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Classification of Civil, Industrial and Medical Nuclear Accidents

In the first volume of this series [AMI 19], we reviewed the definitions of nuclear incidents and accidents, and provided the American classification for military accidents.

The generally accepted definition of an accident is “a fortuitous event that has more or less harmful effects on people or things”. The term accident frequently implies apparent medical damage, morbidity or even mortality [NÉN 01, NÉN 06, NÉN 07]. When the accident is very serious, the terms catastrophe (the event that causes serious disruption and death) or calamity (a public misfortune where misfortune affects a region, a group of individuals) are used. On the contrary, the term incident refers to “an occurrence, a secondary event, generally unfortunate, that occurs during an action and can disrupt its normal course”.

Nuclear accidents in the civil, industrial and medical fields occur involuntarily following either a major natural event (earthquake, tsunami, etc.) or human error with serious repercussions, or could result from an act of terrorism.

The most serious nuclear accidents cause considerable damage to the environment, flora, fauna and humanity. In addition, their socio-economic impacts can be immense.

1.1. Nuclear accident or radiological accident?

To answer this question, it is necessary to define some essential terms in nuclear physics. An atom, an elementary unit, is made up of a nucleus and electrons that gravitate around it. Each nucleus consists of protons (Z) and neutrons (N), the sum constituting the nucleons (A=Z+N). For the same element, the composition of the nucleus may differ in terms of the number of protons and neutrons, each composition constituting an isotope. Some elements can have many isotopes.

The simplest of the elements, hydrogen, consists of a very abundant isotope with a single proton and a single electron. There are two other isotopes: deuterium (nucleus comprising a proton and a neutron) and tritium (nucleus consisting of a proton and two neutrons). The great difference in the constitution of the nucleus explains the exceptional attribution of a particular name. Hydrogen is the most abundant isotope (99.98%), the other two isotopes being very much in the minority. A contrasting example is cesium, where 40 isotopes coexist with a number of nucleons ranging from 112 to 151.

For a given element, some isotopes are unstable and therefore radioactive. To regain their atomic stability, they must get rid of an electron, a helium nucleus or a photon. These unstable isotopes are called radionuclides.

In hydrogen elements, only the tritium isotope is unstable and radioactive. It recovers its stability by losing an electron and thus transforming into helium. In the case of cesium, only one isotope is stable, cesium 133 (^{133}Cs) containing 78 neutrons. All other isotopes are radionuclides, two of which are important: cesium 134 (^{134}Cs) and cesium 137 (^{137}Cs) because they are fission products of uranium 235 (^{235}U).

The return to stability is not always a one-step process. There are often several descendants. For example, there are three main natural families whose leaders are uranium 238 with 14 descendants, uranium 235 and thorium 232 with 11 descendants each.

The toxicity of radionuclides is twofold, chemical toxicity resulting from their elementary characteristics and radiotoxicity from their emission of ionizing radiation. With the exception of uranium, which has a high chemical toxicity, radiotoxicity is considered, for other radionuclides, to be the most dangerous.

As a chemical element, the radionuclide will participate in the usual chemical reactions, disperse into various compartments of the environment and enter living organisms through various pathways (including food). This results in radioactive contamination of the environment and living beings (external and internal contamination).

By definition, any event affecting the entire atom will qualify as atomic. When the event takes place at the nucleus level, the event will be nuclear. The distinction between atomic and nuclear events was abandoned in the 1950s because the term atomic had too negative a connotation and only the term nuclear remained for civil activities. An accident involving releases of radionuclides to the environment will therefore be a nuclear accident. When only ionizing radiation reaches the living being, the event qualifies as radiological. This is the case when radioactive contamination remains external and confined. An accident with an intact radioactive source or linear accelerator will therefore be a radiological accident.

In the case of a nuclear accident, the International Atomic Energy Agency's (IAEA) International Nuclear Event Scale (INES) will be used as a calibration to estimate the severity of the accident. In the case of a radiological accident, another scale such as the ASN-SFRO or radiological scale should be used instead.

1.2. Classification of nuclear accidents. Incident or accident?

Following the accidents at Three Mile Island in 1979 and Chernobyl in 1986, the IAEA decided to create an INES. This scale was implemented worldwide in 1991. It has eight severity levels rated from 0 to 7. For quantifiable events of a comparable nature, the scale is logarithmic, the change from one level to another corresponding to a factor of 10.

