Calculating nuclear accident probabilities from empirical frequencies

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CALCULATING NUCLEAR ACCIDENT PROBABILITIES FROM EMPIRICAL FREQUENCIES

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Summary

Since there is no authoritative, comprehensive and public historical record of nuclear power plant accidents, we reconstructed a nuclear accident dataset from peer-reviewed and other literature. We found that, in a sample of five random years, the worldwide historical frequency of a nuclear major accident, defined as an INES level 7 event, is 14%. This value is 67 % to have at least one nuclear accident rated at level ≥ 4 on the INES scale. These numbers are subject to uncertainties because the fuzziness of the definition of a nuclear accident.

Résumé

En l'absence d'une liste d'accidents nucléaires de référence, exhaustive et publique, nous avons reconstruit l'historique des accidents nucléaires dans les centrales électriques à partir de la littérature scientifique et de diverses sources publiques. Dans un échantillon de cinq années aléatoires, la probabilité d'avoir dans le monde un accident nucléaire majeur (niveau INES 7) est de 14%. Celle d'avoir au moins un accident nucléaire (niveau INES ≥ 4) est de 67%. Ces chiffres sont entachés d'incertitude à cause du caractère flou dans la définition d'un accident nucléaire.

1   Introduction

The major accident that occurred in Fukushima on 11 March 2011 led to a renewed scientific interest in assessing nuclear risks. In the press, there has been a number of declarations such as Laponche et al. (2011) who claimed that the probability of a serious nuclear accident in the next thirty years was a "statistical certainty" for the European Union. Moreover countries such as Austria, China, Finland, France, Germany, India and Italy have responded with the adoption of very diverse nuclear safety and energy policies. Considering the policy importance of this issue, we recompute these estimates constructing our own data set and using a different method.

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Risk has two dimensions: the probability of an accident and the magnitude of its consequences. This paper deals with the first dimension of risk, the probability. The causes that might result in a serious nuclear accident are manifold and they include but are not limited to: design errors, construction problems, material or hardware deficiencies, internal events such as pipe break or fire, external events such as a plane crash or natural hazards (earthquake, floods), and mostly human causes, such as errors in manipulation, insufficient safety information, bad knowledge of instructions. In many cases, the accidents are due to a combination of several factors.

Despite the complexity of causes, nuclear engineers and scientists have tried to estimate the probability of a nuclear accident. One commonly used method is the probabilistic risk assessment (PRA) method that computes, in a bottom-up combination, the probability of an accident as the product of the probabilities of all known different possible failures. This method allows to assess risks and identify potentials to improve safety. However, However, the PRA analysis are bound to be subject to uncertainties since they cannot be totally exhaustive and there are uncertainties in knowledge. This usually results in a small probability.

Table 1 shows how the predictions for the PRA methodology compare to the historical record. In the first column, are indicated given nuclear accident probabilities per reactor per year, denoted ε. The numerical objective defined for core damage frequency, as evaluated from PRA studies, range from 10^{-4} to 10^{-6} for regulators in different countries (NEA-OECD, 2012). The second column shows at the expected number of accidents in the whole history of the nuclear industry for each value of ε. As of end of 2012, 437 reactors were in operation worldwide, and the cumulative nuclear reactor-years of operation worldwide and including all technologies adds up to 15,080 (European Nuclear Society, 2013). These values should correspond to core damage accidents of 0,15 to 1,5 for 15,080 reactor-years (15,080 times ε). This number is small compared to the real number of accidents.

Accident probability per reactor per year	Expected number of accidents since 1950	Probability of at least one accident in 5 years	Probability of at least one accident in 30 years
ε	$15080 * \varepsilon$	$1 - (1-\varepsilon)^{(437*5)}$	$1 - (1-\varepsilon)^{(437*30)}$
10^{-6}	0.015	0,22%	1,30 %
10^{-5}	0.15	2,16 %	12,29 %
10^{-4}	1.5	19,63 %	73,05 %
10^{-3}	15	88,76 %	99,9998 %

Table 1 : Four viewpoints on accidents probability.
The probability of an accident per reactor per year (first column) remains the same along each line. The probability of seeing an accident depends on how many reactors are observed during how many years.

The third and fourth columns indicate the probabilities of having an accident in five and 30 years for 437 reactors, assuming that the reactor-year accident probability is ε. The number of 437 reactors corresponds approximately to the number of nuclear reactors operating in the world today.

