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The effects of using Cesium-137 teletherapy sources as a radiological weapon (dirty bomb)

by Dr. Theodore E. Liolios

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The Director's Message

Nowadays, the most important issues that concern Europe and the entire world are terrorism, arms control and international security. Lack of education and information on the aforementioned subjects can lead to misinterpretation of intelligence which in turn can lead to the wrong political decisions.

The 9/11 terrorist attack introduced an era of uncertainty fear and awe for the civilized world. International terrorism has already attacked many European countries underlining the fact that counter-terrorism is not an American issue as is often suggested. Moreover, the proliferation of weapons of mass destruction (WMD) combined with the inadequate security measures in the countries which possess them enhances the possibility of a destruction of colossal dimensions. It is therefore obvious that Europe should actively embark on a campaign against WMD which will be precise and prudent where no collateral damage will be acceptable.

On the other hand, Europe, instead of passively following the doctrines of the USA, should emerge as an independent and powerful force in the new millennium. A unified well coordinated European Army should balance the universal influence of the USA. The European Armed Forces operating under the aegis of NATO, but without losing their autonomy and independence, could pose as a stabilizing and peace-keeping factor for the entire world.

Admittedly, the military excellence of the USA is largely due to the scientific excellence of their armed forces. It is therefore imperative that the European scientific community mobilizes in order to strengthen the European military science while at the same time informing the public and their governments about all arms control issues. This urgent necessity gave birth to ***ATHENA***.

ATHENA, the Hellenic Arms Control Center, will attempt to challenge the American excellence in the field of Arms Control and Non-proliferation. Of course, this is not an easy task and it might be some time before ***ATHENA*** becomes part of the picture. In the mean time, we are confident that the scientific community, both in Europe and its allied states, will respond enthusiastically to our venture and become members of ***ATHENA***.

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With my Best Regards
The Director and Founder of ATHENA
Dr. Theodore Liolios

HELLENIC ARMS CONTROL CENTER

The effects of using Cesium-137 teletherapy sources as a radiological weapon

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Abstract

While radioactive sources used in medical diagnosis do not pose a great security risk due to their low level of radioactivity, therapeutic sources are extremely radioactive and can presumably be used as a radiological weapon. Cobalt-60 and Cesium-137 sources are the most common ones used in radiotherapy with over 10,000 of such sources currently in use worldwide, especially in the developing world, which cannot afford modern accelerators. The present study uses computer simulations to investigate the effects of using Cesium-137 sources from teletherapy devices as a radiological weapon. Assuming a worst-case terrorist attack scenario, we estimate the ensuing cancer mortality, land contamination, evacuation area, as well as the relevant evacuation, decontamination, and health costs in the framework of the linear risk model. The results indicate that an attack with a Cesium-137 dirty bomb in a large metropolitan city (especially one that would involve several teletherapy sources) although would not cause any statistically significant cancer mortality current radiation safety standards would impose the evacuation of large areas and the relocation of thousands of people.

1. Introduction

The nuclear medicine community has always been very concerned about the effects of nuclear weapons [1,2], while radiological terrorism has recently been the focus of intense study [3,4,5 and references therein] due to widespread fears that nuclear medicine materials [6, and references therein] could be used as radiological weapons (dirty bombs). Some of the effects associated with stealing and mishandling therapeutic radioactive devices became apparent in 1987, when scavengers broke into an abandoned cancer clinic in Goiânia (the capital of the central Brazilian state of Goiás) and stole a cancer treatment device which contained significant amounts of radioactive cesium-137. According to the IAEA report [7], the burglars, after removing a metal canister, which contained 1,375 curies of Cesium-137, from a teletherapy machine, they broke open the canister revealing the Cs-137 source, despite the fact that it had been doubly sealed within two stainless steel capsules. The medical radioactive material in question was in the form of highly soluble Cesium Chloride salt (three times denser than water) which weighted 93 grams inside the canister. Handling the source resulted in distributing some radioactive material among friends and family members. Eventually, the canister and the source ended up in a junkyard, whose owner cut open the source selling the glowing Cesium Chloride powder to curious buyers. A portion of the radioactive powder was carried away by the wind contaminating the environment. According to the Brazilian Nuclear Energy Commission team[7] 200 people were contaminated, 28 people suffered radiation burns, 4 people died and one person had his arm amputated. Decontamination operations generated some 3,500 cubic meters of radioactive waste which also included debris from building demolitions. Finally, about 87% of the radioactive material was recaptured while there were devastating effects on the local economy and quality of life. The Goiânia accident indicates that a similar teletherapy Cesium-137 source could be used as a terrorist radiological weapon, which motivated the present study.