Since 1991, the INES has enabled the establishment of a common language for the assessment of an incident or accident in the nuclear sector. The OECD, then the IAEA, drew heavily on a nuclear event severity scale set up by France in 1987 to design the INES. This common international reference makes it easier to understand public opinion. Information on an event is communicated via the IAEA to all countries that have adopted the INES [LEC 04].

The INES is based on several criteria that are taken into account to define the nuclear event's severity level. The reported events are analyzed according to their consequences at three levels: (1) wider impacts on people or property (worker and/or public health); (2) on-site impacts; and (3) defense-in-depth impacts (presence of several containment barriers). This approach is detailed in Table 1.1.

Type	**INES**	**Wider impact**	**On-site impact**	**Damage to defense-in-depth**
Major accident	7	Major release: widespread effects on health and the environment		
Serious accident	6	Significant release likely to require full implementation of planned countermeasures		
Accident (resulting in wider consequences)	5	Limited release likely to require partial application of planned countermeasures	Serious damage to the reactor or radiological barriers	
Accident (not resulting in a significantly wider risk)	4	Minor release: public exposure within statutory limits	Significant damage to the reactor or radiological barriers, or lethal exposure of a worker	Loss of defenses and contamination
Serious incident	3	Very small release: public exposure represents a fraction of the statutory limits	Serious contamination or acute effects on a worker's health	Accident narrowly avoided. Loss of defense lines
Incident	2	No consequences	Significant contamination or overexposure of a worker	Incident with significant failure of safety provisions
Anomaly	1	No consequences	No consequences	Anomaly not included in the authorized modus operandi
Deviation	0	No consequences	No consequences	Insignificant anomaly from a safety point of view

Table 1.1. *The severity levels of a nuclear event. The INES*

The transition from incident (levels 1–3) to accident (levels 4–7) is characterized by environmental contamination that can damage public health.

Events that occurred before the INES was created were rated retrospectively. In the end, and without being exhaustive, we can note that only two accidents received a rating of 7 (major accident). These are the accidents at Chernobyl (Ukraine) on April 26, 1986 and Fukushima (Japan) on March 11, 2011. One accident was classified as a level 6 accident (serious accident), the Kyshtym disaster in the USSR (Mayak nuclear complex) in 1957. Four events were considered to be level 5 (accident). These were the accident at the Chalk River Laboratories in Canada in 1952, the fire at Windscale (now Sellafield) in the United Kingdom in 1957, the Three Mile Island nuclear accident in the United States in 1979 and the Goiânia nuclear accident in Brazil in 1987 (Table 1.4). This table lists the 10 accidents considered to be the most serious.

1.2.1. *Application of the INES in France*

The INES was adopted in France by the *Autorité de Sûreté Nucléaire* (ASN) in April 1994. The application of the scale concerned all the basic nuclear installations controlled by the ASN (EDF reactors, Areva plants, CEA laboratories, etc.).

The feedback from these industries is based on incidents considered significant, i.e. events that could, in unfavorable circumstances, have combined with others to generate major accidents. In order not to be overwhelmed by the number of events to be recorded and analyzed, the French nuclear manufacturers (EDF, CEA, Orano (previously Areva), etc.) decided to distinguish two groups of events of different severity that are relevant to safety and to apply different methods to them. These two groups are *événements intéressants la sûreté* (events of interest for safety – EIS) and *incidents significatifs pour la sûreté* (significant safety incidents – ISS) [LEC 04].

EIS are entered into a national computerized file managed by EDF, called the *fichier des événements*, “event file”. ISS must be notified to safety organizations and be the subject of a detailed analysis report according to a standard plan. This method should facilitate feedback through broad criteria for recording data in databases.

In addition, proactive security methods have been established. This approach to safety has led to technical advances by producing energy more efficiently (fewer cut-offs, shutdowns, reductions of installed capacity) while making financial gains. As in aviation, relevant information is taken into account while ensuring confidentiality and protection for particularly sensitive industrial information [LEC 04].

1.2.2. *Application of the INES at the international level*

At the international level, three reporting systems are mainly used, namely SOL, IRS and HPIP [LEC 04]. The SOL (Safety through Organizational Learning) system was developed by the Centre for Systems Security Research at the University of Berlin in collaboration with the media outlet TÜV Rheinlandest. It was an approach to event analysis based on the concepts of socio-technical systems and psychological theories of incident genesis (accidents and near accidents). The HPIP (Human Performance Investigation Process) is used by the CRN (*Commission de Régulation Nucléaire*) to investigate events related to human performance in nuclear power plants. Developed by Paradies *et al.* [PAR 93], the HPIP structure contains six main human failure modules. The IRS (Incident Reporting System) is used by the IAEA and the NEA (OECD Nuclear Energy Agency), developed by the WANO (World Association of Nuclear Operators).

