Power-Law Distributions in Events Involving Nuclear and Radiological Materials

by

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Abstract

Nuclear and radiological events are large-impact, hard-to-predict rare events, whose associated probability is exceedingly low. They can exert monumental impacts and lead to grave environmental and economic consequences. Identifying common trends of these events can help to assess the threat, and to combat it with better detection capabilities and practices. One way to achieve this is to model the events with established statistical and mathematical distributions. Power-law distribution is a good candidate because it is a probability distribution with asymptotic tails, and thus can be applied to study patterns of rare events of large deviations, such as those involving nuclear and radiological materials.

This thesis, based on the hypothesis that nuclear and radiological events follow the power-law growth model, assembles published data of four categories of events – incidents of nuclear and radiological materials, incidents of radioactive attacks, unauthorized activities of illicit trafficking, and incidents of nuclear terrorism, and investigates whether specific distributions such as the power-law can be applied to analyze the data.

Data are gathered from a number of sources. Even though data points are collected, the databases are far from complete, mainly due to the limited amount of public information that is available to the outside party, rendering the modeling task difficult and challenging. Furthermore, there may exist many undocumented instances, underscoring the fact that the reporting is an ongoing effort.

To compile a comprehensive dataset for analytical purposes, a more efficient method of collecting data should be employed. This requires gathering information through various means, including different departmental or governmental domains that are available to the public as well as professional insight and support. In addition, to facilitate better management of nuclear and radiological events, technological capacities to track them need to be strengthened, and information sharing and coordination need to be enhanced not only on regional but also on national and international levels.

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1. Introduction

1.1 Objectives of Thesis

Even though power-law distributions have been used for the data set of worldwide terrorist attacks, they have yet to be used to study specific cases involving nuclear and radiological materials. These cases satisfy the assumptions of the power-law growth model that appears to fit many natural systems: 1) new events are created at a regular but random rate and of the smallest size, 2) the growth rate of all existing events is random, and 3) the rate is independent of the size of objects.

Objectives of this thesis, based on the hypothesis that nuclear and radiological events exhibit scaling-invariant properties and thus follow power-law distributions, are 1) to assemble publicly available data of four categories of events – incidents of nuclear and radiological materials, incidents of radioactive attacks, unauthorized activities of illicit trafficking, and incidents of nuclear terrorism, 2) to examine whether there are enough data to be modeled with standard statistical and mathematical distributions, and 3) to investigate if specific distributions such as the power-law can be applied to the data. The application of power-law distributions to nuclear and radiological events will allow us to understand better the trend of those events, enabling us to encounter them with better preparations, strategies, and responses accordingly.

1.2 Nuclear Events as Black Swans

The concept of black swan was originally introduced by Nassim Taleb [Taleb, 2007], an essayist and a mathematical trader. Taleb is interested in the epistemology of randomness and the multidisciplinary problems of uncertainty, particularly in the large-impact, hard-to-predict rare events. A black swan is an event that lies beyond the realm of normal expectations. It is concerned with the interconnection between chance and dynamics of historical events on one hand, and the cognitive biases embedded in human nature that affect the understanding of history on the other.

From a quantitative perspective, a black swan is considered an outlier, which is an atypical observation that is clearly separated from the bulk of the data. An outlier may be due to recording errors or system noise of various kinds, and as such needs to be cleaned as part of the data mining process. On the other hand, an outlier, or a small group of outliers, may be error-free recordings that represent the most important part of the data that deserves further inspection [Martin, 2001].

From a cognitive perspective, a black swan is considered a surprise. Nevertheless, people tend to concoct explanations after the fact, which makes the surprise appear more predictable. Our minds are designed to retain, for efficient storage, past information that fits into a compressed narrative. This distortion, known as the hindsight bias, prevents an adequate learning from the past. Furthermore, because our world is more and more dominated by large deviations with "tail" properties that are impossible to model properly, we understand less and less of the happenings around us.

Nuclear and radiological events can be treated as black swans. Because nuclear events are large-impact, hard-to-predict rare events, the probability associated with them is exceedingly low. Nonetheless, the impacts that they bring are monumental. This thesis studies whether cases involving nuclear and radiological materials, despite their inherent black-swan properties, can be modeled with certain distributions, namely, power-law distributions, which employ the concept of scale invariance.

1.3 Scale Invariance

Scale invariance is a feature of an object that does not change if length scales of the object are multiplied by a common factor. The concept of scale invariance can be illustrated mathematically. When a relation of the form

$$f(x) = ax^{x}, \qquad \text{(Eqn. 1)}$$

or of any homogeneous polynomial form, is modified by scaling the argument x by a constant factor, the result is only a proportionate scaling of the original function:

$$f(cx) = a(cx)^{x} \qquad \text{(Eqn. 2)}$$

$$= c^{k} f(x) \qquad \text{(Eqn. 3)}$$

$$\propto f(x). \qquad \text{(Eqn. 4)}$$

Therefore, scaling by a constant simply multiplies the original power-law relation by the constant c^{k}. As a consequence of this special property, when a solution of a scale-invariant field equation is given, other solutions can automatically be found through the appropriate rescaling of both the coordinates and the fields.

The set of different theories described by the same scale-invariant theory is known as a universality class, which observes that different microscopic systems can display the same behavior at a phase transition. Accordingly, phase transitions in many different systems may be described by the same underlying scale-invariance theory.

1.4 Power Law

A power law is any polynomial relationship that exhibits the property of scale invariance [Simon, 1955]. Because it is a probability distribution with asymptotic tails, it can be applied to the theory of large deviations with extremely rare events. The power-law is graphed in Figure 1.

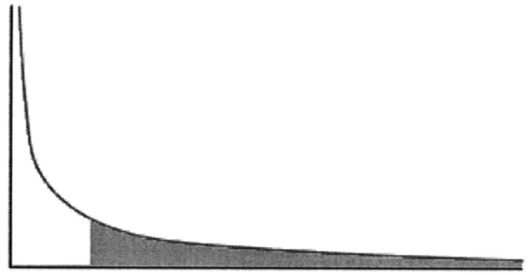

Figure 1: Power law. This skewed distribution is known as the 80-20 rule.

The most common power laws relate two variables and have the form

$$f(x) = ax^{x} + o(x^{k}) , \qquad \text{(Eqn. 5)}$$

where a and k are constants, and $o(x^k)$ is an asymptotically small function of x. k is called the scaling exponent, denoting the fact that a power-law function satisfies the relationship

$$f(cx) \propto f(x), \qquad \text{(Eqn. 6)}$$

where c is a constant. As seen in Equation 6, a rescaling of the function's argument merely changes the constant of proportionality but preserves the shape of the function itself. If logarithm is taken on both sides, the equality becomes

$$\log(f(x)) = k \log x + \log a, \qquad \text{(Eqn. 7)}$$

which has the form of a linear relationship with slope k. Rescaling the argument produces a linear shift of the function up or down but leaves both the basic form and the slope unchanged.

Not all polynomial functions follow power-law distributions because not all polynomials exhibit the property of scale invariance. Typically, power-law functions are polynomials in a single variable, and are explicitly used to analyze the scaling behavior of mechanisms that underlie natural processes. For example, distributions in nature that are composed of a large number of common events and a small number of rarer events can be modeled by power law, because they often manifest a form of regularity in which the relationship of any two events in the distribution scales in a simple way. The study of power law also spans a variety of other disciplines, including physics, computer and information sciences, earth sciences, molecular and cellular biology, ecology, economics, political sciences, sociology, and statistics.

1.5 Power-Law Distributions in Empirical Data

Power-law distributions come in two basic forms: continuous distributions that govern continuous real numbers, and discrete distributions that take only a discrete set of values. Formulas for continuous power laws tend to be simpler than those for discrete power laws, with the latter often involving special functions [Clauset, 2007]. One way to probe for power-law behavior is to measure the quantity of interest x, construct a histogram representing its frequency distribution, and plot the histogram on doubly logarithmic axes. x obeys a power law if it is drawn from a probability distribution

$$p(x) \propto x^{-\alpha}, \qquad \text{(Eqn. 8)}$$

where α is the constant scaling parameter. In real-world situations, α normally lies in the range $2 < \alpha < 3$ [Clauset, 2007]. Studies of empirical data that follow power laws usually give some estimate of α and occasionally also of the lower-bound of the scaling region x_{min}. Estimating α correctly requires a value of x_{min} in the data.

The empirical detection and characterization of power laws are made difficult by the large fluctuations in the tail of the distribution. Therefore, even if a data set is drawn from a perfect power-law distribution, the fit between that data set and the true distribution will on average be poorer than the fit to the best-fit distribution. When analyzing a data set, the challenge is to decide not only what the best parameter choices are but also whether a power-law distribution is even a reasonable hypothesis to begin with. Being roughly straight on a log-log plot is a necessary but not sufficient condition for power-law behavior.

According to Clauset et al, two questions need to be addressed when modeling a data set: 1) whether the data could plausibly have been drawn from a power-law distribution, and 2) whether there exist other competing distributions that fit the data as well or better [Clauset, 2007]. These questions can be answered using goodness-of-fit tests that compare the observed data to the hypothesized distribution. The standard solution is to compute a *p-value*, which quantifies the probability that the data were drawn from the hypothesized distribution, based on the observed goodness-of-fit. If the value is close to 1, then the data may be drawn from a power law. The statistical variation becomes smaller as the sample size n becomes large, implying that the *p-value* becomes a more reliable test as n increases. By combining *p-value* calculations with respect to the power-law and other plausible distributions, a good case for or against the power-law form for the data can be made.

1.6 Power-Law Distributions in Virtual World

When statistically allowed, power law can be used to model real-world situations. For example, Shiode and Batty used power-law distributions to analyze the relationships between population, gross domestic product (GDP), and web data [Shiode, 2000]. The motivation behind the study was that as the development of web sites represents more realistically the cutting edge of the global economy, web sites' sizes and contents are likely to reflect the distribution of population and the urban geography of the real world. The speculation was that as the web develops, all domains will ultimately follow the same power laws as technologies mature and adoption becomes more uniform.

Data indicated that the distributions of population and GDP are much closer over their larger size range to rank-size than any of the web data. The correlation between web and GDP was found to be high [Shiode, 2000], confirming the authors' intuition that the economic development of a domain is all the more important in explaining its size. Based on the study, it was concluded that the distribution of web domains broadly reflects existing economic activity patterns.

