CHAPTER «ENGINEERING SCIENCES»

DEVELOPMENT AND TESTING OF A METHODOLOGY FOR DETERMINING THE EFFECT OF LASER RADIATION PARAMETERS ON THE DESTRUCTION OF MATERIALS USED TO MANUFACTURE UAV

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Abstract. In recent years, there has been a significant increase in the use of unmanned aerial vehicles (UAVs) in military conflicts. This phenomenon has become one of the key trends in modern warfare, affecting the tactics, strategy and outcome of military operations. As the use of UAVs increases, the need for technologies to neutralize them grows at the same time. Modern technologies for neutralizing military UAVs are developing rapidly in response to the increasing use of drones in military conflicts. These technologies are designed to detect, intercept, and destroy UAVs, which can be especially important in protecting critical facilities and units from attacks and reconnaissance. The modern UAV neutralization technologies that have been most actively developed in recent years include the use of high-power microwave pulse installations and laser systems. Accordingly, the task of studying and adequately assessing the results of the interaction of laser radiation with the materials from which UAVs are made remains relevant. The study of the interaction of laser radiation with the materials from which UAVs are made is a critical task for the effective use of

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laser systems in the fight against drones. **The purpose** of this study is to develop an author's own methodology for determining the effect of laser radiation parameters on the destruction of materials from which UAV parts are made. **Methodology.** The data were systematized and a comparative critical analysis of a large amount of information obtained from various sources (news, comments, official statements, interviews, reports of various agencies and organizations, popular science articles, scientific articles, etc.) was carried out in the context of the prospects of using laser systems to combat UAVs. Promising directions of the stages of development of the laser module of a mobile installation for the destruction of UAVs are identified. Different methods of conducting experimental research to study the interaction of laser radiation with the materials from which UAVs are made are considered. The provisions of our own methodology for experimental studies of the interaction of laser radiation with materials from which UAVs are made were developed and experimentally tested on the FR-2 synthetic resin bonded paper. **Results.** The provisions of our own methodology for experimental studies of the interaction of laser radiation with the materials from which UAVs are made have been developed and tested on the FR-2 synthetic resin bonded paper. **Practical implications.** The developed methodology is a multi-stage process that requires in-depth research in the field of materials science, laser physics, and thermal processes. This technique can become the basis for the creation of effective laser air defense systems capable of quickly and accurately neutralizing drones on the battlefield. After analyzing the data obtained after a series of experiments, it can be concluded that to pierce a 2 mm thick FR-2 synthetic resin bonded paper, it is necessary to use a laser operating mode that must have a sufficiently high power density (at least 5000-7000 W/cm^2). This allows the material to pierce the FR-2 samples in most of the conditions presented in the experiment. **Value/originality.** An adequate assessment of the interaction of laser radiation with the materials from which UAVs are made allows developers and military experts to determine exactly what types of lasers are most effective in destroying specific materials from which UAVs are made and what parameters of laser installations are needed to achieve the desired result.

1. Introduction

In recent years, there has been a significant increase in the use of unmanned aerial vehicles (UAVs) in military conflicts [1]. This phenomenon has become one of the key trends in modern warfare, affecting the tactics, strategy and outcome of military operations. Unmanned aerial vehicles are radically changing the conduct of modern warfare [2], allowing for quick and accurate impact on the combat situation without risking the lives of operators [3]. They have become an integral part of the modern military arsenal, and their importance will continue to grow as technology evolves and military strategies adapt to new challenges.

The main reasons for the growing role of UAVs include [4-6]:

1. Technology development. UAV technologies have improved significantly, which has increased their effectiveness in combat. Drones can now perform reconnaissance, fire adjustment, strike, surveillance, and even electronic warfare tasks.

2. Reduced cost and ease of access. With the development of UAV manufacturing technologies, their cost has dropped significantly. This makes them affordable not only for large states, but also for small countries, non-state military organizations (private military companies) and even terrorist groups.

3. Increasing the role of intelligence and surveillance. UAVs are used for real-time reconnaissance, which can significantly improve the situational awareness of the military and, accordingly, increase the efficiency of operations. The data obtained from drones is an advantage in planning offensive and defensive actions.

4 Strike capabilities. Today, drones are not only used for surveillance, but also as strike platforms. Examples of the use of armed UAVs, such as the Turkish Bayraktar TB2 or the American MQ-9 Reaper, demonstrate their ability to deliver high-precision strikes against critical targets such as command posts, artillery installations, and armored vehicles.

5. Asymmetric wars. In many conflicts of today, especially in asymmetric wars, drones are becoming a key tool of the weaker parties.

6. The experience of the war in Ukraine. Since 2022, the war in Ukraine has shown the large-scale use of UAVs by both Ukraine and Russia. Drones are actively used for artillery correction, monitoring troop movements, destroying equipment, and performing specific tasks. Military and civilian

drones such as the Mavic and Phoenix Ghost have become important tools on the battlefield.

As the use of UAVs increases, so does the need for technologies to neutralize them. Modern technologies for neutralizing military UAVs are developing rapidly in response to the increasing use of drones in military conflicts. These technologies are designed to detect, intercept, and destroy UAVs, which can be especially important in protecting critical facilities and units from attacks and reconnaissance.

The main UAV neutralization technologies can be divided into several categories [7-9]:

1. Electronic warfare (EW). EW systems operate by disrupting or blocking communication between the operator and the UAV or interfering with GPS navigation. The main methods of electronic warfare include:

1.a. Jamming: Systems that emit signals that jam or interrupt the drone's control, disabling it. This is one of the most common methods for neutralizing commercial and military UAVs.

1.b. Spoofing: A technology that transmits fake GPS or radio signals to a drone, fooling its navigation systems and forcing it to change course or land.

1.c. Communication jamming: used to cut off communication between a UAV and its operator, making the drone uncontrollable and often leading to a crash.

2. Kinetic destruction systems. These systems involve physical damage or destruction of UAVs using conventional or specialized weapons:

2.a. Air defense missile systems (ADMS): used to destroy drones at long distances. For example, Patriot or S-400 systems can intercept drones at high altitude or range.

2.b. Anti-aircraft guns: specialized artillery systems, such as CIWS or ZSU-23-4 Shilka systems, that can effectively destroy low-flying drones with rapid-fire cannons.

2.c. Combat interceptor drones: specially equipped drones that can shoot down or intercept other UAVs in the air by striking or physically engaging them.

The modern technologies for neutralizing UAVs that have been most actively developed in recent years include the use of high-power microwave pulse installations and laser systems.

Microwave systems use powerful electromagnetic pulses to damage the electronic components of UAVs [10]. This can disable both its electronics and navigation systems [11]. Systems based on powerful microwaves can create a wide "umbrella" of electromagnetic influence, neutralizing several drones at once at close range [12].

Lasers are becoming a promising new tool for fighting UAVs. They use a concentrated beam of energy to heat and damage drone components (e.g., electronics, optics, or propellers), which disables the drone. It can be argued that in the future, lasers will become one of the main tools for fighting UAVs due to their high accuracy, speed of response, and lack of need for physical munitions. This technology is particularly effective against small and maneuverable drones, which can be challenging targets for traditional anti-aircraft or missile systems.

Recently, interest in the use of laser systems to combat UAVs has grown significantly, as evidenced by the abundance of information from various sources, such as news, official statements, expert commentary, as well as research and technical reports that are freely available.