1.2.3. *Other classifications of nuclear accidents*

The IAEA's INES classification, while making great progress, is not always satisfactory, and therefore several proposals exist to classify the severity of nuclear accidents. In particular, the three main classification criteria of the INES cannot be applied to radioprotection, i.e. the protection of individuals against ionizing radiation. Similarly, the INES classification does not take sufficient account of the quantities of radionuclides released into the environment.

1.2.4*. The NAMS classification*

Smythe [SMY 11] proposed a new quantitative scale of nuclear accident magnitude (NAMS). To do this, he used the event magnitude approach by calculating the magnitude of the accident (*M*) from wider releases of radionuclides (*R*). This radioactivity parameter is normalized in iodine 131 equivalents and expressed in TBq. The magnitude is calculated according to the following equation: $M = \log (20R)$.

Using this NAMS, the distribution between frequency and amplitude has been observed for 33 quantified events over the past 60 years. It follows a reverse power law, as in the case of earthquakes. However, the NAMS shows four exceptional accidents that have values 2–3 orders of magnitude higher than other accidents. These four accidents are, in decreasing order of severity, Chernobyl (NAMS 8.0), Three Mile Island (NAMS 7.9), Fukushima Daiichi (NAMS 7.5) and Kyshtym (NAMS 7.3). According to Smythe [SMY 11], such catastrophic accidents can occur every 12–15 years.

1.3. Classification of radiological accidents

Croüail and Lefaure [CRO 03a, CRO 03b] proposed a more radiologically realistic scale for classifying incidents and accidents. This scale makes it possible to take into account radiation protection events affecting patients as part of a radiotherapy procedure. This proposed scale was then discussed at the IAEA. English-speaking countries did not want to use a classification based on the number of people exposed. They only partially gave way on this point by downgrading certain events [ASN 04] by one level.

Therefore, since 2007, in France, a specific scale has been created, called the ASN-SFRO scale, which characterizes the severity of radiation protection events. The guide for the application of the new INES for the classification of radiation protection events (excluding patients) relating to radioactive sources and the transport of radioactive materials is currently being developed. Radiotherapy events affecting patients were classified on the ASN-SFRO scale issued by the ASN in July 2008 [ASN 08b, ASN 13]. The criteria for ranking on this scale focus on: (1) the proven consequences of exposure to ionizing radiation; and (2) the potential effects of the events (Table 1.2). Levels 0 and 1 are used to classify events without clinical consequences for the patient. Levels 2 and 3 correspond to events referred to as “incidents”. Levels 4–7 correspond to accidents (Table 1.3).

The IRSN [IRS 16a] provides some examples of incidents, such as the level 1 incident where, on October 31, 2008, a practitioner and two manipulators were contaminated with iodine 131 due to inadequate follow-up of cleaning procedures for objects that came into contact with this radioactive element. For level 2 incidents, the IRSN selected three examples. Following an irradiation zone error during radiotherapy performed on December 4, 2008, a patient was re-irradiated in an area after he had already been treated. According to doctors, his condition is now satisfactory. An overexposure of a patient occurred on December 24, 2008 during external radiotherapy during control exposures before a second treatment stage. According to the medical team, the patient's condition who is receiving special follow-up is currently satisfactory. On June 15, 2007, when a patient was irradiated, the manipulator was still in the treatment room. Based on the effective dose received (approximately 30 mSv), no health effects were expected for this person.