1.7 Power-Law Distributions in Global Terrorism

Another subject that was studied using power-law distributions is global terrorism. Clauset et al tested the data set of the severity of worldwide terrorist attacks from February 1968 to June 2006 measured against the number of deaths with the power-law hypothesis. Results suggested a moderate support for power law distributions for the data set with *p-value* of 0.68 [Clauset, 2007]. Investigation done by Clauset and Young showed that the relationship between the frequency and the severity of terrorist attacks exhibit the "scale-free" property with a scaling parameter α of close to two, which is required for the fitting of the power law [Clauset, 2005].

The regularity of the scaling in the tails of the distributions of severity observed by Clauset A. and Young M suggests that extremal events are not outliers, but are instead in concordance with a global pattern in terrorist attacks [Clauset, 2005]. Through the generation of *p-values* with the estimated α and x_{min}, it was found that there is insufficient evidence to reject the power law as a model for the distributions of severity. Furthermore, the distribution of event sizes was found to have changed very little over the past 37 years, suggesting that scale invariance is an inherent feature of global terrorism. Thus, even though irregularities are to be expected in a system as complex as global terrorism, the appearance of scale invariance is not.

1.8 Mathematical Analysis of Risks Associated with Nuclear Terrorism

Bunn designed a mathematical model for the risks of nuclear terrorism. He explored several key parameters, with an emphasis on four means that terrorists might use to acquire nuclear materials: outsider theft, insider theft, the black market, and provision by a state [Bunn, 2006]. Unlike some previous models, the model presented by Bunn is based on the more realistic assumption that a limited number of nuclear terrorist groups undertake a limited number of theft attempts, suggesting that the relationship between the risk and the quantity of facilities or materials is less direct.

In Bunn's model, N_n denotes the number of terrorist groups. Each year, each particular group j of these N_n groups will have a probability $P_{a(j)}$ of launching an attempt to acquire nuclear materials essential to making an attack. The expected number of acquisition attempts per year, A, can be found by summing the probabilities of deciding on such an attempt by all the groups:

$$A = \sum_{j=1}^{N_n} P_{a(j)}. \qquad \text{(Eqn. 9)}$$

Acquisition attempts will have probability $P_{o(j)}$ of instigating an outsider theft attempt at a facility, probability $P_{i(j)}$ of instigating a theft attempt by insiders with authorized access to the facility, probability $P_{b(j)}$ of purchasing items on a nuclear black market, and probability $P_{n(j)}$ of provisioning items by a nation-state in possession of them. Each acquisition attempt k will have some probability of being successful, giving rise to $P_{os(j,k)}$, $P_{is(j,k)}$, $P_{bs(j,k)}$, and $P_{ns(j,k)}$. Two more probabilities are introduced: $P_{w(j,k)}$ and $P_{d(j,k)}$. $P_{w(j,k)}$ denotes the probability that a group transforms the items into a workable nuclear explosive capability in the event of a successful acquisition attempt. $P_{d(j,k)}$ denotes the probability that the group decides to deliver the bomb to its intended target and detonate it once the usable nuclear capability is obtained.

The probability $P_{s(k)}$ that any given acquisition attempt k will be successful, and will ultimately lead to a terrorist nuclear attack, is given by

$$P_{s(k)}=(P_{o(j)}\times P_{os(j,k)} + P_{i(j)}\times P_{is(j,k)} + P_{b(j)}\times P_{bs(j,k)} + P_{n(j)}\times P_{ns(j,k)})\ (P_{w(j,k)}\times P_{d(j,k)}). \qquad \text{(Eqn. 10)}$$

From $P_{s(k)}$, the overall probability, P_c, of a terrorist nuclear catastrophe somewhere in the world in any given year, is found:

$$P_c = 1 - \prod_{k=1}^{A} (1 - P_{s(k)}). \quad \text{(Eqn. 11)}$$

This probability can be converted into the risk of nuclear terrorism, R_c, by multiplying it by the consequence of the event, C_c:

$$R_c = P_c \times C_c. \quad \text{(Eqn. 12)}$$

The expected losses, $E(L)$, resulting from a successful nuclear attack, is calculated as

$$E(L) = P_{w(j,k)} \times P_{d(j,k)} \times C_c. \quad \text{(Eqn. 13)}$$

The mathematical analysis developed by Bunn suggests that even rare events such as nuclear terrorist attacks can be modeled in a systematic way. Therefore, it is possible that the various metrics of events involving nuclear and radiological materials, given the statistical database currently available, can also follow certain established distributions.

2. Collection of Data

2.1 Incidents of nuclear and radiological materials

Database of Radiological Incidents and Related Events (last modified on January 29, 2009), organized and managed by Wm. Robert Johnston, is a compilation of general data on radiological accidents and other events that have produced radiation casualties. Featured events include 1) events resulting in acute radiation casualties – both accidents and intentional acts, 2) events resulting in chronic radiation injury but no acute casualties are only included if substantiated links exist between exposure and individual casualties, and 3) accidents resulting in >1 megacurie radiation releases [Johnson, 2009]. Table 1 summarizes the events highlighted in the database, from 1945 to 2007, in chronological order.

Table 1: Events listed in *Database of Radiological Incidents and Related Events*.

Date	Location	Type of Events	Consequences	
			Injuries	Fatalities
08/06/1945	Hiroshima, Japan	Use of nuclear weapon	86,000	130,000
08/09/1945	Nagasaki, Japan	Use of nuclear weapon	75,000	70,000
08/21/1945	Los Alamos Scientific Laboratory, New Mexico, USA	Criticality accident with Pu metal assembly		1
05/21/1946	Los Alamos Scientific Laboratory, New Mexico, USA	Criticality accident with Pu metal assembly	1	1
07/05/1950	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	5	
08/19/1950	Chelyabinsk-40, Ozersk, Russia	Radiation accident at radiochemical plant	1	
09/13/1950	Chelyabinsk-40, Ozersk, Russia	Radiation accident at radiochemical plant	1	
09/20/1950	Chelyabinsk-40, Ozersk, Russia	Radiation accident at radiochemical plant	1	
09/28/1950	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	1	
01/1951	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	1	
07/1951	Chelyabinsk-40, Ozersk, Russia	Unspecified accident	1	
10/01/1951	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	3	1
12/02/1951	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	3	
12/15/1951	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	2	
03/04/1952	Chelyabinsk-40, Ozersk, Russia	Reactor-related accident	1	
06/02/1952	Argonne National Laboratory, Illinois, USA	Criticality accident with uranium particles in plastic	2	

07/04/1952	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	2	
09/20/1952	Chelyabinsk-40, Ozersk, Russia	Radiation accident at radiochemical plant	1	
1952	Chelyabinsk-40, Ozersk, Russia	Unspecified accident	3	
01/04/1953	Chelyabinsk-40, Ozersk, Russia	Unspecified accident		2
03/15/1953	Chelyabinsk-40, Ozersk, Russia	Criticality accident with plutonium solution	3	
09/09/1953	Moscow, Russia	Criticality accident	4	
09/18/1953	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	2	
10/13/1953	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	5	
12/28/1953	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	11	
1953	Chelyabinsk-40, Ozersk, Russia	Unspecified accident	2	
03/01/1954	Bikini Atoll, Marshall Islands, Pacific Ocean	Fallout from atmospheric nuclear test	93+	1
03/11/1954	Obninsk, Russia	Criticality accident	1	
06/28/1954	Arzamas-16, Sarov, Russia	Exposure to source	1	1
09/14/1954	Totsk range, Orenberg region, Russia	Fallout from atmospheric nuclear test		
11/06/1954	Chelyabinsk-40, Ozersk, Russia	Radiation accident at radiochemical plant	1	
01/24/1955	Moscow, Russia	Exposure to source	1	
06/03/1955	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	4	
07/27/1955	National Reactor Testing Station, Idaho Falls, Idaho, USA	Exposure to radioactive source	1	
12/22/1955	Chelyabinsk-40, Ozersk, Russia	Radiation accident at radiochemical plant	1	
04/21/1957	Chelyabinsk-40, Ozersk, Russia	Criticality accident with uranium solution	10	1
06/1957	Moscow, Russia	Accelerator accident	1	
09/29/1957	Mayak Scientific-Production Association, Kyshtym, Russia	Chemical explosion in stored nuclear wastes		
01/02/1958	Chelyabinsk-40, Ozersk, Russia	Criticality accident with uranium solution	1	3
06/16/1958	Oak Ridge, Tennessee, USA	Criticality accident with uranium solution	5	
10/15/1958	Boris Kidrich Institute, Vinca, Yugoslavia	Criticality accident at research reactor	5	1
12/30/1958	Los Alamos Scientific Laboratory, New Mexico, USA	Criticality accident with plutonium solution		1
03/08/1960	Lockport, New York, USA	Exposure to x-ray source	2	
06/08/1960	Moscow, Russia	Suicide by overexposure		1
10/13/1960	Barents Sea, aboard USSR submarine K-8	Submarine reactor leak	3	
1960	Russia	Ingestion of radioactive material		1
1960	Kazakhstan	Exposure to source	1	

