experiments.

	Scenario 1: armed drone interception	Scenario 2: incoming artillery
Target characteristics	Material: 3 mm ABS (Acrylonitrile Butadiene Styrene) Distance of personnel to target 5 to 30 m	Material: 10 mm steel (155mm artillery) Distance of personnel to target 11.5 to 0.1 km
Laser definition	Wavelength 1.07 μm Output Power 30 kW	Wavelength 1.07 μm Output Power 300 kW
From laser hazard assessment > Required laser power setting*	Peak (@5m) > 65 Watts Peak (@30m) > 1.9 Watts	Peak (@100 m) > 913 Watts

* using an 8 cm laser spot diameter.

The laser facility is usually used for experiments using up to 30 kW of optical power. The minimum power obtainable with the setup is 155 W. Therefore, this power was used instead of the lower powers mentioned in Table 1. These experiments are intended as an initial exploration of exposure and the consequences.

1.2 Heat flux

(Reflected) laser irradiation may lead to exposure of the dismounted soldier to a high heat flux caused by interaction of the laser beam with clothing and/or personal equipment or even direct exposure if the material is (partially) transparent. Heat flux encountered in reflected laser scenarios are likely to be high intensity and very short in duration. The role of (protective) clothing is to prevent or minimize skin burn damage by reducing the heat transfer towards the skin underneath the clothing. In these situations the garment is assumed to maintain its integrity during the exposure. For the laser scenarios, the (protective) characteristics of the clothing are derived in a manner similar to what has been done in the past for heat flash [7].

LaChance [8] summarizes harm criteria (injury or lethality) associated with people exposed to flames, high air temperatures or high heat fluxes. Burn injuries may vary in degree (e.g., first, second or third degree burn), but also in the amount of body area covered. The harm is described in both flux intensity (kW/m^2) as well as exposure time (s). This leads to the expression in a thermal dose unit:

$$\text{Thermal Dose Unit} = I^{4/3}t \quad (1)$$

Where I is the radiant flux in kW/m^2 and t the exposure time in seconds.

Table 2 lists some of the thermal doses presented in literature that may result in first, second or third degree burns, as a result of exposure to UV or IR radiation [3]. The dose considers the intensity as well as the time of exposure. The IR radiation range is of most concern for generating burns, and also of concern considering the L30 laser wavelength (1070 nm). These radiation ranges will be compared against the heat flux data retrieved during the experiments for an indication of possible burn severity.

Table 2. Radiation burn data [3].

Burn severity	Threshold dose $(kW/m^2)^{4/3}s$	Threshold dose $(kW/m^2)^{4/3}s$
	UV	IR
First degree	260-440	80-130
Second degree	670-1100	240-730
Third degree	1220-3100	870-2640

The values for the dangerous dose and the LD50 thermal dose levels of infrared radiation are 590 and 1460 $(kW/m^2)^{4/3}s$, respectively [4]. Here a dangerous dose is defined as dose resulting in death to 1% of the exposed population. The LD50 dose is the lethal dose where 50% of the exposed population would die.

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2. EXPERIMENTAL SET UP AND MATERIALS

Experiments at the L30 facility at TNO were performed in an indoor environment (see Figure 3) with a 30 kW multimode laser (IPG, Model YLS-30000-Y18, λ: 1068-1080 nm). The laser system operates using 23 separate modules, each providing approximately 1.3 kW of power. The laser was powered by a generator which was located outside of the building and cooled using 2 chillers which were located inside the building. The laser fibre was connected to a custom-built optical platform (OP) which can focus or defocus the beam over a 2 – 40 m range from the aperture to a spot diameter of 2-15 cm at target. The beam can also be steered up to ±2 degrees in horizontal and vertical direction when necessary. Laser output power can be selected in the L30 software anywhere between 155 W and 30 kW, depending on the number of modules being operational and system settings and calibration.

The target area was located at ~20 m from the optical platform. The diagnostics used (e.g. cameras) were mostly located near the target area. Shown in Figure 3 are the laser unit itself, the OP, and chiller positions, as well as the target location set up, including target rack with sample, TREMs (Target Reflected Energy Measurement unit), back stop, heat flux sensor and multiple cameras.

