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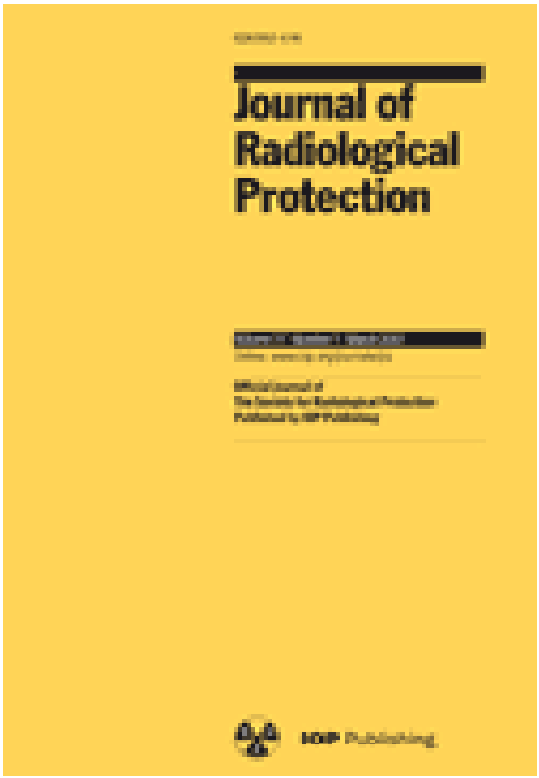

Radiation accidents over the last 60 years

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Abstract

Since the end of the Second WorldWar, industrial and medical uses of radiation have been considerably increasing. Accidental overexposures of persons, in either the occupational or public field, have caused deaths and severe injuries and complications. The rate of severe accidents seems to increase with time, especially those involving the public; in addition, accidents are often not immediately recognised, which means that the real number of events remains unknown. Human factors, as well as the lack of elementary rules in the domains of radiological safety and protection, such as inadequate training, play a major role in the occurrence of the accidents which have been reported in the industrial, medical and military arenas

Table 1. An example of classification for severe radiation accidents, in terms of chronology of recognition and management difficulties.

	Easy to manage (few victims)	Difficult to manage (technically and medically)	Catastrophic (health and environment consequences)
Immediate recognition	France 1981 Norway 1982 Israel 1990 Belarus 1991 Russia 1997 Chile 2005	Peru 1999 Japan 1999	Ukraine 1986
Delayed recognition	Mexico 1962 Italy 1975 Algeria 1978 Morocco 1984 Salvador 1989 Spain 1990 France 1991 Vietnam 1992 Estonia 1994 Egypt 1994 Georgia 2001 France 2004–05 France 2004 Belgium 2006 Senegal 2006 Tunisia 2008	USA 1974–76 UK 1982–91 USA 1985–87 USA 1992 China 1992 Georgia 1997 Panama 2000–01 Poland 2001	Mexico 1983 Brazil 1987 Costa Rica 1996 Thailand 2000
Secret (military/political)		USSR 1961, 1968 Sahara 1962 UK 2006	Marshallese islands 1954 USSR 1957 Spain 1966 Greenland 1968

Table 1 does not include accidents causing exclusively internal exposures. From a historical point of view, this choice may seem arbitrary, since the first exposures to radiation that have caused severe health damage were related to medical practices when deleterious effects of radiation were unknown

- This is the case of the use of ^{232}Th as a contrast material for angiographies and of radium administered for various reasons between the 1930s and 1950s to thousands of patients, resulting in excesses of liver cancers, angiosarcomas, osteosarcomas and mesotheliomas.

- In the 1940s and 1950s, before the strict codification of the handling of sealed sources in nuclear medicine, repetitive contaminations of the workforce were not rare.

- Between 1960 and 1980, 11 fatalities were reported due to internal exposure only, most of them originating from errors in the medical administration of radiopharmaceuticals. A demonstrative example is the dramatic case in 1968, which happened after the injection of an activity of ^{198}Au one thousand times higher than the prescribed one (confusion between μCi and mCi) in the course of a hepatic exploration and which ended in the patient's death.

Accidents that are recognised immediately

Easy to manage: few victims
(workers in industrial field)

✓ France 1981: *three* operators were severely exposed during the loading of a new radiotherapy device with a 137 TBq ^{60}Co source. This accident resulted in amputations of both hands for two men and partial amputation of the prehensile part of the right hand for the third operator.