Thus given the complexity of the overall system, and the discrepancy between the values given by PRA analyzes and the number of accidents, a holistic approach such as the use of historical frequencies is used in this study. We assess the frequency of a nuclear accident and of a major accident from past experience.

In section 2, the basis on which nuclear accidents have been selected to construct the data set is defined and the way in which the discrete INES scale does not take into account the complexities of a reality which is "fuzzy" is explained. Section 3 contains a review of some literature on nuclear accident risks with emphasis on probability estimates and nuclear accident inventories. In section 4, the construction of the data set is described. The method and results are presented in section 5 and 6. Section 7 concludes.

2   INES scale and nuclear accidents

The International Nuclear and Radiological Event Scale (INES) is a worldwide tool for communicating to the public the safety significance of nuclear and radiological events (IAEA, 2009). It was developed by the International Atomic Energy Agency (IAEA) : the IAEA statutes (article II – Objectives) states that "*The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose*" (IAEA, 2012) - and the OECD Nuclear Energy Agency – whose mission is "*To assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required*

for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes. To provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD policy analyzes in areas such as energy and sustainable development."(NEA, 2013)

Events are classified on the scale with 7levels. For communicating to the public, distinct designations have been attributed to each level, from *anomaly* (level 1) to *major accident* (level 7): « *the severity of an event could increase by about an order of magnitude for each increase in level on the scale* » (IAEA, 2009).

According to the IAEA's vocabulary, any *event* whose severity is rated at INES level ≥ 4 on the INES scale is an *accident*. Below level 4, the event is called *incident*. As mentioned above and illustrated on Table 2, there are many types of accidents. The potential consequences of an accident range from those limited to the core, to those contained inside the pressure vessel, to the release of radioactivity in the environment and those affecting the population. Because of this diversity, there are several criteria to assess the severity of an accident and the INES defines a level 4 event by any of the following characteristics:

1. At least one death from radiation.

2. Minor environmental release of radioactive material unlikely to result in implementation of planned countermeasure other than local food controls.

3. Fuel melt or damage to fuel resulting in more than 0.1 % release of core inventory.

4. Release of significant quantities of radioactive material within an installation with a high probability of significant public exposure.

The IAEA criteria provides the only agreed definition of a nuclear accident. However, the construction of an historical nuclear accident data set on the basis of the INES rating is an uncertain process for the following reasons:

-   Back-rating: The INES scale was developed only in 1990. Many previous events are not officially rated on the scale. Unofficial ratings may be found in the literature that may not be adequately justified.

-   Fuzziness: The INES scale is a communication instrument[2], not a safety evaluation tool. The INES manual provides guidance for reporting the events using only a single number, but the proper definition of an accident is complex. The fuzziness of the categorization using the INES level is apparent from the above four criteria : the terms "minor", "likely", "significant" are used. It is also the case for higher levels : one of the characteristics of rating is the quantity of radioactivity released and the

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[2]The first lines of the INES reference User's Manual (2008 edition) state "The need for easily communicating the significance of any event ..." (Foreword, page v.) and "The International Nuclear and Radiological Event Scale is used for promptly and consistently communicating to the public the safety significance of events associated with sources of radiation." (section 1.1)
http://www-pub.iaea.org/MTCD/publications/PDF/INES2009_web.pdf)

boundaries between levels from 4 to 7 are set approximately to 500, 5000 and 50 000 tera-becquerels (IAEA, 2009, p. 17). Moreover, the quantitative variables used to rate accidents, such as the released radioactivity, cannot be always precisely estimated either.

- Heterogeneity: The difficulty to characterize precisely an accident and its consequences, and therefore the ensuing fuzziness of the INES scale, makes the historical and geographical uniformity of assessment difficult to ensure, unlike the Richter earthquake magnitude scale for example. This difficulty could be partially alleviated if there were a world entity in charge of the consistent interpretation and rating of an accident. But rating is the responsibility of the power plant owner, or of the regulation entity in certain countries such as France, which is therefore the unique source of primary information. This can lead to important differences in reporting.

- Secrecy: To be notable, an event must have caused well-attested and substantial radioactivity release and contamination. For example, an accident that occurred in September 1957 in Soviet Union has been acknowledged only decades after :the waste storage explosion at Mayak, a plutonium production reactor for nuclear weapons and nuclear fuel reprocessing plant, near Kyshtym. This accident would have been rated at level 6 on the INES scale, 15,000 square kilometers were contaminated. It was made public to the outside world by Soviet dissident Zhores Medvedev in 1976 (Medvedev, 1976). The fact that serious events are not made public may also occur in the West: on 17 December 1987, eighteen months after the Chernobyl major accident, a serious incident occurred in the Biblis power station in West Germany. It was known internationally nine months later in an expert meeting in Vienna and made public one year later in an article published by Nucleonics Week, and rated at level 1 on the INES scale (Hibbs, et al, 1988). Therefore this serious incident in a purely civilian nuclear power plant was not known to the IAEA when it occurred. These examples underline the fact that some events, which could involve important radiation contamination or potential for much more serious consequences, can be kept secret from the public.