Our investigation is based on complex mathematical modeling of weapons effects but we will avoid using mathematical formulas in order to provoke interdisciplinary interest. Instead, we will present the results in a qualitative way so that the non-specialist in the nuclear medicine community can fully understand all the aspects of a terrorist radiological attack with a similar teletherapy source.

In Section 2 we briefly describe: (a) the Health Physics simulation codes used in this study, (b) the meteorological parameters of the attack (wind speed, stability category, and inversion), (c) the radioactive plume details (quantity, deposition velocity), (d) the energy of the explosion and its height of burst, (e) timing and target conditions (population density and warning), which play a vital role in the effects of the attack. In Section 3 we present the results of our investigation and, finally in Section 4 we propose and discuss effective means of preventing the use of a similar device as a radiological weapon.

2. Materials and methods

One of the most plausible radiological weapons utilizes an explosive mechanism to deliberately disperse radioactive material (in our case Cesium-137) to cause terror or harm (also know as Radiological Dispersion Device: RDD)[3]. Inhaled Cesium-137 commits to humans a 50-year committed effective dose equivalent (CEDE50) of 8.63×10^{-9} sievert per becquerel while its specific activity is 3.26×10^{12} becquerel per gram. According to Argonne National Laboratory, the Lifetime Cancer Mortality Risk Coefficient for inhalation is 8.1×10^{-12} cancers per pCi inhaled (or else 2.19×10^{-7} cancers per kBq inhaled, averaged over all ages and both genders). Note that the Cesium-137 caner mortality risk coefficient is approximately ten (four) times smaller than the Strontium-90 (Cobalt-60) one.

The US Environmental Protection Agency tabulates various principles that can be adopted by the authorities in selecting Protection Action Guides[8] for relocation in nuclear incidents. In our study we adopt its principle #2 (Table E-5) which considers that an upper bound on acceptable risk is an exposure where a person would receive a maximum dose within the first year from the incident corresponding to a total dose of 5 rems (0.05 Sv) in 50 years from exposure.

Regarding land contamination, the US EPA response levels for preventive Protective Action Guides (PAGs)[8] are 3 $\mu Ci/m^2$ (111 kBq/m^2) while levels for emergency PAGs are set at 30 $\mu Ci/m^2$ (1,110 kBq/m^2) for infants and 50 $\mu Ci/m^2$ (1850 kBq/m^2) for adults.

2.1. Description of the “Hotspot” codes

The Hotspot Health Physics codes[9], which are used in the present study, were created to provide emergency response personnel and emergency planners with a fast, field-portable set of software tools for evaluating incidents involving radioactive material. The software is also used for safety-analysis of facilities handling nuclear material. Hotspot codes are a first-order approximation of the radiation effects associated with the atmospheric release of radioactive materials. Its mathematical model is a hybrid of the well-established Gaussian plume model [10], widely used for initial emergency assessment or safety-analysis planning. Virtual source terms are used to model the initial atmospheric distribution of source material following an explosion, fire, resuspension, or user-input geometry. Hotspot takes into account the following crucial parameters of the attack:

2.2. Meteorological conditions

2.2.1 Wind speed

Wind speed a crucial parameter of a radiological attack. In fact, if we assume that all other meteorological parameters are constant and that the radiological material has a relatively large half-life then the dose received at a certain distance downwind from ground zero (GZ) is inversely proportional to wind speed while the area receiving a certain dose is also a rapidly decreasing function of speed. A low, constant wind speed is very favorable because the wind direction is predictable and can help the attacker control the plume. Large wind speeds will quickly disperse the material at large distances thus they are most likely to be avoided by the terrorists. In our worst-case scenario we assume a particularly low wind speed (one meter per second). Any wind speed higher than that will yield lower doses than the ones considered here at a particular distance

2.2.2. Stability category

Meteorologists distinguish several states of the local atmosphere: A, B, C, D, E, F. These states can be tabulated as a function of weather conditions, wind speed and time of day. According to the stability category the attack can result in a wide spectrum of lethal effects. Therefore the attacker will certainly take that into account, just as it happens by war-planners, so that the lethal effects are maximized.
The relation of stability categories to weather conditions are depicted in the following tables

