An objective nuclear accident magnitude scale for quantification of severe and catastrophic events

December 12, 2011

By David Smythe

Introduction and summary

Deficiencies in the existing International Nuclear Event Scale (INES)[1] have become clear in the light of comparisons between the 1986 Chernobyl and 2011 Fukushima Daiichi nuclear power plant accidents.[2–4] First, the scale is essentially a discrete qualitative ranking, not defined beyond event level 7. Second, it was designed as a public relations tool, not an objective scientific scale. Third, its most serious shortcoming is that it conflates magnitude with intensity.

I propose a new quantitative nuclear accident magnitude scale (NAMS). It uses the earthquake magnitude approach to calculate the accident magnitude M=log(20R), where R = off-site atmospheric release of radioactivity, normalized to iodine-131-equivalent terabecquerels. In NAMS the observed frequency-magnitude distribution of 33 well-quantified events over the past 60 years follows an inverse power law, as with earthquakes,[5] but NAMS highlights four exceptional accidents that are greater by 2–3 orders of magnitude than the next largest. These are, in decreasing order of severity, Chernobyl, Three Mile Island, Fukushima Daiichi, and Kyshtym. Such catastrophic accidents can be expected to occur every 12–15 years.

The problem with INES

The International Atomic Energy Agency (IAEA) developed the INES in 1990. It is based in part on a loose analogy with the logarithmic earthquake-magnitude Richter scale, in that one unit difference in event level between 4 and 7 corresponds approximately to a factor of 10 in amplitude. Despite its reference to decade threshold values for off-site radionuclide release for discriminating between levels 4 through 7, the INES is essentially a discrete qualitative ranking. A true location-specific intensity scale measures exposure at a particular time and place due to an accident. Figure 1 shows a popular representation of the scale as a pyramid.

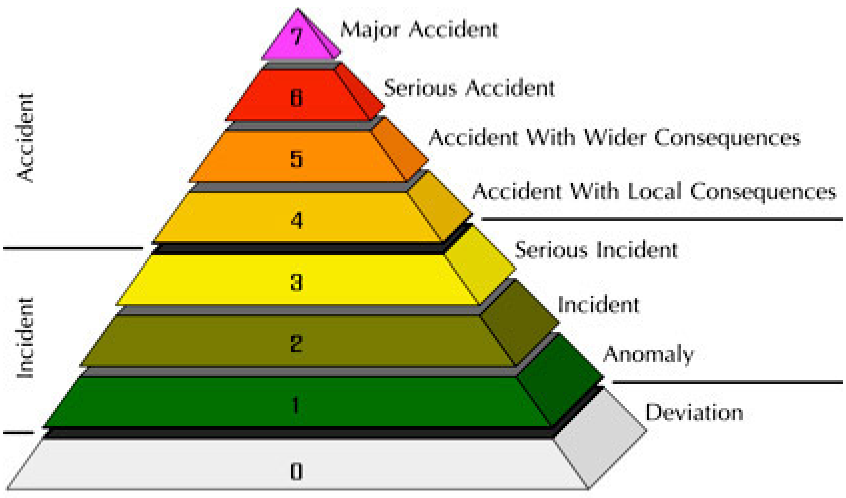

Figure 1. A popular way of depicting the International Nuclear Event Scale pyramid of nuclear event levels 0 to 7. This document is concerned with levels 4 to 7, classed by INES as "accidents," having off-site effects.

The IAEA, although created under the aegis of the United Nations, is a nuclear industry trade association whose aim is to promote civil nuclear power. Article II of its statute reads, "The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." The IAEA has an inherent conflict of interest when it promotes nuclear power while prescribing its use, by purely voluntary guidelines.

Like any large organization, the IAEA cannot be considered impartial in its consideration of failures and shortcomings of what it seeks to promote. Because the INES "should be used as part of a communications strategy," it is therefore more of a public relations tool than an objective scientific measure. The INES guidelines for how to inform the "target audience [of]… the media and the public" omit any mention of quantified radionuclide releases. The INES level, the nearest we get to quantification, has already been seen to be inadequate in the case of Fukushima Daiichi and Chernobyl, both currently assigned to level 7.

Accident magnitude à la Richter earthquake scale

Soon after Chernobyl but before the INES was first drawn up, Ken Hsü pointed out the likely analogy between the earthquake frequency–magnitude relation and nuclear accidents,[6] but he did not present any data. He suggested that factory-years should be the frequency measure and cost in Swiss francs the magnitude measure (he was for a long time a Swiss resident). Ali Mehmet Celâl Sengör has twice drawn attention to Hsü's ideas,[7, 8] but they have never been developed, no doubt because both variables are too difficult to estimate in practice.

