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SIMULATIONS OF THE EFFECTS OF NUCLEAR DETONATIONS USING A PYTHON-BASED PROGRAM DESIGNED

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Abstract: This project introduces an innovative Python program that leverages mathematical models and advanced programming techniques in order to meticulously replicate a wide range of nuclear effects, from thermal radiation to local fallout. This approach not only allows a detailed assessment of potential hazards but also facilitates proper emergency planning. The program, which is based on scientific principles and supported by an efficient Python implementation, is an essential tool with which to analyze and address the impacts of nuclear explosions, thus demonstrating its critical importance in both academic and practical domains.
Keywords: Nuclear explosion, evaluation of impacts, public safety, programming techniques, anti-disaster response

INTRODUCTION

Security and preparedness for risk situations have become fundamental in the world. The need to understand and analyze the effects of nuclear explosions takes on unprecedented relevance. In a global context marked by geopolitical tensions and unexpected challenges, the ability to anticipate and mitigate the impacts of such events has become an unavoidable priority (*Nakamitsu, 2023*). The uncertainty surrounding these conflicts and their potential reach transcends borders, generating palpable concerns in civil society.

Nuclear explosions represent one of the most complex and potentially devastating events that can occur in the present-day world. It is, therefore, imperative to have accurate and effective analysis tools with which to comprehensively understand and address the consequences of these detonations. This paper focuses on introducing an innovative program based on the Python programming language, which has been designed to provide a detailed replication of the most significant effects resulting from nuclear explosions, including the Fireball, Thermal Radiation, Initial Radiation, Overpressure and Local Fallout. For each effects, each subprogram have been programed.

The quest for rapid and accurate simulations that comprehensively capture the effects resulting from nuclear detonations has made it imperative to employ meticulously designed mathematical models. The detonation of a nuclear device triggers a cascade of complex phenomena, each of which demands thorough characterization in order to understand its impact and evolution.

In this context, the implementation of consolidated mathematical models is a solid foundation upon which the analysis program is built. These models not only serve as abstract representations of the physical processes involved but also play a crucial role in generating detailed and reliable simulations. By addressing each significant effect individually, these models capture the essence of the phenomena, providing a precise foundation for simulations. This modeling approach has proven to be an invaluable resource, shaping a computational tool that adapts to the complexity of reality and consequently providing a platform on which to explore and understand the diverse impacts of nuclear explosions.

The foundations of the approach related to this program are rigorous mathematical models based on established and validated scientific principles inthe subprograms comprising this tool addresses a specific aspect of nuclear effects, providing a comprehensive set of calculations and analyses. Python was employed as a programming language because it offers a versatile and accessible platform on which to conduct these calculations, allowing efficient implementation and easy interaction with the results.

Each subprogram is presented in a format that allows the visualization of results, from Excel spreadsheets to interactive maps, thus facilitating the understanding of nuclear effects and their potential impact. Furthermore, the combination of an object-oriented methodology and a modular structure ensures that the program is scalable and easily adaptable to future research and developments in the field of radiological and nuclear security.

The Python-based program regarding the effects of nuclear detonations presented in this paper is an essential tool for the detailed analysis of nuclear effects and informed decision-making in critical situations. This program makes use of robust mathematical models and an object-oriented implementation, thus making a significant contribution to increasing the understanding and management of the consequences of nuclear explosions in present-day security and science.

FUNDAMENTS

The most significant effects resulting from nuclear explosions are the followings: Fireball, Overpressure, Thermal Radiation, Initial Radiation, and Local Fallout. So, in this section, the fundaments of them are explained in detail.

FIREBALL

The disintegration of uranium or plutonium atoms, along with the fusion of hydrogen isotopes in a nuclear weapon, results in an immense release of energy in an extremely brief period and within a limited volume of matter. This causes the fission products, the bomb casing, and other parts of the weapon to reach extremely high temperatures, comparable to those found at the core of the sun. The residues from fission bombs can reach maximum temperatures of several million degrees, in contrast to the maximum of 5000 °C of conventional high-power explosive weapons (*Brickwedde, 1955*).