✓ Norway 1982: *an experienced worker* entered the exposure room as the 2.4 PBq ^{60}Co source was in operating position. It was estimated that his mean whole body dose, although heterogeneously distributed, was around 20 Gy. The victim died 13 days after exposure

✓ Israel 1990: *a worker* entered the exposure room despite two conflicting warning signals and consequently was exposed to the 12.6 PBq ^{60}Co source, resulting in a whole body dose between 10 and 20 Gy. Although the victim received high quality medical care, he died 36 days after the accident

✓ Belarus 1991: accident similar to the two previous ones; *a worker* was exposed to a 28 PBq ^{60}Co source with a dose estimated between 12 and 16 Gy. The patient survived more than three months and died of respiratory complications

✓ Russia 1997: *an operator* was exposed to a high neutron flux. The resulting dose was estimated at about 20 Gy, but some regions received up to 60 Gy. The victim died on the third day

✓Chile 2005: *three workers* were exposed to a ^{192}Ir industrial source which was lost in a working site. One of them was severely exposed, in particular at one hand and the buttock, after he placed the source in his pocket, where it stayed for about 15 min. The patient was evacuated to France. The patient was back in his country after six months in satisfactory healing conditions

Accidents that are recognised immediately

Difficult to manage *(the management of a radiation accident meets difficulties as soon as several people are involved. Most of the time, difficulties are of medical nature)*

✓ Peru 1999: *a welder* placed in the back pocket of his trousers a 1.37 TBq ^{192}Ir industrial source that he had found on the ground, continued his work for 6 h and went back home. During the 10 h preceding the source recovery by the plant staff, four family members (his wife, her breastfeeding 18 month old child and two older children) were also exposed to the source. The welder was hospitalised three months later in France. One year after exposure, the patient was in a hopeless situation.

✓ Japan 1999: *three workers* were severely exposed to mixed neutron–gamma radiation (ratio 60/40) in a fuel conversion plant during the wrong processing of an enriched uranium solution This resulted in a critical excursion. The most exposed victim, with about 10 Gy, died 83 days after the accident; the second worker received about 6 Gy and died 211 days after. The third worker, who received less than 3 Gy, was not confronted with any problems that modern medicine could not solve. Approximately 200 residents living in a 350 m radius were evacuated, 90% of them receiving less than 25 mSv

Accidents that are recognised immediately

Catastrophic accidents, with a large number of victims: Chernobyl

An example of a catastrophic event that was immediately recognised is the *Chernobyl* nuclear plant accident, *Ukraine* (1986), which, on its own, brought together a large number of direct and indirect health consequences and affected the whole of the northern hemisphere. These consequences were not only purely medical; large regions of the USSR were contaminated by radioactive materials that were released by the plant. Two radionuclides raised serious problems, because of their potential effects and the released quantities: 85 PBq of ^{137}Cs and 1760 PBq of ^{131}I.

Three republics—Ukraine, Belarus, and Russia—had large parts of their territories with ^{137}Cs deposits higher than 37 Bq m^{-2}. During the week after the accident, it was proceeded to the evacuation of populations, which resulted in the relocation of more than 135.000 individuals. Between 1986 and 1990, about 645.000 people, the 'liquidators', were employed for site cleaning and decontamination: it is assumed that most of their doses were between 50 and 250 mSv (with an average at 100 mSv). However, the first day rescuers most probably received much higher doses, up to 750 mSv. The Chernobyl accident health consequences concern three categories of individuals: the rescuers (plant personnel, firemen and medical rescuers), the liquidators and the population in general.

Among the rescuers the total number of deaths was 58. Data on liquidators are difficult to interpret, especially because of the collapse of the USSR.
Within the population, while no excess of leukaemia has been demonstrated, there is an unquestionable high rate of childhood radiation-attributable thyroid cancer in specific regions of Ukraine, Belarus and Russia. Between 1990 and 1998, the total number of thyroid cancers detected in children living in these affected regions and who were less than 18 years old when the accident occurred was around 1800. This value corresponds to a 10–100-fold increase of the natural background of this very rare childhood cancer. Ten years after the catastrophe, it was estimated that the total number of thyroid cancers that could be expected could reach 10.000 cases. Recent reports confirm these predictions.