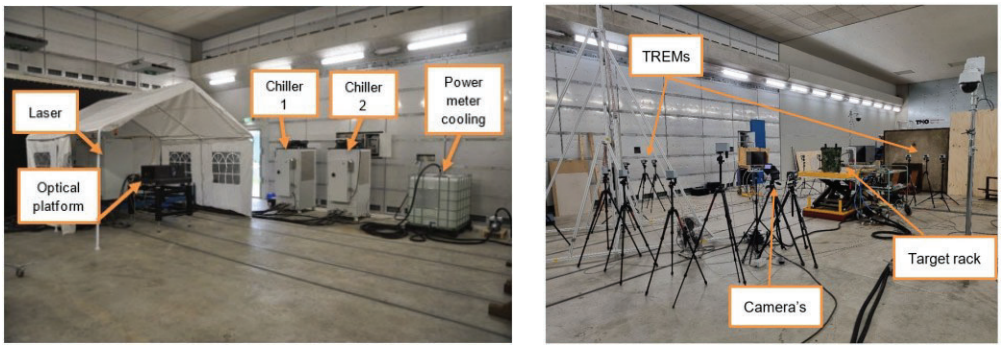

Figure 3. View of the L30 set up, including laser, optical platform and chillers (left) and the target location set up, including target rack with sample, TREMs, back stop, heat flux sensor and multiple cameras.

Figure 4 shows a detailed view of the heat flux sensor position in relation to sample. The sensor was aligned to the centre of the laser spot using the red guide laser of the L30 system. There was an airgap of approximately 1 cm between the sensor and the fabric. The HFS01 is a water cooled sensor that measures heat flux [9]. It is mainly used to test reaction to fire and fire resistance. HFS01 measures heat fluxes in the range of (0 to 800) x 10^3 W/m^2.

Figure 4. View of the sample rack and heat flux sensor position in relation to sample. The sensor was aligned to the centre of the laser spot.

Several samples of combat fabric materials were supplied for the experiments and an indication of the appropriate layering of the samples in relation to the scenarios was given. Table 3 lists the different configurations tested.

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Table 3. Configurations of combat fabric materials for testing.

ID	Layering	Description
1	NFP green *(Woven Fabric for Combat Uniform*)	Single layer worn on arms and legs
2	NFP green FR *(Woven Fabric for Combat Uniform (Flame Resistant)*	Single layer worn on arms and legs
3	Cordura FR Sioen	Cover material Dutch vest and pouches
4	Combat shirt knitwear *(Knit with FR properties)*	Single layer worn on torso
5	NFP green + Underwear (moisture regulating, *Synthetic Knit*)	Double layer worn on torso and lower body
6	NFP Tan FR *(Woven Fabric for Combat Uniform (Flame Resistant)*	Single layer in lighter colour, worn on arms and legs
7	Tarp *(Lightweight Coated Fabric)*	Example behaviour of thin material
8	Snow camouflage *(Lightweight Coated Fabric)* + Rain wear + Combat shirt knitwear + Thermo underwear *(Synthetic Knit)*	Combination of layers worn in arctic circumstances
9	Rain wear *(3 layer Laminated Fabric)* + NFP green	Double layer worn on arms and legs
10	Rain wear + Combat shirt knitwear	Double layer worn on torso and lower body
11	Backpack cover 120L + Cordura Fr WebeR *(Woven Fabric with FR coating for Body Armour, Pouches, etc.,)*	Backpack combination

Where appropriate the samples were cut down to sizes that fit the target rack. The fabric was secured using clamps and tightened to form a (as much as possible) flat surface. The experiments were performed using the appropriate calculated power at target (e.g. 155 W and 913 W), an 8 cm spot diameter and irradiation times of 1 or 5 seconds, or up to a visible effect on the fabric tested (e.g. perforation, burn, melt, smoke formation). In this way a broad experience was gained towards to the effects of laser reflections on clothing.

3. RESULTS

Both power levels, 155 W based on the drone scenario and 913 W based on the 155 mm scenario, are on the high end of what is to be expected in the field under the given circumstances. Typically, samples were exposed to the laser for 1 or 5 seconds to simulate brief and sustained exposure, respectively. Additional experiments were performed where exposure was continued until the samples were visibly affected by the laser illumination or even perforated. Some experiments are discussed below for illustration.