In less than a millionth of a second after the detonation of the weapon, the extremely hot residues radiate a considerable amount of energy, mainly in the form of invisible X-rays, which are absorbed by the surrounding atmosphere within a few meters (*Brode, 1968*). This gives rise to the formation of an extremely hot and highly luminous (incandescent) sphere composed of air and gaseous residues from the weapon, denominated as the Fireball.

In the initial moments after a nuclear detonation in the atmosphere, the rapidly expanding fireball and the shockwave of the explosion are a single entity (*Glasstone et al., 1977a*). In reality, the surface of the expanding fireball constitutes the front of the shockwave.

Once the temperature of the fireball has decreased, the shockwave front and the fireball separate in a phenomenon known as "breakaway" (*Glasstone et al., 1977a*). From that moment on, the shockwave front quickly becomes invisible, as it loses intensity and can no longer heat the air through compression, thus preventing the air from becoming incandescent.

In the program described herein, these phenomena are determined using a mathematical model developed by ((*Glasstone et al., 1977a*), which makes it possible to define the Fireball (equations 1, 2 and 3).

$$R\,(thermal\ minimum) \approx 90 W^{0.4} \quad (1)$$

$$R\,(breakaway)\ aerial\ detonation \approx 110\ W^{0.4} \quad (2)$$

$$R\,(breakaway)\ surface\ detonation \approx 145\ W^{0.4} \quad (3)$$

where R is the radius of the fireball in ft, and W is the energy released by the bomb in kt.

OVERPRESSURE

After a nuclear explosion, immediately, (within milliseconds), a powerful high-pressure wave is generated that propagates from the center of the explosion. This phenomena is called as the shockwave. This shockwave is responsible for a significant portion of the damage accompanying an explosion. The front of this shockwave moves rapidly outward from the epicenter of the explosion, behaving like a kind of moving wall composed of highly compressed air. Approximately 10 s after the detonation, when the 1 Mt fireball of a nuclear bomb has reached its maximum size (about 1700 m in diameter), the shockwave front is approximately 5 km away (*Glasstone et al., 1977b*). After the explosion, 50 years for example, when the fireball is no longer visible, the shockwave has advanced by approximately 20 km. At that point, its velocity is around 350 m/s, slightly faster than the speed of sound at sea level (*Glasstone et al., 1977b*).

The first step involved in developing this subprogram consisted of selecting a mathematical model that was capable of accurately representing the complex phenomena related to overpressure. In this context, the choice was made to use the equations devised by (*Brode, 1987*), an approach that has proven to provide precise and consistent estimates regarding the overpressure generated by nuclear explosions. The scientific community recognizes the ability of these equations to capture the physical aspects and influencing factors in the generation of overpressure.

The adjustment made for maximum overpressure takes the following form (*Brode, 1987*) in equation 4:

$$\Delta P_s = \frac{10.47}{r^{a(z)}} + \frac{b(z)}{r^{c(z)}} + \frac{d(z)*e(z)}{1+f(z)*r^{g(z)}} + h(z,r,y) + \frac{j(y)}{r^{k(y)}}\text{[psi]} \quad (4)$$

Where

$$a(z) = 1.22 - \frac{3.908z^2}{1+810.2z^5}$$

$$b(z) = 2.321 + \frac{6.195z^{18}}{1+1.113z^{18}} - \frac{0.03831z^{17}}{1+0.02415z^{17}} + \frac{0.6692}{1+4164z^8}$$

$$c(z) = 4.153 - \frac{1.149z^{18}}{1+1.641z^{18}} - \frac{1.1}{1+2.771z^{2.5}}$$

$$d(z) = -4.166 + \frac{25.76z^{1.75}}{1+1.382z^{18}} + \frac{8.257z}{1+3.219z}$$

$$e(z) = 1 - \frac{0.004642z^{18}}{1+0.003886z^{18}}$$

$$f(z) = 0.6096 + \frac{2.879z^{9.25}}{1+2.359z^{14.5}} - \frac{17.15z^2}{1+71.66z^3}$$