01/03/1961	SL-1 reactor, National Reactor Testing Station, Idaho, USA	Criticality excursion in research reactor		3
03/20/1961	Moscow, Russia	Accident at facility	1	
06/26/1961	Moscow, Russia	Criticality accident	4	
07/04/1961	North Atlantic Ocean, aboard USSR submarine K-19	Submarine reactor leak	31+	8
07/14/1961	Siberian Chemical, Russia	Criticality accident with U	1	
09/30/1961	Moscow, Russia	Exposure to source	1	
1961	Switzerland	Radiological contamination with tritiated paint	2	1
1961	Plymouth, United Kingdom	Radiography accident	11	
02/06/1962	Moscow, Russia	Accident at x-ray facility	1	
03-08/1962	Mexico City, Mexico	Lost radiography source	1	4
04/07/1962	Hanford Works, Hanford, Washington, USA	Criticality accident with plutonium solution	2	
04/10/1962	Moscow, Russia	Exposure to source	1	
11/02/1962	Obninsk, Russia	Criticality accident	2	
01/11/1963	Sanlian, P.R. China	Orphaned source	4	2
03/11/1963	Arzamas-16, Sarov, Russia	Criticality accident	2	
06/28/1963	Sverdlovsk, Russia	Exposure to source	3	
07/26/1963	Chelyabinsk-40, Ozersk, Russia	Unspecified accident	1	
1963	Chelyabinsk-40, Ozersk, Russia	Accident at nuclear site	1	
1963	Chelyabinsk-40, Ozersk, Russia	Unspecified accident	1	
07/24/1964	Wood River, Rhode Island, USA	Criticality accident with uranium solution	1	1
1964	F.R. Germany	Radiological contamination with tritiated paint	3	1
02/12/1965	Severodvinsk, USSR, aboard K-11 nuclear submarine	Reactor accident during refueling	7	
05/29/1965	Moscow, Russia	Accelerator accident	1	
12/30/1965	VENUS assembly, Mol, Belgium	Criticality accident with research reactor	1	
1965	Illinois, USA	Accident at irradiator	1	
05/20/1966	Moscow, Russia	Unspecified accident	1	
06/11/1966	Kaluga, Russia	Accident at x-ray facility	1	
1966	Chelyabinsk-40, Ozersk, Russia	Exposure to source	1	
04/15/1967	Frunze, Kirgyzstan	Accident at x-ray facility	1	
05/24/1967	Moscow, Russia	Accident at x-ray facility	1	
05/1967	Safdarjang, New Delhi, India	Exposure to source	1	
10/04/1967	Harmarville, Penn., USA	Accident at irradiator	3	
12/09/1967	Moscow, Russia	Accident at x-ray facility	1	
12/22/1967	Moscow, Russia	Exposure to source	1	
1965-1968	Pennsylvania, USA	Attempt to self-induce abortion using x-ray	1	
04/05/1968	VNIITF, Chelyabinsk-70, Chelyabinsk, Russia	Criticality accident with uranium assembly		2

05/1968	Moscow, Russia	Accident at x-ray facility	1	
05-06/1968	La Plata, Argentina	Lost sources	1	
05/24/1968	Barents Sea, aboard K-27 submarine	Reactor coolant leak and partial meltdown	83	9
06/27/1968	Arzamas-16, Sarov, Russia	Accident at facility	2	
08/01/1968	Wisconsin, USA	Radiotherapy accident		1
09/18/1968	F. R. Germany	Orphaned source	1	
12/07/1968	Moscow, Russia	Accident at x-ray facility	1	
12/10/1968	Mayak Enterprise, Russia	Criticality accident with plutonium solution	1	1
01/02/1969	Moscow, Russia	Accident at x-ray facility	1	
01/20/1969	Obninsk, Russia	Accident at nuclear site	2	
02/11/1969	Moscow, Russia	Accelerator accident	1	
03/11/1969	Melekes, Russia	Accident at facility	1	
04/22/1969	MSF-99, Russia	Accident at nuclear site	2	
05/07/1969	Voronezh power plant, Russia	Accident at nuclear site	2	
09/20/1969	Scotland, United Kingdom	Exposure to source	1	
09/24/1969	Tomsk-7, Seversk, Russia	Unspecified accident	1	
10/13/1969	Moscow, Russia	Accident at x-ray facility	1	
10/13/1969	Russian far east	Radiography accident	1	
10/14/1969	Matochkin Shar, Novaya Zemlya, Russia	Accidental radioactive release from nuclear test		
11/24/1969	Novomoskovsk, Russia	Accident at facility	3	
12/20/1969	Moscow, Russia	Accident at x-ray facility	1	
1969	USSR	Accident at radiation sterilization facility	1	
1969	Chelyabinsk-40, Ozersk, Russia	Unspecified accident	1	
01/18/1970	Sormovo, Gorky region, Russia	Radiation accident during construction of submarine nuclear reactor	2	3
02/04/1970	Kiev, Ukraine	Criticality accident	1	
02/13/1970	Russia	Accident at facility	1	
04/15/1970	Moscow, Russia	Accelerator accident	1	
06/23/1970	Australia	X-ray accident	2	
09/1970	Chelyabinsk, Russia	Exposure to source	1	
02/04/1971	USA	Accident at irradiator	1	
02/15/1971	Kurtchatov, Russia	Criticality accident with U	2	
03/1971	Tula, Russia	Exposure to source	1	
05/26/1971	Kurtchatov, Russia	Criticality accident with uranium in water	2	2
09/1971	Voronezh power plant, Russia	Unspecified accident	1	
12/05/1971	Arkhangelsk region, Russia	Exposure to source	3	
1971	Chiba, Japan	Lost sources	3	
1971	Ufa, Russia	Exposure to source	1	
02/29/1972	Sichuan, P. R. China	Irradiator accident	1	
03/31/1972	Moscow, Russia	Accident at x-ray facility	1	

04-10/1972	Harris County, Texas, USA	Use of radioactive material in assault on an individual	1	
06/1972	Moscow, Russia	Accident at x-ray facility	1	
07/1972	India	X-ray accident	1	
10/04/1972	Moscow, Russia	Accident at x-ray facility	1	
10/09/1972	Primorsky region, Russia	Criminal act involving radioactive material	1	
12/22/1972	Irkutsk, Russia	Accident at x-ray facility	1	
12/1972	Wuhan, P. R. China	Accident with medical radiation equipment	1+	
1972	Bulgaria	Suicide by self-inflicted radiation injury		1
01/11/1973	Moscow, Russia	Exposure to source	1	
03/17/1973	Odessa, Ukraine	Criminal act involving radioactive material	1	
03/1973	Kaliningrad, Moscow, Russia	Accident at x-ray facility	1	
04/1973	Moscow, Russia	Accident at x-ray facility	1	
07/26/1973	Elektrogorsk, Moscow, Russia	Accident at facility	1	
09/05/1973	Khokhol, Vladimir, Russia	Exposure to source	4	
12/1973	Donetsk, Ukraine	Exposure to source	1	
01/09/1974	Novosibirsk, Russia	Accident at x-ray facility	1	
05/24/1974	Tomsk-7, Seversk, Russia	Exposure to source	1	
05/31/1974	Semipalatinsk test site, Kazakhstan	Venting from underground nuclear test	100+	
06/1974	Parsippany, New Jersey, USA	Accident at irradiator	1	
08/09/1974	India	X-ray accident	1	
10/24/1974	Perm', Russia	Exposure to source	1	
12/15/1974	Lipetsk, Russia	Criminal act involving radioactive material	2	
1974	Sverdlovsk, Russia	Exposure to source	1	
1974-1976	Riverside Methodist Hospital, Columbus, Ohio, USA	Radiotherapy accident	78	10
05/13/1975	Brescia, Lombardia, Italy	Food irradiator		1
06/20/1975	Kazan', Russia	Accident at facility	2	
07/11/1975	Sverdlovsk, Russia,	Exposure to source	2	1
1975	Tucuman, Argentina	Radiotherapy accident	2	
1975	Rossendorf, East Germany	Exposure to source	1	
1975	Halle, East Germany	Accidental x-ray exposure	1	
1975	F. R. Germany	Accidental x-ray exposure	1	
1975	Iraq	Radiotherapy accident	1	
03/1976	Moscow, Russia	Accident at x-ray facility	1	
07/12/1976	Moscow, Russia	Accident at facility	1	
07/22/1976	Melekes, Russia	Accident at facility	1	
11/12/1976	Pittsburgh, Penn., USA	Radiotherapy accident	1	
1976	F. R. Germany	Accidental x-ray exposure	1	
1976	Hanford, Washington, USA	Intake of radioisotope	1	

1976	USA	Fluoroscopy accidents	2	
01/08/1977	Sasolburg, South Africa	Lost radiography source	1	
03/01/1977	Obninsk, Russia	Criticality accident	1	
03/05/1977	Kiev, Ukraine	Accelerator accident	1	
04/02/1977	Atucha, Argentina	Radiological contamination	1	
09/1977	Rockaway, New Jersey, USA	Accident with irradiator	1	
1977	La Plata, Argentina	X-ray accident	1	
1977	Pardubice, Czechoslovakia	Radiotherapy accident	1	
1977	F. R. Germany	Accidental exposure involving radiogram unit	1	
1977	Gyor, Hungary	Exposure to industrial radiography source	1	
1977	Zona del Oleoducto, Peru	Exposure to source	3	
1977	United Kingdom	Exposure to radioisotope	2	
1977	United Kingdom	Radiography accident	1	
03/07/1978	Primorsky region, Russia	Radiography accident	1	
04/04/1978	Primorsky region, Russia	Radiography accident	1	
05/05/1978	Setif, Algeria	Lost radiography source	6	1
06/03/1978	Protvino, Kaluga region, Russia	Accelerator accident	1	
07/17/1978	West Monroe, Louisiana, USA	Radiography accident	1	
09/21/1978	Moscow, Russia	Accelerator accident	1	
10/17/1978	Moscow, Russia	Accident at nuclear site	1	
11/25/1978	Udmurtia, Russia	Radiography accident	1	
12/13/1978	Siberian Chemical Combine, Russia	Criticality accident with plutonium metal	1	
12/28/1978	Pacific Ocean, aboard K-171 submarine	Reactor accident		3
1978	Buenos Aires, Argentina	Accident from source	1	
1978	Nancy, France	Accidental x-ray exposure	1	
1978	Nykoping, Sweden	Exposure at reactor	1	
1978	United Kingdom	Exposure to source	1	
1978	United States	Accelerator accident	1	
05/08/1979	Sverdlovsk, Russia	Accident at nuclear site	1	
05/11/1979	La Hague, France	Use of radioactive material in assault on an individual	1	
06/05/1979	Los Angeles, California, USA	Lost sources	5	
07/20/1979	Leningrad, Russia	Accelerator accident	2	
09/20/1979	Frunze, Kirgyzstan	Radiography accident	1	
12/01/1979	Semipalatinsk, Kazakhstan	Accident at facility	1	
1979	Parana, Argentina	Radiography accident	1	
1979	Sokolov, Czechoslovakia	Radiography accident	1	
1979	Montpelier, France	Radiation accident	1	
1979	F. R. Germany	X-ray accident	1	
1979	Freiberg, East Germany	Accidental x-ray exposure	1	
1979	USSR nuclear submarine	Unspecified accident	4	
05/23/1980	Chelyabinsk-40, Ozersk, Russia	Accident at x-ray facility	1	