	Events (unforeseen, unexpected)	**Causes**	**Consequences (CTCAE V3.0 grade)**
5–7 Accidents	Death	Dose (or volume irradiated) much higher than normal resulting in complications or outcomes not compatible with life	
4 Accidents	A serious life-threatening event, complication or disabling condition	Dose or volume irradiated much higher than tolerable doses or volumes	Severe, unexpected or unpredictable acute or late reaction, grade 4
3 Incidents	An event causing severe alteration of one or more organs or functions	Dose or irradiated volume greater than tolerable doses or volumes	Severe, unexpected or unpredictable acute or late reaction, grade 3
2 Incidents	An event that causes or is likely to cause moderate impairment of an organ or function	Dose higher than recommended doses or irradiation of a volume that may result in unexpected, moderate complications	Moderate, unexpected or unpredictable acute or late effect, grade 2, minimal or no change in quality of life
1 Event	Event with the dosimetric consequence but no expected clinical consequence	Dose or volume error: for example, dose error or target error during a session that cannot be compensated for over the entire treatment	No symptoms expected
O event	Event without any consequences for the patient	For example, error in identifying a patient treated for the same pathology (compensable)	

Table 1.2. *The ASN-SFRO classification for radiological accidents (adapted from the ASN [ASN 13]. (1) Common Terminology Criteria for Adverse Event, Cancer Therapy Evaluation Program, August 2006, http://ctep.cancer.gov*

Event	Number of individuals and final ranking		
	Minimum ranking	Number of individuals	Final ranking*
Death or lethal dose received		> 10	6
	4	> 1	5
		1	4
Deterministic effect or potential deterministic effect with respect to the dose received		> 10	5
	3	> 1	4
		1	3
Exposure greater than 1 Sv or 1 Gy		> 100	6
	4	> 10	5
		≤ 10	4
Exposure greater than 100 mSv		> 100	5
	4	> 10	4
		≤ 10	3
Exposure of worker(s) to a dose above the annual regulatory limit or of a member of the public to a dose above 10 mSv		> 100	4
	2	> 10	3
		≤ 10	2
Exposure of worker(s) to a dose above the annual regulatory limit or of a member of the public to a dose above 10 mSv		> 100	3
	1**	> 10	2
		≤ 10	1

* The highest ranking should be selected. ** When a dose limit is exceeded as a result of the accumulation of exposure over a certain period of time, the ASN systematically assigns a level 1 classification for lack of a safety culture.

Table 1.3. *Procedure for the classification of an event on the basis of exposures or health consequences related to doses received [ASN 08b, IAE 13]*

1.4. The typology of accidents

Nuclear accidents can be of many different types. Criticality accidents that emit large quantities of neutrons and ionizing radiation are often lethal to workers. Industrial accidents due to fire, lightning, earthquakes, tsunamis and so on can damage any protective measures leading to leaks of radioactive materials. However, radiological protection is rarely broken leading to level 4 accidents. The occurrence of a level 5 accident requires an additional supply of energy. This has already occurred in the case of a core meltdown or could occur during an external attack such as a plane crash or a hollow charge shot (ammunition allowing the armor to be pierced).

1.4.1. *Criticality accidents*

We have seen that criticality accidents (resulting from an unintended chain reaction) were frequent in the military arena between 1945 and 1970 [AMI 19]. This type of accident has also occurred during the manufacture of nuclear fuel for nuclear power reactors, in the latter themselves, and in industrial and medical applications of nuclear technology (linear accelerators, radiotherapy). Accidents can occur in aqueous fissile media, in solid or dry metal media, and in mixed solid/liquid media. On the contrary, no cases have been reported for “powder” media.

Most accidents occurred in the United States (Hanford, Idaho Falls, Los Alamos, Oak Ridge and Wood River Junction) and in the former USSR (Obninsk, Electrostal, Mayak, Tomsk and Novosibirsk) [MCL 00] (Figure 1.1).

Since 1945, 60 criticality accidents, only six of which occurred after 1978, have occurred worldwide, mainly in research reactors and in laboratories. This means that until the early 1980s, there was more than one accident per year. The last three accidents occurred in Tokai-Mura, Japan (two in 1997 and one in 1999).

In a significant number of cases, these accidents resulted in immediate deaths or severe radiation exposure leading to premature death. Criticality accidents resulted in 17 deaths [GAM 07], 19 deaths [IRS 09a] or 20 deaths [MCL 00] depending on the sources. The procedure to be followed in the event of a criticality accident has been detailed by Miele and Lebaron-Jacobs [MIE 05].