$$g(z) = 1.83 + \frac{5.361z^2}{1+0.3139z^6}$$

$$h(z,r,y) = \frac{8.808z^{1.5}}{1+154.5z^{3.5}} - \frac{0.2905+64.67z^5}{1+441.5z^5} - \frac{1.389z}{1+49.03z^5} + \frac{1.094r^2}{(781.2-123.4r+37.98r^{1.5}+r^2)(1+2y)}$$

$$j(y) = \frac{0.000629y^4}{3.493*10^{-9}+y^4} - \frac{2.67y^2}{1+10^7y^{4.3}}$$

$$k(y) = 5.18 + \frac{0.2803y^{3.5}}{3.788*10^{-6}+y^4}$$

x: ground range in kilofeet per kiloton of cubic root.

y: burst height in kilofeet per kiloton of cubic root.

r: slant range in kilofeet per kiloton of cubic root = $\sqrt{x^2+y^2}$

W: yield in kilotons.
$z=y/x$.

THERMAL RADIATION

Primary thermal radiation occurs after the explosion. A significant portion of this radiation appears in the form of X-rays, which are absorbed in a layer of air a few meters thick. This energy is subsequently released again from the fireball in the form of secondary thermal radiation, with longer wavelengths, including ultraviolet, visible, and infrared rays. Although the internal temperature decreases steadily, the apparent surface temperature of the fireball decreases more rapidly for a fraction of a second. This apparent surface temperature then increases again over a somewhat more extended period and finally decreases continuously (*Glasstone et al., 1977c*). Two pulses of surface temperature are, therefore, effectively present: the first is of a very brief duration, while the second is much longer.

These two pulses of surface temperature are related to the emission of thermal radiation from the fireball. In the first pulse, which lasts around 0.1 s in the case of a 1 Mt explosion, surface temperatures are mostly elevated (*Glasstone et al., 1977c*). Much of the radiation emitted during this pulse is of an ultraviolet nature. Although ultraviolet radiation can cause skin burns, in most cases after an explosion, the first pulse of thermal radiation does not pose a significant risk in this regard, for several reasons. Firstly, only about 1 % of thermal radiation is present in the initial pulse owing to its short duration (*Glasstone et al., 1977c*). Secondly, ultraviolet rays are easily attenuated by the air, resulting in a relatively low dose at considerable distances from the explosion (*Deng et al., 2012*). However, it is important to note that, although the first pulse of radiation might be overlooked as a source of skin burns, it could have permanent or temporary effects on the eyes, especially in individuals looking in the direction of the explosion (*Sheedy et al., 2004*).

The second pulse of thermal radiation can last several seconds; for example, around 10 s in a 1 MT explosion, in contrast to the first pulse. This second pulse carries approximately 99 % of the total thermal radiation energy (*Glasstone et al., 1977d*). Since temperatures are lower than in the first pulse, most of the rays reaching the Earth's surface correspond to visible and infrared light (*Glasstone et al., 1977d*). It is precisely this radiation that constitutes the main cause of skin burns of different degrees suffered by individuals exposed at up to 20 km or more, and it also affects eyes at even greater distances (*Glasstone et al., 1977d*).

The subprogram employed to calculate thermal radiation is based on a mathematical model derived from the *"Thermal impulse functions," MinisterstvoOborony SSSR, Iadernoeoruzhie*. This model was later detailed in (*Geist, 2019*), and this program makes use of it.

The characterization of thermal radiation, with visibility, is included in the model employed. This model makes it possible to determine (in cal/cm^2) the thermal radiation present after a nuclear detonation.

This procedure is based on a visibility code that is used in order to measure the distance from which an object of a certain size is visible under certain meteorological conditions. This scale is used in maritime and aerial navigation to assess visibility and communicate it in a standardized manner.