3.1 Experiments on fabric samples

An example of an experiment on the NFP Green material is discussed below (ID1 from Table 3). This material is often worn as a single layer on arms and legs. In the drone scenario the power affecting the dismounted soldier is that of 155 W due to the system limitations as mentioned earlier. Figures 5, 6 and 7 show the experimental data acquired. The sample is exposed to the laser beam (seen as a purple haze) and after 15 seconds the material is perforated, see Figure 5. The temperature data is shown in Figure 6, obtained from the MWIR (MidWave-InfraRed) camera. To convert the IR measurements to temperatures, the emissivity of the target material is required. Because this can change (significantly) during irradiation, it was decided to operate under the assumption that the emissivity equals 1, i.e. the target is a black body. In reality, the emissivity was (slightly) lower, meaning that the produced temperature values are minimum temperatures - an overestimation is not to be expected. Also note that the camera is limited by its dynamic range at a temperature of 140°C. This is due to the available calibration profiles and ranges. In reality, the temperature will have increased to significantly higher

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values. Higher temperatures are typically found for the darker parts of the camouflage pattern, as those absorb more laser radiation. This is also where the material starts to disintegrate.

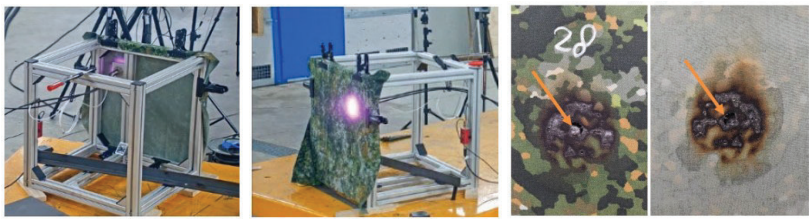

Figure 5. Left and middle: NFP Green non FR during laser irradiation (back and front view), settings: 155W, 8 cm spot diameter. Right: results after 15 seconds (perforation).

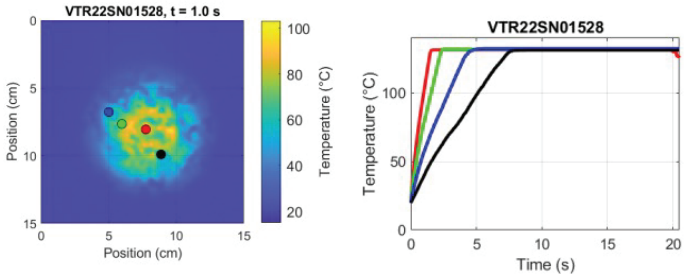

Figure 6. Left: MWIR plot of shot number VTR22SN01528, 155 W, 8 cm spot diameter on NFP Green. Highest temperatures at darkest parts of the camouflage pattern. On the right the temperature on the coloured dots as a function of exposure time is displayed. Note: the emissivity was assumed to be 1, meaning that the converted temperatures shown are minimum values.

The heat flux data is presented in Figure 7. The heat flux through the fabric seemed to increase in several steps which corresponded to effects witnessed at the materials surface; these are indicated with the orange arrows in Figure 7. After 4 seconds the front surface of the sample started to produce some light smoke, while around 8 seconds the smoke is also visibly forming at the rear side of the sample. At this time the material is being scorched (see also Figure 5). Around 15 seconds a perforation occurs in the dark part of the camouflage pattern. The laser is shut off around 17 seconds (visible from the black lines in the graph). Looking at the first few seconds (maximum 5 seconds is of interest in the drone scenario), a heat flux of ~1 W/cm^2 was obtained.

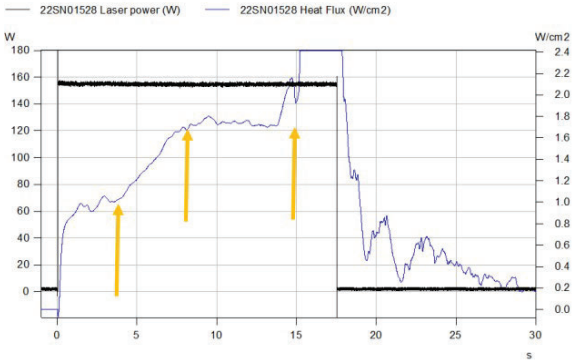

Figure 7. Heat flux data graph of VTR22SN01528, 155 W, 8 cm spot diameter on NFP Green. Different stages of effect are indicated by the orange arrows (explained in the text). Perforation occurred after about 15 seconds, the material scorched between 8 and 13 seconds while also producing smoke.

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The same material was also exposed to 913 W (artillery scenario). The results are shown in Figures 8 to 10. As can be expected the effects occurred much more rapidly. Smoke formation occurred within 2 seconds, after which the material started to burn. Local temperatures reached at least 300°C while a heat flux of ~5W/cm^2 was obtained in the first 2 seconds.

