Replacing The Nuclear Slide Rule

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It has been a humbling and heartbreaking experience to review the totality of the data on the Hiroshima and Nagasaki bombings, and I hope that the health effects classifier described herein that was trained on data from those 36,000+ survivors may be of use in future responses to nuclear disasters.

Abstract

A proposal for the development of a new nuclear slide rule is presented. Analysis of existing problems and how the proposed solution will resolve them is discussed. Tangential benefits are provided, and a novel classifier is developed, which shows promise to evaluate the long-term survival of a subject exposed to a radiological incident and the probability of developing cancer and which types passed on radiation dosages.

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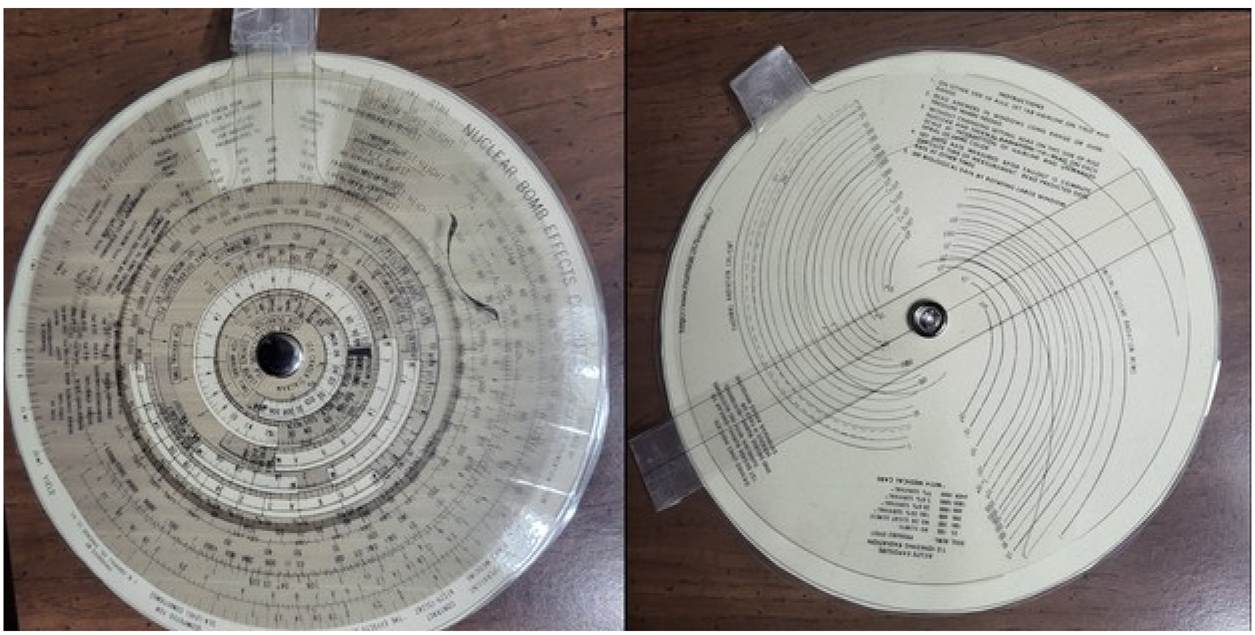
Replacing The Nuclear Slide Rule

Imagine you are an EMT responding to a 911 call from the local power plant. When you arrive at the site, you immediately see multiple sun-burned personnel fleeing the building. If you're lucky enough to have emergency plans in place and available, you pull out your orders, and hopefully, you will also find a circular plastic disk with some numbers on it shown in Figure 1. This is a "nuclear slide rule," initially developed by the U.S. Atomic Energy Commission in the 1950s and 1960s and incorporated into a nuclear bomb effects computer. It was later adapted in the late 1990s (Hopper et al., 1998) to help respond to other kinds of atomic accidents. You are supposed to use this device to determine how much radiation is produced, how far away to establish a perimeter, which of those freshly tanned individuals will die agonizing deaths in the coming months, and which have a chance of survival. Do you know how to use this slide rule? Most don't even know that it exists, which is the situation that first responders to nuclear power plants deal with. Even with trained personnel, the slide rule is woefully inadequate, as evidenced by the ongoing international effort to update it (NCSP D.O.E., n.d.). European researchers created a revised slide rule in 2017 (Duluc et al., 2017), but it still has many shortcomings of previous implementations. To resolve this problem, what is needed is more than a simple algorithm, but a complete set of tools that can aid in modeling a nuclear disaster and provide accurate assessments to first responders of where the danger is, how bad it is, and when and where to egress for their safety.