Seismology employs two distinct but complementary scales, magnitude and intensity. The intensity scale measures the impact of an earthquake on a population at a given place. Seismic intensity is thus analogous to radiological exposure, or dose, at a specific place. Overall, the INES level definitions (requiring a 200-page user manual) more resemble a seismic intensity scale than a magnitude scale. But since intensity varies with location, one level cannot fit a wide region.

The proposed new NAMS simply uses the estimate of the off-site atmospheric release R of radioactive material. The INES already defines approximate order-of-magnitude discrete threshold levels 4 to 7, based on radioactivity released to the atmosphere. The activity of different isotopes is normalized to ^{131}I using the scale of dose equivalence specified in the INES; for example, plutonium-239 is 10 000 times more active for atmospheric release than ^{131}I. Following the INES guideline that boundaries between the INES discrete levels be set every decade (power of 10) of the estimated R, the quantitative relation is $M = \log(20R)$, where R is specified in ^{131}I -equivalent terabecquerels (TBq), and M is the NAMS magnitude. M is a real scalar, not an integer as in the INES. The constant 20 in the equation provides the equivalence between the INES and the NAMS.

The INES user's manual[1] suggests that the boundaries between levels 4 to 7 be drawn approximately at 500, 5000, and 50 000 TBq. So level 4, for example, is in the range of 50–500 TBq. For simplicity, I have set the equivalence between the NAMS and the INES to be at the top of each decade range. So, for example,

500 TBq ≡ upper limit of INES level 4 ≡ NAMS magnitude 4.0.

Near-field and far-field release

A scale reserved for far-field releases of radioactivity, the NAMS is defined only as atmospheric release, like INES levels 4-7. Near field means releases confined within the installation buildings, but it includes direct radiation from a confined source that penetrates walls to the environment immediately outside the installation (see, for example, the Tokaimura 1999 criticality event discussed in the appendix).

With very few exceptions, far-field water contamination is ignored in the present compilation. Exceptions are the evaporation of Lake Karachai near Chelyabinsk in 1967 and the resuspension into the air from contaminated water during the 1955 Sellafield accident. Those can be classed as indirect atmospheric contamination.

Data sources and their compilation

The vast majority of descriptions of nuclear accidents are found only on the Web. My sources also included peer-reviewed journal papers and official government reports. I treated all purported radioactive release estimates with a certain amount of suspicion, and, where possible, I weighed the conflicting claims. This document and its appendix include extensive reference lists with web links, so that readers can view those sources and form their own opinions.

Compilations of international nuclear incidents for the past 60 years are available on many websites, but few descriptions provide a quantitative estimate of radioactive release, and still fewer an estimate of the INES level. Chris Winter has compiled a fairly complete list of nuclear accidents of all types,[9] but his list is probably biased toward military accidents. One INES level-4 French accident is omitted, as are events after mid 2010, including Fukushima Daiichi. He assigns his own INES levels, where none previously existed, to all 985 events. Wikipedia lists civilian and military nuclear accidents separately; a combined nuclear and radiation accident page is incomplete and biased toward US incidents. The civilian list is also incomplete, for example, in its reference to Three Mile Island. In March 2011, the *Guardian* published a list of nuclear power plant accidents.[10] Wikipedia and other websites (see, for example, references 11 and 12) discuss the more serious individual accidents of INES level 3 and greater.

I have removed medical-related accidents from the new classification and retained only accidents that involve civilian power installations and civilian or military nuclear fuel processing or reprocessing. I omit detonations of nuclear weapons, accidents involving airplanes carrying nuclear weapons, and accidents involving nuclear-powered ships or submarines. In addition I omit long-term leaks to the environment because they are difficult to classify as discrete events. Events involving multiple reactors at one site are treated as one accident.

Table 1, which summarizes the data, is restricted to the 33 events to which an INES level has been assigned or can reasonably be estimated and for which the off-site atmospheric release has been or can be estimated. Calculations of the radiological dose equivalences for atmospheric releases are taken from table 2 of the INES manual.[1] Although only INES levels 4-7 have off-site effects, I have included events classified as INES level 3 to ensure that no possible off-site events have been omitted. I have not examined events of INES level 2 or below. However, several events at INES level 3 turn out to have magnitudes well below 3, so all the graphs shown below include events down to $M = 2.0$.

The data sources for the individual accidents and their magnitude calculation are given in the appendix. Eight events (two of INES level 5, five level 4, and one level 3, shown at the bottom of table 1) evidently had significant off-site releases, but the releases remain unquantifiable. Those are also discussed in the appendix, together with an anomalous group called criticality accidents.

