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Group 54

Can You Survive a Nuclear Explosion By Hiding in a Fridge?

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Abstract

The effectiveness of using a lead-lined 1950s fridge as a nuclear bomb shelter in the year 1957 was investigated via Monte-Carlo simulation of the radiation produced and numerical modelling of the internal temperature distribution of the fridge. By analysing the transport of gamma radiation through various media, it was found that to have a survival rate of greater than 50% following exposure to the gamma-ray dose, the fridge must be 4.23 kilometers away from the epicentre of the average Nuclear bomb used in 1957. It was also found that a human in a fridge would have to be 1.90 kilometers away for the duration of a 40 second explosion not to suffer likely-lethal burns.

Introduction

The question of whether a 1950s-era lead-lined fridge could serve as a makeshift nuclear bomb shelter has troubled academics and pop-culture fans alike since Indiana Jones successfully exploited the concept in the 2008 film, "The Kingdom of the Crystal Skull". It is a cross-section at which scientific curiosity meets the seemingly absurd. This research explores the unorthodox survival strategy through the use of historical data and contemporary computational techniques to assess its feasibility. The iconic Plumbbob nuclear test, conducted by the USA in 1957, offers the historical context for this study. The average yield from these tests was 11.8 kilotons (kT) [1]*, and we were able to use this to construct a scenario that, whilst rooted in past events, offers insights into the problems of radiation shielding and thermal dynamics at the most extreme ends of the spectrum. *(one kT represents the explosive energy of 1000 tons of TNT, equal to 4.184 TJ).

Using Monte-Carlo simulations, we modelled the stochastic paths of gamma rays (the lethal penetrating component of nuclear detonation fallout). We then evaluated the attenuation of radiation as it interacts with various media between the epicentre and the lead-lined fridge. Additionally, we used numerical methods to solve the heat equation in 2D, analysing the temperature gradients that would arise within the confines of the fridge. This method enabled us to consider distant-dependent variables and the material properties of the refrigerator, to provide an understanding of the thresholds for both the radiation and thermal exposure that mark the line between life and death.

Theory

The intensity of a gamma-ray beam propagating through a medium follows the Beer-Lambert formula,

$$I(x) = I_0 e^{-\mu(\varepsilon)x}, \quad (1)$$

where $I(x)$ is the intensity of the beam at distance x, I_0 is the initial intensity and $\mu(\varepsilon)$ is the attenuation coefficient which is a function of gamma ray energy. The $\mu(\varepsilon)$ values are found by fitting a curve of the form $a\varepsilon^b + c$ to accepted data, as seen in Figure 1.[2] In the case of a cubic lead a different fitting function was used, due to pair production in lead at these of the form $a\varepsilon^3 + b\varepsilon^2 + c\varepsilon + d$ was used alongside the power law, to account for the effect of pair production to the linear attenuation coefficient of lead .

A dose of radiation is measured in Grays, which is equivalent to the energy absorbed per kg of tissue which absorbs it. This can be converted into an equivalent dose, measured in Sieverts, by the multiplication of the radiation weighting factor which, in the case of a gamma ray source incident on the whole body, is equal to 1.

By modelling the surface of the human as an area of water, the 2D heat equation was used to model the temperature distribution within the fridge,

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right), \quad (2)$$

where α is the thermal diffusivity of the material. The equation shows the rate of change of temperature with respect to time in terms of the spatial coordinates.

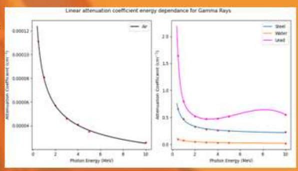

Figure 1. Fit of the energy dependency of the linear attenuation coefficient of gamma rays for various materials.

Computational Methodology | Theory Extended

Photons and associated energies are generated using a Monte-Carlo simulation such that the energy distribution of the photons matches that of gamma rays produced by a nuclear bomb. The passage of these photons through air, lead, steel and human is then simulated using equation (1), where number of photons is used instead of beam intensity. Photon energy distribution and total initial photon yield are calculated from the proportion of fission energy associated with instantaneous gamma ray energy (3.5%), and the known photon energy distribution from a 20kt blast[2]. A photon energy distribution dataset of 1000 bins is generated between 0 and 12MeV proportional to that in [2]. The photon distribution is then attenuated (see Theory) and reduced to the fraction within the solid area of the fridge, to account for distance effects. The energy absorbed by the human is calculated by summing over the product of the absorbed photons and their associated energy distribution.

In order to model the temperature distribution inside the fridge, numerical methods were utilised to solve the heat equation. The spatial derivative by x and y were modelled numerically using the central difference method as $\frac{T_{i+1,j}-2T_{i,j}+T_{i-1,j}}{(\Delta x)^2}$ and $\frac{T_{i,j+1}-2T_{i,j}+T_{i,j-1}}{(\Delta y)^2}$ respectively. Temporally, the heat equation was numerically modelled using the Runge-Kutta 4th order (RK4) method,

$$T_{n+1} = T_n + \frac{\Delta t}{6}(k_1 + 2k_2 + 2k_3 + k_4). \quad (3)$$

These methods, being approximate, therefore introduce error with each step. The uncertainty introduced is of the second and fourth order for the central difference and Runge-Kutta methods respectively. A grid of 3600 spatial points was used, and the simulation ran with a time step of 0.01 seconds. These increments represent a balanced decision between precision and computational efficiency.[6]

Results

1. Radiation Simulation

The data from the radiation simulation is visualised in the Yield-Distance plane as shown in Figure 2. To have more than a 50% probability of surviving the average bomb yield of operation Plumbbob (11.8kT), the fridge would need to be 4.23km away from the epicentre of the explosion. This is shown in Figure 3 which also shows thresholds for other probable side effects.