INITIAL RADIATION

The detonation of a nuclear weapon is associated with the emission of radiation, including neutrons, gamma rays, and alpha and beta particles. All neutrons and a portion of the gamma rays are primarily emitted during the fission process itself. These types of radiation are observed as immediate nuclear radiation because they occur simultaneously with the nuclear explosion. Some of the neutrons released during fission are captured immediately, while others interact in scattering collisions with various nuclei present in the weapon. These processes are accompanied by the instantaneous emission of gamma rays. Moreover, many of the escaping neutrons interact in a similar manner with atomic nuclei in the air, thus creating an extended source of gamma rays around the explosion point. The remaining gamma rays and beta particles are released gradually as the products of fission undergo radioactive decay. Alpha particles are similarly released as a result of the decay of uranium (or plutonium) that has not undergone fission in the weapon.

The initial nuclear radiation is generally defined as that emitted by both the fireball and the radioactive cloud in the first minute after the explosion (*Glasstone et al., 1977e*). This includes neutrons and gamma rays that are emitted almost instantly, along with the gamma rays from the products of fission and other radioactive species in the rising cloud.

The subprogram employed to calculate the initial radiation is based on a mathematical model derived from (*Glasstone et al., 1977f*).

In this method, neutrons, secondary gamma rays from radioactive capture and inelastic scattering in the atmosphere, and gamma rays from the products of fission are described separately (*Glasstone et al., 1977f*). It is important to mention that the alpha and beta particles present in the initial radiation are not considered, as they are easily absorbed and do not propagate more than a few meters, at most, from the radioactive cloud. The contribution of primary fission gamma rays to the dose of radiation at a distance is sufficiently small as to be negligible.

LOCAL FALLOUT

After a nuclear explosion near the surface, particles contaminated with radioactive residues gradually descend, giving rise to the phenomenon known as fallout. This process, which is crucial in the generation of residual radiation, is triggered by the fusion or vaporization of soil and water in the early stages of the fireball. The particles, which are uniformly contaminated with radioactive byproducts, then begin to descend amidst initial turbulence.

The magnitude of fallout, its radioactive persistence, and its configuration are influenced by various factors, such as the energy yield and design of the weapon, the detonation height, and meteorological conditions (*DNA, 1954*). In those situations in which the explosion occurs in the air, particles disperse widely, and the hazard related to them is reduced. However, the risk intensifies in surface-near explosions, thus underscoring the importance of understanding how the fallout, in its two phases—early and delayed—evolves and affects areas surrounding the epicenter for periods that can extend up to several hours after the detonation (*Wolfson et al., 2019*).

This gradual and persistent process, which is a key aspect as regards assessing radioactive risks, becomes visible in the form of larger particles that fall within the first 24 hours, known as early fallout or local fallout, and finer particles that are slowly deposited over extensive areas, termed as delayed fallout (*Glasstone et al., 1977g*). Understanding these fallout patterns is crucial as regards assessing and mitigating the risks associated with nuclear explosions and their impact on the environment near the epicenter.

In order to obtain precise and rapid results in simulation calculations, it is necessary to establish different mathematical models for various cases of contaminant dispersion in the atmosphere (*Leelõssy et al., 2018*). This model is based on the Gaussian model, considering a non-random variation of the plume with wind speed in the x-direction and a Gaussian distribution in the y-direction.

The calculation process utilized for local fallout begins by determining the stable cloud generated after the nuclear explosion, using the SIMFIC model as a basis (*DNA, 1979a*). This stable cloud, which is characterized by its position and shape, serves as a fundamental starting point for subsequent modeling. Equations describing atmospheric dynamics and radionuclide dispersion are employed to calculate the evolution of this cloud over time, using the DELFIC model as a basis (*DNA, 1979b*).

Various factors are subsequently considered in order to calculate the deposition rate of the activity fraction relative to the distance from the detonation point. These factors include the explosion height, wind direction and speed (*Zheng et al., 2023*).

The accuracy of the results is further improved through the incorporation of adjustments and corrections. Of these, the "shear wind correction" takes into account variations in wind speed at different altitudes (*Zheng et al., 2023*). This adjustment is crucial as regards more accurately reflecting the complexity of the atmosphere and optimizing the simulation of the transportation of radioactive particles.