There are several issues with the current slide rule. For starters, it is based on decades-old measurements which have been superseded. The current nuclear slide rule was designed for responding to Uranium-235, which is not the only nuclear fuel used in reactors, nor does it account for the radioisotopes formed during a reaction. The existing slide rule does not account for this simply because of the complexity of such a calculation. Fission products are probabilistic, and to determine what a particular isotope will fission into, you must simulate it.

Moreover, the slide rule does not consider essential variables such as reactor type and is inaccurate at distances over 500 meters. While that seems like a long distance, the estimated plum zone in the U.S. for reactors is between 10-50 miles (NRC Emergency Plans, 1980). In addition to these problems, the issue of training and education arises.

Figure 1



Reproduction of Nuclear Bomb Effects Computer (Original Perret, R. 1963)

As you can see in the A-Bomb computer in Figure 1, there is much information in a relatively small area. The right image shows a basic nuclear slide rule. The intersection between the curved line of the top slide and the vertical line of the second slide indicates both the initial nuclear radiation and the thermal radiation, which are 10^5 Rems and 2,000 calories/cm^2, respectively. Most people without training in radiological hazards do not know what an acceptable dose of radiation is, nor do they understand the different types of radiation, how they might be exposed to it, or even how to use the slide rule. While those working at nuclear reactors will likely have some of this training, it is unreasonable to expect that knowledge from every first responder who might need to respond to a nuclear incident. The slide rule also does not provide much information about the long-term health effects one is likely to see due to their proximity to the radiation. This is further because the research into acute radiation-induced health effects in the long term is sparse. Physicists originally developed the nuclear slide rule to determine the safety of a given area during and after a nuclear incident based on the time that passes. At the time, it was the best we had available; however, we now have better technology to perform the complex calculations needed to make a real difference in our responses. We must update our nuclear slide rule to match our technological capabilities. Doing so will help us prevent the mistakes we've made in past nuclear disaster responses.