This increased interest is due to several factors:

1. Extensive news coverage. The massive use of drones in military conflicts, in particular during the war in Ukraine and the conflict in Nagorno-Karabakh, has drawn the world's attention to effective means of combating UAVs. In these news stories, laser systems are presented as a promising technology that can effectively neutralize threats without launching missiles or using artillery, making them cost-effective. For example, publications such as Defense News, BBC, and Forbes regularly publish articles that examine the prospects of using lasers in the fight against drones.

2. Official statements and military reports. In many countries, laser technologies for countering UAVs are already under active development or testing. For example, the United States, Israel, and China have published official statements about the successful testing of laser systems to destroy drones at different heights and distances. In particular, in 2021, the US Army announced the successful testing of the HELWS (High-Energy Laser Weapon Systems) laser system, which was able to shoot down drones during real-world exercises. In a similar vein, Israel is actively developing its Iron Beam laser system to intercept small drones. One of the most famous

British projects in the field of laser technology is Dragonfire, which was initiated by the UK Ministry of Defense. This program is aimed at developing a highly effective laser weapon with a power of up to 50 kilowatts.

3. Expert commentary. Comments by defense experts, whether presented in interviews, forums, or at specialized conferences, often emphasize the advantages of laser systems over traditional air defense systems. For example, at defense forums such as IDEX or AUSA, experts emphasize that lasers are an important component of future air defense systems due to their ability to respond instantly to threats without the risk of running out of ammunition. Current technical challenges, such as energy requirements and limitations of laser systems in adverse weather conditions, are also discussed.

4. Scientific research. Scientific articles and research focus on the physical and technical aspects of laser use. Scientists and engineers are considering ways to improve the efficiency of laser systems, including increasing the radiation power and optimizing guidance systems. Such work is published in journals such as IEEE Transactions on Aerospace and Electronic Systems or the Journal of Directed Energy, which examine the physical characteristics of laser beams and ways to overcome factors that can affect their efficiency, such as atmospheric conditions or drone materials.

5. Popular science articles. Popular science resources, such as Wired, Popular Mechanics, or The Verge, regularly publish reviews of the latest developments in weapons and technology, including laser systems. They explain the technologies at an accessible level for a wide audience, discuss the prospects for their mass use, and analyze how lasers can change the course of future military conflicts. Such articles usually focus on the practical aspects of laser use, including examples of real-life tests and the possibility of introducing the technology into military structures.

6. Technical reports by defense agencies and companies. Companies such as Lockheed Martin, Raytheon, and Northrop Grumman are actively working on the development of laser systems and regularly publish reports on their achievements. These reports describe the technical characteristics of the new systems, tests, and future plans for their introduction into the armed forces. They also emphasize the economic benefits of laser systems,

such as their low maintenance and ability to effectively counter a large number of threats in a short time.

Although laser systems are considered promising, some challenges still remain. One of the main issues is the need for a large amount of energy to operate high-power lasers, which may limit their use in mobile or remote environments. In addition, atmospheric conditions, such as fog, rain, or dust, can reduce the efficiency of lasers by scattering or absorbing beam energy.

Accordingly, the task of studying and adequately evaluating the results of the interaction of laser radiation with the materials from which UAVs are made remains relevant. The study of the interaction of laser radiation with the materials from which UAVs are made is a critical task for the effective use of laser systems in the fight against drones. An adequate assessment of this interaction allows developers and the military to accurately determine which types of lasers are most effective at destroying specific UAV materials and what powers and wavelengths are needed to achieve the desired result.

The purpose of this study is to develop an author's own methodology for determining the effect of laser radiation parameters on the destruction of materials from which UAV parts are made.

2. Research methodology

The data were systematized and a comparative critical analysis of a large amount of information obtained from various sources (news, comments, official statements, interviews, reports of various agencies and organizations, popular science articles, scientific articles, etc.) was carried out in the context of the prospects of using laser systems to combat UAVs. Promising directions of the stages of development of the laser module of a mobile installation for the destruction of UAVs are identified. Different methods of conducting experimental research to study the interaction of laser radiation with the materials from which UAVs are made are considered. The provisions of our own methodology for experimental studies of the interaction of laser radiation with materials from which UAVs are made were developed and experimentally tested on the FR-2 synthetic resin bonded paper.

3. Analysis of the main advantages and disadvantages of laser anti-UAV systems

The main advantages of laser anti-UAV systems include:

1. Speed of action. Lasers operate at the speed of light, which makes them an almost instantaneous means of defeating targets. As soon as a drone is detected and brought into view, the system can immediately activate the laser beam to neutralize it. This is especially important when dealing with high-speed or maneuverable UAVs.

2. High accuracy. The lasers of an anti-UAV system are usually equipped with target detection and tracking systems that can accurately target critical drone components such as the engine, electronics, or cameras. This makes it possible to quickly disable the drone without causing its complete physical destruction. Accuracy is also important to avoid collateral damage in areas with civilian infrastructure or on a battlefield with close proximity to your own units.

3. Unlimited number of shots. Laser weapons do not require physical ammunition such as missiles or bullets. This means that it can be used continuously as long as there is power supply. This autonomy makes laser systems cost-effective in prolonged conflicts or in situations with a large number of attacking drones.

4. Minimization of collateral damage. Laser engagement systems are highly accurate and can operate at certain distances without risking surrounding infrastructure or people. This makes them ideal for use in densely populated areas or when protecting critical facilities such as airports, power plants, or military bases.

5. Mobile platforms. Many laser systems can be installed on mobile platforms such as cars, ships, or even airplanes. This allows for rapid deployment of the laser system in different environments and provides high maneuverability. For example, military lasers are already being integrated into vehicles to protect against drone attacks on the battlefield.

Laser-based anti-UAV systems are gaining popularity as an innovative means of neutralizing drones in various military and civilian situations. Due to their high accuracy, rapid response time, and lack of ammunition requirements, lasers have the potential to become a key component of air defense systems in the near future. Technological developments in this area continue to improve these systems, expanding their capabilities for use in real-world combat situations.

Laser anti-UAV systems have significant advantages, such as high accuracy, instant response, and no need for ammunition. However, like any other technology, they have a number of disadvantages that affect their effectiveness and application in real-world conditions.

The main disadvantages of laser anti-UAV systems:

1. High power requirements. Laser systems require a significant amount of energy to operate efficiently. The laser power must be sufficient to quickly heat up and damage the materials from which the UAVs are made. This means that laser systems require a reliable power supply, which can be challenging for mobile platforms or for extended operations in remote areas.

2. Limited range. Although lasers can operate over long distances, their effectiveness decreases with distance due to beam energy dissipation. The further away the target is, the more energy is lost due to atmospheric factors. In real combat conditions, especially at long distances, this can significantly reduce the effectiveness of lasers.

3. Vulnerability to weather conditions. Laser radiation is very sensitive to weather conditions. Rain, fog, snow, dust, or even extreme heat can scatter or absorb some of the laser beam energy, making the system less efficient. This is a serious limitation for using lasers in difficult weather conditions or in certain climatic zones.

4. Reflection and absorption of materials. The materials from which UAVs are made can have reflective or absorptive properties, which reduces the efficiency of the laser. For example, metal surfaces or special coatings can partially reflect laser radiation, making it difficult to destroy the drone. In addition, heat-resistant materials may require more power or longer laser exposure times to damage them.

5. Cooling of the laser system. High-power laser operation generates a large amount of heat, so the system needs a reliable cooling system to maintain optimal temperature. This adds complexity to the design and can limit the amount of continuous laser operation. Inadequate cooling can lead to overheating and reduced system efficiency or even damage.