The data compiled in table 1 are unlikely to have excluded any recorded event of INES level 4 or greater, but some unauthorized discharges, especially from the early era of the nuclear industry, could remain undocumented. Those putative hidden events would most probably have occurred in the UK, the former Soviet Union, the US, and France, given those four countries' track records of secrecy and official denial.

Magnitude and frequency

It may seem counterintuitive, but 33 events are sufficient for an analysis to see whether any predictions can be made, as opposed to simple description and classification. Taking the earthquake magnitude analogy further, we examine the nuclear accident equivalent of the Gutenberg and Richter frequency–magnitude relation:[5]

$\log N = a - bM$,

where N is the number of earthquakes greater than or equal to magnitude M occurring in a given area over a given time interval, and a and b are constants, usually determined by a best fit to the data, when $\log N$ is plotted against M. Such a graph is doubly logarithmic because the magnitude has been defined logarithmically. Note the ingenious part of Gutenberg and Richter's definition: "greater than or equal to." That cumulative frequency enables more information to be extracted from small data sets.

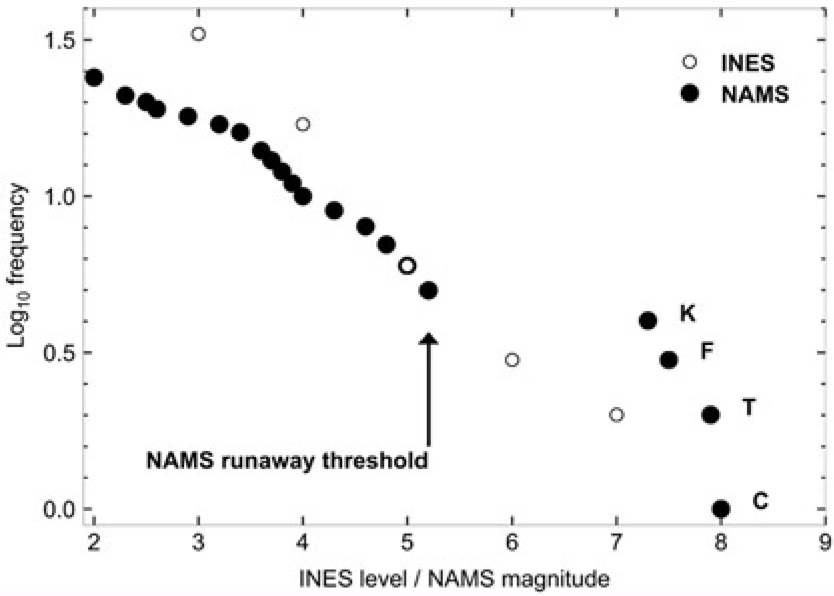

Figure 2. Frequency–magnitude relations for the 33 biggest nuclear accidents as defined in the text and tabulated in Table 1. The vertical scale is the logarithm to base 10 of the number of times during the past 60 years (c. 1950–2011) that an event of a given magnitude or greater has occurred. The horizontal scale is the International Nuclear Event Scale level (open circles) or NAMS magnitude (solid black circles). K—Kyshtym 1957, M = 7.5; T—Three Mile Island 1979, M = 7.9; C—Chernobyl 1986, M = 8.0; F—Fukushima Daiichi 2011, M = 7.5.

The fact that earthquake data can be fitted well to a straight line with slope b reflects the fact that such earthquake distributions empirically obey an inverse power law between frequency and magnitude; this, in turn, suggests that earthquake distributions are fractal. [13]

Figure 2 plots the frequency-magnitude relationship for nuclear accidents. The white circles show the log-frequency versus INES-level relationship of the 33 events of INES levels 3–7, for which both the INES level and the magnitude can be estimated. The distribution is remarkably linear, with a negative slope (the b value, in seismological parlance) of about

0.3. But a surprising difference emerges when we look at the NAMS magnitudes (the black circles in figure 2) in the same manner. Between $2.0 \leq M \leq 5.2$ there is still a strong linear relationship, with a *b* value of about 0.2. But the four biggest events now plot as a group distinct from the lower-magnitude group—a gap in magnitudes exists between 5.2 and 7.3 —in which no events have occurred. So the overall frequency-magnitude distribution is clearly bimodal, suggesting that catastrophic accidents behave in a qualitatively different way from lesser events.

There are nine NAMS events of $M<2.0$ that are not shown in Figure 2. Their absence explains why the left-hand side of the NAMS trend does not attain the same value of 1.519 ($\log_{10}33$) as does the INES plot (white circles) that uses all 33 events.