09/01/1980	Leningrad, Russia	Accident at radiation sterilization facility		1
09/18/1980	Yuzhno-Sakhalinsk, Russia	Exposure to source		1
09/1980	Shanghai, P.R. China	Irradiator accident	1	
12/03/1980	Vladivostok, Russia	Radiography accident	1	
1980	F. R. Germany	Accident with radiogram unit	2	
1980	Bohlen, East Germany	Accidental x-ray exposure	1	
1980	Rossendorf, East Germany	Exposure to radioisotope	1	
1980	Houston, Texas, USA	Radiography accident		7
04/02/1981	Saintes, France	Accidental irradiation with teletherapy source	3	
07/29/1981	Tulsa, Oklahoma, USA	Self-exposure to industrial radiography source	1	
1981	Buenos Aires, Argentina	Exposure to source	2	
1981	F. R. Germany	Accidental x-ray exposure	1	
1981	Berlin, East Germany	Accidental x-ray exposure	1	
01/09/1982	Kramatorsk, Ukraine	Exposure to source		2
03/15/1982	Krasnodar, Russia	Exposure to source	1	
05/19/1982	Smolensk power plant, Russia	Radiography accident	1	
06/14/1982	Ashkhabad, Turkmenistan	Criminal act involving radioactive material	7	
09/02/1982	Institute of Energy Techonology, Kjeller, Norway	Accident at industrial irradiator		1
10/02/1982	Baku, Azerbaidjan	Orphaned source	13	5
12/18/1982	Urengoy, Russia	Radiography accident	2	
1982	La Plata, Argentina	Radiotherapy accident	1	
1982	Prague, Czechoslovakia	Radiography accident	1	
1982	Berlin, East Germany	Accidental x-ray exposure	1	
1982	Vikhroli, Bombay, India	Lost sources	1	
1982	Badak, East Borneo, Indonesia	Radiography accident	1	
01/27/1983	Moscow, Russia	Accident at x-ray facility	1	
04/28/1983	Kharkov, Ukraine	Radiography accident	2	
05/17/1983	Volgograd, Russia	Radiography accident	1	
06/11/1983	Ufa, Russia	Radiography accident	1	
09/23/1983	RA-2 Facility, Constituyentes, Argentina	Criticality accident in research reactor		1
12/07/1983	Ufa, Russia	Radiography accident	1	
1983	Buenos Aires, Argentina	Radiotherapy accident	2	
1983	F. R. Germany	Accidental x-ray exposure	1	
1983	Schwarze Pumpe, Germany	Exposure to source	1	
1983	Mulund, Bombay, India	Radiation accident	1	
02/1984	Ciudad Juarez, Mexico	Lost radioactive source	4	1
02/07/1984	Perm', Russia	Radiography accident	5	
03/19/1984	Casablanca, Morocco	Lost radiography source	3	8
04/21/1984	Chelyabinsk-40, Ozersk, Russia	Accident at x-ray facility	1	

06/12/1984	Ufa, Russia	Radiography accident	1	
06/15/1984	Gorky, Russia	Exposure to source	8	
10/24/1984	MSF-13, Russia	Radiography accident	1	
1984	Mendoza, Argentina	Radiography accident	1	
1984	Tiszafured, Hungary	Exposure to source	1	
1984	Lima, Peru	X-ray accident	6	
03/03/1985	Norilsk, Russia	Exposure to source	3	
06/03/1985	Kennestone Regional Oncology Center, Marietta, Georgia, USA	Radiography accident	1	
07/26/1985	Ontario Cancer Foundation, Hamilton, Ontario, Canada	Radiotherapy accident	1	
08/10/1985	Chazhma Bay, Russia, , aboard USSR submarine K-431	Reactor accident during refueling	49	10
09/26/1985	Ignalinskaya plant, Lithuania	Radiography accident	1	
06/1985	Shanghai, P.R. China	Accelerator accident	2	
10/16/1985	Podolsk, Moscow, Russia	Unspecified accident	1	
1985	P.R. China	Radiotherapy accident	1	1
1985	P.R. China	Radiation accident	3	
1985	Petrvald, Czechoslovakia	Intake of radioisotope	1	
1985	Visakhapatnam, India	Radiography accident	1	
1985	Yamuananager, India	Radiography accident	2	
1985	Odessa, Texas, USA	Radiography accident	1	
1985	United Kingdom	Ingestion of radioisotope	1	
01/1986	Yakima Valley Memorial Hospital, Washington, USA	Radiotherapy accident	1	
03/1986	Beijing, P.R. China	Exposure to source	2	
03-04/1986	East Texas Cancer Center, Tyler, Texas, USA	Radiotherapy accident		2
04-05/1986	Chernobyl nuclear power station, Prypyat, Ukraine	Steam/chemical explosion and fire in graphite-moderated power reactor	238	31
05/1986	Kaifeng City, P.R. China	Exposure to source	2	
06/11/1986	Obninsk, Russia	Accident at facility	1	
08/05/1986	Kalinin power plant, Russia	Radiography accident involving an Ir-192 source	1	
1986	United Kingdom	Radiotherapy accident	1	
01/17/1987	Yakima Valley Memorial Hospital, Washington, USA	Radiotherapy accident		1
02/19/1987	Moscow, Russia	Accident at x-ray facility	1	
07-09/1987	Koko, Nigeria	Radiological exposure	26	
09/12/1987	Goiania, Goias, Brazil	Lost radiography source	20	5
1987	Cirebon, West Java, Indonesia	Radiography accident	1	
1987	Zhengzhou City, P.R. China	Irradiator accident	1	
03/22/1988	Sverdlovsk, Russia	Exposure to source	3	
04/05/1988	Tashkent, Uzbekistan	Radiography accident	2	
07/02/1988	Sao Paulo, Brazil	Radiography accident	3	

08/18/1988	Riga, Latvia	Criminal act involving radioactive material	1	
1988	Zhao Xian, P.R. China	Irradiator accident	1	
1988	Jena, East Germany	Accidental x-ray exposure	1	
1988	Trustetal, East Germany	Accidental x-ray exposure	2	
1988	Dr. Daniel den Hoed Cancer Center, The Netherlands	Radiotherapy exposure	1	
1988	Royal Devon and Exeter Hospital, United Kingdom	Radiotherapy accident		
02/05/1989	Delmed Company, El Salvador	Accident at irradiator	2	1
03/20/1989	Moscow, Russia	Accident at x-ray facility	1	
08/04/1989	Russia	Radiography accident	1	
08/14/1989	Zagorsk, Sergiev Posad, Russia	Accelerator accident	1	
10/30/1989	Moscow, Russia	Accident at x-ray facility	1	
1989	Bangladesh	Accident with source	1	
1989	Beijing, P.R. China	Exposure to source	2	
1989	P.R. China	Radiography accident	1	
1989	Paks, Hungary	Exposure to components	1	
1989	Hazira, Gujarat, India	Radiography accident	1	
1989	Witbank, South Africa	Radiography accident	1	
02/27/1990	Kalinin power plant, Russia	Exposure to source	1	
03/13/1990	Moscow, Russia	Accelerator accident	1	
03/29/1990	USA	Fluoroscopy accident	1	
06/19/1990	Honolulu, Hawaii, USA	Radioiodine exposure to infant via breastfeeding	1	
06/21/1990	Sor-Van Radiation, Soreq, Israel	Irradiator accident		1
06/25/1990	Shanghai, P.R. China	Irradiator accident	5	2
09/13/1990	Kharkov, Ukraine	Exposure to source	1	
11/01/1990	Komsomolsk-on-Amur, Russia	Radiography accident	1	
10/12/1990	Zaragoza Clinical, Spain	Radiotherapy accident	9	18
1990	Sasolburg, South Africa	Exposure to lost source	4	
08/24/1991	Bratsk, Irkutsk, Russia	Attempted homicide using radioactive source	1	
08/13/1991	Forbach, France	Irradiator accident	3	
10/26/1991	Nesvizh, Belarus	Irradiator accident	1	
12/11/1991	Maryland, USA	Irradiator accident	1	
1991	United Kingdom	Radiography accident		1
01/09/1992	Riazan', Russia	Radiography accident	2	
05/25/1992	Axay, Kazakhstan	Radiography accident	1	
11/16/1992	Indiana Regional Cancer Center, Pennsylvania, USA	Radiotherapy accident		1
11/19/1992	Jilin, Xinzhou, PR China	Lost sources	5	3
11/17/1992	Hanoi, Vietnam	Irradiator accident	1	
11/1992	Wuhan, P.R. China	Irradiator accident	4	
1992	Switzerland	Radiography accident	1	
1992	San Antonio, Texas, USA	Radiotherapy accident	1	

04/14/1993	Moscow, Russia	Use of radioactive material in homicide of individual		1
07/12/1993	Vologda, Russia	Exposure to source	1	
08/07/1993	Dimitrovograd, Russia	Accident at nuclear site	1	
11/09/1993	Tula Region, Russia	Exposure to source	1	
1993	United Kingdom	Radiography accident	1	
04/28/1994	Tokyo, Japan	Irradiator accident	1	
10/21/1994	Tammiku, Estonia	Stolen source	4	1
11/28/1994	Voronezh, Russia	Radiography accident	1	
1994	Texas City, Texas, USA	Radiography accident	1	
02/1995	Zheleznodorozhny, Moscow, Russia	Criminal act involving radioactive material		1
03/18/1995	Pervouralsk, Russia	Radiography accident	1	
05/23/1995	Smolensk, Russia	Exposure to source	1	
09/11/1995	Moscow, Russia	Exposure to source	1	
10/03/1995	Nizhny Novgorod, Russia	Radiography accident	1	
1995	France	Exposure to lost source	1	
1995	Tyler, Texas, USA	Radiotherapy accident	1	
01/05/1996	Jilin, Xinzhou, PRC	Exposure to lost source	1	
02/15/1996	People's Republic of China	Intentional poisoning using radioactive material	1	
02/23/1996	Moscow, Russia	Accelerator accident	1	
02/27/1996	Houston, Texas, USA	Exposure to stolen source	1	
06/08/1996	Nizhny Novgorod, Russia	Radiography accident	1	
06/1996	Lilo Training Center, Georgia	Lost sources	11	
07/24/1996	Gilan, Iran	Lost radiography source	1	
08/22/1996	San Jose, Costa Rica	Radiotherapy accident	81	7
06/17/1997	Russian Federal Nuclear Center, Sarov, Russia	Criticality accident with uranium metal assembly		1
11/29/1997	Grozny, Russia	Exposure to source	3	
12/02/1997	Volgograd, Russia	Exposure to source	1	
1997	Republic of Georgia	Lost sources		1
03/18/1998	Moscow, Russia	Exposure to source	1	
10/06/1998	St. Joseph Health Center, Kansas City, Missouri, USA	Radiotherapy accident		2
12/10/1998	Istanbul, Turkey	Lost radiotherapy sources	10	
12/31/1998	Aransas Pass, Texas, USA	Radiography accident	1	
02/20/1999	Yanango, Peru	Lost sources	1	
04/26/1999	Henan, P. R. China	Lost sources	3	
08/04/1999	Hermann Hospital, Texas, USA	Radiotherapy accident	1	
09/13/1999	Gronzy, Chechnya, Russia	Attempted theft of source	3	3
10/01/1999	JCO Fuel Fabrication Plant, Ibarakin, Japan	Criticality accident at fuel fabrication plant	1	2
1999	Kingisepp, Leningrad, Russia	Orphaned source		3
01/24/2000	Samut Prakarn, Thailand	Lost sources	7	3
05-07/2000	Meet Halfa, Qaluobiya, Egypt	Lost radiography source	5	2