6. High cost of development and implementation. Laser systems are an emerging technology that requires significant investment in research, development, and manufacturing. Although they can reduce ammunition costs in the long run, the initial costs of developing laser systems are high.

This may limit the widespread adoption of such systems, especially for countries with limited defense budgets.

7. Ability to counter lasers. Over time, methods of countering laser systems are evolving. For example, the use of drones with reflective surfaces or special coatings can make it more difficult to destroy them with lasers. In addition, there is a growing likelihood that UAVs will be made of materials resistant to high temperatures or with low thermal conductivity, which will make them more difficult to damage with a laser.

8. Limitations in multi-target operations. Although lasers have a fast response and can destroy targets almost instantly, there are certain limitations to the simultaneous destruction of multiple objects. A laser beam can only focus on one target at a given time, which creates a problem with simultaneous attacks by a large number of drones (flock attacks), when several UAVs attack an object at the same time.

Despite the numerous advantages of laser systems for UAV countermeasures, such as high accuracy and speed of response, they also have important limitations. High energy requirements, dependence on weather conditions, vulnerability to special materials and coatings, and high implementation costs are key drawbacks that require further improvement and research. However, the development of technology and engineering solutions can gradually reduce these shortcomings and make lasers more effective in real-world combat.

In this context, research on the development of a methodology for determining the impact of laser radiation parameters on the destruction of materials from which UAV parts are made is becoming increasingly relevant.

4. Analysis of different methods for determining the effect of laser radiation parameters on the destruction of materials from which UAV parts are made

The development and testing of a methodology for determining the impact of laser radiation parameters on the destruction of materials used to make UAVs is a multi-stage process that requires in-depth research in materials science, laser physics, and thermal processes. This technique can become the basis for creating effective laser air defense systems capable of quickly and accurately neutralizing drones on the battlefield.

The development and testing of a methodology for determining the effect of laser radiation parameters on the destruction of materials used to make UAV parts is an important scientific and technical task. This methodology allows to establish the optimal parameters of laser radiation for effective neutralization of UAVs, taking into account the properties of various materials from which their components are made.

Typical stages in the development of a methodology for determining the effect of laser radiation parameters on the destruction of materials from which UAV parts are made may be as follows:

1. Determination of material types. The first step in developing the methodology is to study and classify the materials used in UAV structures. It is important to take into account the mechanical, thermal and optical properties of each material to determine how they will react to laser radiation.

2. Selection of parameters of laser installation modes. These parameters should be adjusted according to the characteristics of the materials to achieve maximum destruction efficiency.

3. Experimental testing. To test the methodology, it is necessary to conduct a series of laboratory experiments on samples of materials from which UAV components are made. The purpose of the tests is to determine the threshold power and time of impact, at which the material destruction begins. The following aspects should be taken into account: melting point of the material; thermal expansion rate; reflectivity of the material; thermal conductivity of the material, etc.

4. Modeling the effect of laser radiation. Computer modeling can be used to refine the results of experiments and understand the mechanisms of material destruction. The models can simulate the behavior of the material under the influence of various laser parameters and will allow more accurate prediction of the effect of laser radiation on the material, in particular, under conditions of variable weather factors.

5. Analysis of results and development of destruction criteria. Based on the experimental and theoretical studies, criteria should be developed to evaluate the effectiveness of material degradation. This may include: the temperature of the onset of thermal destruction of the material; the rate of propagation of cracks or damage on the material; the minimum time and power to achieve the desired effect.

6. Testing of the methodology in the field. After successful testing in the laboratory, the methodology should be tested in real conditions on UAV models or prototypes. This will allow us to assess the impact of additional factors, such as atmospheric conditions (rain, fog, wind), drone movement, and target remoteness. These tests will help to adapt the methodology for use in combat conditions.

7. Optimization of the methodology. Based on the results obtained, the methodology can be optimized to achieve the best results with minimal energy and time. This includes selecting the optimal types of lasers for different materials and operating conditions, as well as improving guidance and control systems.

Let's consider the methods for determining the effect of laser radiation parameters on the destruction of materials used to make UAVs proposed by other developers.

Taillandier and colleagues article reports an experimental contribution to High Energy Laser (HEL) engagement in urban combat by considering two key aspects [13, p. 1]: safety risks for the population due to Ytterbium beam reflectivity on target and vulnerability performance on drone cell structures by comparing Ytterbium and Thulium laser source technologies.

The first section of this article describes the steps undertaken towards the development of a unique high reflective screen, based on ceramic projection [13, p. 3]. The driving parameters of the spraying process, particle nature as well as the microstructure, optical and resistance to heat flux are presented. Then, the experiments related to dynamic Bidirectional Reflectance Distribution Function (BRDF) characterization are presented. The influence of laser beam shape and target material on the time-dependent direction and magnitude of reflected laser beam is reported.

The second section of this article [13, p. 4] describes the experiments involving two different continuous-wave fiber laser sources (wavelengths ~1 μm and ~2 μm) in the Vulnerability Test Facility (VTF) (see Figure 1).

Emphasis is put on the calibration work necessary to guarantee same beam characteristics (profile, power and spot size). Then, a parametric study is performed on laser output power to assess the vulnerability of thermoplastics and a CFRP, against the two laser wavelengths. Vulnerability assessment is based on drilling time and, when available, temperature measurements.

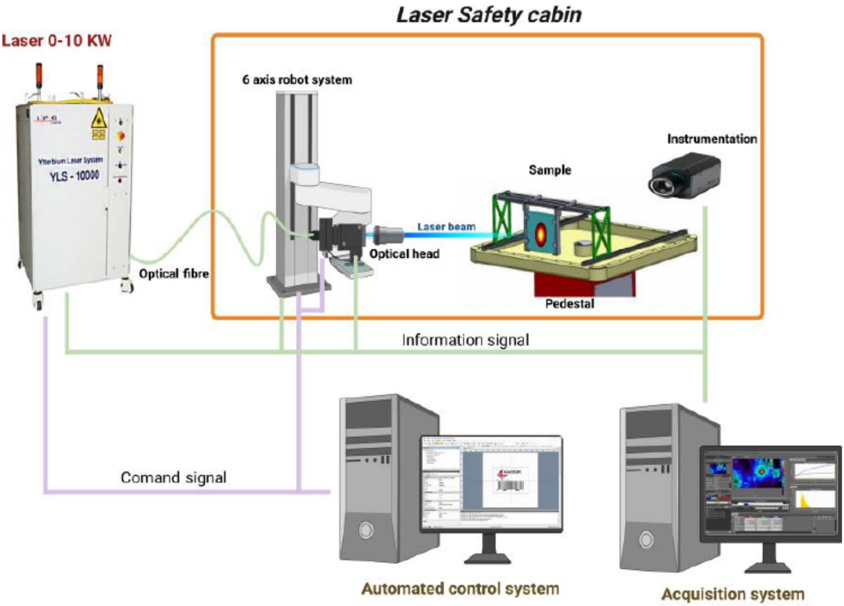


Figure 1. VTF experimental setup and synopsis [13, p. 3]

The basic principles of dynamic BRDF measurements are shown below. The high-energy laser beam interacts with a target material and the scattered HEL radiation is monitored on the optimized Lambertian screen with several cameras (see Figure 2).