Discussion

What is the predictive power, if any, of the new magnitude classification? I have refrained from fitting straight lines to the log–log graphs shown in figure 2; however, the revised scale suggests that about 10 events of magnitude 4 or greater will occur every 60 years, the period covered by the data. Any prediction assumes that the dataset is statistically stationary, so that the past is indicative of the future. Recurrence times using the two scales are compared in table 2.

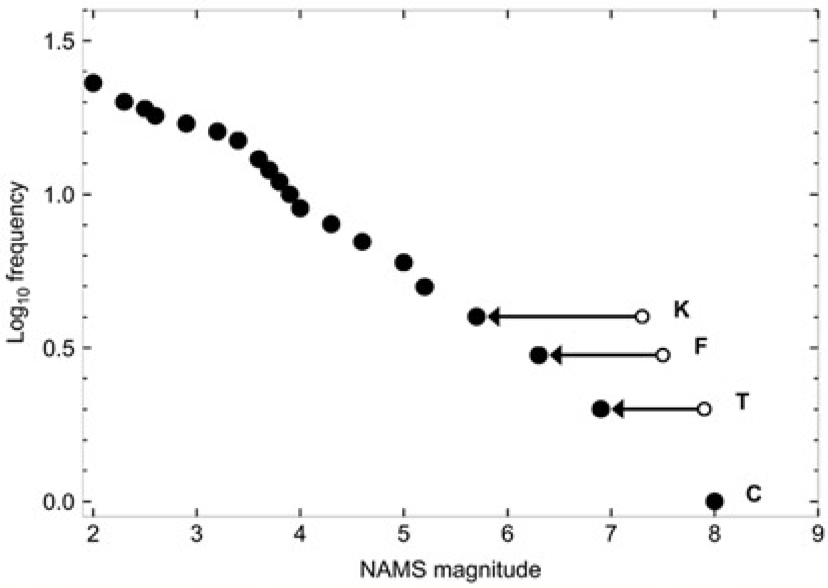

Figure 3. Attempt to linearize the nuclear accident magnitude scale (NAMS) frequency–magnitude relation over the whole scale by arbitrarily reducing the magnitudes of the Three Mile Island, Kyshtym, and Fukushima Daiichi events by an order of magnitude or more. The calculated *M* (open circle) is moved to the left (solid black circle). K—Kyshtym 1957, $M = 7.3$; T—Three Mile Island 1979, $M = 7.9$; C—Chernobyl 1986, $M = 8.0$; F—Fukushima Daiichi 2011, $M = 7.5$.

The INES defines only two level-7 events in 60 years, and three events of level 6 or greater. INES levels 3 and 4 have shorter recurrence periods than NAMS because of the coarser classification of the former. Level 6 and magnitude 6 cannot be compared because no events between magnitude 5.2 and 7.3 have occurred. INES level 7 overestimates the recurrence time by a factor of 2.5 relative to NAMS and underestimates the severity of some events due to the ceiling at level 7. The comparable recurrence time of 12–15 years between $M=$ 5.2 and 7.3 in figure 2 suggests that if an accident approaches magnitude 5, it is likely to increase by two further orders of magnitude—that is, to a full-blown runaway catastrophe. A magnitude 7 or greater accident is to be expected every 12–15 years.

It may be argued that the past 60 years are not a reliable guide to future accidents, because more modern reactor designs are inherently safer; however, an aging worldwide reactor fleet might be expected to become less reliable as time goes on. Furthermore, the accident record, reviewed by Benjamin Sovacool,[14] implies that new designs are more risky, not less so.

To remove the bimodal distribution on the assumption that it is a data artifact, we would have to reduce the magnitudes of the three biggest events below Chernobyl to about 6.9, 6.3, and 5.7; for example, we could arbitrarily reduce the magnitudes of Three Mile Island by 1.0, Fukushima by 1.2, and Kyshtym by 1.6, as shown in figure 3. I consider this scenario to be highly unlikely, as it requires that each be reduced by than one order of magnitude. Equally unlikely, as discussed above, would be the infill of the current gap in magnitudes by major accidents not yet documented in the public domain.