Figure 8. NFP Green with a power setting of 913 W and a spot diameter of 8 cm (artillery scenario). Figures from left to right show smoke formation after 1.5 s, start of burn after 2.3 s and fire after 2.4 s.

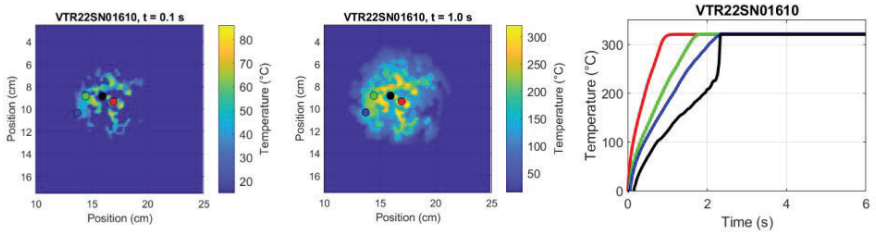

Figure 9. Left and middle: MWIR plots of shot number VTR22SN01610, 913 W, 8 cm spot diameter on NFP Green after 0.1 s and 1.0 s. Darker parts of the pattern heat up faster, as is clearly visible in the leftmost image (t = 0.1 s). On the right the temperature of the coloured dots as a function of exposure time is displayed. Note: the emissivity was assumed to be 1, meaning that the converted temperatures shown are minimum values.

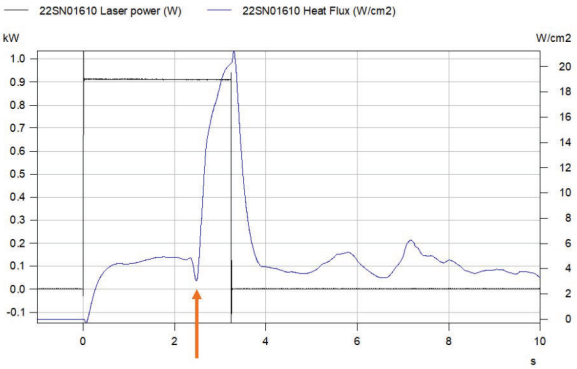

Figure 10. Heat flux data graph of VTR22SN01610, 913 W, 8 cm spot diameter on NFP Green. Indicated by the orange arrow is the fire starting at 2.3 seconds, after which the laser was shut down.

Similar results were obtained for the other materials and layer combinations presented in Table 3. The low weight polyamide materials for the rain wear, tarp and backpack cover, melted upon laser irradiation while the other fabrics started to scorch, smoke or burn (although mostly when exposed to the laser beam longer than 5 seconds as shown for the NFP Green example). A special note is to be made for the combat shirt knitwear which seemed to be transparent for the laser wavelength. Please note that for reflections, a direct 5 second exposure is considered an extreme worst case as reflections tend to be very dynamic in both time and space. The time to perforation varied from sample to sample due to the camouflage pattern in the area irradiated by the laser spot. The darker dye is affected much more rapidly compared to the lighter dyes.

In most experiments the ventilation was set to low when the laser was in operation. This is part of the protocol to reduce smoke and to prevent hazardous gases from moving towards the laser set-up. To determine whether airflow would influence the experimental outcome, some experiments were

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repeated with ventilation off. In some cases these tests resulted in the ignition of the fabric and fire (although not necessarily within a 1 or 5 seconds exposure). In all cases the flames self-extinguished as soon as the laser was shut down.

3.2 Heat flux

Table 2 provided an indication of what the measured heat flux during the experiments could mean to the soldier while wearing an outfit consisting of the clothing layer(s) as used in the experiments. As the underlying study is a first introduction, the data retrieved will only be used as an indication to determine the heat flux caused by laser reflections on military clothing. Besides the heat flux also the effect on the material is of interest. For practical reasons the data is processed for the two scenarios separately, e.g. a 5-seconds 155 W laser exposure in the drone scenario versus the 1-second of 913 W laser exposure for the artillery scenario. Please note that a "mean" value for the heat flux was taken from the heat flux graphs over the given time period (5 or 1 seconds) as the heat flux is not always constant.