- Dual and multiple uses: Some accidents cannot be attributed only to power production. This is the case for those occurring in nuclear reactors producing jointly isotopes and electric power. Also, research and commercial uses cannot be distinguished in the case of large-scale reactor prototypes.

- Simultaneity: Power plants usually have two or more power reactor units. In our study, several simultaneous accidents at one plant are counted as a single one, such as However, in the case of the Fukushima Daichi major accident, results will be provided counting it as one accident as well as three accidents.

3 Previous studies on nuclear accident frequencies

There have been many studies on various aspects of nuclear accident frequencies and their scope is restricted to specific types or to a limited number of accidents. Assessments range from the assertion that « *nuclear power plants are very robust* » (World Nuclear Association, 2012) to the conclusion that « *nuclear power comes with the inevitability of catastrophic accidents* » (Ramana, 2011).

As stated above, Laponche and Dessus (2011) argued that nuclear accidents were statistically certain. They wrote that: "On the basis of the major accidents having occurred these last thirty years, the occurrence probability of a major accident would therefore be about 50% for France and more than 100% for European Union". Giving more details on the calculations, Ghys (2011) estimated this later probability to be about 72 %, based the same data (4 catastrophic core failures - 1 in Chernobyl, 3 in Fukushima - for 14 000 reactor-years).

Stratton (1967) published the first seminal review of criticality accidents. This work is about a subset of nuclear accidents, and does not look at commercial nuclear power plants. It was first revised in 1989 and updated again by McLaughlin et al (2000). The 2000 edition contains 60 accidents, 19 of which are new to it.

Lochbaum (2000), for the Union of Concerned Scientists, studied the risk assessment reports published by the US Nuclear Regulatory Commission and concluded that the probability assessments were biased towards lower values by the use of many unrealistic assumptions regarding plant design, construction and operation, a very limited number of human errors.

Kastchiev et al. (2007) have studied the safety records of nuclear power plants to assess risks and possible consequences of nuclear accidents. Based on the analysis of sixteen events, they concluded that "many nuclear safety related events [...] go either entirely unnoticed by the broader public or remain significantly under-evaluated when it comes to their potential risk".

T. Cochran (2011) gave a testimony where he stated that the historical frequency of core melt accident is about 1 in 1400 reactor-years which is rather far from the probability risk assessment estimate of 2×10^{-5} to 1×10^{-4} events/reactor-year for accidents (INES level ≥ 4) published in 1986 by the US Nuclear Regulatory Commission. Cochran's paper lists 12 nuclear power reactors (including Sodium Reactor Experiment) that have experienced fuel-damage or partial core-melt accidents.

Smythe (2011) proposed a new scale for the magnitude of nuclear accidents. He describes a list of 33 events in which he counts 4 events as catastrophic, leading him to conclude that "A magnitude 7 or greater accident is to be expected every 12–15 years."

Escobar Ranger and Lévêque (2013) have used a statistical - Poisson - model approach and performed a methodological study for the same problem, based on continuous time models and reliability theory. They found that the Fukushima major accident leads to a re-evaluation of previous risks assessments.

4   Construction of the dataset

The Aircraft Crashes Record Office compiles all aircraft accidents in the civilian aviation sector and makes complete and detailed statistics available to the public (ACRO, 2014). On the contrary, int he civilian nuclear energy sector, there is no world data set of nuclear accidents, and there is no way to have harmonized information on such events. The IAEA hosts a website NEWS "The Information Channel on Nuclear and radiological Events" which displays short reports of accidents as they are deposited on the website, but there is no website or directory of accidents including incident and accident statistics with detailed information on specific events. Moreover, in its disclaimer, it declares : "The IAEA makes no warranties, either express or implied, concerning the accuracy, completeness, reliability, or suitability of the information." (IAEA, 2014) Moreover, the IAEA is not legally bound to reply to all queries for information (Kastchier 2007, note page 5).