The Lambertian screen has a 50 mm port hole at its center to account for 0° dynamic BRDF characterizations [13, p. 6]. For angled BRDF measurements, the screen can be tilted up to +45° given the space available in the VTF. Active imagery (810 nm pulsed laser triggered with digital cameras incorporating bandpass filters) on the front side of the illuminated target material permits the complete monitoring of laser-matter interaction (dynamics of melted pool during the interaction) and is triggered with the laser and other instrumentation to be able to associate, at the same time, target degradation key events (begin of laser illumination, begin of target melting, drilling dynamics) with reflectivity distribution and intensity on the screen. Additionally, temperature measurements are performed either at

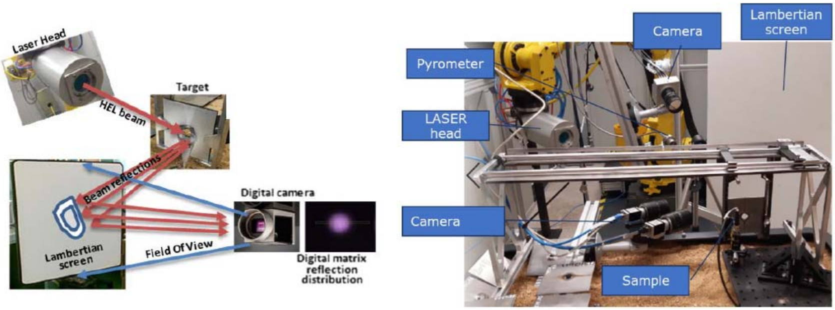


Figure 2. Basic principle of dynamic BRDF in the VTF [13, p. 5]

target level (low-temperature & biochromatic pyrometers) or at reflection screen level with an IR camera. After having passed through several hundred of meters to a few kilometers of atmosphere, there is no reason why a perfectly Gaussian (at beam director output) beam profile remains Gaussian at target level. It is therefore interesting to investigate the effect of laser beam profile on reflectivity distribution (and vulnerability performance).

The Lambertian screen is placed ~0.8 m away from the target materials at a 45° angle [13, p. 7]. For both cases (raw 304L steel and raw 2024 aluminum) presented below, an 8 kW Gaussian beam with 20 mm spot size interacts with the 2.5 mm thick materials. With 304L steel samples (Figure 3), the reflectance of the materials decreases as the samples are heated.

After the surface begins to melt a peak BRDF (intensity) is observed, wandering vertically [13, p. 7]. A cone-shaped structure is formed and rapidly disappearing away from the field of view. At first, it seems that most of the reflected beam shape follows the growth of the molten area of the target surface, in the form of a ring (also reported elsewhere [14] but for thinner samples and different HEL conditions). Nevertheless, the high-speed active imagery (at target level) shows, whilst the material is melting, a fast convective pattern in the molten pool; this forms a “web-like” structure (or “caustics” [14]) on the reflective screen with many local hotspots, that exceed – in size – to a large extent the size of the reflected diverged beam. The intensity is highest in the first instants of the HEL engagement. The infrared camera pointing at the Lambertian screen confirms this and

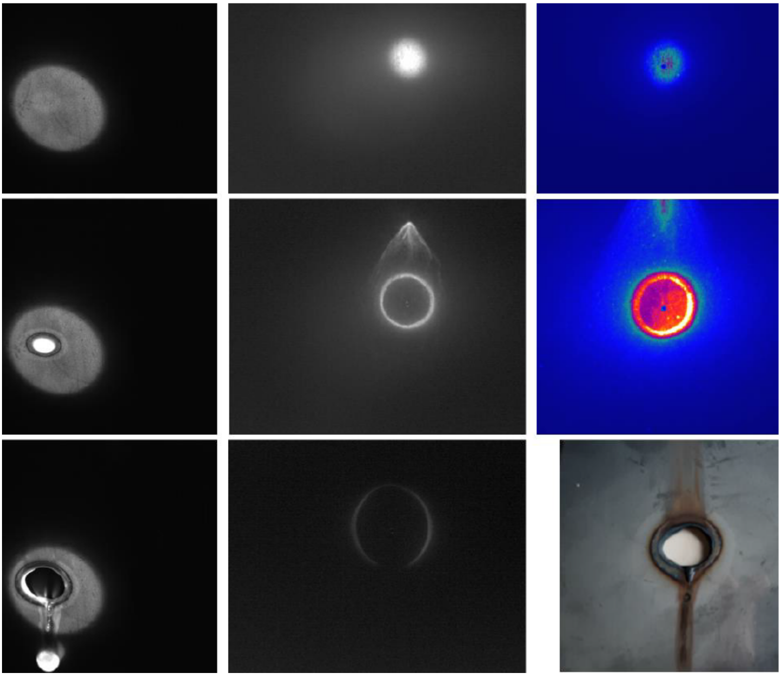


Figure 3. Steel under HEL illumination. Degradation at target level (left), visible reflectivity pattern (center) and IR (right) [13]

shows temperature elevations less than 100°C. Figure 3 (bottom right) also depicts the sample after perforation.

Figure 4 shows the results for 2024 aluminum. Globally, the reflected beam is less energetic than in the case of lasermatter interaction with steel samples. Here also, after the material melts, a reflection pattern appears for a short time in a circular shape. As for the case with steel, the intensity of reflection decreases with irradiation time.

In this work, thermoplastics were also tested [13, p. 12]. The influence of colored PMMA is investigated (colored in the mass). The color affects the transparency behaviour of the material (Figure 5).

The degradation of blue PMMA is more pronounced at ~2 μm than at ~1 μm, where lower average intensities are sufficient to drill the material

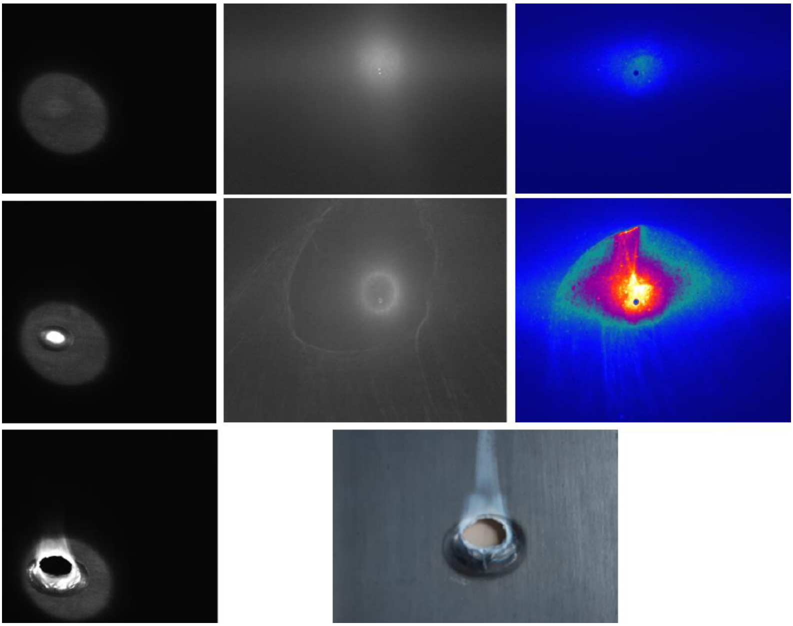


Figure 4. Aluminum under HEL illumination.
Degradation at target level (left),
visible reflectivity pattern (center) and IR (right) [13, p. 8]

(B-4 vs B-2) [13, p. 12]. The efficiency of a ~2 μm against ~1 μm laser source is demonstrated for this material. Similarly, the degradation of green PMMA is more pronounced at ~2 μm than at ~1 μm, where lower average intensities are sufficient to drill the material (see V-4 vs V-2). The efficiency of a ~2 μm against ~1 μm laser source is demonstrated for this material. For purple PMMA, the absorption at ~1 μm and ~2 μm are not far apart, this is highlighted for trials at ~1 μm (Vi-1 and Vi-2) and ~2 μm (Vi-3 and Vi-4) where all specimen were drilled. The holes are more conical in the ~2 μm case. For the thermoplastics investigated here, the thermal heat flux brought by the ~2 μm laser source is more absorbed than the one at ~1 μm. This is visible from the drilling observations during laser-matter interaction. These results are in line with (20°C) reflectance and transmittance measurements.