Wind speed (meter/second)	Strong Insolation Day	Moderate Insolation Day	Slight Insolation Day	Cloudy (100%) Day or Night	Cloudy (>50%) Night	Cloudy (<37%) Night
<2	A	A-B	B	D		
2-3	A-B	B	C	D	E	F
3-5	B	B-C	C	D	D	E
5-6	C	C-D	D	D	D	D
>6	C	D	D	D	D	D

Wind speed (meter/second)	Strong Insolation Day	Moderate Insolation Day	Slight Insolation Day
<2	A	A-B	B
2-3	A-B	B	C
3-5	B	B-C	C
5-6	C	C-D	D
>6	C	D	D

In the Atlantic coastal site the probability of occurrence for the above stability categories is:

A	B	C	D	E	F
4%	5%	2%	39%	32%	18%

According to the Hotspot notes, for deposition velocities less than 0.1cm/sec and release points at or very near the ground level the maximum air concentration and ground surface deposition is always associated with F stability. Moreover, stability class F is usually accompanied by inversions. However, unlike stability categories A to D, stability class F rarely occurs during daytime therefore as regards the worst-case time for such a “broken arrow” there is a competition between the stability classes: Daytimes (i.e. Stability categories A, B) are associated with an increased population density in the streets and relatively low concentrations (and doses) while nighttimes (i.e. stability categories D, F) are associated with a decreased population density but relatively high concentrations (and doses). We have plotted isodose contours for all stability categories A-F under the worst-case scenario described in this work and have found that for the same population densities stability categories A, B result in collective doses which can be five times smaller than those under stability categories D and E. In this study stability category F is adopted in all worst-case HOTSPOT scenaria

2.2.3. Inversion layer

At first sight, it seems perfectly reasonable that temperature should decrease with altitude. However, due to various atmospheric phenomena there is sometimes an altitude at which the temperature gradient is inverted (temperature begins to increase with increasing altitude). The inversion layer acts as a blanket that limits the vertical mixing of the released radioactive material. Inversions can spread over large areas or be quite localized, and can last for many days or be of only a few hours duration. The region below the inversion layer is also referred to as the mixing layer. The mixing layer height ranges typically from 100 m to 3,000 m and can significantly increase or decrease air-concentration values and the respective lethal probabilities. Low altitude inversions occur usually at night (or early morning) due to radiation cooling of the ground. As one can easily realize at night the population density in the streets will be very low.

Thus, it seems that nature somehow is against the terrorist who will have to choose between, (a) an attack during the day when many people will be in the streets but there is a high altitude inversion or no inversion at all and, (b) an attack in the small hours when the population in the streets is sparse but there is often a low altitude inversion. The most lethal choice will be during the early morning rush hour of a foggy day since the presence of fog (or smog in highly polluted areas) is an indication of a low altitude inversion which could motivate the terrorists to attack. This motivation will be enhanced by the fact that fog will increase confusion and make the visible detection of the actual plume difficult. In our study we assume a very low mixing layer height (300 m) consistent with our worst-case scenario

2.3. Radioactive plume details

2.3.1. Radiological material (quantity and nature of the plume)

According to the Gaussian plume model, after a radiological explosion, the air concentration, as well as the dose received by an individual downwind, is directly proportional to the source term (i.e. the quantity of the radioactive material). Therefore, all the results depicted in Figure 1 and Figure 2 for a total activity of 1000 curies scale linearly with the mass (or the activity) of the source.

The Cesium-137 source in question is in the form of highly soluble Cesium Chloride salt. From the total quantity of the material involved in the explosion only a fraction will be rendered airborne while the rest will be scattered around GZ. Moreover, from the airborne fraction only a small amount will have the right dimensions (small or large enough) to become respirable. Particles which are larger than 10μm will be captured in the upper respiratory track while others smaller than 1μm will be inhaled and exhaled without being retained in the organism. In our study we assume that the entire quantity of Cesium-137 involved in the explosion becomes airborne and respirable, bearing in mind that this is indeed a worst-case scenario.