Many online sources, including the IAEA, have been consulted for this study, but with no assurance that any of them is complete. For instance, the IAEA NEWS (2012) web page states that « event reports are filed and updated by participating countries which remain responsible for all related content » and does not contain an archive which is publicly available. The available information include: event description, INES rating, related technical information and press releases. We also consulted accident lists published online by Wikipedia (2012) and other sources, other databases provided by non governmental organizations, or independent researchers, some of them containing a lot of information such as Johnston's (2011) archives and Climatesceptics.org (2012).

In building this sample, the goal was to find and record all events rated at INES level ≥ 3 which occurred at a licensed and commercially operational power plant since 1951, the start of nuclear energy for civilian purposes. Given the lack of standardized and complete world data set, the reconstructed data set suffers from the deficiencies discussed in Section 2 above. There is uncertainty on the number of events and in their rating, since the INES levels are not precise enough, including in terms on released radioactivity, and thus the frontier between accident and incidents is fuzzy.

The present study is only based on accidents with an INES level ≥ 4. [3]

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[3]Since the limits between INES level are fuzzy, accidents rated at level = 3 were also looked for in the research to build the dataset. This will be used, in a later study, to allow more specific tests regarding the influence on the results of this study stemming from a fuzzy frontier between different INES levels.

Examples of accidents related to nuclear power production	Examples of nuclear accidents not related to electricity production, not considered in this paper
Uranium mine. Radioactive waste spill. Church Rock, USA, 1979 (no immediate direct fatality)	**Weapons**. Criticality accident with Pu metal assembly. Los Alamos, USA, 1946 (1 fatality)
Fuel facility. Criticality accident with Uranium solution. Tokaimura, Japan, 1999 (2 fatalities)	**Naval propulsion**. K27 submarine reactor accident. Russia, 1968 (9 fatalities)
Reprocessing facility. Chemical explosion following tank cooling system failure. Kychtym, Russia, 1957 (300 × 50km area contaminated)	**Attack**. Five RPG-7 rockets fired on nuclear plant construction site. Creys-Malville, France, 1982 (minor damage)
Power reactor. Partial core melt. Saint Laurent des Eaux, France, 1969. (no immediate direct fatality)	**Industrial**. Lost gamma radiography source. Conceptión, Chile, 2005 (3 workers injured)
	Medical. Radiotherapy overexposure. Zaragoza, Spain, 1990 (11 fatalities)

Table 2 : Types of nuclear accidents. This paper only considers those involving electricity production (left column).

Several accident types are listed in Table 2. Only events of the categories described in the left column pertaining to the production of nuclear electricity are retained in the dataset. The right column shows that many other types of radiological accidents are not taken into account in the present study : military activities as well as those such as medical activities or industrial activities which cannot lead to major accidents were ignored.

For events having occurred before 1991, when the INES scale became operative, accident descriptions were used to assess a level equivalent to the INES level.

We assembled a data set of all events with an INES level ≥ 3 in the power sector. It contains 68 records summarized in Table 3 (see annex). Excluding level 3 events, Table 4a retains all events with an INES level ≥ 4 in all types of nuclear facilities. Excluding events in test facilities or fuel facilities, Table 4b lists the 13 accidents which occurred in nuclear power plants. Those are the only ones kept for this study.

Figure 1 shows the time distribution of events by INES level and shows a decrease in the number of accidents, but the two[4] major accidents occur in the later decades. Figure 2 shows the number of nuclear reactors in operation as a function of time : the number of reactors is increasing steadily until the mid 80s, and then remains at a roughly constant level until 2012. The comparison of those two figures shows that the bulk of accidents occurred before 1986 and that few accidents occurred when the number of reactors was at its maximum. The absolute number of accidents decreases, but the damage on environment does not decrease.

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[4]Or four major accidents if one considers that 3 major accidents occurred in Fukushima Daichi.

5 Method

An accident being defined as an event with an INES level ≥ 4, the empirical frequency of the number of accidents over T years is computed using the method described below. Over the 61 years from 1951 to 2011, there was 49 years with no accident, 11 with one accident and one year with two accidents. The number of accidents in one year is modeled as a random variable denoted X. This variable takes the value 0, 1, 2 with a probability respectively of 49/61, 11/61 and 1/61.

To consider the number of accidents in T years, each year is independently drawn with re-sampling. This number is described by the random variable Y defined as the sum of T realizations of X.

