RADIATION PROTECTION ASPECTS RELEVANT TO RADIOLOGICAL TERRORISM*

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Abstract. *The paper summarizes some basic issues related to the protection of people against the danger resulting from a radiological weapon or the so-called dirty bomb which can potentially be used in terrorist or other malevolent attacks. The properties of radioactive material utilized for this purpose and the quantification of the exposure of affected persons, the prevention measures against and consequences of radiological acts as well as appropriate arrangements aimed at minimizing their impacts are described. In addition, an overview of global initiatives addressing the fight against terrorism in general, including CBRN terrorism, is also presented.*

Key words: *radiological weapon, dirty bomb, radiation protection, quantification of exposure, mitigation measures, CBRN.*

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1. Introduction

Radiation protection is a well-established branch of the broader area related to the use of radiation and nuclear technologies in industry, medicine, science and many other fields.

The main aim of radiation protection is to ensure the adequate safety of workers, patients and the population as well as the environment against harmful effects of ionizing radiation[1]. In most cases where ionizing radiation sources (radionuclides or radiation generators such as X-ray tubes and particle accelerators) and nuclear reactors are used, the health effects are very low and associated risks are lower or comparable with the risks encountered in most industries or even in our everyday life. Only in cases of incidents or accidents the radiation exposure may reach higher levels where visible detrimental effects occur.

The effects at low exposure (normal situation where everything is under control) show only stochastic (statistical) character, i.e., the effect, mostly the development of cancer in an exposed person, appears with certain probability which is proportional to the exposure. On the other hand, at higher exposures, (exceeding a certain relatively high threshold), deterministic effects, which are characterized by some specific health impairments the severity of which is proportional to the exposure, are evidenced.

Since exposure to high radiation doses can lead to serious health effects in people, there is some potential for misusing suitable radioactive sources for terrorist or other malevolent actions. At present, one cannot completely exclude such a situation and we have to be prepared to take appropriate effective measures in order to prevent this from happening, and, if it happens, to be ready to mitigate the impact of such an emergency.

The philosophy of protection against the harmful effects of a radiological weapon or the so-called radiological dispersive device (RDD) is essentially similar to that applied with regard to any other dangerous weapons within the broad category of CBRN (chemical, biological, radiological and nuclear) material or agents.

2. Principles involved in the use of a radiological weapon

The construction of a radiological weapon (dirty bomb)[2,3] is rather simple: it consists of a specific radioactive substance of sufficiently high activity and a dispersive mechanism or explosive material (Fig. 1). The purpose is to disperse the radioactive substance into the air so as to cause the maximum damage to persons in the place of the attack in terms of their external exposure and internal radioactive contamination. The explosion itself can also caused some damage.

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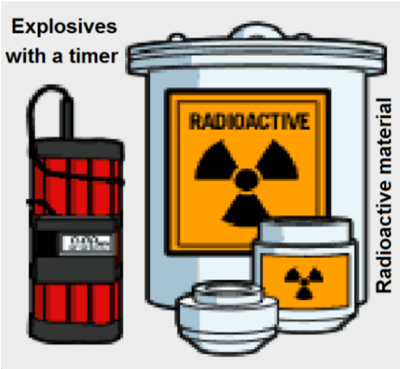

Figure 1. Principal arrangement of a dirty bomb

The purpose of a radiological bomb is to spread radioactive material into the selected populated area and cause panic and anxiety in those who think they are being, or have been, exposed to radiation. The impact of the radiological attack is the radioactive contamination of buildings and the local environment.

Radiological weapons are often discussed together with CBRN where the principle is the same: to use them for terrorist or military attacks. The dangerous and toxic chemical substances and biological agents are used in a similar way as radiological weapons. Nuclear weapons which are based on the fission of heavy nuclei resulting in a release of huge destructive energy as well as severe radioactive contamination are presumed to be out of reach of terrorists.

3. Radionuclides potentially to be used

The most efficient radionuclides would be those with the high activity, not too short half-time, emitting intensive radiation and possessing suitable chemical as well as physical properties.

From a long list of radionuclides frequently used in industry, medicine and some other fields only a few stand out as being suitable for the construction of RDDs. Table 1 shows properties of some of these radionuclides which could be obvious choice for the use in a radiological weapon.