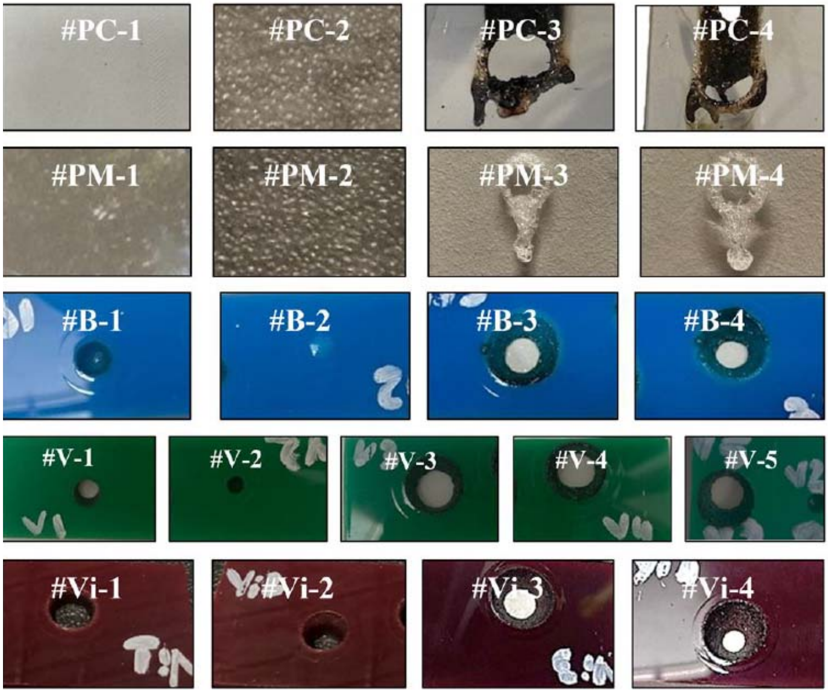
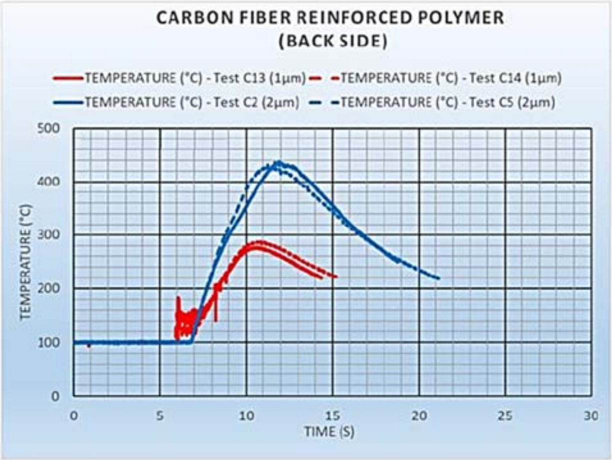


Figure 5. Drilling of various thermoplastics at ~1 µm and ~2 µm [13, p. 12]

The comparison of the behaviour of two families of thermoplastics under medium laser intensity show different degradation mechanisms: PC thermoplastics heat up, combust with the presence of flames, bubbles appear and lead to the perforation at ~2 µm. PPMA thermoplastics heat up, melt and drip before perforation at ~2 µm. For a given thermoplastic family (PMMA), its color modifies the speed and level of degradation depending on the laser wavelength. In general, ~2 µm laser wavelength is more efficient than ~1 µm laser wavelength. Finally, the analysis based on all performed trials on thermoplastics show the interest of ~2 µm laser sources for vulnerability aspects. Nevertheless, this conclusion is nuanced because it might not be the case for all thermoplastics, colors and surface finishes. More parametric trials are necessary to have a clearer overview of the benefit of ~2 µm against ~1 µm laser sources.

Carbon Fibre-Reinforced Polymer (CFRP) materials find a wide use in defense applications, especially in the manufacturing of UAVs [13, p. 13]. From the variability and quality of the nature of their constituents, the fiber to resin proportion and their fabrication method, their process of degradation under HEL can be very different from one another. For the CFRP investigated here, the thermal heat flux brought by the ~2 µm laser source is more absorbed than the one at ~1 µm. This is visible from the backside (apparent) temperature measurements (Figure 6). These results are not in line with (20°C) reflectance measurements that show that absorbance at ~1 µm is slightly higher than at ~2 µm. Moreover, doubling laser power induces an increase of ~30-35% of backside (apparent) temperature no matter which laser is chosen. It is interesting to note that temperature measurements are not perfectly reproducible, despite being in the same laser configuration. This is probably due to the aim-point of the pyrometer on the backside (fiber or resin) or the intrinsic variability in specimen manufacturing. The degradation level of the front face is slightly (qualitatively) higher at ~2 µm no matter what laser power is selected. Flames are present for higher laser average intensities. Overall, the vulnerability efficiency of ~2 µm laser source with respect to ~1 µm against (this) CFRP is demonstrated. Nevertheless, to be truly efficient, the output power of these laser sources needs to be in the kW class to be relevant for Laser Directed Energy Weapon (LDEW) applications

Given the versatility of capabilities offered by the test laboratory, the VTF addresses key topics related to LDEW development such as the effects of laser reflectivity (risk and safety analysis), the effect of the spectral nature of laser sources (1 µm versus 2 µm) for vulnerability [13, p. 14]. Good quality examination of reflection images from dynamic BRDF trials were made possible thanks to the technological development of a proprietary "Reflectivity screen". The images show the chaotic nature of the reflected beam off target materials of various nature for full HEL engagement scenarios. Specular reflectance cannot be approximated by a single Gaussian peak and can have multiple peaks ("caustics") that wander in a region far exceeding divergence of incoming beam. Also, the shape of the beam at target level has a non-negligible influence on the magnitude of



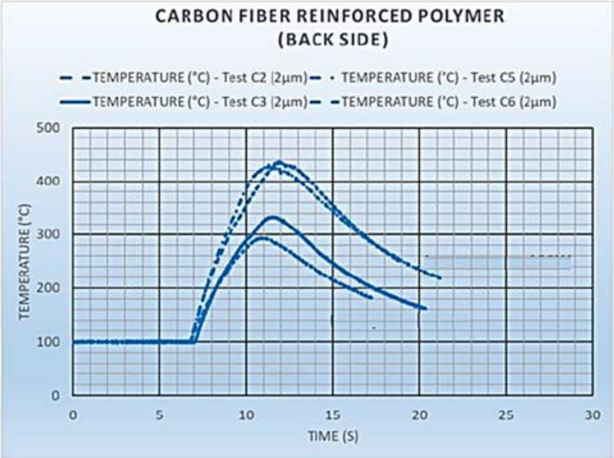


Figure 6. Backside temperature measurements of CFRP under HEL at ~1 µm and ~2 µm (left), effect of doubling laser power at ~2 µm (right) [13, p. 13]

carried energy. Therefore, a static BRDF approach is insufficient for laser safety and hazard analysis when dealing with HEL engagements. LDEW employing wavelengths around ~2 µm are known to be interesting for safety purposes because of the "eye-safe" nature of the laser wavelength. As such, it is also important to study the vulnerability of targets using ~2 μm laser sources. Evidently, the list of material solutions used in the manufacturing of UAV cells and structures is large and constantly evolving (as can be seen in the Ukraine-Russia war since 2022). The first experimental results shown here, clearly show, on the selected thermoplastics, a certain advantage when considering target degradation level and speed. More experimental work on other materials is necessary to truly assess the better efficiency of ~2 μm versus ~1 μm laser sources for vulnerability. Development of ~2 μm laser source technologies should be closely monitored, as they have the potential to offer longer term solutions with greater capabilities. Potential technology breakthroughs, particularly in pump diode technologies leading to more efficient electrical to optical conversion, would be of particular interest, and may accelerate development of future LDEW systems using these wavelengths.