Proposed Solution

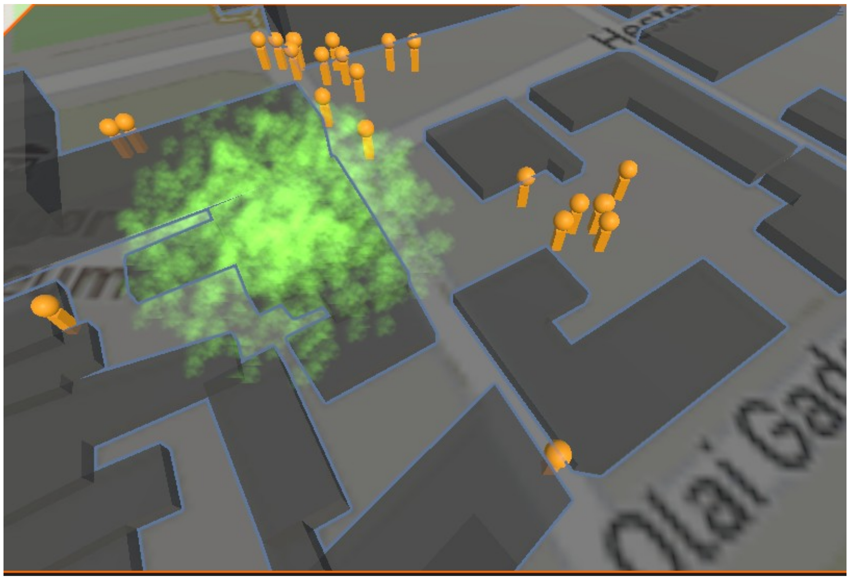
High-Level Overview

The new nuclear slide rule will be a digital software solution. This software will consist of multiple parts that comprise the overall software package. The core parts include a base station with a web-accessible Application Programming Interface (API) that will allow devices to send and receive data to the base station. This base station will include an incident modeler to simulate a given nuclear incident and a criticality classifier to determine whether atomic fission increases or decreases the radiation. Additionally, the base station will provide an individual dosage simulator and a health effects classifier which will be used to determine when responders need to evacuate and help the responders to predict the long-term risks of remaining in a given area. Along with this, a mobile application will be provided that will allow first responders on the ground to update the base station with local radiological data and their current location and get immediate feedback and alerts from the system and response coordinators.

Base Station

The base station is the brain of the response. It displays a 3-dimensional model of the incident area generated based on local topology along with the positions of responders and the position of radiological hazards. An example of the model is provided in Figure 2.

Figure 2



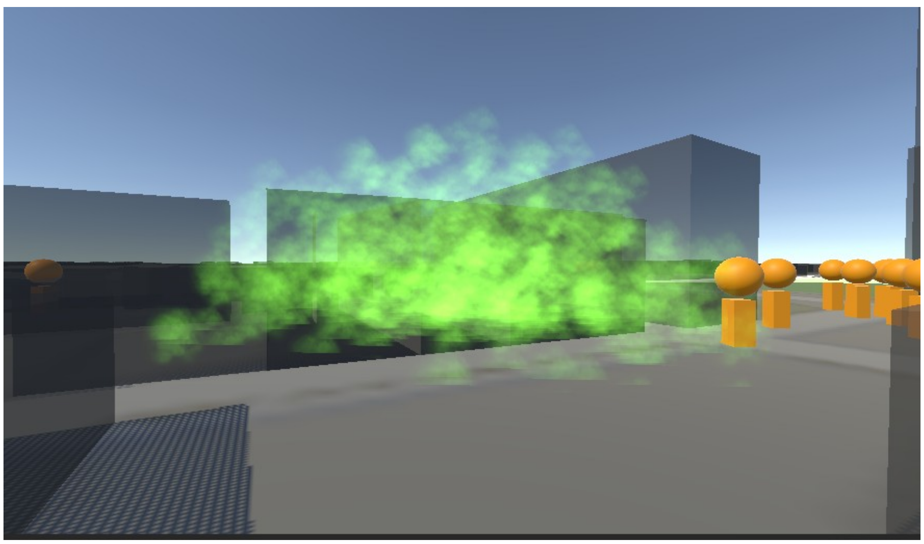
Incident Simulation

The yellow figures indicate crew locations, and the buildings (transparent cubes) are extruded based on satellite imagery. The green fog/cloud represents the radiation in an incident area. As the incident model is 3-dimensional, additional views of an incident will be possible, as shown in figures 3 and 4 below. Figure 3 provides an aerial view of the incident, which includes the response team and radiation positions with a quick operational overview offering a stand-in replacement for aircraft, helicopter, and drone monitoring. Figure 4 demonstrates the ability of response coordinators to "see" what the boots on the ground are seeing, which will help them better coordinate response efforts.

Figure 3

Aerial View

Figure 4



Ground View

Using the API, the base station will synchronize these views and data with the responder's mobile devices. This API will also allow internet-enabled measuring devices to update the base station with data. Since we are using Unity3D for this software, we will also be able to create 3-dimensional models of the reactors and buildings themselves. Far too many factors exist to dictate here fully, so the software must include a plugin system allowing future modifications in design specifications.