From Table 2, the following threshold doses were mentioned for IR radiation [3]:

- First degree burns: 80-130 $(kW/m^2)^{4/3}s$
- Second degree burns: 240-730 $(kW/m^2)^{4/3}s$
- Third degree burns: 870-2640 $(kW/m^2)^{4/3}s$

Figure 11 shows the calculation results for the thermal dose in $(kW/m^2)^{4/3}s$ as derived from the heat flux data during the 5-second exposures simulating the drone scenario. Indicated in red are the thresholds for first (80-130 $(kW/m^2)^{4/3}s$) and second (240-730 $(kW/m^2)^{4/3}s$) degree burns [3]. It shows that first degree burns may be expected behind the NFP Green (*light green*), NFP Green FR (*dark green*), NFP Tan FR (*light brown*), the tarp (*purple*) and the backpack + Cordura FR Weber (*brown*) layer combinations. No experiments resulted in levels exceeding the second degree burn limit, only combat knitwear (light blue) got close.

Figure 12 shows the calculation results for the thermal dose in $(kW/m^2)^{4/3}s$ as measured by the heat flux sensor obtained during the 1-second exposures simulating the artillery scenario. Indicated in red are the thresholds for first and second degree burns [3]. It shows that first degree burns may be expected for (*light green*), NFP Green FR (*dark green*), NFP Green + moisture regulated underwear (*yellow*), NFP Tan FR (*light brown*), the tarp (*purple*) and the backpack + Cordura FR Weber (*brown*) layer combinations. Second degree burns may be expected when the soldier only wears one layer of combat knitwear (*light blue*).

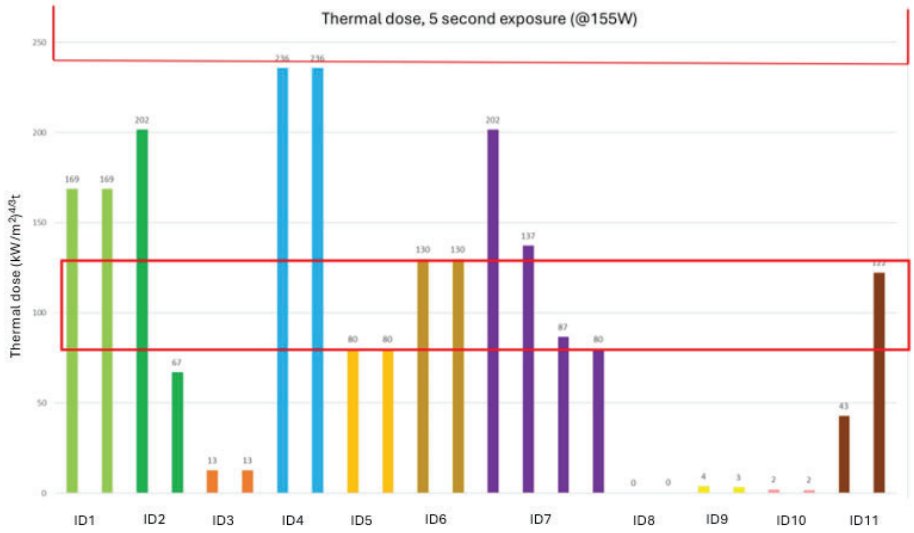

Figure 11. Thermal dose in $(kW/m^2)^{4/3}s$ as measured by the heat flux sensor behind the fabric as obtained during the 5-second exposures simulating the drone scenario. ID# as indicated in Table 3. Indicated in red are the thresholds for first (80-130 $(kW/m^2)^{4/3}s$) and second (240-730 $(kW/m^2)^{4/3}s$) degree burns [3].

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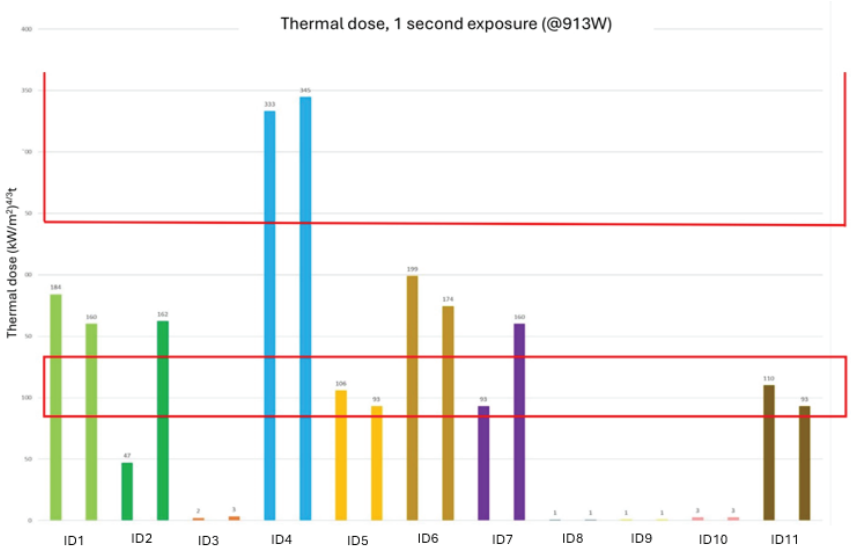

