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THERMAL BARRIER CONCEPTS AGAINST CONTINUOUS LASER IRRADIATION

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Abstract

Rapid development in the high-power laser technology poses new requirements on the thermal protective materials. Military laser applications have been characterized and the examples have been presented. Existing materials, which may be used as a protection against high-energy laser beam, have been discussed. Several concepts of the new thermal barrier materials have been proposed. The proposals include multilayer structures, porous materials, systems with phase change materials (PCMs), and systems with various thermal contact resistance for different contact pairs. Comparative study based on numerical simulation results has been performed to assess efficiency of each proposal.

Three major candidate technologies were considered: the CO_2 laser, the HF/DF chemical laser, and the Nd-glass solid-state laser. The CO_2 combustion driven gas laser was built in mid-seventies. Its power was 500 kW with the poor beam quality. In the context of thermal protection against laser, high conductive material component in a complex structure might be especially useful, since irradiated surface is usually limited to a small size.

Keywords: *laser weapons, thermal barriers, multilayer structures, phase-change process, thermal contact resistance*

1. Introduction

An extensive research in the laser weapons field is being seen for decades now, however, in the last few years operational systems have been introduced in several armies across the globe. The potential for speed of light response provide a new level of adaptability and flexibility on the battlefield. Laser systems provide unique damage mechanisms, enhanced by multi-target engagement. Use of such a weapon allows selecting from a range of lethal through non-lethal effects [17].

Another advantage of the directed energy weapons is their low shot-to-shot operational cost. The cost of firing is of orders of magnitude lower than that of conventional ballistics [3].

The recent advancements in the military lasers technology pose new requirements on the protection systems. A very high concentration of the energy focused to a tiny spot, various wavelength of the radiation and the number of phenomena, which occur during laser-solid interaction, are only some of the reasons why design process of the modern thermal barrier against lasers radiation is a highly complex task.

In this article, selected concepts of the thermal barriers against laser beam are presented based on the research program [11]. A special attention is given to the physical processes associated with the energy transfer during electromagnetic wave and solid interaction.

2. Laser weapons

The potential of the laser was recognized soon after demonstration of the lasers in the early sixties of the twentieth centaur. A broad program of weapons-oriented laser research and development has been conducted by various federal agencies across the U.S. [15].

In 1984, a Strategic Defence Organization was set up in the United States. The organization was intended to develop an advanced missile defence system based on directed energy weapons (DEW) technology [4].

Three major candidate technologies were considered: the CO_2 laser, the HF/DF chemical laser, and the Nd-glass solid-state laser. The CO_2 combustion driven gas laser was built in mid-seventies. Its power was 500 kW with the poor beam quality. In 1984, a HF/DF chemical laser of megawatt class power output was realized.

In the 1970s, a special aviation complex was established at Taganrog to develop airborne laser technology for the Soviet military. The first test-bed aircraft was a Beriev A-60, a modified Il-76 transport plane that made its first flight in 1981 and was equipped as a flying laboratory in 1983. Another A-60 joined the program in 1991. Reportedly, the system employed carbon dioxide laser of 1 MW power. In 2009, the 1LK222 laser system was developed from the original A-60 program [16]. In the same year, a successful test of illuminating Japanese satellite AJISAI, which was at an orbital height of 1500 km, was conducted.

In the last decade, China disclosed details on the most recent space-based laser weapon program. The concepts, composition, applications, and key techniques of the laser development and aperture mirror have been presented by [8]. A successful satellite blinding experiment has been conducted in 2005. The blinding action was done using 50-100 kW laser gun mounted in Xinjiang province. The target was a low orbit satellite with a tilt distance of 600 km. The diameter of the telescope firing the laser beam was 0.6 m. The accuracy of acquisition, tracking and pointing was below 5 μrad [9].

In the second decade of the twenty first century, a broad range of laser weapons exists. Based on output power classification, the following groups can be distinguished: (i) blinding laser weapons, (ii) kilowatt-class lasers, (iii) megawatt-class high-energy lasers (so called DEWs).

Blinding laser weapons are designed to cause permanent blindness to unenhanced vision (the naked eye or the eye with corrective eyesight devices). These are low energy, battlefield, or tactical devices, which can be distinguished from directed energy weapons that use high-energy laser systems.