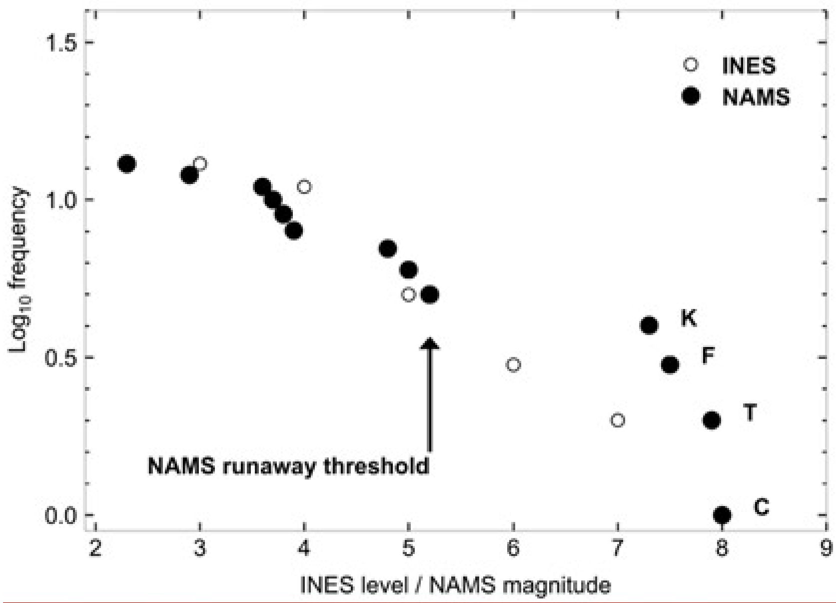

Figure 4. Frequency–magnitude relation for 13 non-Sellafield events, for comparison with Figure 2. K—Kyshtym 1957; T—Three Mile Island 1979; C—Chernobyl 1986; F—Fukushima Daiichi 2011.

Given that 20 of the 33 classified events in table 1 are Sellafield accidents,[15], is it possible that Sellafield is distorting the magnitude-frequency relation? To address that question, figure 4 shows the graph for just the 13 non-Sellafield events, but otherwise to the same scale as figure 2. The data are clearly much sparser, but the two-orders-of-magnitude gap remains. The roll-off (the flattening out of the data trend on the left-hand side) below level or magnitude 4 is presumably due to underreporting of non-Sellafield accidents in the INES range 3-4. It would be useful to have detailed reports and analyses, as Webb and coauthors have done for Sellafield,[15] to quantify accidents at the following major nuclear installations:

1. Chalk River, Ontario (Canada)
2. Saint Laurent, La Hague, Marcoule, and Tricastin (France)
3. Idaho National Laboratory, Rocky Flats, Oak Ridge, Los Alamos, Savannah River, and Hanford (USA)
4. Tokai (Japan)
5. Hanau (Germany)

Some of the above feature prominently in an IAEA report on significant incidents at nuclear installations.[16] The list is, of course, incomplete. So Sellafield is serving here as a proxy for many other undocumented accidents, which, if they were included in figure 2, would raise and steepen the main sequence part of the NAMS curve.

Conclusions

The NAMS highlights four exceptional accidents that are greater by 2–3 orders of magnitude than the next largest. Those are, in decreasing order of severity, Chernobyl, Three Mile Island, Fukushima Daiichi, and Kyshtym. Such catastrophic accidents can be expected to occur every 12–15 years. The INES, in contrast, fails to reveal that bimodality and underestimates the frequency of severe accidents.

The NAMS makes no predictions about impact and dose, for the same reason that earthquake magnitude does not necessarily indicate damage.

Liquid contamination should in future be included in the NAMS accident quantification. The problem here, which is beyond the scope of the present paper, is how to estimate the radiological equivalences for the various isotopes and to return a value for the magnitude, given also the variety of paths by which activity might eventually be ingested. Alternatively, a separate NAMS scale for liquid contamination could be devised. It would once again be analogous to seismic magnitude scales, where a particular scale is defined by how the magnitude is estimated. The off-site consequences part of the INES (levels 4–7) needs to be completely rewritten. As with seismological scales, decimal real numbers should be reserved for the NAMS magnitude *M*, and Roman numerals should be used for a proposed revised INES intensity scale based on dose at a specific place and time.

Finally, the NAMS magnitude of an accident having off-site consequences is simple to compute; all that is needed is the estimate of off-site releases of radionuclides. The NAMS can be corrected or updated instantly. It is easily understood by the general public, who are accustomed to earthquake magnitudes, and it is more honest than the INES level. But if the raw release data to enable a calculation are not being made available immediately after an accident, we need to ask why.

References

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Table 1

The 33 accidents of International Nuclear Event Scale (INES) levels 4—7 for which the magnitude *M* can be quantified. Eight further accidents of level ≥3 are appended, but for which the off-site release, and therefore *M*, cannot currently be quantified. Sources of the quoted INES level are the reference numbers in the last column (reference 0 = this paper; W = Wikipedia; A = Appendix).

