OPEN COMPREHENSIVE NUCLEAR EVENTS DATABASE

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Abstract: Motivated by a lack of open comprehensive information, and the goal for scientific study (e.g., precursor analysis) and deeper learning from operating experience, we have constructed an open comprehensive database of events in the civilian nuclear sector. Involving expert review, and with more than 90% of events having official sources, it contains about 900 anomalies, incidents, and accidents. Both safety and cost aspects of events are captured, where safety -- relating specifically to core damage states and atmospheric releases -- is of utmost importance, and well assessed by a combination of PSA and statistical assessment; and is roughly measured by INES scores, either officially given or assigned by us. And estimated cost of total consequences informs the severity side of the risk equation, and is essential for a full appreciation of safety. Risk in nuclear power is heavy tailed, with the three historical major accidents clearly dominating consequences, as quantified by approximate estimated full costs. Insights include surprisingly many significant incidents occurring in plants not at full power, a high contribution of human errors in triggering events, and multiple events with challenging interaction of multiple units and even sites.

Keywords: Comprehensive open database, nuclear power incidents and accidents, learning from experience.

1. INTRODUCTION: RISK INFORMATION & LEARNING FROM EXPERIENCE

Understanding and improving safety are crucial issues for the nuclear sector. Quoting the IAEA (International Atomic Energy Association), "nuclear safety requires a continuing quest for excellence", supported by the technical principle of learning fully from safety research and operating experience [1]. It is thus clear that all relevant scientific techniques should continually be brought to bear. In this context, we make *three claims*:

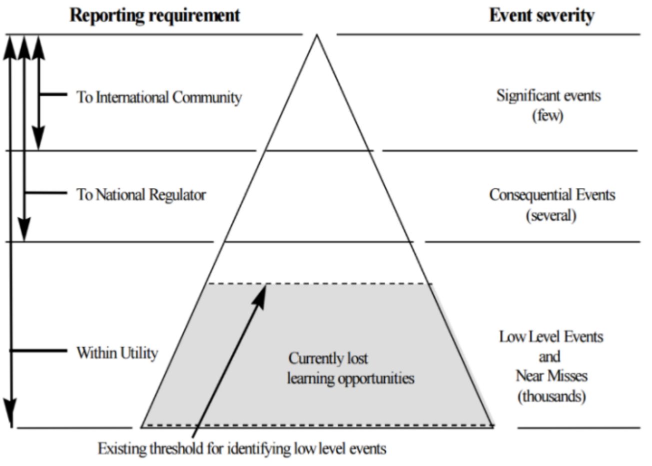
1) More lessons can be learned from the operating history, incl. through comprehensive statistical analysis;
2) There is a lack of open comprehensive information for scientists and the public about events (anomalies, incidents, and accidents) in nuclear energy facilities; and
3) The total consequences of events must be studied to understand the true value of safety investments.

Addressing the ***first claim***, the primary framework for studying and regulating safety within the nuclear community is PSA (Probabilistic Safety Assessment) (e.g., [2]). In PSA, there are three escalating levels of analysis that are performed on a plant- and site- specific basis: Level 1 concerns reactor core damage as characterized by the CDF (Core Damage Frequency) per reactor-year (ry); predicated on a core damage, Level 2 concerns containment failure and radiological release categories characterized by the LERF (Large Early Release Frequency); given a release, Level 3 is concerned with the consequences [3]. Levels 1 and 2 are legally required in most countries, with the international guideline for demonstrating compliance for CDF being 10^{-4}/ry (per reactor-year) for operating plants. However, Level 3 -- the study of consequences -- has only been done on relatively few occasions, by academics.

The methods to determine the CDF and LRF are theoretical: One must identify the multitude of initiating triggers, and event sequences that can lead to the core damage or large release end-state, and assign probabilities to all of these chains in the absence of statistical experience at the system level. As PSA are always done on a plant specific basis, results can vary by a factor of 100, inter alia due to both differences in quality of safety systems and exposure to natural hazards, as well as differences in PSA methods, quality and scope. Despite PSA being an integral component of learning and improvement within the nuclear sector, even the best PSA has limitations [4] emphasized in reviews following "Fukushima"[5]. Among these, a fundamental issue is that one cannot prove (mathematically) that the set of included sequences is complete. The importance of this is demonstrated by the fact that thirty percent of non-negligible accident precursor events, in the US between 2000 and 2010, were not captured by their PSA [6].