The Chernobyl accident had also effects caused by drastic changes of societal, political and economic impact: in 1993 life expectation had decreased to 59 years for men (from 65 in 1987).
In addition, it was recognised in 1992 that fear of radiation may have caused more harm than radiation itself.

Accidents with delayed recognition

The most important accidents, independently of the number of victims, can be summarized as follows.

Workers in industrial field

✓ In Brescia, Italy (1975), at a cereal irradiation facility with four ^{60}Co sources *a worker* entered the irradiation room by climbing onto the conveyor belt. His first symptoms of exposure (nausea, vomiting, headache and erythema) were attributed to insecticides. For more than two days, his exposure to an unshielded 500 TBq source remained unknown to the physicians. He died 13 days after his exposure; his whole body dose was evaluated at 12 Gy, non-uniform.

✓ In San Salvador, El Salvador (1989), *three workers* at an industrial sterilisation plant were exposed to a ^{60}Co source of 0.66 PBq by the time of exposure, when attempting to unblock the source holder. Radiation exposure was only identified when a burn appeared on the third day. The three victims were transferred to a specialised hospital in Mexico City. Two patients each had a leg amputated; one of them had his second leg amputated and the other one developed a respiratory complication, which caused his death.

✓ In Forbach, France (1991), *three handlers* at a linear accelerator were exposed during repeated reparations and maintenance on the device, while only the electron source was cut off but accelerator voltage maintained in order to save time. Under these conditions the residual dose rate was a few gray per second. When the first skin injuries appeared, they were attributed to sunburn and it was only after several days that the cause was suspected, when the serious health deterioration in one of the victims justified his hospitalisation. This patient underwent repeated skin grafts during a whole year. He was in a precarious state up to his death in spring 2007, 16 years after exposure.

✓ In Hanoi, Vietnam (1992), at a physics institute *an engineer* suffered severe overexposure of both hands from a linear accelerator beam, while positioning a sample for analysis. Although the victim was immediately aware of the accidental exposure and reported it, his burns were only linked with the real initiating event two weeks later, when his clinical state became serious. Four months later, he was transferred to France, where the only possible therapeutic decision was to amputate his right hand fully and his left hand partially

Accidents with delayed recognition

Abandoned radioactive sources

✓ In Mexico City (1962), a whole family was wiped out by a ^{60}Co source, found on a dump. *A 10 year old boy* died after one month, followed by *his mother and 3 year old sister* a few months later; it is only at this time that the origin of these three deaths was discovered. Death of *another relative* could not be avoided seven months after the accident. The father was the only family member who survived, because of the short periods of time he spent at home

✓ In Setif, Algeria (1978), and Casablanca, Morocco (1984), ^{192}Ir sources (925 and 600 GBq, respectively) were lost and picked up by families. Diagnoses were only made after 38 and 80 days, respectively. In all, the Algerian accident caused the death of *a 47 year old woman*, four serious life-threatening whole body exposures of *four women* aged 14–20 and multifocal localised overexposures in *two young boys* aged 3 and 7. The Moroccan accident resulted in *eight or even more deaths*: four young children died from severe aplasia a few days after their parents, and several relatives were affected by haematological depression at various degrees.

✓ In Juarez, Mexico (1983), a teletherapy machine consisting of some 6000 ^{60}Co pellets (15.6 TBq) was dismantled without subsequent control of disposal. The machine was sold to a scrap yard and then to foundries in Chihuahua and Durango, resulting in various metal products becoming contaminated. The problem was discovered by chance six weeks later when concrete reinforcing irons triggered alarms in the Los Alamos Military Centre (USA). It was estimated that *4000 individuals from the general public were exposed* to non-trivial doses. No death occurred, mainly because exposure was spread over time. The environment was declared safe four months post-accident, which necessitated control of 17.000 houses

✓ In Goiânia, Brazil (1987), a radiotherapy source, made of highly soluble ^{137}Cs chloride (51 TBq), was dismantled without subsequent control of disposal and sold to two scrap merchants. Their first signs of ARS (Acute Radiation Syndrome) were attributed to a tropical disease, and two weeks elapsed before the accident was recognised. During this two week period, the two dealers continued to dismantle the device, resulting in the large dissemination of radioactive powder and subsequent exposure of their families. Children were especially exposed, since they played with this 'magic' luminescent powder. *Four victims died* and *28 had to undergo surgery*, consisting in grafts or amputations. The town and its surroundings were considered acceptably free of radioactive contamination three months later.