Table 1 The characteristics of typical radionuclides which might be used in the dirty bomb

Radio-nuclide	Physiochemical form	Application of sources and their max. activity
Co-60	Metal	Sterilisation irradiator (400,000 TBq), telethe-rapy machine (1,000 TBq)
Sr-90	Ceramic ($SrTiO_3$)	Radionuclide thermo-electric generator (10,000 TBq)
Cs-137	Salt (CsCl)	Sterilisation irradiator (400,000 TBq), telethe-rapy machine (1,000 TBq)
Ir-192	Metal	Industrial radiography source (50 TBq)
Ra-226	Salt ($RaSO_4$)	Old therapy source (5 TBq)
Pu-238	Ceramic (PuO_2)	Radionuclide thermo-electric generator (5,000 TBq)
Am-241	Pressed ceramic powder (AmO_2)	Well-logging operations (1 TBq)
Cf-252	Ceramic (Cf_2O_3)	Well-logging operations (0,1 TBq)

There should be strict regulatory control over these sources in order to prevent their theft or any unauthorized access.

It is obvious that not all radioactive sources are equally dangerous. Special attention should be paid to high-activity sources where categories 1 and 2 (in accordance with the IAEA categorization[4]) should be considered in the first place. Category 1 includes sources which, if not safely managed or securely protected, would be likely to cause permanent injury to persons who handled them, or were otherwise in contact with these sources for more than a few minutes. It would most probably be fatal to be close to these sources especially if they were not properly shielded

On the other hand, the sources of category 2 are such sources which, if not safely managed or securely protected could, result in severe injury to any person who handled them, or was otherwise in contact with them for a short time (minutes to hours). It could possibly be fatal to be close to such unshielded sources.

4. Quantification of the exposure

In principle, persons can be affected by external penetrating radiation emitted by radionuclides present in the source and by internal exposure produced by radiation emitted by radionuclides which enter the body, in particular by inhalation or ingestion.

In the quantification of exposure of persons, two cases should be considered: low level exposure where only stochastic effects (induction of cancer and genetic disorders) can be expected, and high exposure which can cause harmful tissue reactions[1].

The strength of radioactive sources is usually quantified in terms of the quantity of activity measurable in Bq (becquerel) which is is extremely small unit (1 disintegration per second)and this is why prefixes such as k (kilo), mega (M), giga (G) and even tera (T) are often used.

For the assessment of stochastic effects a universal quantity, the effective dose, has been introduced. This quantity depends essentially on the average doses to major individual organs and tissues in the human body. All these doses have to be weighted by relevant factors reflecting various degrees of damage initiated by different types of radiation as well as specific biological sensitivities of individual organs and tissues exposed.

The quantification of the detriment due to harmful tissue reactions is usually based on the dose with the specification of irradiation conditions and the type of radiation. Recently, the unit of Gy-Eq has been used to take into account the specific radiobiological effectiveness (RBE) of radiation exposure at high doses applying the quantity RBE-weighted dose (Fig. 2).

4.1. External exposure

Since the average dose to individual organs cannot be directly monitored, other quantities (operational quantities) which can be measured are used instead. These quantities approximate the relevant effective dose. Two types of such quantities were introduced for this purpose: the personal dose equivalent (for the monitoring of persons), and the ambient dose equivalent (workplace monitoring). These quantities reflect the contribution of the external exposure to the total effective dose.

4.2. Internal exposure

This exposure is due to radionuclides which enter the body by inhalation of contaminated air or by ingestion of contaminated food and water. In the case of radiological attack, it is sufficient to consider only the inhalation pathway. The contribution of the internal exposure to the total effective dose, called the committed effective dose, is assessed by means of the activity which entered the body (intake) where the type of a radionuclide and its chemical and physical properties must be taken into account.

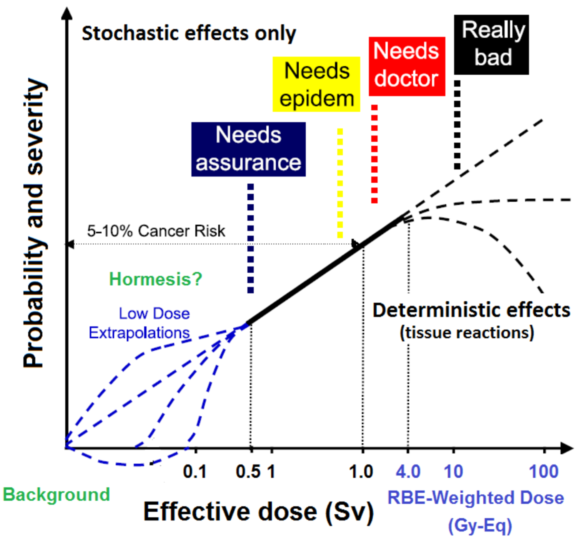

Figure 2. Probability and severity of biological effects vs. the exposure levels expressed in Sv and Gy Eq (everything suggests that at low exposures only stochastic effects occur while at higher exposures deterministic effects occur; in exposure range between these two areas more epidemiological studies are required to establish the relationship the exposure vs. harmful effects).