The use of these kind of weapons is prohibited under the 1995 Protocol on Blinding Laser Weapons [13]. However, there are applications (i.e. PHASR) which are not covered by the protocol and are currently being utilized as a regular weapon on the battlefield.

Kilowatt-class high-energy lasers lethality is limited to the target that can be neutralized by heating a small area on its surface. These kinds of targets are explosive devices, where the main charge or the detonator is easily ignited by heat, or control surface of aerial vehicles, often fragile and flammable. Optical sensors and cameras are also inherently sensitive to laser radiation [14]. Blinding of electronic equipment is both a regular warfare activity and subject of an extensive research [8, 16].

Area Defence Anti-Munition (ADAM) system is a ground-based laser weapon (10 kW fibreglass laser) developed by Lockheed Martin. It is designed to provide a defence against short-range threats, including rockets, unmanned aerial systems, and small boats [12].

High Energy Liquid Laser Area Defence System (HELLADS) program was initiated by the Pentagon's Defence Advanced Research Projects Agency. The project aims to develop 150 kW laser weapon system for integration onto tactical aircraft, such as the Avenger Unmanned Aerial Combat Vehicle from General Atomics. One of the requirements of the program is to create a high-energy laser system that weighs less than 5 kg/kW at a size of only 3 m^3. In 2015, HELLADS completed acceptance test and was shipped to undergo an extensive series of live fire tests against the number of military targets [10].

Examples of the megawatt-class high-energy laser weapons are anti-missile systems developed by China based on free electron laser (FEL) and chemical oxygen-iodine laser (COIL). FEL research started at the Chinese Academy of Engineering Physics in 1985, resulting in the activation of the SG-1 laser in 1993. The output power was equal to 300 MW [18]. The Dalian Institute of Chemistry and Physics started research on COIL in the 1980s and an early model was tested to a range of 140 km in 1993 [1].

3. Thermal barriers

Multi-layer thermal protection composes of multiple layers of often-thin sheets with various thermal properties. In the space technology, multi-layer insulation (MLI) is used to reduce heat loss by thermal radiation. The layers should not be in contact with each other to reduce as much as possible heat transfer thought conduction. Application where the contact is necessary should maintain high thermal contact resistance. A typical space insulation blanket has over 40 layers [7]. Internal layers are usually made of thin plastic coated on both sides with silver or aluminium. The outer layers are typically reinforced with fiberglass.

Thermal barrier coatings (TBC) are also utilized in a multi-layer thermal protection concept. Coatings are widely used in gas turbine and aero-engines technology. Their primary role is to insulate components from significant heat loads for a certain amount of time. The most common design of TCB consists of three layers: (i) the metal or alloy substrate (protected component), (ii) metallic bond coat, and (iii) ceramic topcoat. The topcoat needs to feature low conductivity and maintain phase stability at the operating temperatures. Typical TBC materials are Yttria-stabilized zirconia, La2Zr2O7, YSZ/Gd2Zr2O7 [2].

Insulation and screening functions can be implemented by controlling thermal contact resistance between adjusting layers. In the multi-layer systems, various values of the thermal conductance across the interfaces can enable redistribution of the heat in the system.

High conductivity materials are used in the complex structure thermal protection systems. An example can be a composite material featuring high conductive carbon fibres, which are intended to transport heat inside the system. Surrounding solid material features much lower heat conduction coefficient. This kind of solution is intended to help avoid sudden temperature increase on the front wall in case of exposure to high thermal load [5, 6]. Carbon fibres are capable of effective heat transport, while the surrounding material maintains its structural function.

Another way to enhance performance of the protective material is to utilize a phase-change material (PCM). These kinds of materials are widely used in heat storage applications. In the complex thermal management structures, phase-change materials enable to maintain temperature of a given area below certain threshold level by utilizing latent heat of fusion. Materials with the high latent heat of fusion, melting temperature in the desired operating range and small volume changes on phase transformation are good candidates for the multi-layered thermal protection systems.

In the context of thermal protection against laser, high conductive material component in a complex structure might be especially useful, since irradiated surface is usually limited to a small size. Therefore, it is necessary to redistribute heat across the system to avoid local heat build-up. Furthermore, a configuration featuring high conductivity material together with thermal barrier layer (or various thermal contact resistance across the system) enables to redirect heat and shield certain areas at the same time.

4. Numerical simulation

The numerical simulations of the various concepts of the thermal protective systems against laser irradiation have been carried out. Ansys Workbench and Fluent commercial codes have been employed during the investigation.