It is therefore useful to compare, and calibrate PSA models with data/experience. Further, given the rare nature of major accidents and their precursors, there is a need to pool experience. Given the common generation, designs, and vendors for different sites, as well as sharing the same dominant internal and external risks, there is an opportunity to pool experience from comparable units to support aggregate statistical analysis and a fuller learning from operating experience, as indicated by the IAEA* (see Fig. 1). Such an approach was used in [7] to document a reduction in CDF over time, and compare CDF in different fleets.

Figure 1: Schematic of the reporting of events at different levels. Taken from the IAEA [8].



For the ***second claim***, there is a large amount of technical information about events -- some of which is openly accessible, and some for only regulators or operators:

- The IAEA has the IRS database, containing about 4'000 events from all countries, with varied reporting behavior by country. Only about 400 events have an INES (International Nuclear Event Scale) score, and none are above INES level 2. Access may be granted to regulators and research institutions. Via the NEWS website, the IAEA publishes a minor number of INES scores for recent radiological events.
- The WANO operating experience database is restricted to consenting member utilities. It contains several thousand reports per year, worldwide, including very minor events, and is understood to be of high quality and degree of technical detail.
- The EU JRC "Clearinghouse on Operating Experience" database exhaustively draws on reports from US and European national regulators since 2006, having a database of about 600 events since then. So far it provides practical useful safety lessons-learned. It contains sixteen INES=2 events, and one INES=7. Access is available upon request.
- National regulators have databases according to strict legal reporting criteria. The US NRC LER database is open-access. It contains tens of thousands of reports since 1980, but unfortunately there is no searchable severity measure to enable comprehensive practical use. The Korean KINS OPIS Nuclear Event Evaluation Database is an exception, providing a useful search-able database of hundreds of events -- most of which are INES 0 / below scale. The national regulators have different reporting practices: Many have annual reports that are

* "[to improve safety] the reporting threshold should be lowered from incidents to anomalies with minor or no impact on safety. This will provide an insight on precursors, which are near misses or low-level events that provide information for determining advance warnings" [8].

available on-line, with a limited history, typically including INES scores for events above some threshold for that year[†].

- In particular, the US NRC Accident Precursor Program provided comprehensive open reports, quantifying hundreds of core damage accident precursors based on their conditional core damage frequency [6].

As illustrated in Fig. 1, according to the IAEA, there should be a deeper sharing of experience (here events) across countries/actors. Event reporting requirements are currently such that: only the “few” significant events need to be reported to the international community; the “several” consequential events only need be reported to national regulators; and the “thousands” of low-level events above existing thresholds need not be shared outside of the utility. The multitude of events beneath the threshold have been identified as “currently lost learning opportunities”.

Furthermore, for scientists and the public, without exceptional effort, they are limited to studying small numbers of INES scores, distributed across diverse documents and sources (e.g., [9-10]). INES is the official scale for event severity [11], having discrete escalating levels from 0 to 7. An event of 4 or larger is termed an accident, and below an incident. Concerning either fatalities, radiation release, or precursor/near-miss (so-called degradation of defense in depth) severities, each INES level roughly corresponds to an increase by an order of magnitude. Problematic for scientific use and general interpretation is how these different aspects are combined: A single fatality, or a small off-site release with neither fuel damage nor measurable consequences, will be called an accident (INES 4). But a severe precursor event -- say where there was a high probability of a major accident that was avoided by "chance" -- can achieve a maximal score of 3. Therefore, it is not directly useful for the study of safety. In detail, consider a >10% chance of an INES 7 major accident. Due to the exponential scale the pure risk would be $>0.1 \times 10^7$, implying an INES score of 6. However, a maximal score of 3 would be given. Further, by its definition, it is not an integral/full measure of consequences.

Concerning reasonable metrics: For safety, near-miss potential must be captured, as is done with precursor analysis where, given some degraded condition (e.g., an eroded reactor pressure vessel), a *conditional PSA* is done to determine the CCDF and CLERF (conditional probability of core damage and large release per condition event). These are the frequency with which core damage and large release are expected to occur in an instance of the given condition. A recent prime example is Fukushima Daini -- the coastal neighbour to Dai-ichi, about 10km southbound -- where the 2011 tsunami also caused flooding, which can be thought of as the conditioning event. With some luck (e.g., crucially a single one of the multiple external power lines remained, allowing control information, unlike at Dai-ichi [12]), and outstanding accident management, the large four-unit site avoided accident. Unfortunately, only the US has made precursor analysis results available. For integral consequences, overall cost to society should be considered, which may also be used to compute accident externalities, and is discussed further below.