The probability law of Y can be computed from the probability law of X. This is a classical problem of probability. The combinatorial counting required here is mathematically the same as the counting involved in the expansion of polynomial. This leads to use the so-called moment-generating function of a discrete variable X, defined by $g_X(z) = \sum_k p(X=k)\, z^k$.

$$g_X(z) = 49/61 + 11/61\ z + 1/61\ z^2$$

The moment-generating function of Y can be obtained from the moment-generating function of X by polynomial expansion:

$$g_Y(z) = g_X(z)^T$$

The coefficients of $g_Y(z)$ directly give the probability distribution of Y.

The results are shown in the Table 5a for $T = 5$, and in Table 5b for $T = 30$.

Regarding the number of major accidents, where there has been 59 years with none, and 2 years with one, the same method has been used with the generating function $59/61 + 2/61\ z$. The results are shown on the second lines on Table 5a and table 5b .

Numerical results were verified with a different statistical method: the bootstrap method. This method relies on iterated computer simulations. It involves drawing five years randomly in {1951, ..., 2011} and counting the accidents in these years. This is then repeated for 100,000 times to look at the statistical distribution of results. Since the repetition number is large enough, the statistical distribution of results is a satisfying approximation of the law of Y. The sample is represented in Figure 1 since it contains the number of accidents per year.

The results are shown in the Table 6a for $T = 5$, and in Table 6b for $T = 30$.

6 Results

Calculations were performed for a five-year time-span, which correspond to a typical decision-making time horizon, and for the same 30-year time-span, as used by Laponche, Dessus and Ghys.

The results presented in Table 5a show that for a sample of five random years, assuming that probability distribution of accidents is constant over the considered time span, the probability of having one year with one nuclear major accident (INES level = 7) is 14.3 %, and the probability of having two major accidents is 1.0 %. The probability of having at least one nuclear accident (INES level ≥4) in the same five random year sample is 66.6 %.

The results in Table 5b show that for a sample of thirty random years the probability of drawing at least one year with a major accident is 63.2 %, and the probability for two or more major accidents is 25.8 %. These results are in agreement with the previously published studies.

Table 6a and Table 6b show the analogous results using the bootstrap method: the absolute differences with the numbers shown Tables 5 and 6 are always less than 0,2%. This validates the numerical computations of this study since the generating functions method is exact, while the bootstrap method is approximate.

Systematic errors due to the inherent ambiguities and uncertainties in the construction of the data set as discussed in Section 2 have been estimated. For example, since the study is limited to operational nuclear power plants, it does not take into account the Kychtym accident nor the Tokai-Mura criticality accident. It could be argued that one should count all accidents related to the nuclear power industry, even those that occurred in reprocessing installations. As a sensitivity analysis study, probabilities were computed including the Kyshtym event to the 13 accidents dataset. The frequency of five-year samples with no accidents drops from 33.4 % to 30.2 %.

The main assumption underlying the computation of accident frequencies from past data is that the accident probability distribution in past years is constant. Since our sample has low statistics, our discussion on auto-correlation and trends could be only qualitative (see Hofert 2011, section 3.1 for a quantitative analysis of these questions). Auto-correlation could occur for several reasons. The occurrence of an accident in a given year may tend to decrease the risk in the following year, because of increasing awareness of plant managers and regulators worldwide. On the other hand, an accident in a reactor may increase the risk of accident in another reactor of the same plant as was the case in Fukushima.

As a sensitivity test, the same calculation was done considering what happened in Fukushima as three major accidents (INES level = 7). The results are presented on table 7.

7   Conclusion

Accidents at operational power plants have been considered for this study, an accident being defined as an event rated at INES level ≥ 4, and a major accident, as an INES level 7 event. Drawing samples of five random years from the past and assuming that they are all equi-probable, the probability of having a year with

a nuclear major accident in a five-year is 14.3%. The probability of having two major accident in a five-year time span is 1.0%. The probability of having at least one nuclear accident is 66.6% in a five-year sample (Table 5a). For a 30-year sample, we found that the probability of having at least one major accident was 63.2%, and a 25.8% probability of having at least two (Table 5b). Our results are in agreement with previously published studies.

Improving safety in the nuclear industry requires transparency. Since the dataset completeness is a most important parameter in risk studies, we strongly support the establishment of a complete and public international historical report of incidents and accidents worldwide with the obligation for plant owners to report. We consider that the IAEA should be the most suited organization to host such a data set since this task would very well fit in its objectives recalled above.