A baseline system configuration has been set up in order to perform a comparative study. Two-dimensional outline, boundary condition and the transient simulation results can be seen in Fig. 1. The details of the boundary condition and the simulation parameters can be seen in Tab. 1.

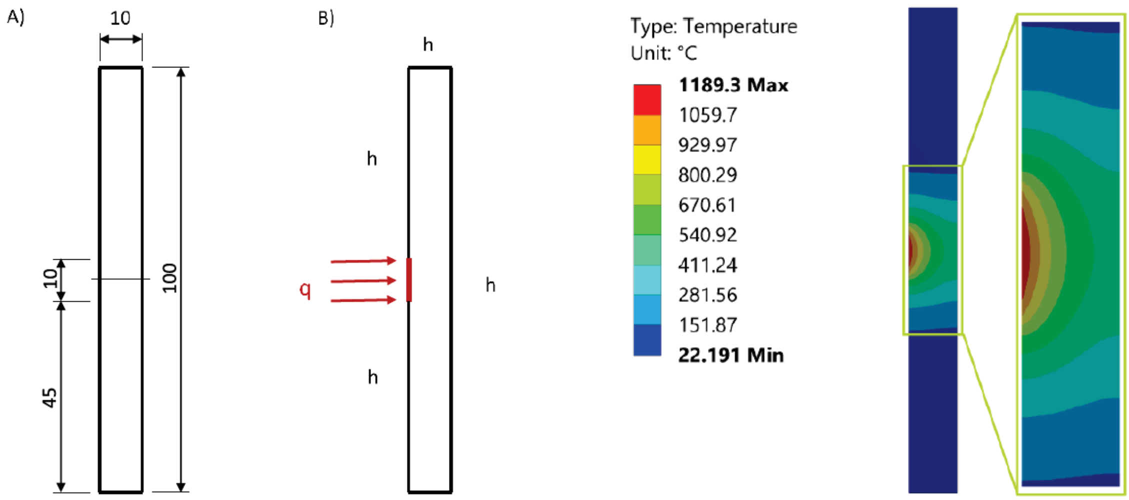

Fig. 1. Baseline configuration. The geometrical outline, the boundary condition and the transient simulation results after t = 5s

Tab. 1. Numerical simulation parameters

Parameter	Value	Unit
Heat flux, *q*	$1\cdot10^7$	W/m^2
Heat transfer coefficient, *h*	20	$W/m^2\cdot K$
Duration time, *t*	>5	s
Time step, *dt*	0.01	s
Ambient temperature, *T*	22	ºC

The analysis has been performed to investigate the evolution of the temperature distribution in the irradiated system. The baseline configuration material is the structural steel. After 5 seconds the right wall temperature equals to 500ºC and it is set up as the limit, above which the inner structure of the protected system is considered to be damaged.

In the same time, the left face of the system reaches temperature close to 1200ºC, which is set up as the second limit for further analyses.

In order to enhance thermal performance of the base configuration, multilayer structure materials have been proposed. Each proposal bases on the concept of redirecting heat in the system from the critical area of the irradiated spot.

Since laser delivers energy as a focused beam, protection structure needs to redistribute heat in a way to be able to maintain its shielding function as long as possible. This means redirecting absorbed energy in a direction transverse to the incident radiation.

The first protection concept with the middle plate assumes a high conductivity metal insertion, which enhances distribution of heat in the vertical (top and bottom) direction. Three material choices are being investigated: graphite, copper, and synthetic diamond. For each material, three geometrical configurations have been taken into account, as seen in Fig. 2.

Throughout the numerical calculations, the number of elements of the grid for the middle plate arrangement was selected to be 4000, which corresponds to 13,243 nodes.

From all the three materials, the longest operational time before reaching the threshold temperatures was obtained for the synthetic diamond configuration.

In Fig. 3, we can see the chart summarizing the synthetic diamond configuration temperature evolution on the both control surfaces. The 2 mm high conductivity middle plate configuration reaches the right wall limit as the first one at 12.14 seconds, with the left wall below its limit. Configurations with 3 mm and 4 mm high conductivity middle plates reach the right wall limit at 12.34 and 12.14 seconds, respectively. As in the case of 2 mm configuration, the left wall temperatures are still below the limit. While comparing to the baseline geometry, configurations 2 mm, 3 mm and 4 mm show an increase of the time-to-limit parameter by 143%, 147% and 143%, respectively.