08/16/2000	Samara oblast, Russia	Lost radiography source	3	
10/13/2000	Dubna, Russia	Accelerator accident involving exposure to a proton beam	1	
03/24/2001	Instituto Oncologico Nacional, Panama City, Panama	Radiotherapy accident	11	17
02/06/2001	Nizhny Novgorod, Russia	X-ray accident	4	
02/27/2001	Bialystok Oncology, Poland	Radiotherapy accident	5	
05-06/2001	Kandalaksha Nature Preserve, Murmansk, Russia	Orphaned source	4	
06/21/2001	Stavropolskij Kraj, Russia	Radiography accident	1	
08/01/2001	Salavat, Russia	Radiography accident	2	
12/2001	Liya, Tsalenjikha, Republic of Georgia	Orphaned radiothermal generators	3	
05/2002	Guangzhou, P.R. China	Use of radioactive material in assault on an individual	75	
09/01/2002	Nizhny Novgorod, Russia	Radiography accident	1	
06/09/2003	Saint Joseph's Hospital, USA	Radiotherapy accident	1	
08/08/2003	Community Hospital, Indiana, USA	Accidental radiotherapy exposure to fetus	1	
11/13/2003	Kola Harbor, Russia	Orphaned source	1+	
01/26/2004	St. Joseph Regional Medical Center, Indiana, USA	Radiotherapy accident	3	
09/03/2004	St. Petersburg, Russia	Homicide		1
11/02/2004	Riverside Methodist Hospital, Columbus, Ohio, USA	Accidental radiotherapy exposure to fetus	1	
11/2004	Lyon, France	Radiotherapy overexposure		1
05/2004	Epinal, France	Radiotherapy overexposure	13	1
12/14/2005	Ranquil, Chile	Exposure to lost source	4	
01-02/2006	Glasgow, United Kingdom	Radiotherapy overexposure		1
03/11/2006	Fleurus, Belgium	Irradiator accident	1	
05/26/2006	McLeod Regional Medical Center, Florence, USA	Accidental radiotherapy exposure to fetus	1	
08/2006	Dakar, Senegal, and Abidjan	Exposure to source	4	
11/01/2006	London, United Kingdom	Poisoning using ingested radioactive substance	2	1
08/01/2007	Clinton, Michigan, USA	Exposure to sources	1	

2.2 Incidents of radioactive attacks

Attacks involving the use radioactive materials often go unreported, either because of the ignorance on the part of authorities or because of the attempts to suppress evidences. Due to these reasons, the reporting of radioactive and nuclear attacks is made difficult and challenging.

In *A Global Chronology of Incidents of Chemical, Biological, Radioactive and Nuclear Attacks: 1950-2005*, Mohtadi and Murshid compiled a relatively large dataset composed of 448 observations, covering a 45-year period from 1961 to 2005 [Mohtadi, 2006]. Because of a limited number of nuclear attacks included in the database, Table 2 summarizes only the incidents that are categorized as radioactive attacks from the database.

Table 2: Incidents of radioactive attacks listed in *A Global Chronology of Incidents of Chemical, Biological, Radioactive and Nuclear Attacks: 1950-2005.*

Date	Agent	Location	Target of attack	Consequences	
				Injuries	Fatalities
01/03/1961	Vandalism/sabotage	USA	Nuclear installation	1	3
1966-1977	Unknown	Europe	Nuclear installation	N/A	N/A
07/01/1969	Enriched uranium	USA	Educational Institution	0	0
1974-1986	N/A	USA	Nuclear installation	N/A	N/A
04/17/1974	Iodine-131	Austria	Transportation	0	0
08/15/1975	Explosives	France	Nuclear installation	N/A	N/A
05/12/1976	Explosives	USA	Nuclear installation	0	0
10/10/1977	Explosives	USA	Nuclear installation	N/A	N/A
12/18/1977	Explosives	Spain	Nuclear installation	0	1
03/08/1978	Explosives	Spain	Nuclear installation	14	2
04/01/1978	Explosives	Spain	Nuclear installation	N/A	N/A
1979	N/A	France	Nuclear installation	0	0
01/1979	Uranium-dioxide	USA	Citizens and property	0	0
02/1979	Explosives	Switzerland	Nuclear installation	0	0
05/10/1979	Sodium hydroxide	USA	Nuclear installation	0	0
05/11/1979	Radioactive graphite	France	Citizens and property	1	0
06/13/1979	Explosives	Spain	Nuclear installation	0	1
10/06/1979	Tritium	USA	Business	0	0
11/05/1979	Explosives	Switzerland	Nuclear installation	0	0
11/11/1979	Explosives	Spain	Nuclear installation	0	0
1981	Vandalism/sabotage	USA	Nuclear installation	0	0
07/29/1981	Iridium-192	USA	Attempted acquisition	0	1
01/19/1982	Rockets	France	Nuclear installation	0	0
12/1982	Explosives	South Africa	Nuclear installation	N/A	N/A
1983	Vandalism/sabotage	Germany	Military	0	0
11/12/1984	Vandalism/sabotage	USA	Installation/military	0	0
04/1985	Plutonium	USA	Food or water supply	0	0
06/1985	Vandalism/sabotage	USA	Installation/military	0	0
11/28/1987	Explosives	USA	Nuclear installation	0	0
01/03/1988	Thallium	UK	Citizens and property	0	1
02/1990	Explosives	Russia	Nuclear installation	N/A	N/A

03/1992	N/A	CIS	Attempted acquisition	0	0
08/1992	Low enriched U, fuel assembly	Lithuania	Theft	0	0
10/1992	Plutonium	Bulgaria	Business	0	0
11/23/1992	Cesium	Ukraine	Attempted acquisition	0	0
1993	N/A	Russia	Citizens and property	0	1
01/20/1993	Cesium	France	Attempted acquisition	0	0
01/20/1993	Cesium, beryllium, and uranium	Lithuania	Attempted acquisition/sale	0	0
11/1993	Warheads	Russia	Attempted acquisition	0	0
1994	Cesium	Estonia	Attempted acquisition	0	1
02/1994	Radium	Bulgaria	N/A	0	0
03/1994	Firearms	Russia	Nuclear installation	N/A	3
05/23/1994	Cesium	Russia	Attempted acquisition	0	0
07/1994	Uranium	Bulgaria	Possession only	N/A	N/A
10/01/1994	Phosphorus-32	China	Citizens and property	1	0
12/1994	Cesium	Russia	Possession only	0	0
11/23/1995	Cesium-137	Russia	Citizens and property	0	0
12/1995	Vandalism/sabotage	France	Nuclear installation	0	0
03/08/1996	Low enriched U	Romania	Attempted acquisition	0	0
03/17/1996	Cesium	Tanzania	Possession only	0	0
11/26/1996	Cesium	Georgia	Attempted acquisition	0	0
04/01/1997	Cesium	Russia	Attempted acquisition	10	0
03/1998	Cesium	USA	Attempted acquisition	0	0
06/18/1998	Cesium	Azerbaijan	Attempted acquisition	1	0
12/1998	N/A	Russia	Transportation	0	0
03/18/1999	Uranium	Lebanon	Attempted acquisition	0	0
08/19/1999	Phosphorous-32	USA	Citizens and property	1	0
08/19/1999	Monazite	Japan	Government	N/A	N/A
08/24/1999	Uranium	Cambodia	Possession only	0	0
08/30/1999	Nuclear components	Romania	Attempted acquisition	0	0
09/1999	N/A	Chechnya	Attempted acquisition	1	1
09/20/1999	Strontium-90	Ukraine	Possession only	0	0
12/03/1999	Cesium	South Korea	Attempted acquisition	0	0
03/06/2000	Explosives	Russia	Chemical installation	2	0
03/30/2000	Strontium-90	Kazakhstan	Possession only	0	0
05/10/2000	Uranium	Cambodia	Possession only	0	0
06/06/2000	Monazite	Japan	Government	0	0
07/11/2000	Cesium	Ukraine	Possession only	0	0
10/14/2000	Cesium	Russia	Attempted acquisition	0	0
12/20/2000	Iodine-25	Japan	Infrastructure	0	0
03/06/2001	Cesium	Russia	Attempted acquisition	0	0
05/31/2001	Cesium	Moldova	Attempted acquisition	0	0
06/2001	Strontium	Russia	Attempted acquisition	2	0
06/20/2001	Cesium	Moldova	Attempted acquisition	0	0
09/06/2001	Cesium	Russia	Attempted acquisition	0	0

12/2001	Strontium	Georgia	Attempted acquisition	3	0
05/2002	Cesium	Russia	Attempted acquisition	3	0
05/2002	Iridium-192	China	Citizens and property	75	0
05/30/2002	Cesium-133	Russia	Possession only	0	0
07/02/2002	Plutonium	UK	Plot	0	0
07/19/2002	Plutonium, cesium, strontium, uranium	Russia	Attempted acquisition	0	0
09/18/2002	Cesium	Kazakhstan	Possession only	0	0
06/13/2003	Cesium	Thailand	Attempted acquisition	0	0
07/22/2003	Cesium	Russia	Attempted acquisition	0	0
09/03/2003	Cesium	Poland	Attempted acquisition	0	0
05/06/2004	Cesium	Ukraine	Attempted acquisition	0	0
01/22/2005	Cesium-137	Ukraine	Possession only	0	1
02/08/2005	Radioactive scrap	Kazakhstan	Attempted acquisition	0	0

2.3 Unauthorized activities of illicit trafficking

The IAEA (International Atomic Energy Agency) Illicit Trafficking Database (ITDB), established in 1995, is a response to the increasing demand for timely and complete information on illicit trafficking and other related unauthorized activities involving nuclear and other radioactive materials. The ITDB facilitates the exchange of authoritative information on reported incidents among participating Member States, and is a key contributor to the IAEA's activities to help strengthen nuclear security worldwide and to prevent nuclear and radiological terrorism.