Date	INES level	Location	Release (TBq)	M	INES Ref.
1949-12-02	4	Hanford, WA, USA	289	3.8	9
1955-03-25	4	Sellafield, UK	1000	4.3	15
1955-07-14	3	Sellafield, UK	0.0002	-2.4	15
1955-12-08	3	Sellafield, UK	0.0001	-2.7	15
1957-09-11	5	Rocky Flats, CO, USA	7800	5.2	0, 9
1957-09-29	6	Kyshtym (Mayak), Russia	1,000,000	7.3	15, W
1957-10-07	5	Windscale (Sellafield), UK	1786	4.6	15, W
1961-01-03	4	SL-1, Idaho Falls, ID, USA	41	2.9	W
1961-06-19	3	Sellafield, UK	540	4.0	15
1965-01-20	4	Lawrence Livermore, CA, USA	259	3.7	0
1967-04-01	5	Chelyabinsk; Lake Karachai, Russia	5600	5.0	0
1968-05-01	4	Sellafield, UK	550	4.0	15
1969-03-05	3	Sellafield, UK	2.1	1.6	15
1969-05-11	4	Rocky Flats, CO, USA	10	2.3	0
1969-10-12	4	Sellafield, UK	9	2.3	15
1970-02-10	3	Sellafield, UK	5	2.0	15
1970-03-10	3	Sellafield, UK	18	2.6	15
1970-08-06	4	Lawrence Livermore, CA, USA	222	3.6	0

1970-11-29	3	Sellafield, UK	16	2.5	15
1971-03-19	3	Sellafield, UK	4.8	2.0	15
1971-12-15	3	Sellafield, UK	74	3.2	15
1972-12-06	3	Sellafield, UK	2.2	1.6	15
1973-09-26	4	Sellafield, UK	5.4	2.0	15
1979-03-28	5	Three Mile Island, PA, USA	3,700,000	7.9	W
1979-07-16	3	Sellafield, UK	3.7	1.9	15
1979-09-11	4	Sellafield, UK	130	3.4	15
1980-09-22	3	Sellafield, UK	2.0	1.6	15
1981-10-01	3	Sellafield, UK	0.9	1.3	15
1984-07-17	3	Sellafield, UK	2.9	1.8	15
1986-04-26	7	Chernobyl, Ukraine	5,200,000	8.0	W
1993-04-06	4	Seversk (Tomsk-7), Russia	3500	4.8	W, A26
2003-04-10	3	Paks, Hungary	360	3.9	W, A27
2011-03-11	7	Fukushima -Daiichi, Japan	1,592,000	7.5	W
		Not currently quantifiable			
1952-12-12	5	Chalk River, Ontario, Canada			W, W
1969-10-17	4	Saint Laurent, France			W
1972-12-21	≥4	Pawling, NY, USA			0
1975-11-28	4	Leningrad, Russia			W
1977-02-22	4	Jaslovské Bohunice, Slovakia			W
1980-03-13	4	Saint Laurent, France			W, W
1982-09-09	5	Chernobyl, Ukraine			W
1983-11-01	3	Sellafield, UK			15

Table 2

Comparison of recurrence times for the INES and the NAMS magnitude scales.

INES level or NAMS magnitude	INES Period (y)	NAMS Period (y)
4 / 4.0	4	6
5 / 5.0	8	12
6 / 6.0	20	-
7 / 7.0	30	12-15

Appendix: Specific accidents

December 12, 2011

Chernobyl, 1986

The accident at Chernobyl, in Ukraine, remains the most catastrophic event of the past 60 years. Its magnitude of 8.0 is a more useful discriminator than International Nuclear Event Scale (INES) level 7.

Kyshtym, 1957

The event at the Soviet Union's Kyshtym plant of INES level 6 is poorly quantified, with estimates ranging from 74 to 1850 petabecquerels, or magnitudes 6.2 to 7.6. I have used an intermediate figure of 1000 PBq, or magnitude 7.3.

Sellafield, 1955 and 1957

The UK's Sellafield complex, which includes Windscale and Calder Hall, has long been one of the world's largest nuclear installations. The frequent occurrence of Sellafield in the incident database[1] may be explained in several ways:

1. There has been an abnormally meticulous record of incident reporting.
2. Sellafield is much more accident prone than other nuclear installations.
3. Nuclear installations in general are underreporting events of level 4 and below.

The truth is probably a combination of all three.

Geoffrey Webb and colleagues classified the magnitude of the 25 March 1955 Sellafield release as INES level 4 and estimated that "up to a few tenths of a [terabecquerel] could have been released to atmosphere"[1]—say 0.1 TBq, multiplied by the equivalence factor of 10 000 and based on the assumption that the "beta/gamma radioactivity" comprised plutonium.