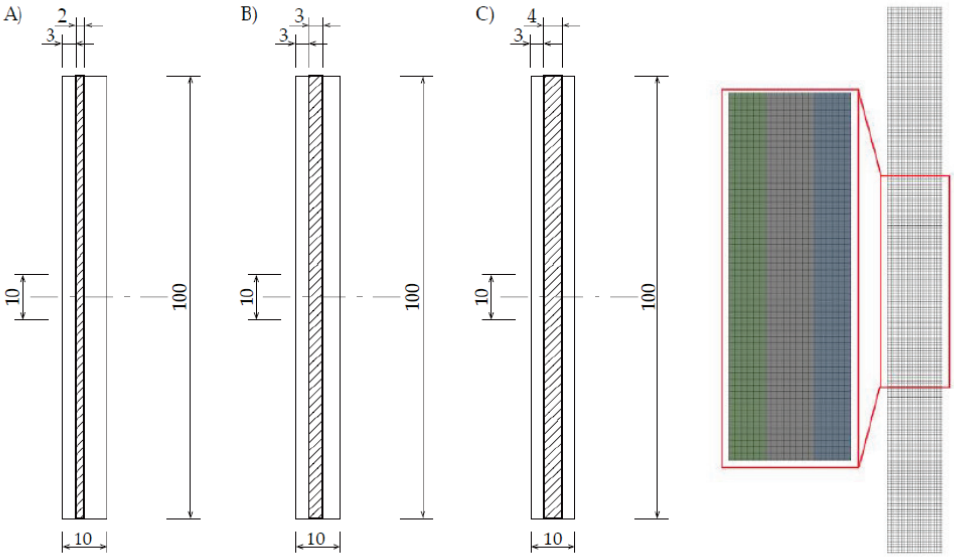

Fig. 2. Geometrical configurations and example of the mesh of the high conductivity middle plate concept

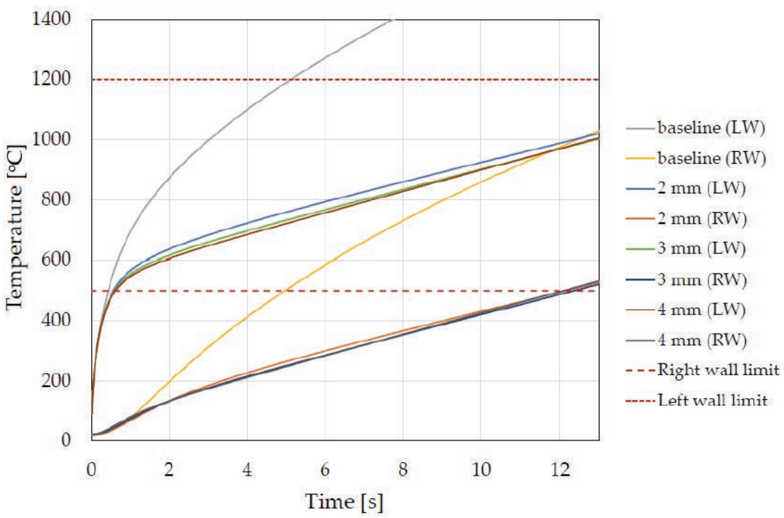

Fig. 3. Synthetic diamond middle plate – control surface temperature evolution

In Fig. 4, temperature maps of each geometrical case are shown in the time point when the right wall reaches 500ºC limit. Compared to the baseline, all the configurations show improved heat distribution in the vertical direction.

A similar concept with the additional layer of the thermal barrier coating placed on the right side of the high conductivity middle plate has been investigated. The aim of this concept is to enhance the screening function for the back wall and at the same time maintain the redistributing function by utilizing the high conductivity middle plate.

For this concept, the synthetic diamond case turned out to be the most effective one. Fig. 5 illustrates the temperature evolution of the investigated geometrical configurations.