The paper Schleijpen with co-authors [15] report on a first series of experiments of High Energy Laser effects on drones and drone components at Netherlands Organisation for Applied Scientific Research (TNO). After a description of the 30 kW L3O laser facility at TNO, the experimental results be discussed. The experiments were performed in an indoor facility and some considerations be given on how to set up the experiments to enable "translation" of the experimental results to outdoor operational scenarios [15, p. 1]. The results illustrate that there can be large variations in the illumination time of the High Energy Laser on the target before fatal damage is observed, depending on the specific drone component selected as target. This illustrates that target aimpoint selection is critical for the result and a good understanding of the weak spots of drones is required to enable High Energy Laser systems to be effective against drones.

The first scenario is a public event in a large stadium, where a small armed UAV is launched and flies towards the stadium [15, p. 1]. The second scenario is a military compound where a UAV is launched and flies towards the perimeter of the compound. In both cases the launch is at a range between 1 and 5 km from the object to be defended. After detection of the drone threat the HEL system engages the drone at 4 to 0.5 km distance. Approaching speed of the drone is assumed to be 25 m/s. At short ranges the engagement time of the High Energy Laser system becomes critical due to the limited remaining flight time of the drone to its target destination. The experiments focus on the interaction of the laser beam with the drone. The initial detection and identification of the drone and subsequently tracking of the and precision pointing of the laser beam were out of scope of the experiments. The experiments were set-up to simulate the power levels and engagement duration times relevant for the scenarios selected. The TNO L3O facility provided sufficient flexibility for the current experiments to cover a range of conditions such as laser power from 130 W up to 30 kW laser, variable spot size on the target between 2 and 12 cm diameter and controllable target illumination time from typically 0.5 to 60 seconds. The drones used as targets in the experiments cover a range in size and weight. An overview is given in Figure 7. All these drones can fly

4x Eachine E520S GPS 5G WIFI FPV  40 x 28 x 7.5cm, 0.9 kg GPS positioning 200-300m RC range Speed: unknown	1x 3D Robotics Y6 + blades  52 x 36 x 20 cm, 2 kg GPS positioning RC range unknown Speed 25 m/s
2x DJI Phantom 2  40 x 28 x 7.5 cm, 1.0 kg GPS positioning 1000 m RC range Speed 15 -20 m/s	1x Walkera Voyager 3  30 x 46 x 47 cm, 3.6 kg GPS positioning RC range unknown Speed unknown

Figure 7. Drones as used in the experiments including typical dimensions [15, p. 2]

pre-programmed trajectories based on GPS and would be capable to operate in the scenarios outlined in the introduction.

For interfering with the operation of a drone the laser operator can select various components of the drone to aim at and to attack [15, p. 2]. Failure of the selected component should result in disabling of the drone. The following target components were identified: motor; rotor; motor mount; camera; antennas for remote control; electronics; battery. Motor, rotor and motor mount were selected as the test components for the experiments. Malfunction of these components will interfere with the capability to fly, and thus prevent the drone from reaching its goal. An additional test on drone cameras were included. Preventing the use of the camera will also prevent the drone to reach its target or to fulfill the mission. Attacks on batteries as target component could not be performed yet, because although the L3O facility operates in a bunker allowing work with explosive materials, working with potentially exploding materials will start in a later stage. To avoid explosions the batteries were removed. Since this significantly changes the heat capacity in the environment of the battery where the electronics are located, it was decided that testing the electronics as target would not provide a realistic situation either. Also aiming at the antennas without functioning electronics was considered less useful.

Laser power from 130 W up to 30 kW laser, spot size on the target between 2 and 12 cm diameter [15, p. 3]. Target illumination time from typically 0.1 seconds to 2 minutes have been selected. The specified full range is from 1 ms to 20 minutes depending on the power level selected. The laser operates at a wavelength near 1.07 μm. The target position is located at approximately 20 m from the laser position. The target area is surrounded by a shelter, to avoid light scatter of the HEL beam. Plywood was chosen as sacrificial shelter material to identify strong reflections by scorch marks. The target area itself is instrumented with a number of cameras for analysis of the interaction of the HEL beam with the target. These cameras cover the spectrum from visual (0.4-0.7 μm), visual/NIR (0.4-1.1 μm), via Short Wave Infrared (SWIR = 0.9-1.7 μm) to Mid Wave Infrared (MWIR = 3-5 μm). Special care is taken to select the camera settings such to avoid unintentional saturation during the HEL illumination of the target. Notch filters for the laser wavelength and Neutral Density filters are applied for some of the cameras to avoid saturation.

The motor mount materials in the drones in the experiments differed quite significantly: ABS (acrylonitrile-butadlenestyrene), Carbon fibre and Aluminium [15, p. 5]. In the experiments, the duration of the laser illumination was adjusted to the time needed to observe visible effects on the motor mount during the test. Selected examples of the tests on the different motor mounts are summarised in Table 1. Photographs of the resulting damage after HEL illumination are shown in Figure 8.

Table 1

Selected tests on motor mounts of different drones [15, p. 6]

Test	Laser setting	Observation
DJI Phantom		
(901)	4 cm, 30 kW, 3 atu	Motor mount damaged but stiffness maintained
(902)	4 cm, 5 kW, 18 atu	Motor mount damaged but stiffness maintained outer part damaged
Walkera Voyager 3		
(895)	4 cm, 5 kW, max illumination time	Motor mount did not bend or break during illumination. Apparent temperature up to 2400°C has been observed. After switching of the laser the structure was severely weakened
3D Robotics Y		
(917)	8 cm, 30 kW, 15 atu	Although aimed at motor, significant damage on mount. Laser stopped before damage complete
(918)	8 cm, 30 kW, 12 atu	Although aimed a motor, the mount was melted and broke off after laser stopped

The results on the DJI Phantom motor mount (901, 902) suggest that the energy delivered during the illumination (30 kW×3 atu or 5 kW×18 atu), was insufficient to break the mount [15, p. 6]. A longer illumination indeed broke the mount in one of the other tests. Note that the actual energy absorbed by the motor mount of the DJI is smaller, because the size of the motor mount is too small to intercept the full beam (Figure 8).