8   Acknowledgments

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INES level	NA	3	4	5	6	7	Total
All facility types, all years	22	17	22	4	1	2	68
Only power reactors, all years	16	14	9	2	0	2	43
Other facility types, all years	6	3	13	2	1	0	25
Only 1991-2011, all facility types	4	17	2	0	0	1	24

Table 3: Summary of the HJ 20120608 dataset of nuclear accidents. INES levels for pre-1991 events assessed by the author's.
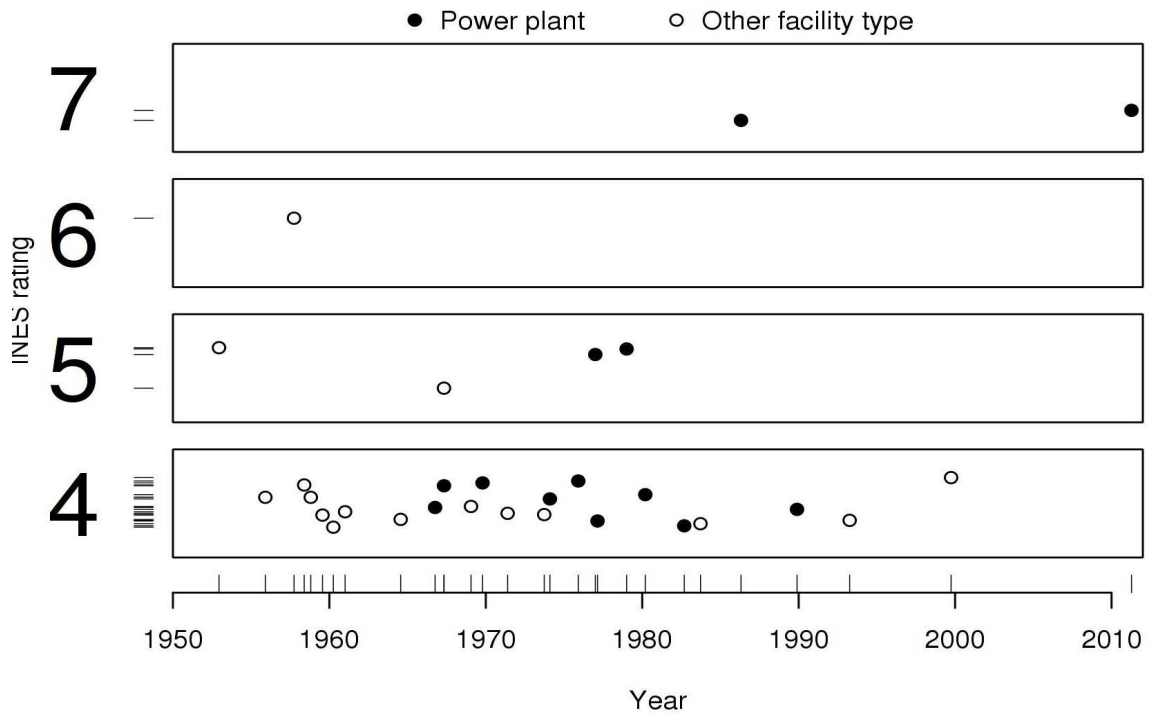
DATE	LOCATION	COUNTRY	FACILITY	REACTOR	TYPE	DESCRIPTION	INES
12/12/52	Chalk river	Canada	Test reactor	NRX		Core damage partial loss of coolant H2 explosion radioactivity release	5
29/11/55	Idaho Falls	USA	Test reactor	EBR-1		fast neutron reactor partial (approx half) core melt - no exposure	4
29/09/57	Kyshtym	Russia	Waste storage			Chemical explosion following tank cooling system failure	6
24/05/58	Chalk river	Canada	Test reactor	NRU		Fuel rupture and fire during unloading	4
25/10/58	Vinča	Yugoslavia	Test reactor			Criticality excursion 6 personnel irradiation (1 fataly)	4
26/07/59	Santa Susana Field Lab.	USA	Test reactor	SRE		Power excursion + approx 1/3 fuel melt + radioactivity release	4
03/04/60	Waltz Mill	USA	Test reactor			Core melt accident (1 fuel element)	4
03/01/61	Idaho Falls	USA	Test reactor	SL-1		Main control rod manual removal + steam explosion – 3 fatalities	4
24/07/64	Rhode Island	USA	Fuel fabrication			Criticality accident with Uranyl nitrate solution	4
05/10/66	Newport	USA	Power reactor	Unit 1	Sodium fast breeder	Two fuel assemblies out of 105 melted at Enrico Fermi Unit 1	4
01/05/67	Chapelcross	UK	Power reactor	Unit 2	Magnox	Fuel element melt and fire in part of core	4
01/05/67	Chelyabinsk	Russia	Fuel fabrication			Radionuclides dispersal from dried out lake Karachay bed (Mayak PA dumpsite)	5
21/01/69	Lucens	Switzerland	Test reactor			Coolant loss + power excursion and explosion. Radioactivity contained by cavern	4
17/10/69	Saint Laurent	France	Power reactor	Unit A1	UNGG	Partial (approx 50kg U) core melt during loading	4
26/05/71	Moscow	Russia	Test facility	SF-3		Kurchatov Institute SF-3. Fuel rods fall out of support plate - criticality - 2 fatalities	4
26/09/73	Windscale	UK	Reprocessing	Shop B 204		Gas leakage inside plant, Ruthenium 106 contamination, 35 workers injured	4
06/02/74	Leningrad	Russia	Power reactor	Unit 1	RBMK-1000	Secondary circuit rupture - 3 fatalities	4
30/11/75	Leningrad	Russia	Power reactor	Unit 1	RBMK-1000	Power excursion + partial core melt + atmospheric release	4
01/01/77	Beloyarsk	USSR	Power reactor	ABM-200	early RBMK	Unit 2 - half core melt	5
22/02/77	Jaslovske Bohunice	Slovakia	Power reactor	KS 150	HWGCR	A-1 unit refueling accident + primary and secondary circuits contamination	4
02/01/79	Three mile Island	USA	Power reactor	TMI-2	PWR	Reactor core melt	5
13/03/80	Saint Laurent	France	Power reactor	Unit A2	UNGG	Partial (approx 20kg U) core melt	4
09/09/82	Tchernobyl	Ukraine	Power reactor	Unit 1	RBMK-1000	Partial core melt – fuel assembly channel 62-44 destroyed	4
23/09/83	Buenos Aires	Argentina	Test reactor	RA-2		Operator died during a modification of the reactor core.	4
26/04/86	Tchernobyl	Ukraine	Power reactor	Unit 4	RBMK-1000	Criticality accident + fire + steam explosion	7
24/11/89	Greifswlad	Germany	Power reactor	Unit 5	VVER	Near core melt - 10 fuel elements damaged	4
06/04/93	Tomsk	Russia	Reprocessing			Explosive mechanical failure in a stainless steel reaction vessel	4
30/09/99	Tokimura	Japan	Fuel fabrication			Criticality accident with U solution at conversion test building	4
12/04/11	Fukushima daichi	Japan	Power reactor	Units 1 2 3	BWR	Multiple core damage by loss of all cooling function	7