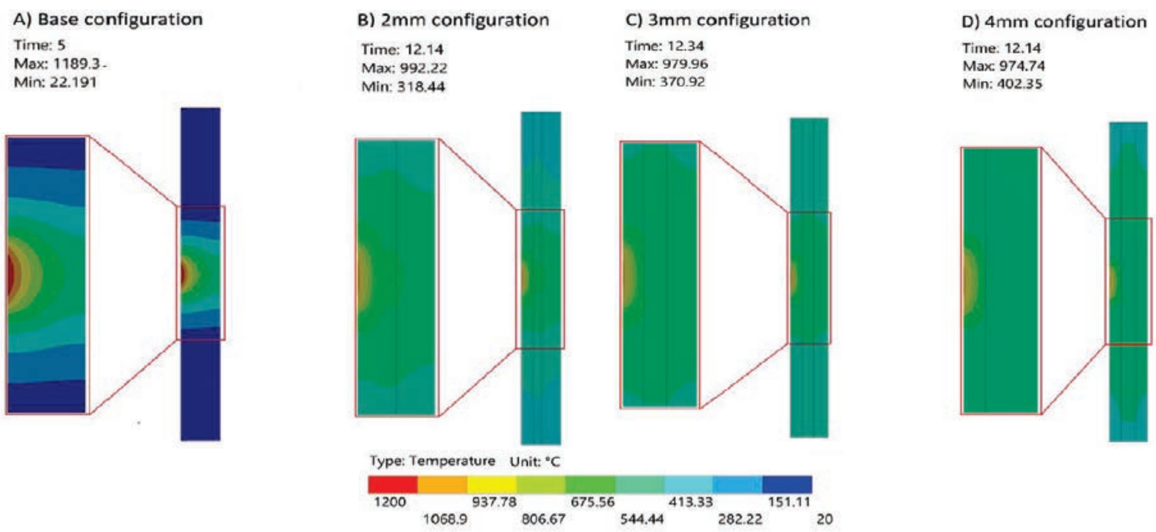

Fig. 4. Synthetic diamond middle plate – temperature plots at the limiting temperature time point

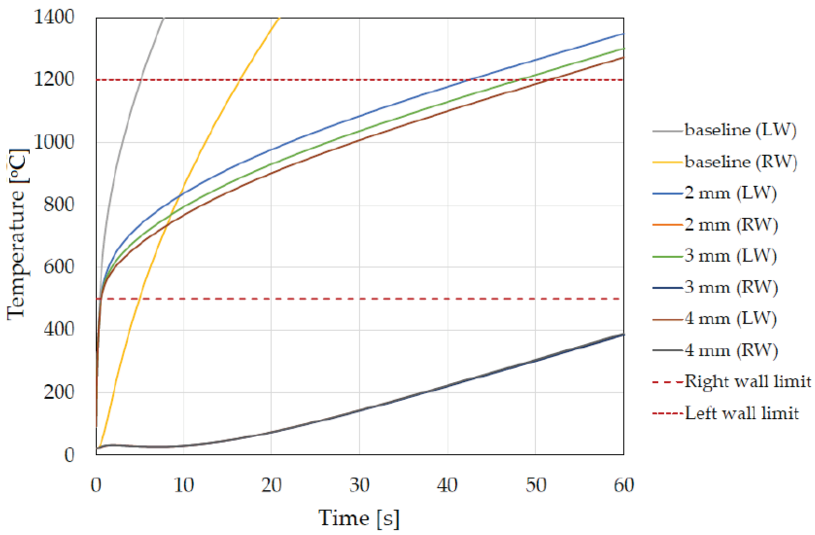

Fig. 5. Synthetic diamond middle plate with TBC – control surface temperature evolution

In case of the concepts featuring PCM, in addition to multilayer structure, a porous material configuration has been investigated. Three geometrical variants were considered. It was assumed that pores are filled with the aluminium material that is supposed to undergo a phase change.

It can be seen from Fig. 6, that at the time when all the systems reach right wall limit, the left wall in PCM configurations shows a lower temperature level than the baseline. It is the opposite for the right wall. All investigated systems with pores show worse performance in terms of the right wall temperature than the base configurations.

The final concept features two different values for thermal contact resistance pairs. The first contact pair value, which is closer to the irradiated wall, assumes good contact and low resistance (50,000 W/m^{2}K). The second contact pair (the one closer to the back wall) simulates worse contact condition (2,000 W/m^{2}K). By introducing such a configuration, heat can propagate better through the first interface, entering high conductivity material. At the same time, the second interface is screening the back wall of the system. The screening effect can be seen in Fig. 7.

All the diamond configurations show improvement in terms of time-to-limit parameter with regard to the baseline arrangements. The highest improvement is for the (thickest) 3 mm middle layer set up and it is equal to 9.34 s, which is over 86% difference relative to plain configuration with no middle plate.