The test for the 3D Robotics Y6 provided information on an aluminium motor mount [15, p. 7]. The beam was centred at the motor just above the mount, but using the 8 cm diameter HEL beam, the motor mount was still in the beam. The first experiment was just at the damage threshold; the second actually did break off the mount. The power density in the 8 cm diameter

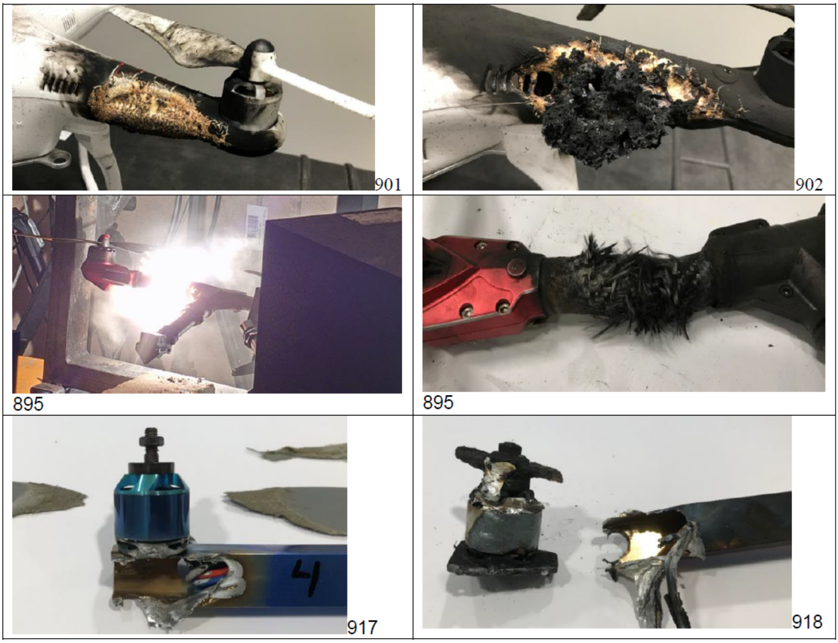


Figure 8. Images of the inflicted damage on the various motor mounts. The numbers correspond to the experiments [15, p. 6]

beam is 4 times smaller. The energy deposited in the area of the motor mount is estimated to be similar as in the examples for the DJI Phantom around (30/4 kW×12 atu).

Note again that as in all previous ceases not all energy is intercepted by the motor mount. For the carbon tube of the Walkera Voyager 3 motor mount even much higher energy levels need to be delivered to inflict damage. In the first experiment (895) the energy delivered on the motor mount was insufficient to break it. The laser was stopped at its maximum pre-determined illumination time. The second test (896) 4 time as much energy was delivered at the moment when the mount broke. The amount of energy to inflict damage on the carbon fibre mount is roughly one order of magnitude higher than for the Phantom DJI drone.

5. Development of the author's methodology for determining the influence of laser radiation parameters on the destruction of materials from which UAV parts are made

The first stage of the work is carried out on the laser installation DY044 with a maximum laser power of 4.4 kW available in the E. O. Paton Electric Welding Institute. This unit is stationary and cannot be moved to conduct field experiments with a large distance to the irradiation object. Further in the text, when describing the planned work, Part #1 is constantly mentioned. All items of this plan are planned to be repeated cyclically for each subsequent type of Part #N, when its characteristics (material type; thickness; surface roughness; surface color; geometric shapes, etc.) Accordingly, all of the following items are repeated for Part #2; Part #3, Part #4, ... , Part #N.

The purpose of the work at the first stage is to establish the answers to the following questions:

1.1. How does laser radiation interact with the material of UAV Part #1 (absorbs/reflects/partially absorbs, and partially reflects and scatters)?

1.2. What is the required laser radiation power density for the destruction of the material of UAV Part #1 (how many watts of laser radiation power must be applied per unit area for destruction to begin, W/cm^2), under conditions when the laser beam and the sample simulating UAV Part #1 are stationary relative to each other?

1.3. What should be the energy exposure of a beam of a certain laser radiation power density for the destruction of the material of Part #1 of a certain thickness, under conditions when the laser beam and the workpiece are stationary relative to each other (how much time (in seconds) should a beam of a certain laser radiation power density (W/cm^2) affect the material of Part #1 of a certain thickness to destroy Part #1)?

1.4. What is the effect of changing the angle of incidence α in the range of 10°

6. Testing of the developed methodology

The experiments were carried out using the scheme, depicted on the Figure 9.

Characteristics of laser radiation: laser power (P) is measured in W (1000…4000); deam diameter (D) is measured in mm (5.0…20.0); irradiation

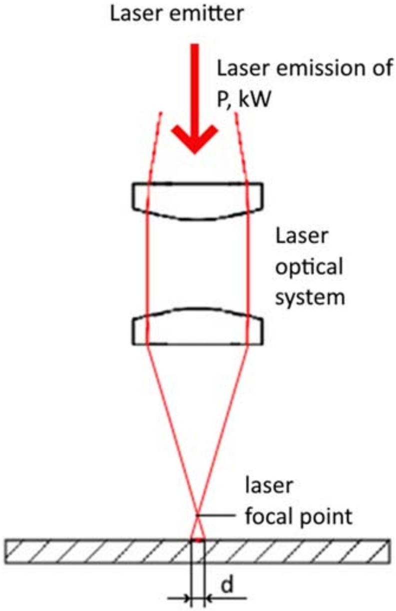


Figure 9. Scheme of interaction on the material using laser radiation

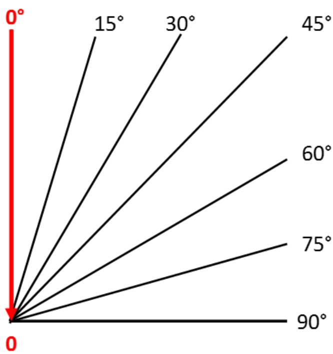


Figure 10. Measurement of angles from the laser beam to the sample

time (T) is measured in seconds (0.2…10.0); power density (Q) is the ratio of power to beam area, W/cm^2.

Measurements of angles during the experiment are shown on Figure 10.

Radiant exposure (E) is the amount of energy per unit area, measured in J/cm^2 and calculated via this formula:

$$E = Q * T.$$

The provisions of the developed methodology were tested on a getinax (2 mm thick FR-2 synthetic resin bonded paper). The graphs of the reference points of guaranteed penetration at all angles except 30° are reduced to very close, if not identical, values, which may indicate that the material characteristics are homogeneous at these angles (see Figure 11). A large difference between the values in the range of 45-90° and the values at 30° is noticeable. This may indicate a sufficiently high level of reflection or high thermal conductivity of the material. However, in a number of conditions, such as piercing the material while it is moving, as well as piercing the material at a very sharp angle, the required power density increases to 10000-15000 W/cm^2.

After analyzing the data obtained after a series of experiments, it can be concluded that to pierce a 2 mm thick FR-2 synthetic resin bonded paper, it is necessary to use a laser