Mobile Application

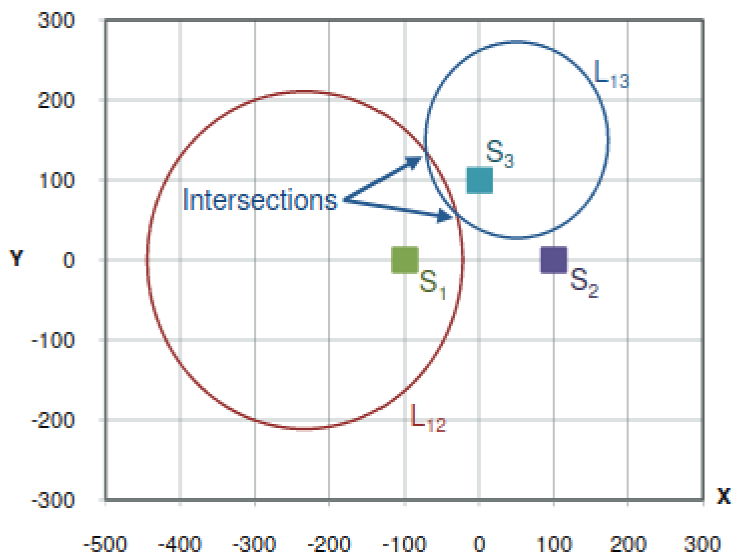
Responders to an incident will use personal mobile devices loaded with the client application to aid in their response, submit measurements, and get updated information about the health risks their current level of exposure has caused. The app will provide an incident map for first responders, so they know which areas they should avoid to prevent them from receiving a high dose of ionizing radiation. The app will continuously update the Base Station with its' location, allowing response planners to know the exact location of each responder, the predicted radiation dosages and provide a means for responders to upload measurements from Geiger counters and personal radiation detectors.

According to a study by the Pew Research Center, 85% of Americans own a smartphone making it a ubiquitous tool (Pew, 2021). Since smartphones have such a high level of adoption, it should be trivial to train new users to submit and read data with this application. This can be made even easier by adopting intuitive design practices in the graphical development of the application.

Incident Modeler

The application will geo-tag the Geiger and location data submitted with the latitude and longitude from where users took measurements. This data includes the radiation intensity, which the Incident Modeler will use to locate the radiation source. This process works because radiation intensity decreases with distance, as the inverse square law describes. (Ballard, n.d.) Because the distance is proportional to the radiation intensity, we can estimate the furthest and closest distances of a radiation source from where a user took a measurement. Using these distances as the diameter of a circle originating from the measurement and plotting the circles on a map, we can find the only possible locations of the radioactive material in the intersections of the circles, as shown in Figure 5.

Figure 5



Trilateration of A Dirty Bomb (Chin et al., 2008)

An efficient algorithm using iterative pruning (ITP) was developed in 2008 specifically for locating so-called dirty bombs that release radioactive material within populated areas. Pseudo-source code for this algorithm was provided, which will make the integration of this algorithm into the modeler a straightforward exercise. As shown in Figure 4, the algorithm can locate the radiation source on a 2-dimensional map with two or more geographically distinct measurements. Low-intensity radiation sources likely found in 'dirty bombs' can be localized with this algorithm to 32.5 meters accuracy using only one sensor per 1,100m^2. More sensors, measurements, and higher intensity radiation allow for greater precision, and these factors are likely present during a nuclear incident. (Chin et al., 2008)