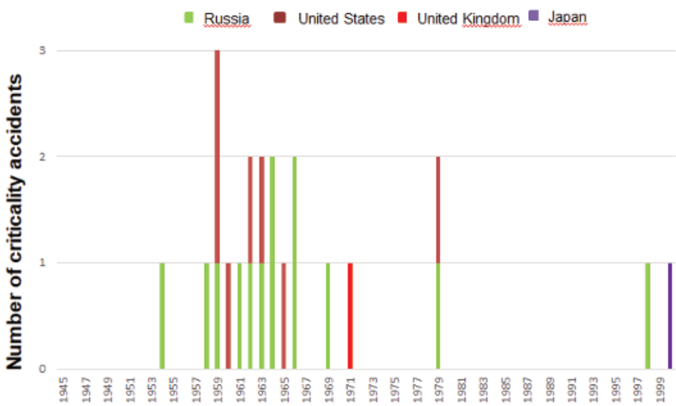

Figure 1.1. *Chronology of the main criticality accidents (adapted from [MCL 00]). For a color version of the figure, see www.iste.co.uk/amiard/industrial.zip*

1.4.2. *Accidents in nuclear power reactors*

Experimental nuclear reactors or power generators have been the subject of several accidents. The two largest nuclear disasters concern four nuclear power reactors (Chernobyl-4, Fukushima Daiichi-1, 2 and 3). All nuclear facilities were affected by a severe accident of levels 4–7. The economic consequences can be enormous.

1.4.3. *Losses of radioactive sources*

Highly radioactive sources are used for industrial purposes (non-destructive testing, food irradiation, etc.) or medical purposes (radiotherapy, brachytherapy). When these sources are lost, they can be found by the public. Since they are discrete (usually a small plastic cylinder), they can radiate strongly and for a long time, affecting any person in contact with this source, as well as their professional or family entourage. The number of accidents of this type is high, and the number of fatal cases is also relatively high. Among the most serious accidents of this type were those in Mexico City (Mexico) in 1962, Chiba (Japan) in 1971, Algeria in 1978, Brazil in Goiânia in 1987, Istanbul (Turkey) in 1999, Grozny (Russia) in 1999 and Samut Prakan (Thailand) in 2000. Each time several deaths were reported.

1.4.4. *Radiotherapy accidents*

Many types of cancers are treated by radiotherapy. The irradiation dose must be carefully calculated to kill all cancer cells. If underexposed, the patient has not been treated adequately and is at risk of dying from cancer. In the event of overexposure, healthy cells are irradiated and the risk of secondary cancer is not negligible. These cases of under- or over-exposure are most often a result of human error, either through the misuse of irradiation equipment (incorrect calculation of the irradiation dose, incorrect adjustment of the irradiation equipment) or through improper transmission of information.

1.4.5. *Terrorist attacks*

The possibilities for terrorists to cause a more or less major nuclear accident are numerous. National and international authorities must be vigilant and develop strategies to combat this risk of terrorism.

1.5. What are the main nuclear accidents?

The question is relatively simple but the answer is complex and subject to variation depending on sources [SOV 08, ROG 11, LEL 12, HAD 14, ASN 16]. Some of the discrepancies result from the criteria used to measure the severity of an accident. Is it the number of immediate deaths? Is it the amount of radioactivity released into the environment? Is it the area of land that has been condemned for centuries?

In the absence of a comprehensive and public reference list of nuclear accidents, we have reconstructed the history of nuclear accidents in power plants from scientific literature and various public sources.

The list of significant events classified at various levels on the INES is similar depending on the source for severity levels 6 and 7. On the contrary, for the lower levels, the lists diverge greatly. For information purposes, we provide in Table 1.4 those from the ASN [ASN 16]. The ASN thus retained two level 7 accidents, one level 6 accident, one level 5 accident, six level 4 accidents and 16 level 3 incidents.

Year	Site	Country	Case
Level 7			
1986	Chernobyl	Ukraine	Explosion of reactor 4 at the nuclear power plant
2011	Fukushima	Japan	Explosion of reactors 1, 2 and 3 at the nuclear power plant
Level 6			
1957	Kyshtym	USSR	Explosion of a radioactive product tank at the reprocessing plant
Level 5			
1979	Three Mile Island	USA	Partial fusion of the reactor core
Level 4			
1973	Windscale	UK	Release of radioactive materials following an exothermic reaction in a tank during reprocessing
1980	Saint-Laurent-des-Eaux	France	Damage to the A2 reactor’s core
1999	Tokai-Mura	Japan	Criticality accident in a fuel manufacturing facility
2006	Fleurus	Belgium	Irradiation by a cobalt 60 source of a worker working in an ionizing radiation sterilization facility
2010	New Delhi	India	Discovery of radioactive materials in scrap metal stores and irradiation of a scrap metal dealer
2011	Use of radiography	Bulgaria	Irradiation by a cobalt 60 source of four workers involved in an ionizing radiation sterilization facility
Level 3			
1981	The Hague	France	Fire in a storage silo
1991	Smolensk	Russia	Exceeding the operating boundary conditions during restart tests following a maintenance shutdown of reactor 2 at the nuclear power plant
1992	Sellafield	UK	Nitrated plutonium leak in a containment cell at the Sellafield fuel reprocessing facility