For the ***third claim***, we emphasize that the study of consequences is not legally required [2], seemingly in contradiction to the legal requirement that plants must be made as safe as *reasonably achievable*, which is regulated via cost-benefit analysis of safety investments. E.g., in the US,
“cost-benefit determinations are conducted within regulatory analyses... Onsite property costs include replacement power, decontamination costs, and costs associated with refurbishment or decommissioning. Off-site property costs include ... e.g., property values, tourism, manufacturing, and agriculture disruption.” [13].

The NRC guidelines [13], and 2013 OECD/NEA workshop [14], provide useful guidelines for estimation of the cost of full consequences, unifying diverse categories: on-site loss of capital, loss of life, environmental degradation, disruption of economy, etc. Here we consider all costs to be measured in USD (2017 US Dollars). Often there is disagreement about what costs to include, and what costs are

[†] US NRC since 1980, French ASN since 1999, German BFS since 1979, Japanese NRA since 2011/(1990 [JNRA]), Swiss ENSI since 2005, UK ONR since 2000, Belgian FANC since 2002, Finnish STUK since 1999, Indian AERB since 2000, etc.

knowable. However, for experienced major accidents, many of the significant -- even dominant -- costs are known (cost of replacement power, loss of capital, public compensation, etc.). Here a rough compilation of such information is done to provide a realistic cost figure, needed for a full appreciation of safety systems, and calculation of the nuclear accident externality.

Responding to these issues, in this paper, we detail our open comprehensive database of events in nuclear power, with both safety and cost aspects. This database is considerably larger and of much higher quality that a previous database from Sovacool, focused on cost [15].

2. THE DATABASE

2.1. Structure & Approach

We provide a comprehensive open database on events in nuclear power that is useful for both scientific study and for the public. Its covers all facilities in the life-cycle of all types of commercial nuclear power, for all countries, from the 1950s until the current date. The database contains around nine hundred events with the following information:

- A sound, yet brief, description, covering the trigger, chain and consequences of the event.
- INES scores, from the IAEA when available, and otherwise specified according to the IAEA manual [11].
- A cost measure of order-of-magnitude integral consequences
- *Unit information; Operating mode:* full power, transitory, shut down; *Activity:* Fuel loading, testing, maintenance, etc.
- *Trigger origin*: “nuclear island”, “secondary” part (turbo generator, turbine hall, power supply and substation, aux cooling), and “external” (incl. natural hazards, LOOP, and events (fires, explosions, etc.) at aux buildings)
- *Failure mode:* human and/or mechanical; *Event type*: actual and/or potential (i.e., an accident precursor); Identifying fore-runners, common-cause failures / generic issues, and precursors.

To serve as an introduction, a selection of interesting events are given in the appendix. To construct the database, over one thousand diverse source documents were consulted, and more than 90% of which have official sources. The primary sources were: annual reports from national regulators, published IAEA INES scores, and other open access official documentation. We have also done a broad Internet search including also academic publications and newspaper articles. Official sources were then identified whenever possible -- for instance using the LERSearch tool for US events [16]. When not possible, multiple journalistic and scientific sources were consulted and reviewed by an expert of nuclear technology. If a reasonable high-level understanding of the event was not possible, then the event was excluded.

The database should be reasonably complete/representative over a certain threshold for safety-relevance (we think INES 2 and above), as well as including highly cost-relevant events (cost in excess of 100 Million USD with at least some safety relevance). For lower level events (INES<2) the database is of limited completeness, due to a massive number of such events as well as a lack of open access to details. For instance, the Finish regulator, STUK, reports five INES=1 events at Olkiluoto in 2008, which are not in the database [17]. Also, in particular for lower level events, the database will be more complete for some countries than others. For instance, some national regulators with relatively open and comprehensive event reporting are: USA, Germany, Switzerland, Korea, Sweden, Finland, etc; while Russia, China, Japan and India provide varying levels of information.

With these limitations in mind, the database enables: 1) convenient lookup and analysis of individual events, and 2) statistical analyses of trends, fractions, and absolute figures. Importantly, it may also be used for a statistical characterization of the frequency and severity of accidents in nuclear power as done in [7].

The database is open, and a process will be provided for interested members of the public to provide feedback, subjecting the database to rigorous open peer review. The database is therefore a living ongoing project involving continuous update. The goal is to provide a comprehensive resource for scientific learning from the history of nuclear power.