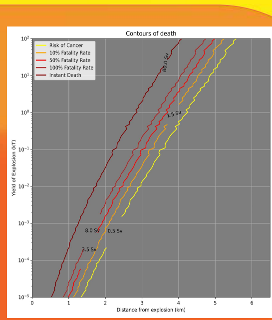

Figure 2. Contours of constant survival probabilities in the distance from epicenter – bomb yield plane.

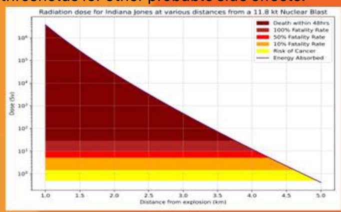

Figure 3. Dose of radiation against distance from epicenter, with survival probability

2. Temperature Simulation

Various distances from the explosion were investigated by considering the temperature of the inner layer of the fridge. This was determined by calculating the thermal energy absorbed using the same methodology as the radiation simulation in Figure 4. The fridge wall temperatures at various distances were used in the temperature distribution simulation to determine the time required under such conditions to experience a likely-lethal burn. A minimum distance of 1.9 kilometers from the epicentre of the explosion was found to likely prevent a fatal third-degree burn in a 40-second blast scenario as seen in the 2008 film.

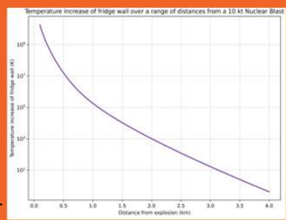

Figure 4. Temperature of fridge wall interior against distance from epicentre.

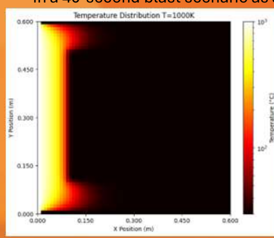

Figure 5. Temperature simulation distribution at time of lethal burn for 1000 Kelvin.

Temperature (K)	Time (s)
1000	269.7
50000	50.35
100000	43.43
120000	41.92
150000	40.21
160000	39.74

Figure 6. Fridge wall simulation temperatures and the times required to achieve a lethal burn.

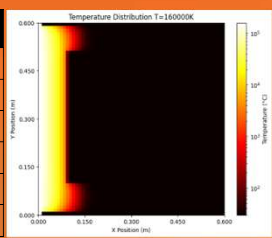

Figure 7. Temperature simulation distribution at time of lethal burn for 160000 Kelvin.

QR code: Temperature distribution from 0 to 35 seconds for T=160000K.

Discussion

The main result of the radiation simulation is that to survive an 11.8kT explosion you would need to be 4.23km away from the blast. The distance in the absence of a fridge is 5.42km and hence the fridge does have a significant effect on survivability. A limitation of this simulation is that the time of simulation ~ N(data points)^2, which constricts the simulation as fewer data points are used. This results in some residual randomness being visible in the final graph. The temperature model, leveraging the Finite Difference Method (FDM), encounters limitations due to the non-linear response of materials at high temperatures – characterised by material properties such as conductivity and specific heats. Additionally, the FDM is susceptible to discretization errors, especially at sharp interfaces and steep gradients, where it may not capture the precise temperature profiles induced by the extreme heat. An investigation into the effects of FDM discretization by means of convergence analysis would be a useful extension to this project and would help in generating more accurate and stable simulation results.

Assumptions

- The Fridge is assumed to be bolted down and facing the blast.
- Fridge having dimensions of 84.14 x 88.27 x 173.99 cm, consistent with fridges in the 1950s [4].
- The human inside the fridge is assumed to be a cuboid of water, with height, width and depth consistent with a male in the 95th percentile of size [3].
- Gamma Rays are produced with energy distribution consistent with a 20kT nuclear blast [2].
- A likely fatal third-degree burn is used as a determining factor for survivability in the temperature simulation. It is defined by a period of 10 seconds where the outer layer of 'human' (skin) is kept at a minimum of 55° C [5].

Conclusion

In sum, a nuclear blast **IS** survivable in this fridge, provided the fridge is 4.23km away from the blast . To survive the temperature effect of the blast, the fridge needs to be a mere 2km away – unsurprisingly the radiation exposure from a nuclear weapon is the principal concern. Order of magnitude calculations were used to support the theory going into the simulation section of the project where two aspects were considered, radiation effects and temperature effects. Furthering the scope of this project could include simulating the pressure wave caused in the explosion and its impact on the fridge, which would cause the fridge occupant to experience a presumably fatal impulse.

References

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