✓ In Xinzhou, province of Shenxi, China (1992), a worker found a 100 GBq ^{60}Co source in a deep hole in the ground and took it home. The hole happened to be an ancient site for radiation source storage, closed in 1980 after 20 years of operation. The worker kept the source in his trouser pocket. *He* and *his father and his brother died after two and three weeks* in hospital, their death being attributed to an infectious disease. In the meantime, his wife, who assisted in care, and about 100 people (nurses, physicians, visitors and workers who took care of the waste transportation) were exposed to the source. It was only after the patient deaths that the real cause of the injuries was discovered. The source was found more than two months after its discovery.

✓ In Meet Halph village, near Cairo, Egypt (1994), a 61 year old farmer found in the sand a 1 TBq ^{192}Ir source, lost by a welding company. It seems that this loss had not been reported to national authorities. It was only after *two deaths* (the farmer and a 9 year old boy, 30 and 42 days after exposure, respectively) and transfer of family members to a Cairo hospital that the cause was recognised. Seven victims, who had been exposed for seven weeks, survived doses of 3–4 Gy. During this period of time, about 150 inhabitants of the village received doses around 25–150 mGy, and about 100 rescuers 15–100 mGy

✓ In Tammiku, Estonia (1994), an abandoned military 1.6 TBq ^{137}Cs source was stolen from a waste repository (devoted to medical low activity β waste) and kept in a house for 27 days. During this period of time, the *death of the young man*, who had placed the source in his pocket before keeping it at home, was attributed to traumatic toxaemia. It was not until a 14 year old boy (the previous victim's nephew) was found suffering from a haematological disorder and hand burns that the origin of the diseases was discovered by a well educated paediatrician. The alarm was raised in the night following recognition of the radiation accident nature, and all the inhabitants in a 200 m radius around the house where the source was recovered evacuated.

✓ At the Lilo Training Centre, Georgia (1996–1997), *11 young frontier guards* were exposed to some of the several military radioactive sources, previously used for nuclear war training, which had been abandoned by the Soviet troops when they left the country. Four severely injured victims were evacuated to France and seven to Germany. For the first time in the case of skin radiation injuries, artificial skin grafts were used for deep lesions and demonstrated their efficiency

✓ In Samut Prakarn, Thailand, near Bangkok (2000), a teletherapy 15.7 TBq ^{60}Co machine, which had never been used since it had been bought in 1974, was stolen by four scrap collectors and rapidly resold. For almost three weeks, 13 people were exposed. Ten of them were hospitalised for haemorrhages and burns. The cause was recognised very late. *Three victims*—18, 23 and 44 years old—*died* during the second month following the theft. Information on the other injured individuals remains contradictory; probably in order to avoid any panic among the population the national authorities were remarkably quiet. Nevertheless, it could be established that about ten people necessitated intensive medical care and some required amputations. Some 44 individuals exhibited signs that might have been due to an overexposure. This accident was considered as a national catastrophe.

✓ Near a village named Lia, Georgia (2001), a few hundred kilometres west of Tbilissi, *three woodcutters* found on the ground two metallic cylinders around which snow was melting. During the following cold night, they used these devices as heating sources. After a few hours, all three presented classical prodromal signs of ARS (Acute Radiation Syndrome). The radiological cause was recognised three weeks later, when the suspect cylinders were discovered to be thermoelectric generators functioning with a 1.3 PBq ^{90}Sr source. All three had their backs severely burned and in addition one showed injuries on his hands and legs. Three months later, available medical means were judged insufficient and two patients were transferred to a French burn unit, where they were grafted (artificial skin graft followed by auto-graft). The third patient was transferred to a Russian hospital.

Accidents with delayed recognition

Medical field

(9 accidents; 5 of which happened in Europe)

✓ In Columbus, OH, between 1974 and 1976, a wrong calibration due to an error in the ^{60}Co halftime resulted in the overexposure of *426* patients; their doses were 15–45% higher than the prescribed doses, depending on the time where they were treated. Among the 183 patients still alive one year after treatment, more than one-third had severe complications of the central nervous and gastrointestinal systems.