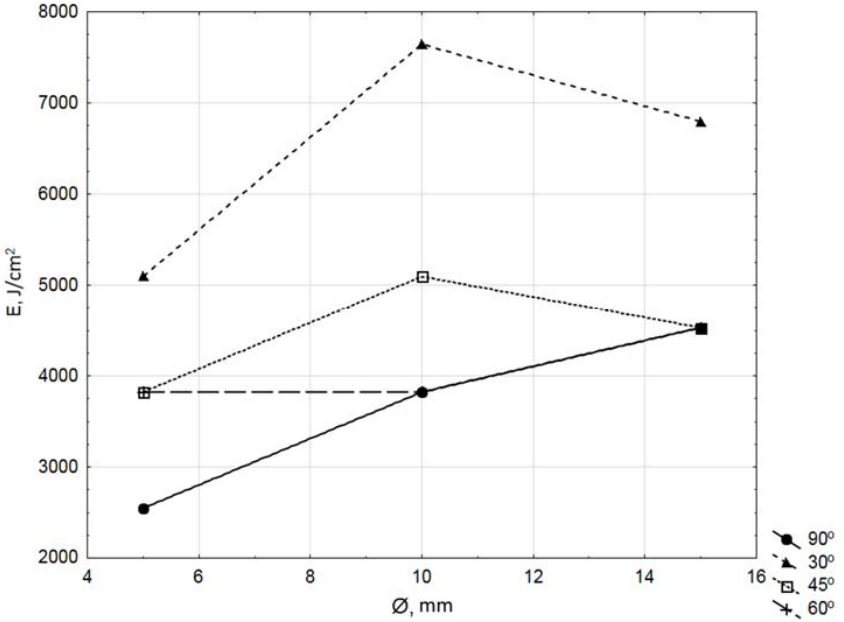


Figure 11. Graph comparing the reference lines of guaranteed FR-2 synthetic resin bonded paper penetration depending on the values of radiant exposure and laser beam diameter

operating mode that must have a sufficiently high power density (at least 5000-7000 W/cm^2). This allows the material to pierce the FR-2 samples in most of the conditions presented in the experiment.

7. Conclusions

As the use of UAVs in military conflicts increases, so does the demand for effective means of neutralizing them. Modern technologies, ranging from electronic warfare to kinetic and laser systems, demonstrate a wide range of approaches to solving this problem. Innovations in this area continue to evolve, contributing to improved security on the battlefield and protection against new threats.

Information about laser systems to combat UAVs is increasingly being disseminated in various sources, from scientific journals to the media.

This indicates a significant interest in this technology, which, although still facing some technical challenges, is already showing great promise for the future. As the energy and technical challenges are resolved, laser systems are expected to become an important element of air defense in the fight against emerging threats.

Despite its advantages, laser weapons have certain limitations. To function effectively, they require powerful energy sources, which can be a challenge in mobile environments. In addition, the effectiveness of lasers can be reduced by weather conditions such as rain, fog, or dust, which dissipate the beam's energy.

A methodology for determining the effect of laser radiation parameters on the destruction of materials used to make UAVs has been developed and tested on the Getinax. The developed methodology is a multi-stage process that requires in-depth research in the field of materials science, laser physics, and thermal processes. This technique can become the basis for creating effective laser air defense systems capable of quickly and accurately neutralizing drones on the battlefield.

However, in a number of conditions, such as piercing the material while it is moving, as well as piercing the material at a very sharp angle, the required power density increases to 10000-15000 W/cm^2. After analyzing the data obtained after a series of experiments, it can be concluded that to pierce a 2 mm thick FR-2 synthetic resin bonded paper, it is necessary to use a laser operating mode that must have a sufficiently high power density (at least 5000-7000 W/cm^2). This allows the material to pierce the FR-2 samples in most of the conditions presented in the experiment.

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References:

1. Gargalakos, M. (2024). The role of unmanned aerial vehicles in military communications: application scenarios, current trends, and beyond. *The Journal*

of Defense Modeling and Simulation, 21(3), 313–321. DOI: https://doi.org/10.1177/15485129211031668

2. Karpowicz, J. (2021). Warfare use of unmanned aerial vehicles. *Safety & Defense,* 2, 51–64. DOI: https://doi.org/10.37105/sd.135

3. Elmeseiry, N., Alshaer, N., & Ismail, T. (2021). A detailed survey and future directions of unmanned aerial vehicles (UAVs) with potential applications. *Aerospace,* 8(12), 363. DOI: https://doi.org/10.3390/aerospace8120363

4. Hadi, H. J., Cao, Y., Nisa, K. U., Jamil, A. M., & Ni, Q. (2023). A comprehensive survey on security, privacy issues and emerging defence technologies for UAVs. *Journal of Network and Computer Applications,* 213, 103607. DOI: https://doi.org/10.1016/j.jnca.2023.103607

5. Telli, K., Kraa, O., Himeur, Y., Ouamane, A., Boumehraz, M., Atalla, S., & Mansoor, W. (2023). A comprehensive review of recent research trends on unmanned aerial vehicles (UAVs). *Systems,* 11(8), 400. DOI: https://doi.org/10.3390/systems11080400

6. Mohsan, S. A. H., Othman, N. Q. H., Li, Y., Alsharif, M. H., & Khan, M. A. (2023). Unmanned aerial vehicles (UAVs): Practical aspects, applications, open challenges, security issues, and future trends. *Intelligent Service Robotics,* 16(1), 109–137. DOI: https://doi.org/10.1007/s11370-022-00452-4

7. Shaohui, X., Ji, F., Baohua, W., Fengge, W., Yong, H., Jiajia, M., & Ye, W. (2023). Development of a shooting strategy to neutralize UAV swarms based on multi-shot cooperation. *Journal of Physics: Conference Series,* 2460(1), 012035. DOI: https://doi.org/10.1088/1742-6596/2460/1/012035

8. Ajakwe, S., Kim, D. S., & Lee, J. M. (2023). Radicalization of airspace security: prospects and botheration of drone defense system technology. *The Journal of Intelligence, Conflict, and Warfare,* 6(1), 23–48. DOI: https://doi.org/10.21810/jicw.v6i1.5274

9. Kim, J., Choi, J., & Kwon, H. (2024). A study on the development directions of a smart counter-drone defense system based on the future technological environment. *KSII Transactions on Internet and Information Systems (TIIS),* 18(7), 1929–1952. DOI: https://doi.org/10.3837/tiis.2024.07.011

10. Karcz, K., Sitkiewicz, A., Błaszczyk, J., & Mierczyk, Z. (2023). New electromagnetic threat protection systems. *Problems of Mechatronics. Armament, Aviation, Safety Engineering,* 14(4), 59–82. DOI: http://dx.doi.org/10.5604/01.3001.0054.1648

11. Yang, C. X., Cui, D. H., Chen, Z. H., Xiao, Y. J., & Zheng, C. (2023). High-power microwave damage assessment method for UAV. *Journal of Physics: Conference Series,* 2478(8), 082011. DOI: https://doi.org/10.1088/1742-6596/2478/8/082011

12. Kanu, N. J., Gupta, E., Pendkar, S. M., Sakhare, S. A., Munot, A., Gupta, V. K., & Verma, G. C. (2024). A few suggestions to improve anti-drone measures for combating against the drone menace. *Journal of The Institution of Engineers (India): Series C,* 105, 761–787. DOI: https://doi.org/10.1007/s40032-024-01047-x

13. Taillandier, M., Peiffer, R., Darut, G., Verdy, C., Regnault, C., & Pommies, M. (2023). Duality safety/efficiency for laser directed energy weapon

applications. *High Power Lasers: Technology and Systems, Platforms, Effects VI,* 12739*,* 60–74. DOI: https://doi.org/10.1117/12.3001871

14. Henrichsen, M., Schwarz, B., Ritt, G., Azarian, A., & Eberle, B. (2021). Laser safety assessments supported by analyses of reflections from metallic targets irradiated by high-power laser light. *Applied optics,* 60(22), F71–F87. DOI: https://doi.org/10.1364/AO.424722

15. Schleijpen, R., Van Binsbergen, S., Geljon, M., Meuken, D., Deiana, D., & van Leeuwen, B. (2020). 30 kW laser experiments against drones. *Technologies for Optical Countermeasures XVII; and High-Power Lasers: Technology and Systems, Platforms, Effects IV,* 11539*,* 34–44. DOI: https://doi.org/10.1117/12.2574461