The scope of ITDB includes incidents that involve unauthorized acquisition, provision, possession, use, transfer, or disposal of nuclear materials and other radioactive materials, whether intentional or unintentional and with or without crossing international borders, including unsuccessful and thwarted events. The scope of ITDB also includes other related unauthorized activities, including incidents involving inadvertent loss and discovery of uncontrolled nuclear and radioactive materials, e.g. orphaned sources [IAEA, 2005, 2006].

In the database, the majority of confirmed cases with nuclear materials involved low-grade nuclear materials (low enriched uranium, LEU) mostly in the form of nuclear fuel pellets, and natural uranium, depleted uranium, and thorium. These cases involved criminal activities, such as theft, illegal possession, illegal transfer, or transaction. Some of these incidents indicate that there is a perceived demand for such materials on the "black market", signaling that profit seeing is the principal motive behind them.

As of December 31, 2005, the ITDB contained 827 confirmed incidents, of which 224 involved nuclear materials, 516 involved other radioactive materials, mainly radioactive sources, 26 involved both nuclear and other radioactive materials, 50 involved radioactively contaminated materials, and 11 involved other materials [ITDB, 2005]. In 2006, a total of 150 occurred incidents were reported, of which 85 involved thefts, losses, or misrouting of nuclear or other radioactive materials (Cs-137, Am-241, Ir-192, I-125, I-131, Mo-99, Tc-99m, Pd-103, etc.), and 51 involved other unauthorized activities, such as recovery of sources, discovery of orphaned sources, detection of materials disposed of in an unauthorized way, etc [ITDB, 2006].

Figures 2-6 show various metrics of the data compiled and published by the ITDB [ITDB, 2005, 2006].

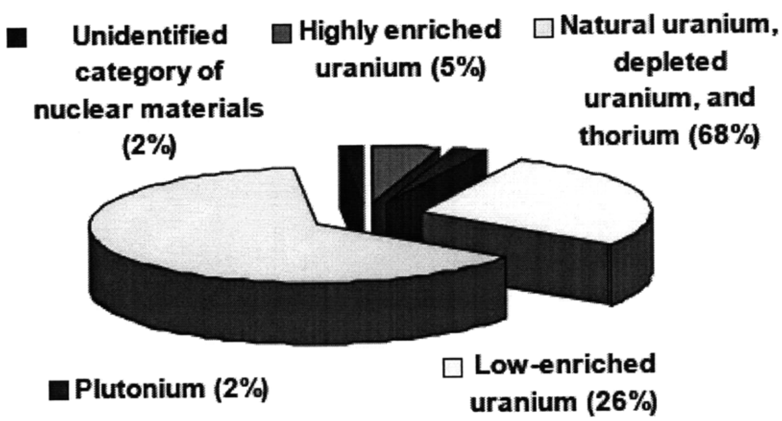

Figure 2: Incidents involving nuclear materials confirmed to the ITDB, 1993-2005.

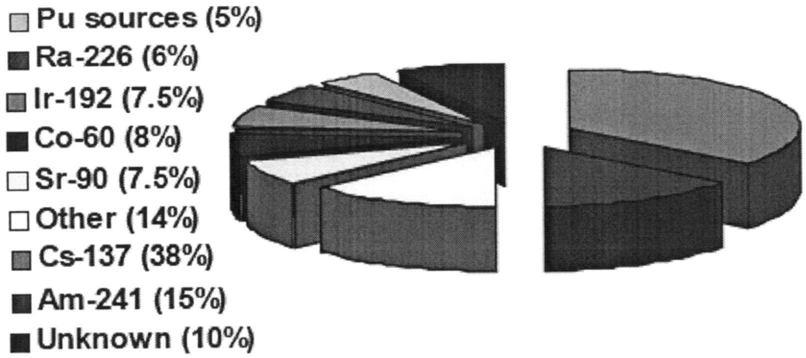

Figure 3: Incidents involving radioactive sources confirmed to the ITDB, 1993-2005.

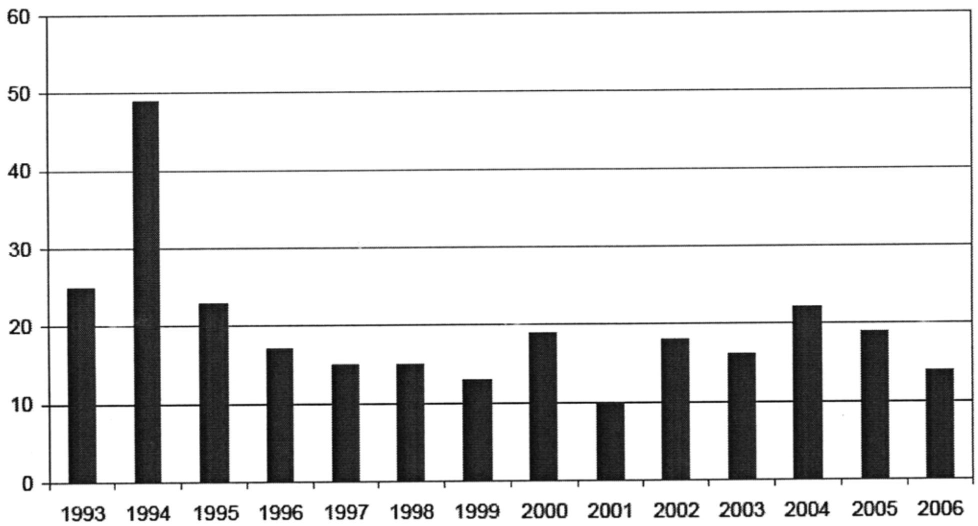

Figure 4: Incidents reported to the ITDB involving unauthorized possession and related criminal activities, 1993-2006.

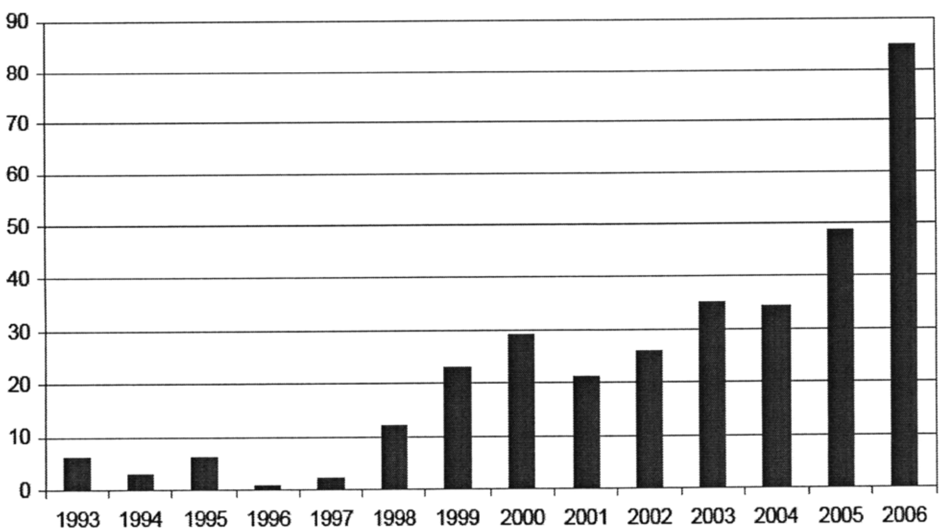

Figure 5: Incidents reported to the ITDB involving theft or loss, 1993-2006.

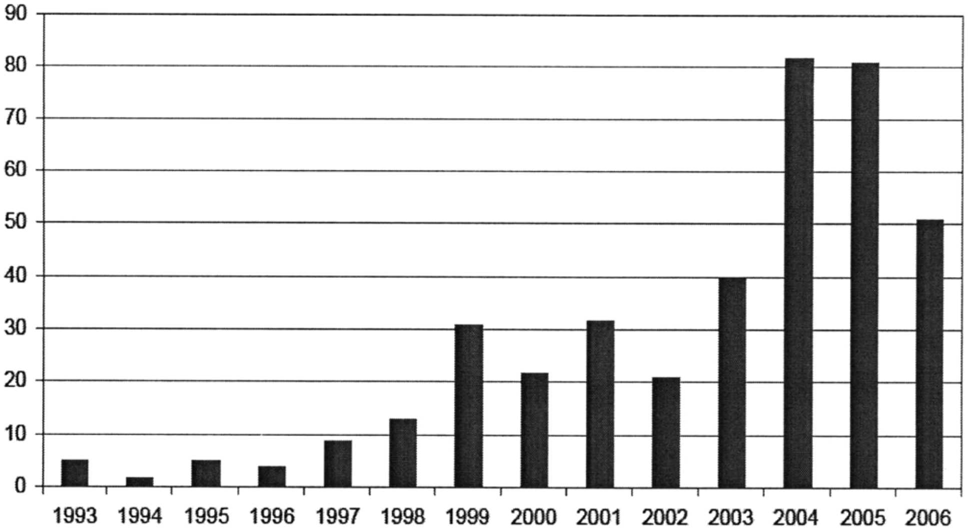

Figure 6: Incidents reported to the ITDB involving other unauthorized activities, 1993-2006.

2.4 Incidents of nuclear terrorism

Database of Radiological Incidents and Related Events compiled by Wm. Robert Johnston lists incidents of nuclear terrorism between 1961 and 2001. Nuclear terrorism, according to the database, is defined as a group of acts of violence, both politically and non-politically, involving radioactive materials, assaults on nuclear facilities, and thefts of nuclear warheads. Table 3 summarizes the nuclear terrorism incidents highlighted in the database [Johnson, 2009]

Table 3: Nuclear terrorism incidents in *Database of Radiological Incidents and Related Events*.