2.3.2. Deposition velocity

The heat and smoke of the explosion will lift small particles of Cesium up into the air and according to the nature of the released radioactive material these particles will settle to the ground as they are carried along by the wind contaminating the ground surface. Large particles will contaminate the immediate vicinity of the explosion while smaller (fine and mostly respirable) ones will travel large distances or will rise up at high altitudes until they are deposited on the ground. The velocity at which this deposition takes place is called deposition velocity. Obviously, non-respirable material will have a much larger deposition velocity than respirable ones.

Field and laboratory measurements of deposition velocities for gases have shown that biological and chemical activity play key roles in gaseous deposition. Relatively inert gases, such as carbon monoxide, have negligible deposition velocities (on the order of 0.001 cm/sec). For chemically or biologically active gases, however, the deposition velocity is likely to be on the order of 0.5 cm/sec to 3 cm/sec. The distribution of such velocities cannot be accurately known for the entire respirable and non-respirable fractions so we need to consider worst- and best-case scenarios in order to bracket the lethal effects of the radioactive cloud. According to Ref [13] we can safely assume that dry deposition velocity values range from 0.001 cm/sec to 10 cm/sec for all particles whose diameter ranges from 0.1μm to 10 μm (respirable fraction). Note that HOTSPOT assumes a default value for respirable (non-respirable) material generated by the explosion of 0.3 cm/sec (8 cm/sec).

2.3.3. Altitude of explosion (Height of Burst: HOB)

The effect of altitude is clear and predictable. All relevant simulations indicate that radioactive plumes resulting from ground explosions yield higher doses than those resulting from high altitude ones. All simulations show perfectly clear that a ground explosion is by far the most lethal choice of a terrorist and we will focus our study on it.

2.3.4. Explosive energy (yield)

The geometry of the radioactive plume as well as its granularity depend on the energy of the explosion. The more energetic the explosion the larger the temperatures attained by the radioactive material and thus the finer the particles generated by the explosion (molecular bonds break more easily at high temperatures). Moreover, the more energetic the explosion the larger the dimensions of the initial cloud and, thus the smaller the concentrations of the radioactive particles in the air and on the ground. It is obvious that, as far as the energy of the explosion is concerned, there is a competition between the percentage of the respirable aerosols and their concentrations in the environment. In any case, if the terrorists manage to assemble a very fine powder of Cesium Chloride then very small amounts of explosives would be necessary to convert such powder into fine respirable aerosols. Consistent with our worst-case scenario (to maximize lethality) we will assume that the radioactive Cesium Chloride powder is dispersed by means of a very small quantity of explosives (one kilogram of TNT).

2.4. Timing

The time of attack is indeed a very decisive parameter, which needs special attention. During daytime many people will be in the streets and the radioactive plume will be easily mixed with other gases which form the usual urban pollution. The cloud will not be easily detected but this is not the case with the explosion itself. Early detection can help since it may provide some warning to the public which can avoid inhalation of the cloud by finding shelter in nearby buildings (or staying indoors if are not caught in the streets). At nighttime a radiological attack against urban targets would cause fewer casualties as most people will be indoors during the plume passage and the population density in the streets will be very small. Admittedly the attacker could escape much easier at night but as it has often been proved it is very easy to remotely detonate an explosive device in broad daylight without being arrested.

Moreover, as we have already pointed out, inversion occurs when low night temperatures follow high day temperatures reaching its peak early in the morning. This indicates that during the early morning rush hour the attack will be most likely met with an inversion, which would increase lethality. On the other hand the public will be particularly vulnerable during the rush-hour since most commuters will be either walking in the streets or using public means of transportation or in the driver's seat of their own cars blocked in some traffic jam.

Rain will definitely reduce casualties since it will actually wash down all radioactive particles and drive them down the sewers, therefore cloudy days, at first sight, won't be the terrorist's choice due to the possibility of rain. However, cloudy days are most likely to bring about a stable atmosphere (e.g. Stability D) which is more lethal than the unstable one (Stability A).

Regardless of the conflicting effects of timing our study assumes the most lethal meteorological conditions and an average (reference) population density thus establishing a worst-case scenario.

2.5. Target conditions

2.5.1. Population density

It is common sense that the terrorists will choose a densely populated metropolitan area so that the lethal effects of their attack are maximized. Once we have estimated the lethal areas then we can simply multiply the population density by that area to estimate the number of casualties.