1993	Narora	India	Loss of power supply to reactor 1 at the nuclear power plant
1993	Kola	Russia	Emergency shutdown of reactor 1 at the nuclear power plant
2002	Roissy	France	Incident during the transport of a package by Federal Express between Sweden and the United States via Roissy airport
2002	Davis–Besse	USA	Discovery of a cavity in the vessel cover on the power plant reactor due to boric acid corrosion of the metal
2002	New Orleans	United States	High dose rate measured on a package from Sweden containing iridium 192 sources
2003	Paks	Hungary	Release of radioactive gases from cracked fuel rods stored in a cleaning tank located next to the fuel pool at the plant
2004	Puerto Rico	Puerto Rico	Irradiation by a cobalt 60 source of two workers involved in an ionizing radiation sterilization facility
2005	Sellafield	UK	Detection of a radioactive leak on a pipe in the THORP fuel reprocessing facility
2008	Toulouse	France	Irradiation by a cobalt 60 source of a worker working in an irradiation bunker on the ONERA site
2008	Fleurus	Belgium	Abnormal release of iodine 131 from the chimney of the *Institut des radioélements* building during a transfer of liquid effluent between tanks
2008	São Paulo	Brazil	Irradiation of an American and a Brazilian worker during the replacement of the cobalt 60 source of a cobalt therapy device in a state hospital

Table 1.4. *List of nuclear accidents in the civil field classified in order of decreasing severity according to the INES classification (severity 7 to 3). Significant events classified by the ASN [ASN 16] and by the IRSN [IRS 17e]*

Level 7 is used by all for the Chernobyl accident [IAE 13] and Fukushima [IRS 17e], level 6 for Kyshtym and level 5 for Three Mile Island [IAE 13]. On the contrary, the ASN [ASN 16] classifies the 1957 Windscale accident as level 4 and the IAEA [IAE 13] as level 5. In its list, the ASN ignores the Goiânia accident in Brazil in 1987 [IAE 13] and the accident at the Chalk River nuclear laboratories in Canada in 1952 [MOR 15], classified at level 5.

The ASN ignores the accident of October 17, 1969 in Saint Laurent with the fusion of 50 kg of uranium from the Saint-Laurent-A1 nuclear power plant in France during loading [IRS 15a]. Similarly, the ASN ignores the core fusion at the Lucens nuclear power plant in Switzerland on January 21, 1969 [CAN 11], classified at level 5 by the OFPP (*Office fédéral de la protection de la population*) [OFP 15]. The ASN [ASN 16] classifies the Fleurus accident (*Institut national des radioélements*) in Belgium in 2006 as level 3 and the IAEA [IAE 13] as level 4.

The level 3 incidents reported by the various official sources widely differ. While the ASN retains the Sellafield accident in 2005 [IAE 13] and the silo fire in The Hague in 1981 [FRA 14], several incidents reported by the IAEA [IAE 13], such as the loss of a source causing severe burns in 1999 in Yanango (Peru) or the same year in Ikitelli (Turkey) [IAE 13], are ignored. Further examples are the exposure of a worker to a radioactive source at ONERA in Toulouse (March 18, 2008) and of three temporary employees who entered an industrial accelerator in operation and were heavily irradiated in Forbach (Moselle) in 1991 [IRS 17e]. This was also the case for a radioactive leak (^{192}Ir) from a drum shipped from Sweden to the United States, transiting through Roissy (December 2001–January 2002) [ANO 02].

The most serious nuclear accidents involving reactors are those involving the melting of the fuel contained in their core. From an analysis of the various lists of nuclear accidents [SOV 08, ROG 11], we can consider that at least 12 reactors have been destroyed by this phenomenon since 1952. These are the Windscale plutonium cell (United Kingdom) in 1957 (but which we classified as a military accident), the Chalk River CANDU reactor (Canada) in 1958, the Simi Valley sodium-cooled experimental reactor (California) in 1959, the Monroe sodium-cooled demonstration breeder reactor (Michigan) in 1966, the Chapelcross reactor (United Kingdom) in 1967, the Lucens experimental reactor (Switzerland) in 1969, the pressurized water reactor at Three Mile Island (Pennsylvania) in 1979, the graphite-gas A2 reactor at Saint-Laurent-des-Eaux (France) in 1980, the Chernobyl reactor (Soviet Union) in 1986 and the three reactors at Fukushima (Japan) in 2011.