4.3. Total exposure

The total exposure, in terms of the effective dose (E), represents the sum of the contributions from external and internal exposure which are expressed by relevant additive quantities, namely by the sum of two components, i.e., external (E_{ext}) and internal (E_{int}) components

$$E = \sum_T w_T \sum_R w_R D_{T,R} = E_{ext} + E_{int}$$

where $D_{T,R}$ is the average (organ) dose to the organ or tissue T due to the radiation of type R, w_R is the radiation weighting factor related to the radiation R and w_T is the tissue weighting factor associated with the organ or tissue T.

The external component of the total effective dose can be assessed by personal dosimeters calibrated in the personal dose equivalent $H_p(d)$ or by radiation monitors calibrated in the ambient dose equivalent $H^*(d)$ where d is the depth corresponding to the point under the surface of the body given in mm. For whole body exposure by penetrating radiation d is taken to be 10 mm. For the assessment of the skin dose, a depth of 0.07 mm is considered.

On the other hand, the internal exposure is determined by the measurement of the radionuclide intake expressed by the activity (A) using relevant conversion factors for the inhalation $e_{j,inh}$ and for the ingestion $e_{j,ing}$ attributed to a radionuclide of type j. The external component (E_{ext}) is usually referred to as the committed effective dose over 50 years following the intake – $E(50)$.

Consequently, the total effective dose can be expressed in the following form

$$E = E_{ext} + E(50)$$

where depending on the type of external radiation monitoring

$$E_{ext} = H_p(10)$$

or

$$E_{ext} = H^*(10)$$

The total committed effective dose can be expressed as

$$E(50) = \sum_j e_{j,inh}(50) \,.\, I_{j,inh} + \sum_j e_{j,ing}(50) \,.\, I_{j,ing}$$

where $I_{j,inh}$ and $I_{j,ing}$ are the inhaled and ingested activity of a radionuclide j, respectively.

In cases of external exposure to low-penetrating radiation, e.g., beta particles, $H_p(10)$ cannot sufficiently assess the effective dose. In such cases $H_p(0.07)$ may be used to assess the equivalent dose to the skin and its contribution to the effective dose by applying the tissue weighting factor of 0.01 for the skin.

4.4. Estimation of the exposure caused by radioactive contamination

While external exposure is facilitated through penetrating radiation such as gamma or neutron radiation, internal exposure is due mainly to the absorption of weakly penetrating radiation (alpha and beta particles) emitted by radionuclides which enter the body (primarily by inhalation). One has to realize that while external exposure is received only during the period of exposure to radiation, internal exposure is initiated by the intake of radioactive material but exposure occurs during the whole period this material is in the body.

In order to assess the impact of individual radionuclides to the total exposure, the dose rate from external radiation and the committed effective dose caused by intake can indicate the approximate degree of corresponding health effects (Table 2).

Table 2. The rough conservative estimates of external and internal exposures of selected radionuclides which would also depend on irradiation conditions and parameters of inhaled particles (based on [5, 6, 7])

Radio-nuclide	Dose rate from a 1 GBq point source at a distance of 1 m (μSv/h)[a]	Committed effective dose[c] per 1 MBq of an inhaled radionuclide (mSv)
Co-60	306	30
Sr-90	x[b]	150
Cs-137	76	6.7
Ir-192	113	6.2
Ra-226	173	3,500
Pu-238	0.2	43,000
Am-241	5	40,000
Cf-252	1 200 (neutrons)	20,000

[a] At a shorter distance the exposure will be much higher,
[b] Depending on the contribution from bremsstrahlung which is essentially related to the material surrounding the source,
[c] Maximum estimated values due to inhalation.

In specific situations we have to consider all relevant components contributing to the total exposure which include:

- External exposure from contamination on outdoor surfaces, including ground (the exposure depends on the type of the radionuclide, its surface activity and geometry configuration);
- External exposure from contamination on indoor surfaces, floors, walls, furniture etc (the exposure depends on the same factors as above);
- External exposure from contamination on clothing and human skin (the exposure depends on the type of radionuclide and surface activity, a correction for the absorption in cloth should be taken into consideration);
- External exposure from the passing contaminated plume (the exposure depends on the type of the radionuclides and activity concentration within the plume);
- Internal exposure from inhalation during plume passage (the same as above and also physical and chemical characteristics of the radioactive substance);
- Internal exposure from inhalation of contaminated air due to the re-suspended radioactive dust (the surface activity, characteristics of the ground as well as meteorological conditions).