2.5.2. Warning

Warning is an extremely effective countermeasure. If the public has early enough warning it can simply evacuate the area thus avoiding any exposure to the lethal effects of the attack. Even on a very short notice the public can simply remain indoors, have recourse to shelters or avoid being in the streets at the time of attack. The radioactive plume will simply pass over the city and after some hours the air will be much safer than at the time of plume passage. As regards warning we will assume that the public is totally unaware of the attack thus adopting a worst-case scenario about passive defenses.

3. Results

According to the aforementioned assumptions, we have used HOTSPOT to simulate the explosive release of 1000 Ci of Cesium-137 and estimated the relevant 50-year committed effective dose equivalents as well as the resulting ground surface contamination. Figures 1 and 2 illustrate our results.

In Figure 1 we estimate and plot on a logarithmic scale the centerline Total Effective Dose Equivalent (TEDE50) in sievert (Sv) (defined as the sum of all effective doses due to inhalation, submersion and ground shine within fifty years after exposure) committed to a recipient downwind as a function of distance from ground zero for very unfavorable atmospheric conditions assuming a normal breathing rate of $3.3\times10^{-4}\mathrm{m}^3\mathrm{s}^{-1}$. This is the reference man breathing rate for an 8-h workday. For a more elaborate approach age-specific breathing rates might be considered (e.g. $1.17\times10^{-4}\mathrm{m}^3\mathrm{s}^{-1}$ for a child and $4.44\times10^{-5}\mathrm{m}^3\mathrm{s}^{-1}$ for an infant). Three deposition velocities are assumed (u_d=0.001 cm/s, 1cm/s, 10 cm/s) which bracket the entire range (see previous relevant discussion). In the same plots the TEDE50 is translated into mass (μg of Cs-137, middle left ordinate) and activity (kBq of Cs-137, far left ordinate) inhaled by a recipient at a normal breathing rate. Actually, the TEDE50 values include doses from submersion and ground shine but in the case of Cs-137 they are negligible compared to inhalation doses. On the right ordinate the committed TEDE50 is translated into Lifetime Cancer Mortality Risk following the recommendation of Ref.[14]. Figure 1 also yields an approximate estimate of the daily evacuation costs (top scale, at a very plausible reference cost) and the number of people that should be evacuated (bottom scale) according to a 360° potential-hazard zone that will be adopted by the authorities. Alternatively, the bottom scale can be used to estimate the number of people who stand a non-zero probability of receiving a particular TEDE50 (indicated by the relevant curve). All the above numbers are calculated for a population density of 1,000 people per square kilometer, typical of metropolitan city areas and they are linear functions of the total activity of the source, the population density and, the evacuation cost per person-day. For example in areas with ten times larger (smaller) population densities the evacuation costs and the number of the evacuees would be ten times larger (smaller).

In a research project[15] sponsored by the US National Cancer Institute [16] researchers compiled the treatment costs for 932 adult cancer patients who were enrolled in trials between Oct. 1, 1998, and December 31, 1999. They then compared these costs with those for 696 cancer patients who were treated outside of clinical trials. For each patient, treatment costs were calculated for a period averaging 2.5 years from the date of the individual's cancer diagnosis. Included were doctor visits, hospital stays, diagnostic tests and procedures, and all drugs given in a doctor's office, hospital outpatient department, or other treatment settings. Patients' out-of-pocket costs were included as well as costs reimbursed by third-party payers. The researchers concluded that treatment costs for trial participants were 6.5 percent higher than they would have been if these patients had not enrolled in a trial: $35,418 for trial participants and $33,248 for nonparticipants. Therefore in the framework of the linear risk model we can make the plausible assumption that the average treatment cost per cancer is approximately $34000 (2003 FY dollars). Implementing the results of Ref. [15] we can also estimate the minimum health costs per person (far right ordinate) in Fig.1.

In Figure 2 we plot the ground surface contamination (logarithmic scale) as a function of distance from ground zero for the same scenario described in Figure 1. The general notation scheme is the same as in Figure 1 while we also indicate two PAGs zones: preventive and emergency ones, according to Ref [8]. The top scale yields an approximate estimate of the evacuation costs due to ground surface contamination and the operational costs entailed in the necessary decontamination procedures. An approximate estimate of the contaminated area (within a 3600 radius from ground zero) is provided at the far bottom scale in the same figure.