With the material located and the distance is known, we can again use the inverse square law along with the sensor efficiency to determine the approximate nuclear reactions per minute of the material. The formulas for these calculations are provided:

$$I_1 \stackrel{\text{def}}{=} Intensity\ at\ point\ 1$$
$$I_2 \stackrel{\text{def}}{=} Intensity\ at\ point\ 2$$
$$D_1 \stackrel{\text{def}}{=} Distance\ of\ point\ 1$$
$$D_2 \stackrel{\text{def}}{=} Distance\ of\ point\ 2$$
$$\frac{I_1}{I_2} = \frac{D_2^2}{d_1^2}$$
$$I_2 \times d_2^2 = I_1 \times d_1^2$$
$$I_1 = \frac{I_2 \times d_2^2}{d_1^2}$$

$$C \stackrel{\text{def}}{=} Counts\ per\ minute$$
$$De \stackrel{\text{def}}{=} Detector\ efficiency$$
$$TC \stackrel{\text{def}}{=} Total\ counts\ per\ minute$$
$$¿\, TC = C / De$$

$$I_1 = TC$$
$$TC = \frac{I_2 \times d_2^2}{d_1^2}$$

The number of nuclear reactions per minute of natural decay depends on the radioisotopes present and the number of nuclei that make up the atomic mass. Uranium-235 and Uranium-238 are the most common isotopes used in reactor fuel (IAEA, n.d.), although different fuels exist for newer reactors, such as Thorium. Another isotope that may be found in high quantity is Cesium, and more radioisotopes can be added for analysis if desired. These isotopes' radioactive decay rates are known, meaning one can calculate an approximation of the mass of radioactive material in a given area. A formula for this approximation has been derived from the above formula and the Law of Radioactive Decay (IAEA, n.d.):

$$N \stackrel{\text{def}}{=} Number\ of\ nuclei$$
$$t \stackrel{\text{def}}{=} time$$
$$\lambda \stackrel{\text{def}}{=} Prob.\ of\ decay\ per\ unit\ time$$
$$\Delta N = \lambda N \times \Delta t$$
$$\lambda = \frac{(-\Delta N / \Delta t)}{N}$$

$$A \stackrel{\text{def}}{=} Atomic\ mass\ of\ isotope$$
$$TM \stackrel{\text{def}}{=} Total\ mass\ of\ material$$
$$N \stackrel{\text{def}}{=} Number\ of\ nuclei$$
$$N \times A = TM$$

$$TC / t = \lambda \times N \times t$$
$$TC = \lambda \times N \times t^2$$
$$\frac{TC}{\lambda \times t^2} = N$$
$$N \times A = TM$$
$$\frac{TC}{\lambda \times t^2} \times A = TM$$

With the mass approximated for each possible isotope and presuming a ‘worst case scenario’ wherein the shape of the mass is a sphere (Nuclear Power, 2021), nuclear criticality, that is, whether the material is undergoing sustained fission, can be determined. Different shapes can be included as needed for more accurate predictions. This is incredibly important for the response team because it indicates whether there is fission and whether it is becoming more intense or less intense. This process will be repeated for every pocket of radiation identified, and for those determined to be critical or super-critical, the modeler will create a nuclear simulation.

Reaction Simulator

The Base Station uses the reaction simulator to simulate the nuclear reactions of several hundred atoms that appear in each area of interest. The primary focus of this simulation is radiation level. However, ERTs can add additional factors to aid in overall disaster management. By loosely coupling this simulator to a generic object in the base station code, it will be possible to load many different kinds of nuclear simulators, allowing reactor-specific simulations to be developed. One example is the VVER-type reactor parameter modeling described by Varga and Fazekas, which considers many factors such as reactor temperature, primary and secondary circuit pressure, and more (Fazekas, 2008). These simulation models can be made arbitrarily complex and modified to suit the needs of assessing the primary and secondary dangers of a given reactor design or nuclear weapon. One example might be including calculations for the production of hydrogen gas, which lead to the massive explosions of Fukushima (Miraikan, n.d.).

The nuclear simulator will also embed a criticality classifier to determine the K-value, which determines whether the reaction is in a sub-critical, critical, or super-critical state. The K-value representing the exponential rate of fission increase feeds back into the reaction simulator to validate the previous simulation and is used to determine how many atoms undergo fission in each step.