Other factors influencing radiation and radioactive contamination level and its distribution may include means of dispersal (e.g. explosion, spraying, fire) and local topography, location of buildings, and other landscape features. If all relevant parameters are known, the situation can be simulated using mathematical models and codes.

A number of methods have been developed for assessing the exposure in each of the encountered situations. Some simple calculators are also available to evaluate exposure based on parameters which can be obtained from monitoring results (e.g., reference[7]).

In principle, two different types of monitoring can be used to assess the situation around the place of a radiological attack, namely devices for measuring external radiation and surface contamination, and air samplers to measure the activity concentration in the air based on the airborne radioactivity sampling. In addition to these workplace (area) monitors, personal dosimeters can track the exposures received by an individual.

In most cases, appropriate general purpose survey meters using scintillators, GM tubes, ion chambers or semiconductor detectors are used. Some of this equipment can also be used for sophisticated searching and identification of unknown radioactive sources.

The results of the monitoring, or the information about the activity released, can serve as a basis for setting up zones characterized by specific external radiation levels or radioactive contamination.

5. Consequences of radiological attack, protection and mitigation measures

The impact of the radiological attack depends on the type and activity of radioactive material dispersed. The distribution of radioactive contamination will always be affected by the morphology of the place and meteorological conditions in the time of the attack.

5.1. Impact on people and the environment

Most of people in the place where radiological weapon was used receive relatively low exposure which will only contribute to stochastic effects (i.e., the probability of cancer occurrence sometime in the future). A small number of persons may receive high enough exposure to generate deterministic effects.

One concern of radiation exposure is an elevated risk of developing cancer later in life, although studies have shown that radiation is a relatively weak carcinogen. Exposure at the low radiation doses expected from a RDD would increase the risk of cancer only slightly over naturally occurring rates.

Some further impacts might involve disruption to lives and livelihoods as the contaminated area is being cleaned up. This impact could continue even long time after the site has been cleaned up and people would be rather reluctant to return to the affected area.

The most dangerous consequences would be associated rather with the creation of panic and chaos which can result in many casualties especially when the place of the attack is heavily overcrowded. Some economic impact can also be expected because of the radioactive contamination of the surrounding areas.

The contamination of the area around the epicenter of the attack can be mapped in terms of ambient dose equivalent rate (in $mSv.h^{-1}$) or surface contamination (in $Bq.m^2$). The isolines of the dose rate caused by a radioactive plum affected by the wind direction in a town can be presented on suitable maps. This information is very useful to assess the exposure received by rescue workers engaged in the mitigation operations. This is also important for the selection of suitable personal protective equipment.

In some emergency situation there always may be some people exposed to high radiation doses. Radiation sickness, known as acute radiation syndrome (ARS), is a serious illness that occurs when the entire body (or most of it) receives a high dose of radiation, usually over a short period of time. Many survivors of the Hiroshima and Nagasaki atomic bombs in the 1940s and many of the firefighters who first responded after the Chernobyl NPP accident in 1986 became ill with ARS.

The first symptoms of ARS typically are nausea, vomiting, and diarrhea. These symptoms will start within minutes to days following the exposure. They will last for minutes up to several days, and may come and go. Then the person usually looks and feels relatively healthy for a short time, after which he or she will become sick again with loss of appetite, fatigue, fever, nausea, vomiting, diarrhea, and possibly even seizures and coma. This seriously ill stage may last from a few hours up to several months.

5.2. Prevention measures

The best prevention arrangement against radiological terrorism would be strict control and security of all high-activity radioactive sources including their production, transport, use, storage and disposal. Adequate measures should also be introduced at the borders to prevent illicit trafficking where radioactive sources may be smuggled from countries with insufficient control to other countries where they may be used for malevolent actions.

To construct an RDD, a terrorist group must obtain radioactive materials, use those materials to fabricate a weapon, deliver the weapon to the attack site, and detonate the device. Each of these steps suggests some specific measures that can be used to help prevent an attack. Obtaining radioactive materials requires access to the radioactive sources which must be either purchased or stolen. This is why keeping any high-activity radioactive material under strict control is so important.