Table 4a: Subset list of civilian nuclear accidents with INES ≥ 4.

Date	City	Country	Reactor	INES	Description
1966-10-05	Newport	USA	Unit 1	4	Two fuel assemblies out of 105 melted
1967-05-01	Chapelcross	UK	Unit 2	4	Fuel element melt and fire in part of core
1969-10-17	Saint Laurent	France	Unit 1	4	Partial (approx 50kg U) core melt during loading
1974-02-06	Leningrad	Russia	Unit 1	4	Secondary circuit rupture - 3 fatalities
1975-11-30	Leningrad	Russia	Unit 1	4	Power excursion + partial core melt + atmospheric release
1977-01-01	Beloyarsk	USSR	ABM-200	5	Unit 2 - half core melt
1977-02-22	Jaslovske Bohunice	Slovakia	A1	4	Refueling accident + corrosion + primary and secondary circuits contamination
1979-01-02	Three Mile Island	USA	Unit 2	5	Reactor core melt
1980-03-13	Saint Laurent	France	Unit 2	4	Partial (approx 20kg U) core melt
1982-09-09	Tchernobyl	Ukraine	Unit 1	4	Partial core melt – fuel assembly channel 62-44 destroyed
1986-04-26	Tchernobyl	Ukraine	Unit 4	7	Criticality accident + fire + steam explosion
1989-11-24	Greifswald	Germany	Unit 5	4	Near core melt - 10 fuel elements damaged
2011-04-12	Fukushima daichi	Japan	Units 1 2 3	7	Multiple core damage by loss of all cooling function

Table 4b: Subset list of the 13 accidents in civilian nuclear power reactors with an INES level ≥ 4