Individual Dosage Simulator

The individual dosage simulator will take in the geographical position of the user as well as the simulated and known radiological conditions for the incident area. The base station will supply this information to a Monte Carlo dosage simulator, and the dosage simulator will generate dosage estimates for neutron and gamma radiation. The specific dosages to be measured are free in-air (kerna), colon, and marrow. The existing prototype targeted these specific variables and organs as they were estimated using the DS02 measurements of the survivors of Hiroshima and Nagasaki that had been used to train the health classifier described later. ERT planners can add additional organ dosages to train the classifier as the data becomes available. The base station will then pass this dosage information into the health classifier to determine each person's survivability and cancer probability.

Health Classifier

As determining the health effects is one of the more difficult tasks with less research, a sample health classifier has been developed to provide an immediate and actionable solution to this significant shortcoming in nuclear response (Wood, 2022). The classifier design was based on the Breast Cancer Classifier from The Practice of Computing Using Python 3rd Edition and has been trained on the Nagasaki and Hiroshima datasets (Preston et. al., 2004) to determine:

1 Survivability

2 Cancer probability

3 Differential Cancer Dx:

 3.a Solid (tumor types)

 3.b Hematopoietic (liquid)

 3.c Leukemia

Training and testing with random samplings of the Nagasaki dataset show that the predictive accuracy of this classifier is as follows:

Survivability: 77%

Cancer Prediction: 90.73%

Solid Cancer: 90.73%

Hematopoietic Cancer: 99.08%

Leukemia Cancer: 99.35%

As data around radiological incidents improve, more organs and effects can be targeted and included to estimate dosage and health effects on a given individual. This health classifier is, to my knowledge, the first and only publicly available machine learning algorithm to determine long-term survivability and cancer rates based on radiation exposure. Further research is needed to validate this model, and the survivability model likely suffers from survivor bias due to a lack of training data on radiation victims. Establishing a global database to share such data and formatting said data into something which classifiers can easily digest is something that will prove beneficial in the long run for the development of future ML algorithms for radiological hazards.

Alternative Solutions

The nuclear slide rule has two primary competitors: MCNP and SCALE. Both algorithms share many of the same shortcomings with the nuclear slide rule simply because they do not and cannot account for the incredible number of variables involved. Furthermore, the data produced by these models are roughly the same as those produced by the nuclear slide rule, with around a 5% variance (NSR update, 2017). These solutions and the existing slide rule do not go far enough to help response teams deal with the many factors in a nuclear incident. Moreover, these algorithms are far more complex than the original slide rule and offer no perceivable benefit in crisis response.

Cost & Time

Since we will be integrating 3D modeling capabilities and require some form of a server, we can quickly resolve the application's core using the Unity3D engine for the base station. Unity will provide networking, 3D modeling capabilities, mobile app development, server development, and terrain mapping. Many map and terrain solutions for Unity allow the software to generate the incident area terrain based on satellite data. The most challenging part of this project will be simulating the nuclear reactions; however, this is a solved problem, and many references are available to make accurate simulations. Calculating radiation dosages is another solved problem. The program CALDOSE exists, which can determine organ and radiation dose based on body mass, position, gender, and other variables. CALDOSE was developed initially for X-Ray calculations and used a Monte Carlo simulator; however, it could also be adapted to calculate dosages for neutron and gamma radiation. (Caldose.org, n.d.)

The health classifier prototype took around 20 hours to develop. With 20 hours as the minimum time necessary per significant component, the minimum estimated time is 120 hours. The average hourly rate of a software engineer in the U.S. is $36 (Salary.com, n.d.), for a minimum cost of $4,320 to develop a prototype of the proposed solution. Additional funding will be needed at a later point for the complete software package. A rough estimate for the total development costs for the initial application is $100k-250k with an estimated time of 6-10 months to delivery. (Wilson, 2021)

The operating cost of this model will be low. Using Amazon Web Services, Heroku, Google Cloud, or any other number of cloud providers to host a base station server, one could implement this system and have it ready to use at a moment's notice. These cloud platforms are designed to handle massive loads, with thousands of users downloading gigabytes of data for fractions of a penny. In the game world, rented servers costs between $5-150/month depending on usage, with massive servers that have 50k+ users at any given time costing ~$1,500 per month, and that is 50k active users 24/7 uptime (EasyPC, 2022). Due to the lack of regular use, the actual cost is likely to be much lower than this. As an alternative to cloud solutions, an emergency response team can also choose to host a server for deployment locally.

