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# A4_1 Archimedes Death Ray

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**Abstract**

This paper investigates the physics behind Archimedes' 'Death Ray', which used the shields of defending soldiers to focus sunlight onto approaching ships, causing them to burst into flames. By examining the thermal properties of wood we determine that $\approx 230\text{m}^2$ of shields could provide enough solar radiation to ignite the ships. We examine the relative position of the boat and the shields, determining the required elevation of the sun to be $\approx 34^o$.

### Introduction

Greek mathematician Archimedes is credited with the invention of various war machines, built for defense against the Romans. One such weapon was a "heat ray". According to legend, Archimedes aligned the shields of Syracuse soldiers such that they each acted as a parabolic reflector, focusing sunlight onto approaching ships, causing them to burst into flames. Here we examine the plausibility of this weapon. We use autoignition theory to calculate the heat flux required to burn a ship, and consider the geometry involved.

### Thermodynamics

We will take our target to be a typical Roman ship from 200BC, made from wood (typically oak), with linen sails. By considering the cooling effect of the sails from the wind, and their higher reflectance, we determined the wooden hull of the ship to be more likely to ignite. The autoignition temperature of wood is between $300-400^o$C [1]. We will use the upper value of $400^o$C, noting that some of the heat will be lost via convection with the ocean winds. The autoignition equation [2] indicates the amount of time required for an object to reach its autoignition temperature when exposed to a given heat flux, and we can rearrange this to give Eq. (1)

$$Q = (T_i - T_o)\left[\frac{4t_i}{\pi k \rho c}\right]^{-\frac{1}{2}} \tag{1}$$

where $Q$ indicates the heat flux required to ignite an object with ignition temperature $T_i$ in time $t_i$, given a material with thermal conductivity $k$, density $\rho$, and specific heat capacity $c$. For an oak ship, with a thermal conductivity of 0.17 $\text{Wm}^{-1}\text{K}^{-1}$ [3], density of $850\text{kgm}^{-3}$ [4], and specific heat capacity of $2400\text{Jkg}^{-1}\text{K}^{-1}$[5], we calculate that the minimum heat flux required for the wood to go from $0^o$C to $400^o$C and alight within 10 seconds is around $66\text{kWm}^{-2}$.

This is the energy required to burn the wood, however not the total incident energy required. We must account for some incident heat flux being reflected back as radiation. Using the albedo of the wood (0.15) [6], we calculate the incident heat flux required to be $\approx 80\text{kWm}^{-2}$. Assuming this heat flux is concentrated over one square meter on the boat, we determine that the total power required to ignite the ship is around 80kW. The shields of the defending soldiers were likely covered in a thin sheet of bronze [7]. The reflectance of this alloy varies with the wavelength of the incident radiation, but we can use an average reflectance of 0.7 [8]. This means that for the weapon to burn the boat, we need the total power incident to the shield array to be $\approx$ 114kW. Assuming average solar irradiance of 1000W$m^2$, this means we need a reflecting surface area of 114$m^2$. This equates to 200-250 shields, each with an area of 0.5$m^2$ (i.e. a radius of $\approx 0.4$m). This is logistically plausible.

### Geometry

We can now consider the geometry of the situation. Soldiers defended Syracuse from siege from a height of 40m above sea-level. According to legend, the incoming boats were within bow-shot, indicating they were around 60m away from the shoreline [9].

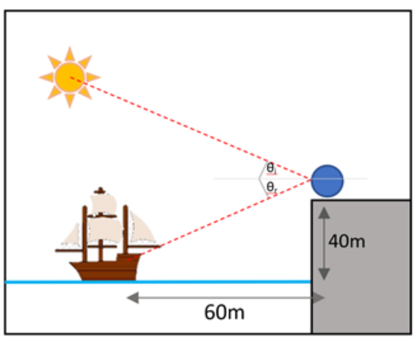


Figure 1: Diagram showing relative positions position of Archimedes' death ray, the sun, and the incoming ship

Using trigonometry, we find that the angle of reflection must be $33.7^o$. Given the equation

$$\theta_i = \theta_r \quad (2)$$

where $\theta_i$ and $\theta_r$ are the angles of incidence and reflection, the sun must be $\approx 34^o$ elevation in relation to the defending soldiers. For a focal length of 60m we use Eq. (3),

$$f = \frac{2}{R} \quad (3)$$

where $f$ indicates the focal length and $R$ is the radius curvature of the reflecting surface. The radius of curvature for each of the shields must be 120m. Again, this is entirely plausible.

### Conclusion

Using our understanding of the properties of wood and solar radiation, we have determined that it is plausible that an array of shields could be used to focus sunlight onto a ship, causing it to ignite. The total power needed to ignite a typical Roman ship is 80kW, and a sufficient number of shields in the right position, could reflect and focus this power from the sun. This is not to say that the legends are true, and there are certainly practical issues (i.e. aiming 250 shields in unison), however it is not impossible when considering the basic physics principles involved.

### References


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