Figure 12. Thermal dose in $(kW/m^2)^{4/3}s$ as measured by the heat flux sensor behind the fabric as listed for the 155 mm reflective scenario for a 1 second exposures. ID# as indicated in Table 3. Indicated in red are the thresholds for first (80-130 $(kW/m^2)^{4/3}s$) and second (240-730 $(kW/m^2)^{4/3}s$) degree burns [3].

The dangerous dose and L50 dose stated by TNO in CPR 16E [4] (being 590 and 1460 $(kW/m^2)^{4/3}s$, respectively), were not exceeded in any experiment. Considering the thresholds defined by Pew [3], one may expect first degree burns after exposure to the reflections, even when exposed for only 1 second. Second degree burns are less likely: only for Combat shirt knitwear the measured heat flux exceeded the thermal dose in the 155 mm reflective scenario. In addition, more fabric layers provide better protection.

4. DISCUSSION AND CONCLUSIONS

The dynamic nature of the power, size and direction of the laser reflections means that even for well-defined scenarios, one can justify a wide range of typical values, often ranging from harmless to very harmful. While (future) laser safety models should be able to generate probabilistic results, this aspect is expected to remain a significant uncertainty in future work. Doses that cause pain should be considered while looking at heat flux, what are the affected surfaces of the skin (actual irradiated area from reflections) and within what time can one withdraw from the exposure. This is also part of the work performed internationally on establishing a probabilistic laser risk approach.

Slightly different conditions or targets (position, orientation, material, movement, etc) can result in significant changes to reflected intensities. Therefore, the presented results should not be extrapolated to, for example, another 'drone scenario' without critical consideration. The heat flux meter measures both (broadband) thermal radiation from heated objects such as fabric or flames, as well as (narrowband) laser radiation, as its functionality is purely based on absorption of radiation in visible and IR wavelengths. This means the measured heat flux is a combination of both aspects. As long as it is assumed that both have the same effect on skin this does not pose a problem. However, considering the difference between thermal dose limits found in heat flux literature and MPE's as set by laser safety standards, this may not be the case.

The camouflage pattern on the fabrics plays a significant role as to where the effect of the laser radiation occurred. Darker areas of the camouflage pattern absorb more of the laser energy compared to the lighter parts. Reproducibility of results therefore varies between the duplicate tests. For example, the 'black green' colour in the NFP Green material is known to have a reflectance of ~10% at the wavelength of the laser, whereas the lightest colour, 'light grey' has a reflectance of ~60% [10].

The low weight polyamide rain wear, tarp and back pack cover materials melted quickly upon laser irradiation, while the other fabrics, blends containing cellulose, started to scorch, smoke or burn

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(although mostly when exposed to the laser beam longer than 5 seconds). Due to the extremely dynamic nature of reflections, a continuous 5-second exposure should be considered as an absolute worst case that can only be achieved for static targets and personnel.

Ultimately, thermal doses observed for single-layer experiments in some cases exceeded the thresholds for first degree burns, but never did so for second degree burns with a single exception (Combat shirt knitwear). This is the case for higher laser power (913 vs. 155 W) and longer exposure times (5 vs. 1 s). For two or more layers of clothing, the thermal doses were shown to be significantly lower in the majority of cases. Taking into account that the laser-based MPE (skin) value is just below the second degree burn heat flux threshold, and that scenarios were evaluated for worst-case assumptions, one should be able to conclude that as long as skin is covered, reflections of the simulated laser engagements should not be expected to cause skin damage.

The dangerous dose or L50 dose stated in CPR 16E [4] was not exceeded in any experiment. However, considering the thresholds defined by Pew [3], one may expect first degree burns after exposure to the reflections, even when exposed for 1 second only. Second degree burns are less likely and more layers provide better protection, unless the (top) layer perforates.

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