Tangential Benefits

Developing this software solution will also provide us with an easy way to simulate nuclear reactions and radiation exposure based on topological factors. This allows us to extend this software into reactor research, design, and simulation. In fact, by integrating this system into reactor control systems, operators will be able to perform more advanced reactions simulations to help control the reactor and ultimately improve the safety of reactors. By providing feedback to the software from the reactor, the simulator will also be self-improving, so as time goes on, the simulations will become more accurate, improving both the reactor controls and disaster response calculations.

Anticipated Opposition

Communication Reliability

With any disaster, communications may be adversely affected. Having no contact with a base station would render this system useless. This is a real threat to the system as it requires a centralized server to accomplish computationally complex calculations that may be too heavy for a mobile device to perform. While ionizing radiation does not threaten communications (Hageman, 2015), the possible causes for the initial damage do pose a threat. Whether the damage to a reactor is environmental or artificial, there may be damage to communications infrastructure preventing accessing the Base Station from a mobile device.

The mobile app can perform quick dosage and exposure calculations client-side based on local inputted measurements to allow for a fail-safe if it cannot reach the base station. If/when a connection is made, the client will notify the base station of the measured values and retrieve the more accurate calculations from the base server. Additionally, disaster teams could have a server on standby to deploy locally. Existing grid-down applications such as LORA-WAN and MeshNet exist as a last resort. However, many existing emergency response teams are already equipped with cellular repeaters enabling them to quickly create a private cellular network for the responders, thereby allowing them to connect to a local base station.

Radiation Interference

Electronic devices can suffer from many issues when exposed to radiation. Gamma radiation, for example, damages insulating materials in electronics and can degrade semi-conductors structures, leading to computation errors. However, the amount of radiation required to accomplish this is several orders of magnitude greater than the amount of radiation that would be deadly. (Hageman, 2015) If one was bathed in enough radiation to harm their mobile device, their chance of survival, regardless of the duration of exposure, is zero. For military response, it may be advisable to use radiation-hardened devices to ensure mission-critical data is processed even if the responder receives many times the lethal dose, although this is likely overkill for non-world-ending nuclear disasters.

EMP/CME/TEOTWAWKI

There is a belief among many that an electromagnetic pulse produced by a nuclear bomb or a coronal mass ejection would destroy all electronic devices. The size of mobile devices is relatively tiny, giving them a small cross-section to absorb energy, and while they may be susceptible to interference and damage from an EMP, even basic passive shielding, such as sitting inside of a car's glove compartment, should be sufficient to prevent catastrophic damage to the delicate electronics internals.

If this threat is severe enough that ERTs consider it when planning, or if one is planning for global thermonuclear warfare, then an ERT should provide several cellphones and a local base station with a cellular repeater to be made available if all available electronics are otherwise unavailable. All these devices and the base station itself should remain inside a Faraday cage to be shielded from electromagnetic radiation until needed. An excellent potential option for this would be a simple box trailer with radiation and faraday shielding.

Conclusion

The existing nuclear slide rule is known to be insufficient for current needs in responding to nuclear disasters. The proposal suggests that what is needed is not just an updated nuclear slide rule but an entire platform to assist in response to nuclear disasters. Additionally, the proposal introduces a novel classifier for long-term survivability and cancer prediction with differential diagnosis of individuals during radiological disasters with marrow, colon, and kerna doses X where $250 \leq X \leq 80{,}000$ mSv. The accuracy of this novel classifier, when tested and trained with random samples, demonstrates the immediate benefits to the field of nuclear science that this proposal would provide.

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