Historical dataset of nuclear accidents (HJ-20130724)
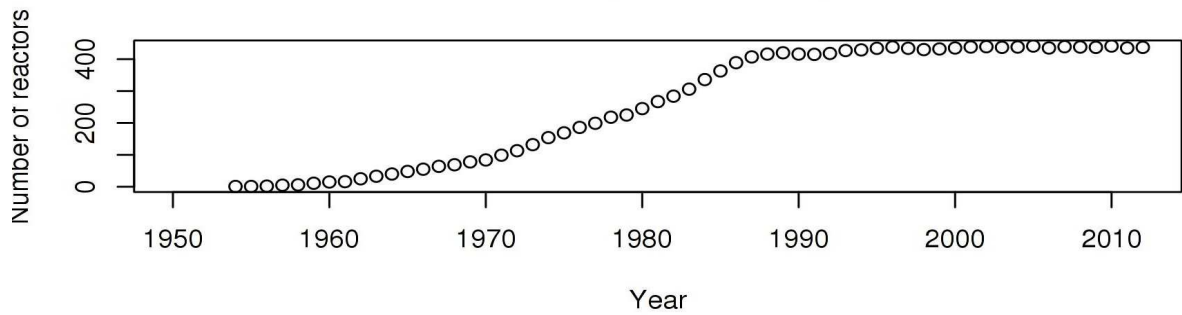

Figure 1 (top) : Chronology of accidents in this study's dataset of civilian nuclear accidents with INES level ≥ 4 for all facilities

Figure 2 (bottom) : number of nuclear power reactors in operation, 1954-2012 (Source: IAEA, Nuclear power reactors in the world, 2013 edition)

Severity of events	P(N_i = 0)	P(N_i = 1)	P(N_i = 2)	P(N_i ≥ 3)
Accident (INES≥4)	33.4 %	37.5 %	20.3 %	8.7 %
Major Accident (INES=7)	84.6 %	14.3 %	1.0 %	<0.1 %

Table 5a

Severity of events	P(N_i = 0)	P(N_i = 1)	P(N_i = 2)	P(N_i = 3)	P(N_i = 4)	P(N_i = 5)	P(N_i = 6)	P(N_i = 7)	P(N_i = 8)	P(N_i ≥ 9)
Accident (INES≥4)	0.1 %	0.9 %	3.2 %	7.0 %	11.5 %	15.1 %	16.3 %	15.0 %	11.9 %	19.0 %

Severity of events	P(N_i = 0)	P(N_i = 1)	P(N_i = 2)	P(N_i = 3)	P(N_i ≥4)
Major Accident (INES=7)	36.8 %	37.4 %	18.4 %	5.8 %	1.6 %

Table 5b

Table 5 : probabilities of nuclear accident or major accident worldwide in 5-year (table 5a) and 30-year (table 5b)

Severity of events	P(N_i = 0)	P(N_i = 1)	P(N_i = 2)	P(N_i ≥ 3)
Accident (INES≥4)	33.6 %	37.9 %	19.9 %	8.5 %
Major Accident (INES=7)	84.5 %	14.4 %	1.0 %	<0.1 %

Table 6a

Severity of events	P(N_i = 0)	P(N_i = 1)	P(N_i = 2)	P(N_i = 3)	P(N_i = 4)	P(N_i = 5)	P(N_i = 6)	P(N_i = 7)	P(N_i = 8)	P(N_i ≥ 9)
Accident (INES≥4)	0.1 %	0.9 %	3.1 %	7.1 %	11.5 %	15.1 %	16.4 %	14.8 %	11.8 %	19.2 %

Severity of events	P(N_i = 0)	P(N_i = 1)	P(N_i = 2)	P(N_i = 3)	P(N_i ≥4)
Major Accident (INES=7)	37.0 %	37.2 %	18.5 %	5.7 %	1.6 %

Table 6b

Table 6 : probabilities of nuclear accident or major accident worldwide in 5-year (table 6a) 30-year (table 6b) using the bootstrap method

Severity of events	P(N_i = 0)	P(N_i = 1)	P(N_i = 2)	P(N_i ≥ 3)
Accident (INES≥4)	33.4 %	34.1 %	17.3 %	15.0 %
Major Accident (INES=7)	84.6 %	7.2 %	0.2 %	8.0 %

Table 7a

Severity of events	P(N_i = 0)	P(N_i = 1)	P(N_i = 2)	P(N_i ≥ 3)
Accident (INES≥4)	33.3 %	34.3 %	17.5 %	15.1 %
Major Accident (INES=7)	84.7 %	7.1 %	0,2 %	7.9 %

Table 7b

Table 7 : probabilities of nuclear accident or major accident worldwide in 5-year (table 7a) and using the bootstrap method (table 7b) counting the Fukushima event as 3 major accidents