The Sellafield events mostly turn out to have a lower magnitude than the INES level to which they were assigned. The 1957 Windscale fire, for example, is classed at INES level 5 but has $M=4.6$. On the other hand, the 14 July 1955 fire released some (unspecified) alpha radioactivity. The 8 December 1955 fire is said to be similar to the 25 March one. So although I have used Webb and colleagues' estimates of activity released,[1] I have been unable to apply any equivalence factor to their release estimates. That means that the magnitudes of −2.4 and −2.7, respectively, for the two accidents may be too low by orders of magnitude if, for example, uranium was burnt.

Three Mile Island, 1979

Determining the releases from Pennsylvania's Three Mile Island, an INES level 5 accident, has been contentious. There is convincing evidence that the releases were underreported by a minimum of one order of magnitude. The official Nuclear Regulatory Commission (NRC) figure is 10 megacuries (370 PBq).[2] Joy Thompson, Randall Thompson, and David Bear quote 22 MCi (814 PBq),[3] whereas Arnold Gundersen estimates anywhere between 100 and 1000 times the NRC figure.[4] Gundersen also points out that the sum of the NRC releases yields 36 MCi. I use a conservatively low figure of 100 MCi (3 700 000 TBq). Lastly, epidemiological studies, which are themselves controversial,[5–13] point to a significant epidemic of cancer that is clearly related to Three Mile Island and that would not have occurred if the NRC figure were correct. However, even if we use the incredible NRC figure of 10 MCi, it would yield $M = 6.9$. The accident clearly belongs in the catastrophic group.

Fukushima Daiichi, 2011

The INES level of the Fukushima Daiichi accident in Japan has been revised upward several times from level 4 to the current level 7. In April 2011 the independent Nuclear Safety Commission estimated 630 000 TBq of atmospheric release,[14] as did the Tokyo Electric Power Company.[15] That is very close to the estimate of 670 000 TBq by Masamichi Chino and colleagues,[16] but in June 2011 the Nuclear and Industrial Safety Agency gave an estimate of 770 000 TBq,[14, 17–18] used herein. That yields magnitude 7.2 on the revised scale. The latest estimate (October 2011) by Andreas Stohl and colleagues[19] is 1 592 000 TBq, yielding a magnitude of 7.5.

Rocky Flats, 1957 and 1969

For the Rocky Flats accidents in Colorado, John Till and colleagues estimate that the median total quantity of Pu released in the 1957 fire was 780 GBq and in the 1969 fire was a range of 0.37 – 2.2 GBq.[20] For the latter I assume 1 GBq. With the radiological equivalence of 10 000 applied,[21] the iodine-131-equivalent releases are 7800 TBq in 1957 and 10 TBq in 1969. Those quantities correspond to INES levels 5 and 3, respectively, and magnitudes 5.2 and 2.3, respectively.

Chelyabinsk, Lake Karachay, 1967

The incident at Chelyabinsk in the Soviet Union was due to the desiccation of the polluted Lake Karachay during a very dry summer. Christopher Winter assigned it INES level 6, based on a claimed release of 190 PBq.[22] Another website estimated 22 TBq.[23] Dmitriy Burmistrov and colleagues estimated about 20 TBq.[24] I have calculated the release of 5600 TBq using the data of Peremyslova and colleagues.[25] That value corresponds to INES level 5 and a magnitude of 5.0.

Seversk (formerly Tomsk-7), 1993

The Seversk accident in Russia is classed as an INES level 4. The atmospheric release of 4.3 TBq of long-lived isotopes[26] has been divided into uranium and plutonium in the same proportion as the solution in the tank that exploded. That yields a total atmospheric release of about 3500 TBq, ^{131}I equivalent, or magnitude 4.8.

Paks, 2003

The releases due to the accident at the Paks nuclear power plant on 10 April 2003 are found in the Hungarian Atomic Energy Commission's report.[27] It is an INES level-3 event but a NAMS (nuclear accident magnitude scale) magnitude 3.9.

Tokaimura, 1999 (criticality accident)

During the 20-hour duration incident in Japan, some 2500 PBq (2.5×10^{18} fissions) of activity, greater than the amount released at Fukushima, were generated in a mixing tank. The INES guide cites it as an example of a level-4 accident.[21] However, because the fission activity was confined in the tank, there were only local (near-field) effects from the direct neutron, beta, and gamma radiation. The World Nuclear Association states, "While 160 TBq of noble gases and 2 TBq of gaseous iodine were apparently released, little escaped from the building itself."[28] That assertion directly contradicts the estimate of Chino and colleagues of 8×10^{12} Bq/h (which, summed over 20 hours would yield 160 TBq) for radioactivity released to the atmosphere; they made the estimation by back-calculating from observations taken over a wide region around the site.[29] If their figure is correct, and the release contained 99% noble gases as claimed by the World Nuclear Association, then the total of released ^{131}I may be around 2 TBq—a NAMS magnitude-1.6 event. So although it is classified as an INES level-4 event, it has a very small magnitude *M*.