✓ At the hospital of Stoke-Upon-Trent, UK (1982–1991) *1045* patients received during a nine year period doses 5–35% lower than expected. Consequences cannot be precisely evaluated, especially as comparison of recoveries and prolonged remissions in correctly treated patients with those who were underexposed is very difficult to interpret

✓ In four hospitals in the USA between spring 1985 and winter 1987, five series of overexposures happened that were caused by an operator error in programming the machine. This series of accidents caused severe damage, including burns, myelitis, paralysis and other complications, which resulted in deaths

✓ In Zaragoza, Spain (1990), *22 patients* were exposed to higher than intended doses. Previously, the cause of a malfunction had been wrongly identified and the subsequent repair resulted in an unexpected change in electron energies. During 10 days, patient doses were three to seven times higher then the prescribed ones, depending upon the chosen energies. Patients, especially those treated for cervical and thoracic tumours, developed pulmonary, oropharyngeal and bone marrow lesions, complicated by vascular and cutaneous damage. Since all patients were treated for cancers in their severe evolution phase, it is difficult to assess precisely the real participation of this overexposure in the lethal issues; nevertheless, it is assumed that this accident caused at least *13 deaths*.

✓ In San José, Costa Rica (1996), the overexposure of *114* patients, including children, was a national tragedy. Errors in the calibration of a new ^{60}Co radiotherapy source resulted in exposures 50–60% higher than the prescribed doses; the error was due to a confusion in the time unit, the second versus 1/100 of a minute. As in any overexposure during the course of a treatment, the error was recognised only when a large series of patients exhibited abnormal signs of radiation injuries and consequently evoked the real cause. The number of deaths directly related to the accident is difficult to assess; among the *63 deaths* within two years it is likely that *13* can be directly attributed to their overexposures and *four* to radiation-induced complications. Among the *51 patients still alive* two years later, two were suffering from late severe complications and 12 exhibited marked and disabling consequences

✓ In Panama (2000), an error in determining doses delivered by a ^{60}Co source caused *28* victims. The error was due to a modification in the computerised treatment, which aimed to introduce additional shielding in order to reduce the radiation field. Although the computer did not accept the modification, treatment was given and doses were much higher than expected; among the victims, treated for genital cancer, *three died within one year and the 20 surviving patients developed severe digestive and urinary complications*

✓ In Bialystok, Poland (2001), due to a malfunctioning of a linear accelerator used for the treatment of breast cancer, *five patients* were overexposed at their 22nd fraction (currently 2 Gy per fraction with 8 MeV electrons). Later on, breast doses to the most exposed patient were evaluated around 56±10 Gy

✓ In Lyon, France (2004), because of an erroneous handling when treating *a patient* for a non-malignant tumour, a larger area than prescribed was exposed. This error was due to confusion in the unit used to determine the surface to be irradiated—millimetre *versus* centimetre. Several months after treatment, severe injuries caused the *death of the patient*

✓ In Epinal, France (2004–2005), *23* patients treated for prostate cancer were recognised as having received doses 20% higher than those prescribed. This accident had three main causes: *error in dosimetric computation, lack of program ergometry and insufficient training of personnel*. The subsequent complications were recognised as related to this misadministration about one year after treatment. The consequences were very severe: one death could be rapidly attributed to the accident, while 13 patients showed disabling complications. This event is too recent to establish the complete consequences, especially since all conclusions have not yet been drawn

Accidents that are kept secret

In general, secret accidents belong to the military arena and were common during the Cold War

✓ At Bikini Atoll, Marshallese Islands, Pacific Ocean (1954), the US Army performed a thermonuclear test. The unexpected power coupled with unfavourable meteorological conditions resulted in high-activity fallout. The follow-up of the affected population during a 25-year period shows mainly the development of thyroid abnormalities, with growth retardation in a number of exposed Rongelap children, as well as the development of thyroid nodules, hypothyroidism and thyroid hypofunction, appearing 10–20 years later