2.2 Data Summary

Based on our comprehensive data, we confirm that the bona fide historical core damage accidents at commercial NPP include the three affected units at Fukushima-Daiichi, 2011; and one each at Chernobyl, 1986; and TMI, 1979. While a number of events have happened at experimental, demo/prototype facilities[‡] and weapons facilities, it is improper and misleading to include these[§]. Finally, there have been a number of minor (<1% of core) melt events at commercial units[**] which are important precursors to full core damage accidents. Precursors[††] are highly interesting, and expand the sample for study of core damage frequency -- see [7] for an analysis based on this database.

The event breakdown, excluding 17 at military/weapons related facilities (all but 3 took place before 1970), are:

Civilian use facilities: 870 events

- Power plants: 787
- Reprocessing: 43
- Demo/Experimental/Research: 24
- Fuel Fabrication/Preparation/Recovery: 10
- Uranium Mine/Processing: 5
- Waste Disposal: 1

Power Plants: 787 events

- PWR: 455
- PHWR: 83
- BWR: 190
- (HW)GCR: 33
- LWGR: 19
- FBR: 3
- HTGR: 4

Focusing on civilian nuclear power plants there are 571 assessed to have potential core safety relevance, 430 of which with non-negligible core damage relevance (assessed to have INES>0 related to degradation of defense in depth). Of these events:

- 15% were when powering up or down, 11% were with the unit "cold", and 74% at full power.
- The share of events by region (with share of global reactor-years' experience in parenthesis): North America: 55% (29%), North and Western Europe: 23% (37%), Asia: 13% (19%), and Eastern Europe: 9% (15%).
- More than 165 events were found to have a significant or event dominant human element (incl. design, maintenance by own staff or contractor, operation, etc.).
- The origin of the trigger/cause by location breakdown as: nuclear 65%, secondary 23%, and external 13% -- demonstrating the importance of triggers outside of the primary nuclear part.

A selection of interesting events, highlighting the role of human error, difficult to model complexities including multi-unit interaction, and external events are given in the appendix. In Figure 2, the events assessed to have core safety relevance are plotted according to their INES scores. Note the low number of incidents prior to 1990, when INES was introduced, and a tendency for fewer large INES scores over time.

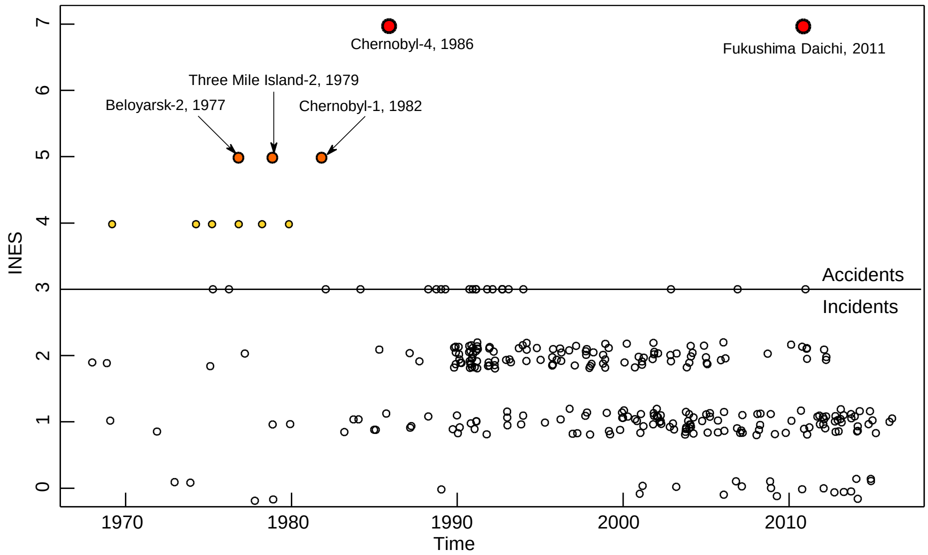
[‡] Chalk River,1952; EBR-I, 1955; SRE, 1959; SL-1, 1961; Fermi, 1966; Lucens, 1969; and Ågesta, 1968.

[§] Experimental and demo facilities can be left out due to their small size. Weapons facilities were designed and operated under radically different conditions and oversight, and with a different purpose -- the 1957 Windscale fire being a good example

[**] E.g., Greifswald-5, 1989: 10-30 fuel elements – being a small fraction of a single assembly, out of more than 100 assemblies in the core – overheated, but did not melt. St. Laurent A-2, 1980: melting of one channel of fuel (out of >1000). St. Laurent A-1, 1969: 50kg of fuel melted (out of >100 tons, similar fuel damaged to above event).