4. Discussion

Figure 1 yields a multitude of conclusion about the health risks that would result from a radiological attack (under the above worst-case scenario) which should be interpreted in the following probabilistic framework: there is **a non-zero probability** that an individual standing at a distance of 300 m (or closer) downwind from GZ will receive a TEDE50 above 0.05 Sv (PAG relocation level, approximately 1.5% additional lifetime cancer mortality risk) in the next 50 years of his life (due to inhalation of the radioactive cloud, submersion in it and ground shine). Therefore, as far as TEDE50 is concerned, all people (282 people at the assumed population density) within a radius of 300 meters from GZ (approximately an area of 0.28 km^2) should be relocated. If they remained without shelter during the plume passage they would all run a risk of inhaling such quantities of the radioactive that could presumably increase their lifetime cancer risk mortality by 1.5%. The relevant daily evacuation costs would be $28,274 while the total additional medical costs (in the framework of the linear risk model) could reach approximately $12,000 (a very small amount indeed since the total life-long exposure would not suffice to cause even a single fatal cancer).

To fully realize the effects of scaling we can observe that if the terrorists used 5000 Ci of Cesium-137 (the equivalent quantity of four teletherapy sources such as the one involved in the Goiânia) the evacuation zone should be extended to a distance of one kilometer from ground zero while the relocated population would amount to 3,140 people, among which four additional cancers might ensue. Similarly, the relevant daily evacuation costs would be $314,000 while the total additional medical costs would be $136,000

Figure 2 shows that there is a non-zero probability that some areas within a radius of five kilometers from GZ can be so heavily contaminated with Cs-137 that emergency PAGs should be applied. Such a decontamination procedure, which should invariably be preceded by radiation detection procedures, would definitely force the authorities to evacuate the population at least within a radius of five kilometers from GZ. Therefore, even if the Cesium-137 inhalation hazard cannot extend to large distances, ground contamination should definitely stretch evacuation distances to (at least) five kilometer from GZ. No agricultural products from such areas should reach the market unless they have been screened for radiological contamination. Large building that could not be decontaminated should be demolished and there would surely be areas that would have to be abandoned for years if decontamination had not been able to reduce the risk below official radiation safety standards.

Moreover, at distances up to ten kilometers from GZ, soil contamination might warrant the application of preventive PAGs. Large scale emergency procedures at a metropolitan city (1,000 people per sq.km.) would entail the evacuation of citizens living in areas of 78 km^2, that is 78,000 people. A daily evacuation cost of $7,800,000 should be anticipated by the authorities while the decontamination operational costs would be $78,000,000 (assuming arbitrarily an operational cost of one million per sq.km which should eventually be scaled accordingly).

Note that the non-zero probability mentioned in the interpretation of Figures 1 and 2 becomes certainty if the assumed meteorological conditions are true and the wind blows constantly and directly towards an individual who never leaves his/her position throughout the entire plume passage. Moreover, we should bear in mind that all Gaussian model predictions are approximate estimates, therefore all the above TEDE50 and ground surface concentrations, given accurate input parameters, might be overestimated/underestimated by a factor of three to five[17]. Of course, even if our predictions are, for example, overestimated by a factor of five, since they are always derived per (1000 Ci) of Cesium-137, we can eliminate the overestimation by assuming that the terrorists might assemble several such sources (e.g. four 1375 Ci source such as the one of Ref[7]) into one single bomb.

It has now become obvious that although a Cesium-137 dirty bomb (especially one that would involve several teletherapy sources with a total activity of a few thousand curies) would not cause any sta