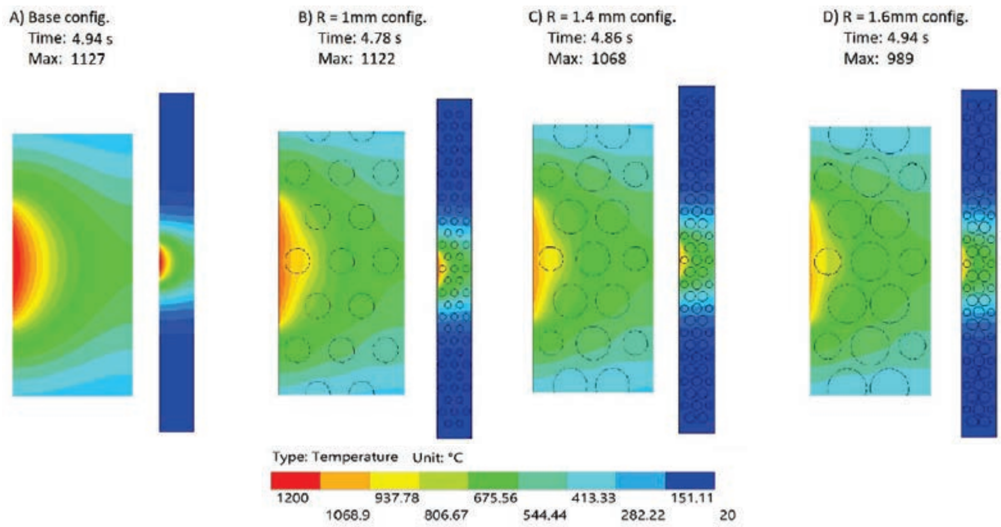

Fig. 6. Temperature distribution in the porous material (circular cross-section channels)

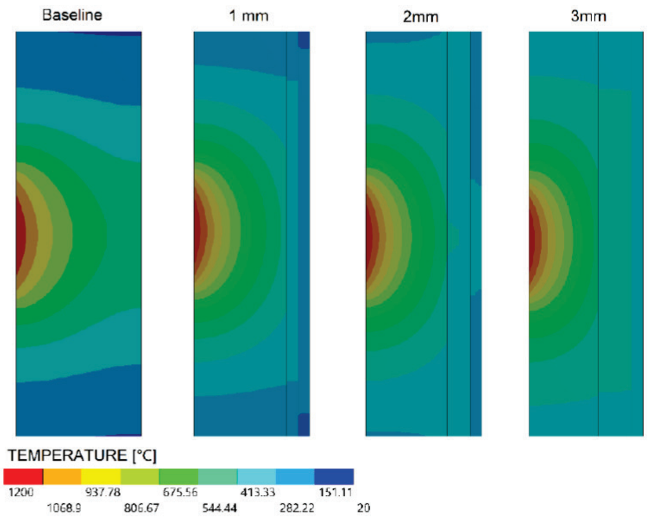

Fig. 7. Synthetic diamond intermediate plate – thermal contact resistance. Temperature plots shown for the time step at which particular configuration reaches back wall or front wall temperature limit

5. Conclusions

A comparative analysis of various concepts of the hardware protection against continuous work laser has been carried out. In order to enhance thermal performance of the base configuration, complex structure materials have been proposed. Performance of the proposed protective configurations and associated physical processes have been quantified and assessed.

Each proposal presented bases primarily on the concept of redirecting heat in the irradiated system from critical areas in the direction transverse to the incident radiation.

Throughout the numerical simulations, it was demonstrated that it is possible to enhance protective capabilities of materials by using suitable geometrical arrangements and by employing certain physical processes. It was shown that the combination of multi-layer structures, phase-change materials and thermal contact resistance might significantly increase operational time of the particular system under an extreme thermal load before it will reach the limiting temperature.

Laser-matter interaction and associated heat transfer process are very complex phenomena. Both are still subjects of extensive research efforts. Prediction of the temperature field in the irradiated solid requires not only a comprehensive heat transfer model, but also reliable material properties.

It is also crucial to point out that all the considerations on the particular protective system should be done in the context of the laser wavelength, which determines the absorption mechanism and its rate. If one knows the wavelength of the radiation source, then the set-up of the dedicated material configuration and associated physical processes can be chosen accordingly.

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