Unquantifiable releases

The failure of the NRX reactor at Chalk River in Ottawa, Canada,[30] on 12 December 1952 is classed as an INES level-5 event because of the off-site release. About 10 KCi (370 TBq) of fission products were released into the cooling water and hence off-site; however, there are conflicting accounts of atmospheric release. Peter Jedicke claims there was no atmospheric release,[31] whereas the German Wikipedia page on nuclear accidents asserts that 100 TBq of fission products were released to the atmosphere in addition to 400 TBq into the water. I have omitted that event from the main list until an off-site atmospheric release can be confirmed.

Two accidents of INES level 4 occurred at the Saint Laurent nuclear power plant on the River Loire in France in 1969 and 1980. Between 535 and 740 MBq of ^{239}Pu and ^{240}Pu activity are said to have been deposited in the river sediments as a result of the 1980 accident.[32] Many French-language websites mention that the Institute of Marine Biogeochemistry of the École Normale Supérieure in Paris carried out a study that proves the existence of Pu in the sediments of the River Loire from the reactor site to the estuary and ascribes its presence to one or both of the accidents. The study was written by Jean-Marie Martin and Alain Thomas, but neither a title nor a date of publication are available. The institute is presumably now part of the department of biochemistry and ecology of continental environments, which publishes its research papers online (but with a seemingly incomplete record) back to 1984. The online pollution monitoring program run by the Institut de Radioprotection et de Sûreté Nucléaire shows ongoing ^{239}Pu and ^{240}Pu pollution of the Loire by the Saint Laurent site.[33]

In November 1975 the core of one of the reactors at the Soviet Union's Leningrad nuclear power plant was partially destroyed. Radioactive gases were vented to the exterior over a period of a month as part of the emergency cleaning.[34] The German Wikipedia page on nuclear accidents states that it was an INES level 4–5 event, but it gives an incorrect date of October 1974. The Greenworld website (Russian, with English translation), in contrast, assigns it to INES level 3. The estimates of releases vary from 0.5 – 55 PBq, but no sources for those figures are available. A paper on the Bellona website cites the same INES and release figures.[35] Greenworld states that there was a release of "uranium fission products (^{137}Cs, ^{134}Cs, ^{144}Ce, ^{90}Sr, etc.) and transuranics (^{238}Pu, ^{239}Pu, ^{241}Am, etc.) into the reactor graphite cladding," whereas the nuclear accident compilation in the Proposition One website[36] states that the atmospheric release was mainly ^{131}I.The accident was evidently severe, but neither the INES level nor the NAMS magnitude can be estimated to better than an order of magnitude, mainly because of the uncertainty about what fission products and how much of them were released to the atmosphere.

The INES level-4 accident in the A-1 reactor at Jaslovské Bohunice, Slovakia, in 1977 caused it to be shut down and subsequently decommissioned. There was also an accident the previous year. Releases are not stated; however, Jozef Kuruc and L'ubomír Mátel ascribe the presence of ^{90}Sr, ^{239}Pu, ^{240}Pu, and ^{241}Am contamination in soils of the surrounding region as due in part to the A-1 accidents.[37]

The November 1982 accident at Chernobyl, classed as INES level 5, undoubtedly released radioactivity into the atmosphere,[38] but the available individual dose rates cannot be integrated into an overall release estimate.

The November 1983 discharge at Sellafield resulted in around 50 TBq entering the sea and thence as particulate matter onto local beaches, which were temporarily closed.[1] That is an example of discharge into water, followed by transfer of the activity back to land, but it is difficult to quantify in terms of radiological equivalence.

In December 1972 there was a fire and two explosions at the Gulf United Nuclear Corporation fabrication plant near Pawling, New York, where Pu fuel was being manufactured for fast breeder reactors. An undetermined amount of Pu was dispersed off-site,[39] so the event can hardly be less than INES level 4. A NAMS magnitude-4.0 event would be produced by the release of the order of just 10 g of ^{239}Pu and ^{240}Pu to the atmosphere; given that the fire and explosions were serious enough for the plant to be closed down, it is likely that the release could have been one or two orders of magnitude above that weight of Pu. Furthermore, the incidence of chronic myelogenous leukemia (CML) in Pawling is apparently 3 in a town of 5000,[40] when the expected value would be 1–2 per 100 000 population. The CML Wikipedia webpage states, “The only well-described risk factor for CML is exposure to ionizing radiation.” So the CML cluster at Pawling suggests that at least one serious release occurred from the plant.

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