✓ In Kyshtym, Ural Mountains, Russia (1957), a very large stretch of land was contaminated by fission products released after the explosion of a storage tank in a secret plant dating from the post-war period. The release of some 700 PBq of radioactive products contaminated about 20.000 km^2 in the regions of Chelyabinsk and Sverdlovsk, with a population of nearly *300.000 inhabitants*. More than 1000 individuals were living in areas with a ^{90}Sr deposition concentration higher than 40 MBq m^{-2}. The accident was only revealed in 1990, 33 years later, by a political refugee. Following the accident, 20 villages with 7500 inhabitants were permanently evacuated. The most exposed groups of the population show a significant increase of leukaemia and solid cancers

✓ The accident which happened in the Atlantic (1961) shows the potential consequences of the quest for secrecy at any price: in order to prevent a nuclear submarine being recovered by a foreign navy, the Soviet authorities ordered the crew to carry out makeshift repairs; several crew members received high doses and at least *eight died* as a result, but the vessel could be brought back to its home port

✓ In the Hoggar Desert, Sahara (1962), on the occasion of a nuclear weapon test, the underestimation of power combined with a wrong appreciation of the prevailing weather conditions caused the contamination of the command site and staff

✓ Near Palomarés, Spain (1966), following a mid-air collision between an US bomber carrying nuclear weapons and its refuelling plane, the contents of three nuclear devices were spread over the ground around the town, while a fourth bomb fell into the sea. Seven crew members died and four survived. About 150 m^2 of earth and vegetation were removed and transported to the USA. The device in the sea was recovered after three months. No contamination could be detected in the inhabitants

✓ Near Thulé, Greenland (1968), a US plane crashed onto the ice field, causing the explosion and dispersal of the content of four nuclear bombs. The accident killed one crew member. The clean-up operation, complicated by extreme climatic conditions in the polar night, involved more than 700 military personnel helped by American and Danish scientists and workers. The quantity of plutonium dispersed was estimated at more than 3 kg, most of which was captured in the upper layer of ice. Land decontamination included collecting ice, and snow in 167 tanks of 100 m^3 each.

Malevolent Actions

Some rare criminal actions, using radiation sources, have been reported during the past decades

Two attempted murders in the 1970s have brought their authors in front of courts of justice

✓ The first attempt occurred in the USA in 1974: for revenge, a man deliberately exposed his son, five times in six months, to a 37 GBq ^{137}Cs source that he was holding for oil prospecting. The origin of the radiation-induced injuries was recognised two years later, after the victim had suffered several surgical interventions. One of the most serious consequences was a functional castration

✓The second attempt occurred in France: a reprocessing plant employee, intending to cause severe injury to a colleague, placed under the seat car a radioactive bar that he had stolen from the workshop. The attempt was revealed by chance when the car passing through the plant exit activated the alarms. The exposure was too short to cause serious effects

Other malevolent actions have been reported

- ✓ in the USA, a complaint was lodged by a pregnant scientist in 1995, for ^{32}P poisoning
- ✓A Russian publication reports at least four cases of criminal actions with γ radiation sources, three of which with the source being placed under the targeted victim's seat; in fact, these few cases constitute isolated criminal acts, motivated by desire for revenge and, consequently, do not strictly correspond to the definition of malevolence

The assassination in London, UK (2006), of a Russian citizen by poisoning with ^{210}Po, apparently for political reasons, was an unprecedented event. After the high specific activity *a* emitter had been poured into his drink, the victim became rapidly severely ill and *died within a few days* from multi-organ failure (kidney, heart, bone marrow). A remediation process aiming to reduce the risk to public health from exposure to radioactive internal contamination, monitoring public areas, hotels, hospitals and transportation means, control of waste required great efforts and mobilised a large number of experts and large workforce (in more than 100 people measurable intakes of ^{210}Po were found).

Conclusions (1)

Any registry of the various types of accident could give the wrong impression that such events are not rare and always result in serious consequences.

In reality, when compared with the total number of operations involving radiation, the number of accidents resulting in consequences on humans and/or environment is small, especially when the accidental rate is compared with the corresponding rate in other industries, medical and occupational activities.

Conclusions (2)

For example, in the medical field, in the years 1991-1996, the number of worldwide radiotherapy prescriptions exceeds one million per year. On the other hand, since most of the serious consequences, as well as their causes, could have been avoided, it should be stressed that this small number is still too high. Consequently, all efforts should be made in the fields of radiological safety and protection to reduce to a minimum the number and magnitude of the potentialities for accidents to occur