5.3. Protection measures and mitigation of consequences

Any protection measures and tool are effective only in cases when they are applied correctly. This refer not only to emergency and rescue workers but also to members of the general public. The first responders are highly qualified and experienced professionals who can assess the emergency situation realistically. The perception of any risks, including the risk due to the exposure, is highly exaggerated by the public the opinion of which is usually based on the information from rumours and unreliable sources. Therefore, it is important to communicate with the public not only after the accident but rather continuously making use various appropriate contacts including disseminating correct information through the mass media.

The psychological effects from the fear of being exposed may be one of the major consequences of a dirty bomb. It is important to ensure sound understanding of the situation and cooperation of the public with authorities involved in the mitigation of an attack or accident.

Some simple instruction provided to the public may significantly reduce the impact of an emergency. If people are near the site of the detonation of a dirty bomb or release of radioactive material, they should be advised to:

- Stay away from any obvious plume or dust cloud;
- Cover the mouth and nose with a tissue, filter, or damp cloth to avoid inhaling or ingesting the radioactive material;
- Go inside a building with closed doors and windows as quickly as can be done in an orderly manner and listen for information from emergency responders and authorities;
- Remove contaminated clothing as soon as possible and place them in a sealed container such as a plastic bag (the clothing could be used later to estimate a person's exposure);
- Gently wash the skin to remove possible contamination.
- Those already inside an intact building should stay there and close windows and reduce outside air intake if possible.

People should make sure that no radioactive material enters the mouth or is transferred to areas of the face where it could be easily moved to the mouth and ingested. One obviously has not to eat, drink, or smoke. Questions such as when it is safe to leave a building or return home, what is safe to eat and drink and when, and how children will be cared for if they are separated from their parents would be answered by authorities who would have to make decisions on a case-by-case basis depending on the many variables of the situation.

Professionals engaged in rescue and mitigation operations are equipped with special personal protective equipment and other relevant accessories to ensure their protection.

5.4. Global initiatives in fighting radiological terrorism

Radiological terrorism as well as terrorism related to other dangerous CBRN materials has become a global problem and, consequently, it has to be fought worldwide[8]. Efficient cooperation and coordination of all countries and international organization has to be mobilized. In this regards, an important role is played by the United Nations, and especially its agencies the IAEA (International Atomic Energy Agency) and the UN Interregional Crime and Justice Institute). The EU with its Joint Research Centre (JRC) has become very active in this field recently. Interpol and Europol also play some special role in this context.

The EU CBRN Action Plan[9] represents the main EU policy document aimed at the protection of the EU Member States against CBRN threats. The Action Plan constitutes a political commitment and may be considered as a roadmap of intentions and measures to be taken in the coming years. It recommends actions concerning prevention, detection, preparedness and response, as well as horizontal measures in the context of high-risk CBRN materials. As to its implementation, the Action Plan should be conducted with full respect for international law, including human rights and the principle of the rule of law.

The EU Action Plan includes some specific prevention measures as a) Developing lists at the EU level of high-risk CBRN materials; b) Identifying and reporting suspicious transactions and behavior; c) Enhancing security and control of high risk CBRN materials; facilities and transport infrastructure; d) Contributing to the development of a high security culture of staff, improving information exchange, e) Strengthening the import/export regime; f) Enhancing cooperation on the security of CBRN as well as dual material.

The Plan is also focused on efficient preparedness measures including: a) Improved emergency planning, b) Stronger countermeasure capabilities, c) Upgraded domestic and international information flows regarding CBRN emergencies, d) The development of new modelling and better decontamination and remediation capacities, and e) Ensuring greater capacity to conduct criminal investigations.

In accordance with the EU requirements, the responding measures should require: a) Enhanced international cooperation, b) Improved lines of communication with the public; c) More robust information tools for CBRN security, d) Advanced training courses for first responders, e) Improved personnel security, and f) Ensuring that legislation is put in place to tackle CBRN terrorism.

The goals of EU CBRN policy to minimise the threat and damage have also to address the following aspects: a) Use of a risk-based approach to security, b) Effective protection of CBRN materials including their storage and transport, c) Improved exchanges of security-related information among countries, d) Further development of detection systems, and e) Provision of the necessary tools to manage CBRN incidents and accidents.

The EU CBRN Centres of Excellence (CoEs) Initiative[10] was launched in 2010 in response to the need to strengthen the institutional capacity of countries outside Europe to mitigate CBRN risks, including criminal activities (e.g. CBRN proliferation or terrorism), natural disasters (e.g. swine flu) and accidental disasters (e.g. Bhopal or Fukushima).