Date	Location	Description of incidents
01/03/1961	United States	Criticality incident at SL-1 test reactor by murder-suicide
1966-1977	Europe	10 terrorist incidents against European nuclear installations
Before 1974	Austria	Radioisotope indium-113 applied to a railroad car
1974-1986	United States	32 acts of intentional damage/sabotage at domestic nuclear facilities
1974-1980	United States	~80 incidents of nuclear threats, two prompted NEST deployment
08/15/1975	France	2 bomb explosions at Mt. d'Arree NPS in Brittany
05/12/1976	Maine	2 bomb explosions in Central Main Power Company in Augusta
10/10/1976	Oregon	Bomb explosion next to visitor center at Trojan NPS
12/18/1977	Spain	4 ETA terrorists attacked guard post at Lemoniz NPS
03/17/1978	Spain	Bomb explosion in steam generator of Lemoniz NPS
1979	France	Environmental terrorists caused $20M in damages at a nuclear plant

1979	Virginia	2 plant operator trainees damaged four new fuel assemblies
01/1979	North Carolina	Extortion letter with sample of UO_2 sent to a manager of GE facility
06/13/1979	Spain	ETA guerillas planted bomb in turbine room of Lemoniz NPS
11/11/1979	Spain	ETA guerillas planted explosives at Equipos Nucleares factory
Before 1980	France	Radioactive graphite fuel element plugs placed under driver's seat
1981	New York	Fuel oil filter drains closed on generators a Nine Mile Point Unit 1
1981	Ohio	Water valve shut intentionally at Beaver Valley NPS
1982	France	5 rockets fired into Creys-Malville nuclear facility
08/1982	New Jersey	Values closed on backup diesel generator at Salem Unit II NPS
1983	West Germany	4 West Germans attempted to destroy a missile with crowbars
11/12/1984	Missouri	Catholic activists damaged equipment at Minuteman ICBM site
04/1985	New York	New York City's reservoirs contaminated with plutonium
06/1985	Arizona	Intentional tampering with water valves at Palo Verde NPS
After 1987	Pennsylvania	Mentally ill man drove through the fence at Three Mile Island plant
11/28/1987	California	Bomb explosion in parking lot of Sandia National Laboratories
02/1990	Azerbaijan	Rebels attacked a Soviet military depot near Baku
01/1992	Iran	Iran bought three Soviet nuclear warheads from Kazakhstan
03/1992	CIS	Radioactive materials stolen from Pridniestroviye, Transdnestr
1993	Russia	Radioactive substance planted in the chair of Vladimir Kaplun
11/1993	Russia	2 nuclear warheads stolen by employees of Zlatoust-36 Bldg. Plant
03/1994	Russia	Russian soldier opened fire at SS-25 ICBM site at Barnaul in Siberia
11/23/1995	Russia	Shamil Basayev directed to a parcel of CS-137 buried in Moscow
12/1995	France	Saboteurs put salt into a cooling contour of a Blayais power reactor
01/09/1996	Russia	Chechen fighters attacked a Russian military airfield at Kizlyar
06/1996	New York	Several individuals plotted to kill Republican officials
After 1996	Russia	Gunman barricaded himself in a nuclear submarine
05/1997	Russia	A number of Soviet ADMs disguised as suitcases were missing
11/1997	Russia	Several threats made to sabotage submarine nuclear reactors
08/19/1999	United States	Andris Blakis spread P-32 on the chair of a co-worker in LA, CA
06/06/2000	Japan	Uchinishi sent letters laced with monazite to government offices
12/20/2000	Japan	A man scattered a small amount of I-125 at a subway ticket gate
2001	Worldwide	6 incidents involving terrorism with nuclear/radiological materials

3. Analysis of Data

3.1 Incidents of nuclear and radiological materials

Data from the *Database of Radiological Incidents and Related Events* are grouped according to type of incidents in Table 4, and incidents by five-year periods in Table 5, and are plotted in Figures 7-11. The codes of the type of incidents are provided in Appendix A.

Table 4: Listed incidents by type in *Database of Radiological Incidents and Related Events.*

Type of incident	No. of Incidents	Fatalities	Injuries
Accident involving nuclear reactor	11	0	31
Accident involving naval reactor	8	33	179
Accident involving power reactor	1	31	238
Criticality accident	27	17	51
Criticality accident involving research reactor	2	4	5
Accelerator accident	14	0	16
Accidental dispersal of radioactive material	1	0	0
Accidental internal exposure to radioisotope	10	12	79
Irradiator accident	21	8	28
Medical radiotherapy accident	31	70	217
Medical x-ray accident	5	0	16
Orphaned source accident	23	29	91
Accidental dispersal of orphaned source	2	6	24
Radiography accident	60	1	75
Accidental exposure to source	42	5	66
X-ray accident	51	0	62
Radiation accident (unspecified or other)	44	3	93
Intentional exposure of individual (assault)	9	4	81
Criminal act (unspecified)	5	0	12
Intentional self-exposure	5	3	2
Exposures resulting from theft of source	8	7	17
Nuclear weapon test	3	1	93
Total	382	234	1475

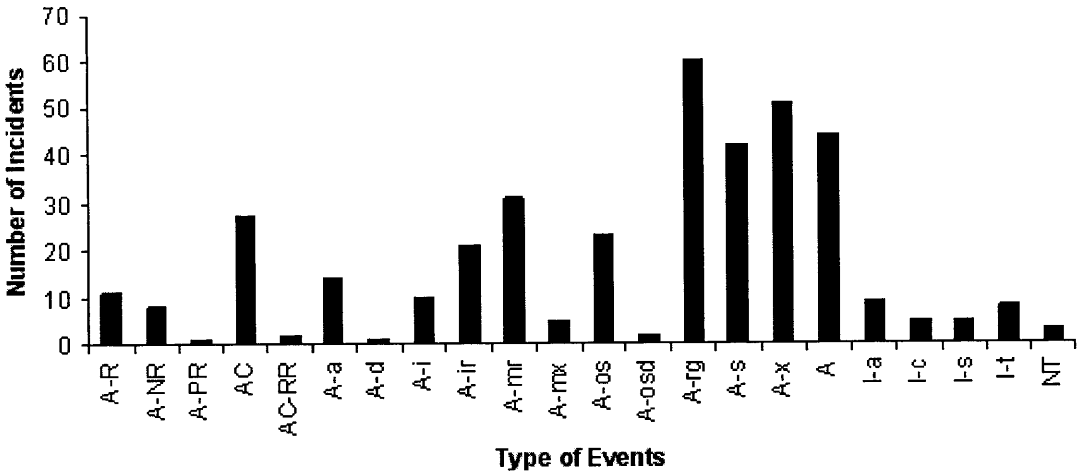

Figure 7: Type of incident vs. frequency of occurrence.

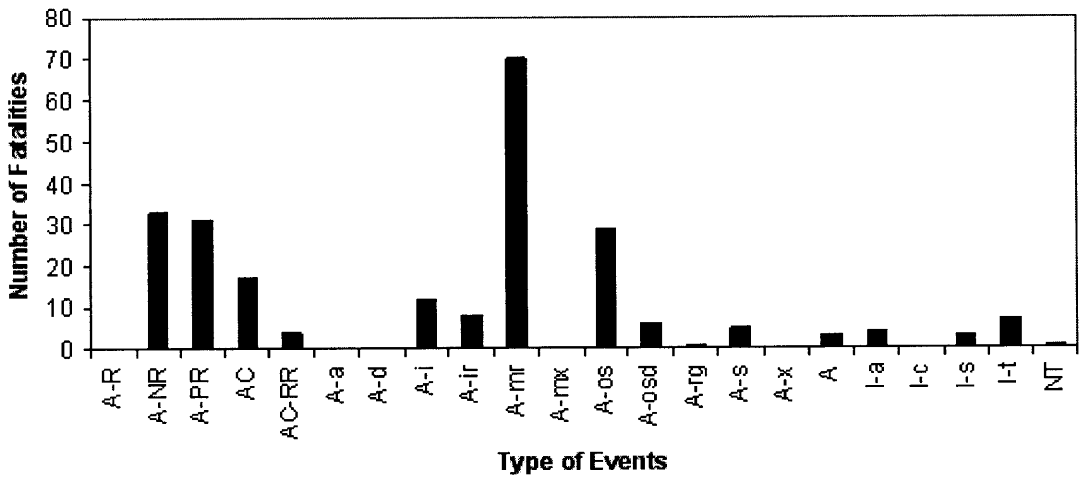

Figure 8: Type of incident vs. number of fatalities of each incident.

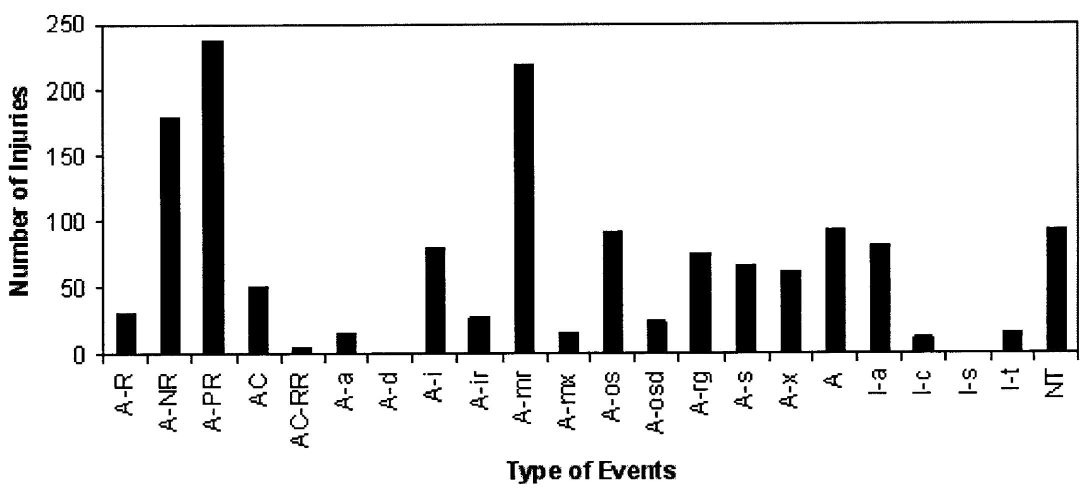

Figure 9: Type of incident vs. number of injuries of each incident.

