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A1_3 I believe in MIRACLs, where're you from?

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Abstract

The Mid-Infrared Advanced Chemical Laser (MIRACL) antimissile system is currently being developed by the US Army. Its aim is to destroy incoming missiles with lasers. This paper determines that there is a maximum of 10 minutes preparation time (assuming the missile is fired from at least 10 minutes flight time away), and it would take a 1 MW laser about 0.82 seconds to destroy a typical missile made of aluminium. It does not however cover the practical difficulties involved with implementing such a system.

Introduction

The Mid-Infrared Advanced Chemical Laser (MIRACL) is an experimental laser system under development to shoot down incoming projectiles such as missiles. The US Army is currently having several technical issues with the system [1]. The current lasers being tested use a deuterium fluoride chemical laser with a wavelength of 3.8 µm. Due to the design of the laser, the resulting beam is square in shape with sides of 14 cm. Press releases indicate that it operates at a power of several megawatts [2]. This report will determine whether a 1 MW laser provides enough energy to destroy a typical missile, such as the AGM-114 Hellfire, and if there is time to do so.

Discussion

First we need to determine approximately how much time a laser would need to destroy a missile. To do this the following assumptions are made: the missile casing is made of aluminium [3]; the laser system is capable of locking onto a missile and tracking it; and if the laser delivers enough energy to melt the aluminium casing it will destroy the missile. The laser must provide enough energy to heat aluminium to its melting point and then overcome its latent heat of fusion. The total energy needed is [4],

$$\Delta E = mC\,\Delta T + mH_{\mathrm{f}}, \qquad (1)$$

where m is the mass of aluminium being heated, $C = 960\,\mathrm{J\,kg^{-1}\,K^{-1}}$ is the specific heat capacity of aluminium, $\Delta T = 615\,\mathrm{K}$ is the change in temperature (assuming an ambient temperature of $20\,°\mathrm{C}$) [5], and $H_{\mathrm{f}} = 3.98 \times 10^5\,\mathrm{J\,kg^{-1}}$ is the latent heat of fusion of aluminium [6]. The mass of aluminium m is calculated by considering the area A of the missile the laser will hit. The total mass of the material needed to be heated is equal to $A\tau\rho$, where τ is the thickness of the missile casing and $\rho = 2{,}810\,\mathrm{kg\,m^{-3}}$ is the density of aluminium [5]. An exact value for τ is not available, but we assume it to be around 15 mm. The laser has a square beam, with an area of projection of $A = 0.0196\,\mathrm{m^2}$ [2]. These values of τ and A yield $m = 826\,\mathrm{g}$ and putting this into Equation 1 gives a total required energy of $\Delta E = 816\,\mathrm{kJ}$.

Next, we determine how long it would take to deliver this energy to the missile casing. There is an energy loss rate Q due to conduction through the sides of the missile, which we can model as a cylinder. We start with the equation of heat flow through a material [7],

$$Q = -kS\frac{\mathrm{d}T}{\mathrm{d}r}, \qquad (2)$$

where $k = 155\ \mathrm{W\,m^{-1}\,K^{-1}}$ is the coefficient of thermal conductivity for aluminium [5], S is the area of heat flow and $\mathrm{d}T/\mathrm{d}r$ is the temperature gradient. This situation is assumed to be similar to that of heat flow through a cylinder. Then Equation 2 can be rewritten as [8]

$$Q = -2\pi k \tau \frac{\Delta T}{\ln(r_c/R)}, \qquad (3)$$

where $r_c = A^{1/2}/2 = 0.07\ \mathrm{m}$ is the effective radius of the laser, and $R = 0.28\ \mathrm{m}$ is the "radius" of the surface, here approximated to be half the length of the missile [3] (we assume that the laser hits the dead centre of the missile). By approximating the missile surface in 2D, we obtain a maximum value for Q, as heat would also dissipate through the real 3D surface via an additional direction. Thus $Q_{\max} = 6{,}481\ \mathrm{W}$, a factor roughly 120 times smaller than the laser power $P =$ 1 MW. This allows us to assume a negligible heat loss due to conduction.

The time required for the laser to melt the casing is $t = \Delta E/P = 0.82\ \mathrm{s}$.

The plausibility of MIRACL is dependent on how long the laser would be able to fire on a target. For the purposes of this report we consider the tracking speed of the laser to be very fast – if the target is in range, it can be hit. This means that the only limit to the laser's range is the attenuation that will occur as the beam travels through the air. To determine this we can use the Beer-Lambert law [9],

$$I = I_0 \exp(-\alpha x), \qquad (4)$$

where I_0 is the intensity of the beam at the source, I is the intensity of the beam at a range x, and α is the attenuation coefficient.

In order to find out how much the laser beam is attenuated by scattering due to air particles, we consider solar radiation of a similar wavelength travelling through the densest section of the atmosphere (the bottom 14 km). About 80% of this radiation at a wavelength of 3.8 µm reaches the Earth's surface, so $\alpha \cong 16\ \mathrm{\mu m^{-1}}$ [10]. When the laser's power is reduced by a factor of 50, we can no longer assume that the energy reaching the target is much higher than the energy being conducted away. For this reason, it has been decided to find x for $I_0/I = 50$, using Equation 4. This gives $x = 245\ \mathrm{km}$. Given a maximum missile speed of $425\ \mathrm{m\,s^{-1}}$ [11], the laser would have about ten minutes to shoot it down. In reality however there would be less time as the missile could be fired from a closer range.

Conclusion

This report does suggest that a laser could shoot down an AGM-114 Hellfire missile. However, this does not mean that the system is practical. In reality the missile is cylindrical spreading the laser beam over a greater surface area than is assumed in this paper increasing the time to destroy the missile.

References

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