The initiative addresses the mitigation of and preparedness against risks related to CBRN material and agents. The origin of these risks can be criminal, accidental or natural. The Initiative seeks to boost cooperation at regional and international levels, and to develop a common and coherent CBRN risk mitigation policy at the regional level. Risk mitigation comprises prevention, preparedness and post-crisis management. The initiative is implemented and funded by the European Commission in cooperation with the Joint Research Centre (JRC), the United Nations Interregional Crime and Justice Research Institute (UNICRI) and a governance team. The Initiative is implemented with the technical support of relevant experts from EU Member States, international organisations and individual experts in the field[7,8].

The establishment of regional CoEs is a cornerstone of these activities: they offer a coherent and comprehensive approach covering legal, regulatory, enforcement and technical issues. The European Commission (EC) adopted a policy package on CBRN security with the aim off strengthening the protection of EU citizens and improving protection against CBRN danger in other regions.

Within the CBRN CoE structure a series of Regional Secretariats (Fig. 3) have been established. The CBRN CoE Regional Secretariats will operate in the following eight regions: African Atlantic Façade; Central Asia; Eastern and Central Africa; Gulf Cooperation Council Countries; Middle East; North Africa; South East Asia; and South East Europe, Southern Caucasus, Moldova and Ukraine.

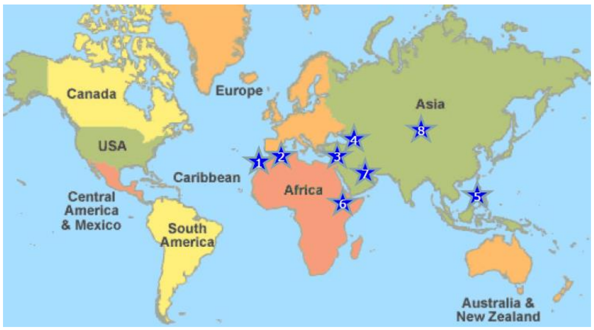

Figure 3. Geographical distribution of Centres of Excellence in individual regions: 1-Rabat, 2-Algier, 3-Amman, 4-Tbilisi, 5-Manila, 6-Nairobi, 7-Abu Dhabi.

5. Conclusion

Dirty bombs use conventional explosives to spread radioactive material. The conventional explosion may cause a number of casualties, but deterministic effects from the radiation are unlikely. The panic and fear of people on the scene, however, will probably have a more significant impact than any casualties or environmental damage. Although there is concern that terrorist groups may use dirty bombs, so far none has actually been detonated. This does not mean that we can ignore such threats. On the contrary, because of a potential possibility of the use of this kind of weapon, members of the public and especially relevant national Authorities should be prepared for a terrorist attack aimed at spreading radioactive material.

The disruption to live and commerce that may especially occur if a RDD is detonated in a notable public and commercial area is more important in some situations. Consider a RDD being used in a major historical city with a large commercial centre and tourism trade. A long lived radionuclide could render the area unusable for decades depending on activity and decontamination issues. This would have not only a large financial impact but a significant psychiatric impart on not only the local population but the country at large.

Communication with the public is essential in order to provide them with relevant basic information about the nature and potential impact of a dirty bomb, and especially how to behave in a situation following the use of such a bomb in order to protect against exposure to radiation and radioactive contamination to minimize health effects.

The concerns of both society and individuals about the adverse effects from radiation are logically amplified many times when radiological terrorism is considered. The spectrum of possible events includes industrial sabotage, the use of an explosive or nonexplosive radiological dispersal device, and the placement of a radiological exposure device in a public facility; we may also expect the use of an improvised nuclear device sometime in the future.

Planning is done on the basis of scenario modelling; medical response planning includes medical triage, the distribution of victims to care by experienced physicians, the development of medical countermeasures to mitigate or treat radiation injury, counselling and appropriately following exposed or potentially exposed people, and helping the local community develop confidence in their own response plan. Optimal response must be based on the best available science. This requires scientists who can define, prioritise and address the gaps in knowledge with a range of expertise from basic physics to biology to transnational research to systems expertise to response planning to healthcare policy to communications. Not only are there unique needs and career opportunities, but there is also the opportunity for individuals to serve their communities and country with both their education regarding radiation effects and by formulating scientifically based government policy.

Substantial collaborative efforts have to be established and maintained among relevant national agencies and between the government and international partners and local responders to ensure our collective safety.

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