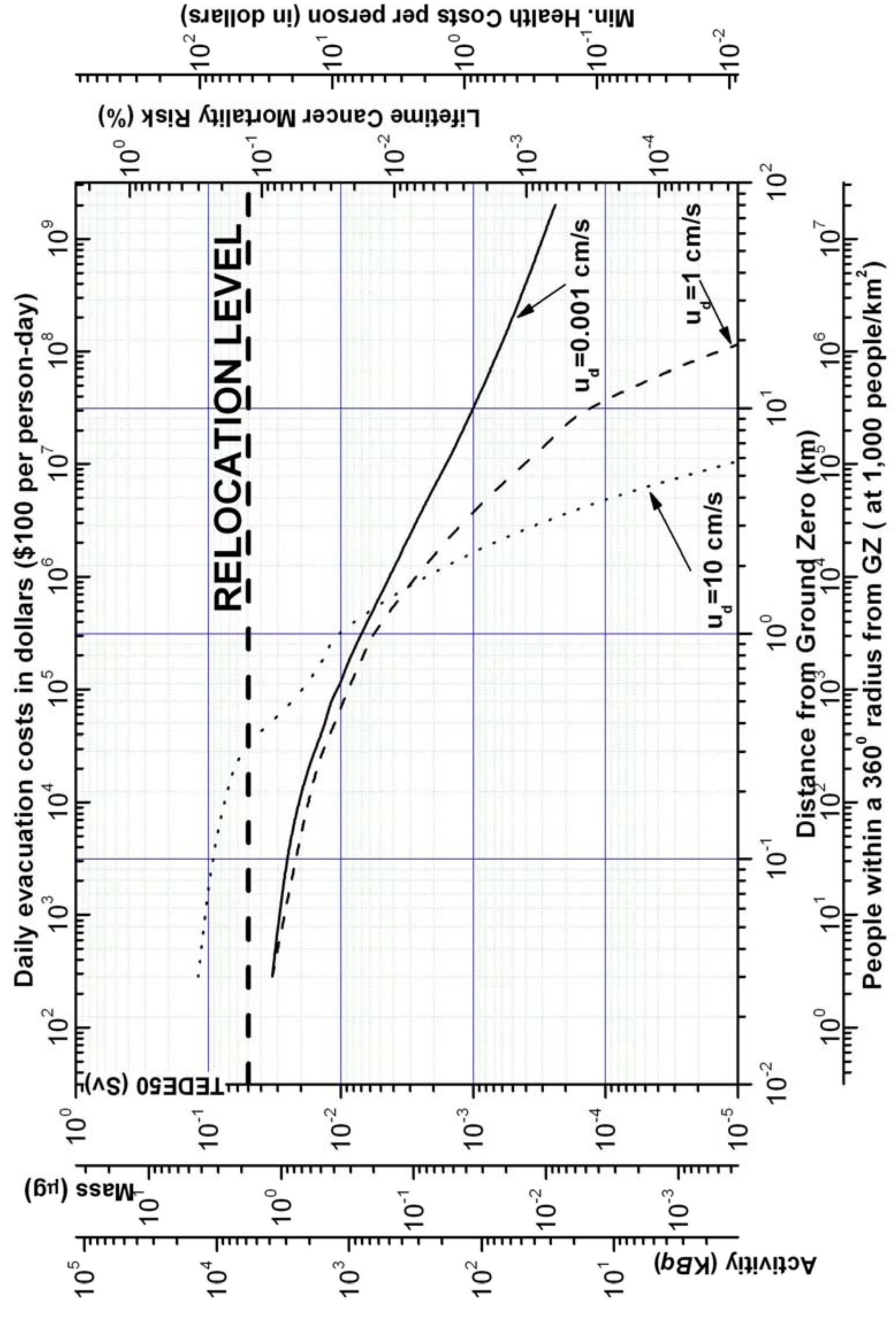

Fig.1. TEDE50 with respect to distance from GZ, for the explosive release of 1000Ci of Cs-137 (one kg of TNT, constant wind speed of 1m/s, inversion layer of 300m, stability categ. F). Solid/Dash-Dotted/Dashed/Dotted curves indicate plumes with deposition velocities of 0.001/0.3/1/10 cm/s respectively. Also shown: Evacuated population, Daily evacuation costs, Lifetime Cancer Mortality Risks and relevant Health Costs (see text for details).

tistically significant cancer mortality current radiation safety standards would impose the evacuation of large areas and the relocation of thousands of people. In a large metropolitan city, such large scale evacuation and relocation operations, apart from costing millions of dollars, would also cause a social and financial crisis with devastating effects.