Moreover, the "far field correction" focuses on adjusting calculations when the distance from the zero point is considerable (*Zheng et al., 2023*). These corrections ensure that the mathematical model adapts more precisely to real-world conditions, thus enhancing the validity and usefulness of simulations in the analysis of local fallout after a nuclear explosion.

Upon completing the calculation process using the program, the rate of exposure generated by local fallout is accurately obtained. This magnitude, which is expressed in Röntgen per hour (R/h), represents the fundamental measure required in order to assess the radioactive risks associated with the dispersion of contaminated particles in the vicinity of the epicenter of a nuclear explosion.

PROGRAMME AND RESULTS

The nuclear explosion effect analysis program has been developed in the Python programming language, leveraging its versatility and efficiency. Python is a particularly suitable choice for this project owing to its clear syntax, wide variety of libraries, and its ability to handle scientific calculations and the visual representation of data in an effective manner.

INPUTS AND PARAMETERS OF THE PROGRAM

The user interacts with the program by providing various key inputs. These inputs include the total bomb tonnage, the tonnage corresponding to fission, the detonation height of the bomb, visibility at the detonation site, and the direction and speed of the wind. These parameters are crucial as regards calculating the most significant nuclear effects, such as the fireball, overpressure, initial radiation, thermal radiation, and local fallout.

CLASSDIAGRAM

The class diagram corresponding to the nuclear detonation effect analysis program is shown in *Fig. 1*. The classes shown in the class diagram above are detailed as follows:

Bomba: This is responsible for characterizing the bomb under study. It is necessary to enter its main characteristics (name, bomb tonnage, fission tonnage, detonation height, and parameters corresponding to the existing wind).

Fireball: The dimensions of the fireball generated by the nuclear explosion are determined.

Overpressure: The overpressures generated because of the shockwave are calculated.

Initial Radiation: The various components of initial radiation, including dose rates from fission products, initial neutrons and secondary gamma rays, are calculated. Cálculos de las diferentes componentes de la radiación inicial, incluidas tasas de dosis por productos de fisión, neutrones iniciales y rayos gamma secundarios.

Thermal Radiation: The thermal radiation resulting from the detonation is determined..

Local Fallout: The dimensions of the radioactive cloud and the consequent exposure rate of local fallout are analyzed.

GRAPHICAL USER INTERFACE(GUI)

A user interface in the form of a desktop application has been implemented in order to facilitate users' interaction with the program (*Fig. 2)*. This interface was made possible using the tkinter library, and it allows the intuitive and straightforward entry of the parameters mentioned earlier.