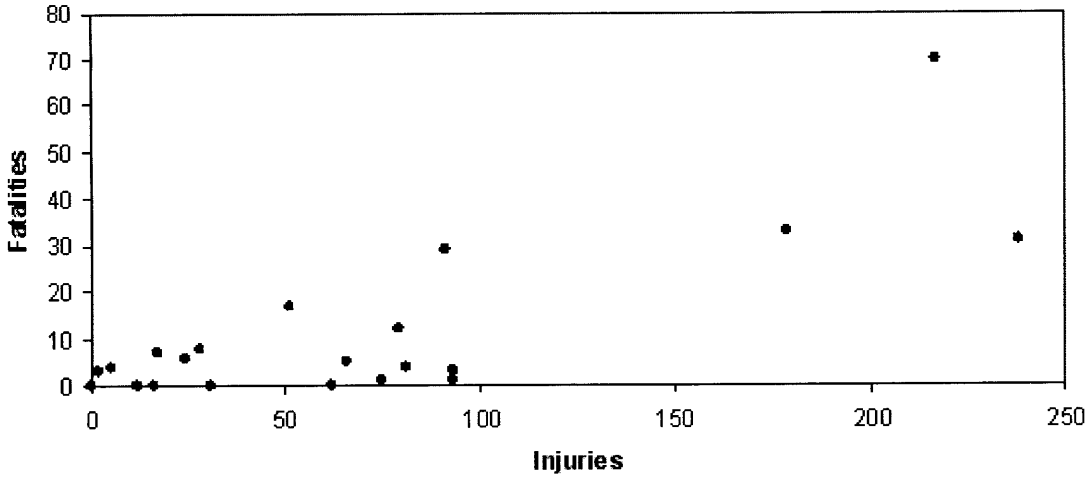

Figure 10: Combination of numbers of injuries and fatalities. Each point represents one incident.

Table 5: Listed incidents by five-year period in *Database of Radiological Incidents and Related Events*.

Period	Incidents	Fatalities	Injuries
Pre 1945	3	9	72
1945-1949	2	2	2
1950-1954	27	5	151
1955-1959	11	6	29
1960-1964	26	22	80
1965-1969	39	13	132
1970-1974	37	16	126
1975-1979	56	6	74
1980-1984	46	28	85
1985-1989	47	51	388
1990-1994	32	29	55
1995-1999	29	20	127
2000-2004	21	25	142
2005-2007	7	2	13

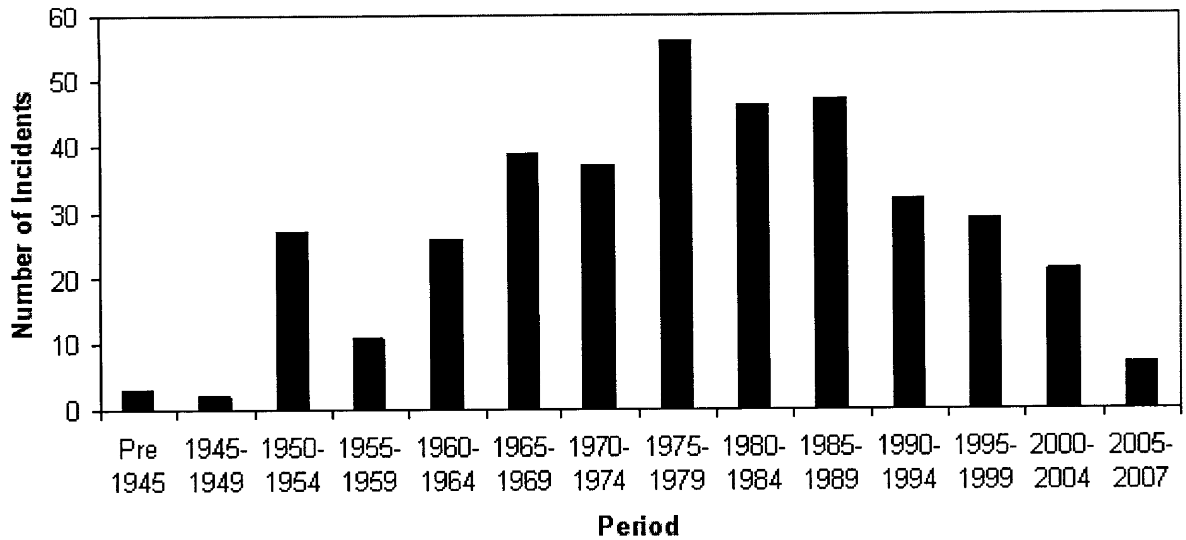

Figure 11: Number of incidents in five-year periods from 1945 to 2007.

3.2 Incidents of radioactive attacks

Data of radioactive attacks provided by *A Global Chronology of Incidents of Chemical, Biological, Radioactive and Nuclear Attacks*: *1950-2005*, as listed in Table 2, are summarized in Figure 12, with number of injuries plotted against number of fatalities for each attack.

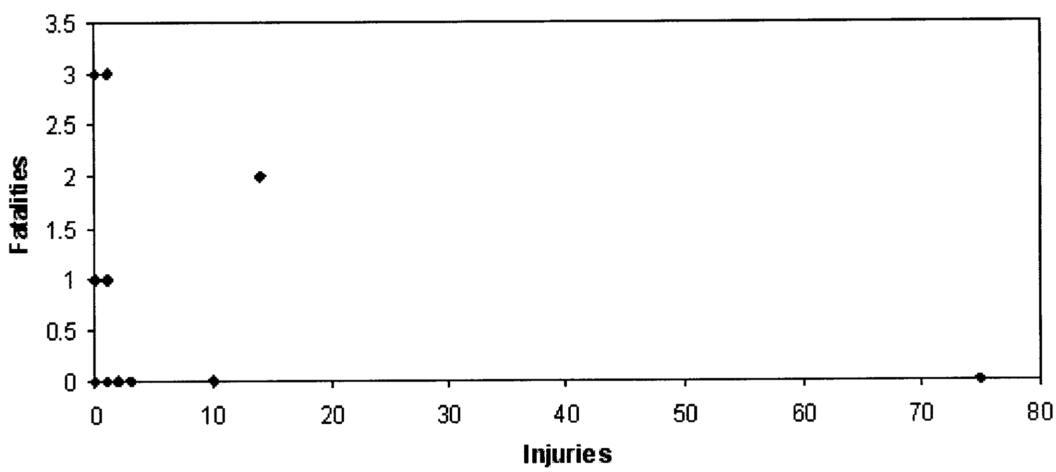

Figure 12: Injuries vs. fatalities. Each point represents one radioactive attack.

4. Results and Discussion

Data were gathered from a number of sources: *Database of Radiological Incidents and Related Events* compiled by Wm. Robert Johnston [Johnson, 2009], *A Global Chronology of Incidents of Chemical, Biological, Radioactive and Nuclear Attacks* compiled by Mohtadi and Murshid [Mohtadi, 2006], and the IAEA (International Atomic Energy Agency) Illicit Trafficking Database (ITDB) [IAEA, 2005, 2006]. Although these databases include most of the worst nuclear and radiological incidents, they are far from complete. They are most incomplete regarding events that have caused only minor injuries. Despite the information provided by the IAEA through its public domain, full or partial versions of the dataset are not released to the outside party. In addition, there may exist many instances that have not been documented, underscoring the fact that the reporting is an ongoing effort.

Therefore, even though incidents involving nuclear and radiological materials satisfy the assumptions of the power-law growth model – new events are created at a regular but random rate, growth rate of existing events is random, and rate is independent of the size of the objects – the limited amount of public data has rendered the analytical and modeling task difficult and challenging. One main initial objective is to model the severity of the events involving nuclear and radiological materials. Nonetheless, the small consequences of those publicly known events, i.e. small numbers of injuries and fatalities, as shown in Figures 10 and 12, do not conform to a well-distributed manner than can be mathematically analyzed with an established model. Furthermore, even though Figure 7 shows relatively large frequencies of occurrence for certain types of events, a consistent pattern cannot be observed.

From the section *Analysis of Data*, it can be seen that that in order to successfully model the data with standard statistical and mathematical distributions and to observe the trend of the events involving nuclear and radiological materials, more data need to be collected over a wider range of period. To achieve this, a more efficient method of collecting the data should be employed. This requires gathering information through various means, including different department or government related domains that are available to the public as well as professional insight and support.

With sufficient data, one way to probe the power-law behavior is to construct a histogram representing the frequency distribution of the consequences of the events, including both injuries and fatalities, and plot the histogram on doubly logarithmic axes. The quantity of interest, which is severity, obeys a power law if it can be drawn from the probability distribution according to Equation 8, where the exponent is the constant scaling parameter.

5. Conclusion

Events involving nuclear and radiological materials can exert monumental impact. For example, uncontrolled radioactive sources can harm human health and the environment, and unauthorized discarded or disposed radioactive sources can lead to grave environmental and economic consequences. Specifically, illicit trafficking in nuclear materials is a potential threat to the security of states and nations worldwide, as it can be a shortcut to nuclear proliferation and to nuclear terrorism. Thus, identifying common trends of these events helps to assess threat, to evaluate current weakness in material security, and to improve detection capabilities and practices.

Nuclear and radiological events are treated as black swans due to their large-impact, hard-to-predict nature. One way to study these events is to model them with statistical and mathematical distributions. Power-law distribution is a good candidate because it is a probability distribution with asymptotic tails, and thus can be applied to study patterns of rare events of large deviations.

Data of four categories of events were researched and gathered: incidents of nuclear and radiological materials, incidents of radioactive attacks, unauthorized activities of illicit trafficking, and incidents of nuclear terrorism. Even though more data are desired to efficiently perform the modeling with power-law distributions, the applications of using statistical and mathematical distributions have become increasingly important to study the trends of rare events. In order to compile a comprehensive dataset for analytical purposes, regional, national, and international capacities to track nuclear events need to be strengthened, and information sharing, management, and coordination need to be enhanced.

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Appendix

Appendix A: codes of type of incidents of nuclear and radiological materials.

A	Radiation accident (unspecified or other)
A-R	Accident involving nuclear reactor
A-NR	Accident involving naval reactor
A-PR	Accident involving power reactor
AC	Criticality accident
AC-RR	Criticality accident involving research reactor
A-a	Accelerator accident
A-d	Accidental dispersal of radioactive material
A-i	Accidental internal exposure to radioisotope
A-ir	Irradiator accident
A-mr	Medical radiotherapy accident
A-mx	Medical x-ray accident
A-os	Orphaned source accident
A-osd	Accidental dispersal of orphaned source
A-rg	Radiography accident
A-s	Accidental exposure to source
A-x	X-ray accident
I-a	Intentional exposure of individual (assault)
I-c	Criminal act (unspecified)
I-s	Intentional self-exposure
I-t	Exposures resulting from theft of source
NT	Nuclear weapon test