These are not the only reactors whose cores have suffered. For example, according to Wing and Hirsch [WIN 06], at least four of the reactors located at the Santa Susana Field Laboratory (SSFL) site have suffered such accidents. These are the AE6 reactor which suffered a release of gaseous fission products into the environment in March 1959, the SRE which had a power excursion and partial core meltdown in July 1959, the SNAP8ER which in 1964 suffered 80% damage to its nuclear fuel and the SNAP8DR which in 1969 suffered similar damage to one-third of its nuclear fuel. Let us also recall the accident in 1961 of the Idaho Falls SL-1 experimental reactor discussed in the previous volume [AMI 19], or that of the Jaslovske Bohunice reactor (Czechoslovakia) in 1977, but where the consequences were much more limited.

For nuclear workers, the number of accidents with clinical consequences is limited and tends to decrease for criticality accidents. On the contrary, the number is greater and tends to increase for accidents with radionuclides and especially for accidents related to sealed sources (Figure 1.2).

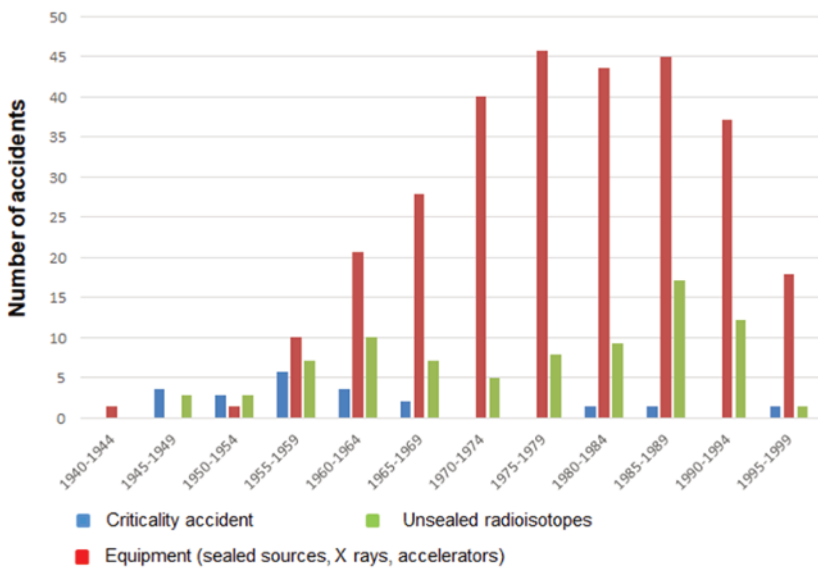

Figure 1.2. *Trends in the various types of nuclear and radiological accidents with clinical consequences for nuclear workers (adapted from [UNS 00a]). For a color version of the figure, see www.iste.co.uk/amiard/industrial.zip*

1.6. Information on nuclear energy

For a long time, public information on radioactive risk has been deficient and even biased, not only in the military field but also in civilian applications of atomic energy. Thus, most of the accidents that occurred in the 1950s and 1960s were kept secret. It was only after the Three Mile Island accident in 1979, and especially the Chernobyl accident in 1986, that public information became more free and taken seriously. The IAEA has mainly developed its communication policy since 1990.

In France, public information on nuclear events is provided by the ASN, created only in 2006. Level 0 incidents, about a thousand per year, are not systematically made public. They may be published if they are of particular media interest. All incidents classified at level 1 and above are systematically reported on the ASN website. Annually, there are approximately a hundred level 1 cases in France. Information on incidents at level 2 and above are published and, in addition, brought to the attention of journalists through press releases and telephone contact. In France, they only represent a few cases per year.

A follow-up of nuclear incidents was set up in 2001 by the CEPN and the group *Personnes Compétentes de la Société Française de Radioprotection* (SFRP), in cooperation with the IRSN and INRS. It is the RELIR system (http://relir.cepn.asso.fr/) that brings together the most interesting events for worker training and incident prevention. The selected incidents are presented in the form of descriptive sheets guaranteeing the anonymity of the exposed persons, companies and materials involved.