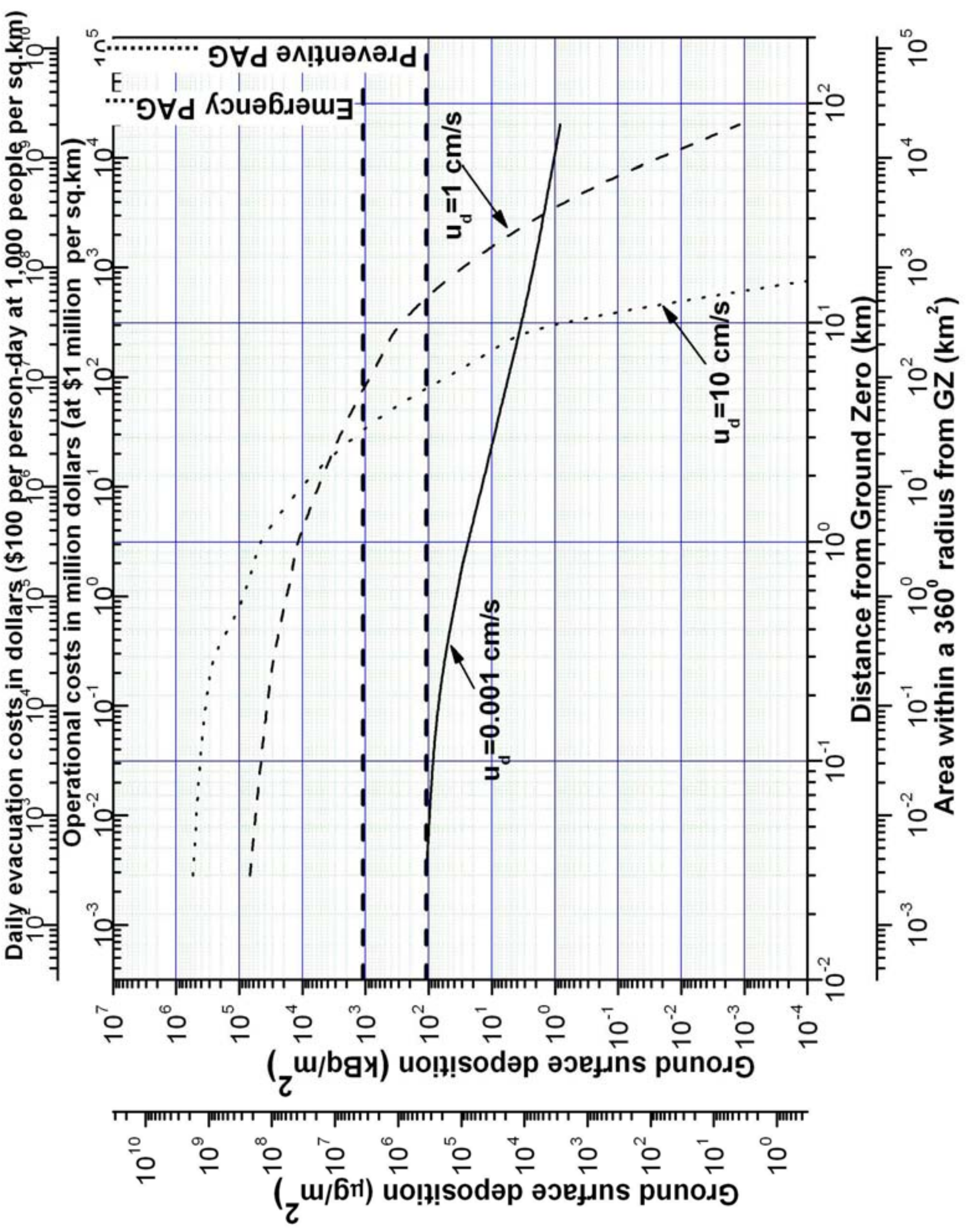

Fig.2. Ground surface deposition with respect to distance from GZ for the explosive release of 1000Ci of Cs-137 (one kg of TNT, constant wind speed of 1m/s, inversion layer of 300m, stability class F). Solid/Dash-Dotted/Dashed/Dotted curves indicate plumes with deposition velocities of 0.001/0.3/1/10 cm/s respectively. Also shown: Daily evacuation costs, and total operational cost. (see text for details).

In view of the above we present the following recommendations:

Because the solubility and ease of dispersion of radioactive cesium chloride used in teletherapy sources makes them a very attractive radiological weapons manufacturers should devise new, more solid and compact sources, which would inhibit the dispersion of the radioactive material.

International and national authorities should extend their preparedness beyond the possibility of a radiological accident involving medical radioactive sources, considering seriously the prospect of a terrorist act.

Nuclear doctors should be educated (and educate the public and the authorities) about the effects of an accidental (presumably explosive) release of the nuclear material involved in diagnostic and therapeutic devices. This way exaggerated fears would be dispelled and the actual dimensions of the risk would be clarified.

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