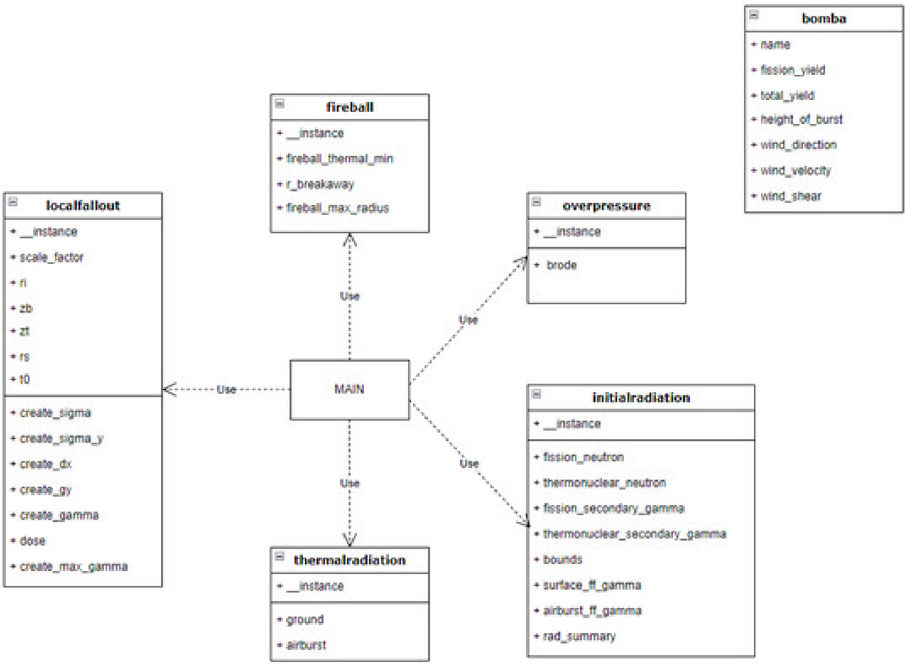

Fig. 1. Classdiagram

Fig. 2. Program interface

VISUALIZATION IN EXCEL AND MAPS OF THE RESULTS

The calculation results are shown in visually understandable formats. Representations are generated on Excel spreadsheets and interactive maps.

The solutions are displayed in pop-up windows, thus allowing the user to effectively visualize the nuclear effects at the selected location (*Fig.3, Fig.4*).

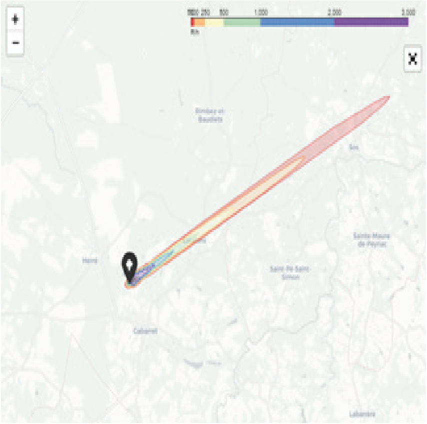

Fig. 3.Visualization of local fallout.

Fig. 4.Visualization of initial radiation.

GEOSPATIAL INTERACTIVITY

The application interacts with the user in order to determine the location of the explosion. Users are prompted to indicate where they wish to place the nuclear bomb, thus enabling precise geospatial analysis.

BOMB MANAGEMENT

The user interface incorporates functionality required in order to manage previously detonated bombs. The application allows users to load previously saved bombs at any time, thus providing flexibility and enabling the user to work with multiple detonation scenarios.

CONCLUSIONS

This project has culminated in the development of an innovative program based on the Python programming language, designed to comprehensively analyze the nuclear effects resulting from explosions. Rigorous mathematical models and an object-oriented structure have made it possible to achieve a precise representation of complex phenomena such as the fireball, overpressure, initial radiation, thermal radiation, and local fallout.

The implementation of consolidated mathematical models supported by established scientific principles provides fast and accurate simulations. The modularity and flexibility of object-oriented programming facilitate code organization and allow future improvements and extensions.

The GUI enhances interaction, thus allowing users to input parameters intuitively. The visualization of results in formats such as Excel spreadsheets and interactive maps facilitates the understanding of nuclear effects and their potential impact.

FUTURE WORK

- Improvement to Mathematical Models: Refine and update the mathematical models used to represent different nuclear effects, incorporating the latest research and scientific advances.
- Incorporation of Environmental Factors: Consider environmental factors, such as seasonal variations and specific atmospheric conditions, in more detail to improve the accuracy of simulations.
- Program Performance Optimization: Make improvements to the efficiency and speed of the program in order to handle larger and more detailed simulations, which could be crucial in scenarios that are more complex.
- Inclusion of Biological Effects: Expand the scope of the program to include models that estimate the possible biological effects of radiation, thus providing a more comprehensive assessment of the risks associated with nuclear explosions.
- Study of Mitigation Strategies: Explore strategies and mitigation measures with which to reduce the adverse effects of nuclear explosions, using the program as an analysis tool in order to evaluate the effectiveness of these strategies.

In summary, this project establishes a foundation for nuclear effect analysis, but continuous evolution and expansion into complementary areas could enhance its utility and contribute to increasing the understanding and management of the impacts of nuclear explosions.

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