[††] In particular, core damage precursors are quantified with their conditional core damage frequency (CCDF), being the probability of core damage given the initiators and degradations/unavailabilities within the event.

Figure 2: INES scores for events at commercial nuclear power stations. Including only events deemed to have core-safety relevance (e.g., excluding Tokai-mura, 1999), from the database. The incident points are spread around their INES value for visibility. The INES 4 events include: 1969 St Laurent-1; 1974 and 1975, Leningrad-1; 1977 Bohnice-1; 1978, Beloyarsk, which has INES 3-4; and 1980, St Laurent-2.



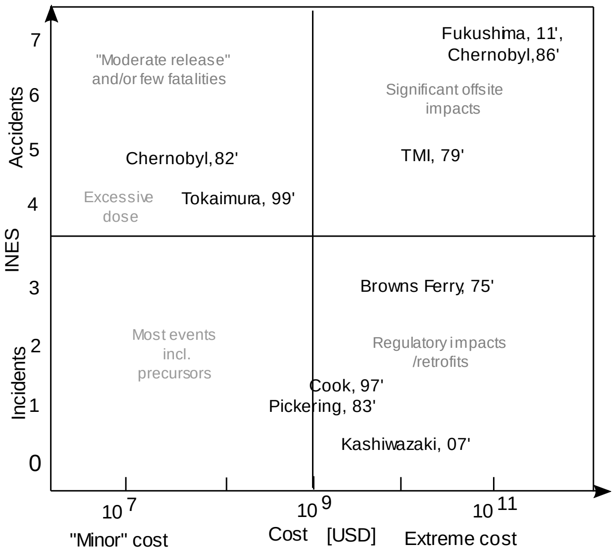
3. COST & SAFETY

Here we compare the estimated full cost of the consequences of experienced events in commercial nuclear power with safety relevance, as measured here by INES. This is important to decide how to define risk in nuclear power in terms of relevant events, and their frequencies and severities.

For an integral measure of consequences, we use total cost, largely following the cost categories and methods defined within US NRC Regulatory Analysis [13]. Our goal is not to provide precise specific cost estimates but rather order-of-magnitude cost estimates that allow for aggregate statistics. This is reasonable given the extreme nature of costs in nuclear power -- where consequences on the order of hundreds of billions of USD are possible, and have been experienced. The basic idea: There are few events where there is an off-site radiological impact -- namely large releases following core-melts and lack/failure of containment, as well as more minor leaks/contamination during operation of plants and fuel cycle facilities. For Fukushima Dai-ichi (2011) and Chernobyl (1986), there are multiple official and scientific reports on different consequences and their cost which we have attempted to reconcile and combine. In other cases, where there is no radiological release, costs can still be of major interest -- including for the public, which often pays through higher rates. Here the cost of downtime (depreciation, operating cost, and incremental cost of replacement power), as well as onsite repair/cleanup can be estimated as well as found in industry operating experience documents (e.g., [18]), and annual financial statements from the utilities -- often reported within the local media.

What we emphasize is that many events, being rather minor from a safety perspective can be highly costly, especially when coupled with mismanagement, concealment, and regulatory ratcheting. Precursor events on the other hand are by definition of utmost safety relevance, yet typically inconsequential. Such events are shown in Figure 3 and the cases where cost and safety conflict are discussed below. This shows that one should neither look at INES or Cost alone. Rather, precursors and other methods may be used to assess frequency of accidents, and cost used to inform their severity. In the next section the predominant contribution of major nuclear accidents to risk is argued.

Figure 3: Comparing cost and safety severity of historical incidents and accidents.



First considering accidents with minor costs, examples are:

1999, TOKAIMURA Fuel Preparation Facility (Ibaraki Prefecture, Japan), 1999, INES=4. Human error and violation of safety principles led to a criticality accident in this small fuel preparation plant. The criticality exposed three operators to excessive doses (two proved fatal) and 116 others to doses below permissible limits. Total cost of this accident is estimated to be $200-300 million: $12-20 million for impact on employee health, $175 million for public economic damage, costs of emergency response (evacuation of 161 people from 39 households within a 350-meter radius), and plant loss.

Chernobyl-1 (Pripyat, USSR / Ukraine), 1982, INES=5. Rupture of pressure pipes led to contamination of the reactor building and release of radioactive aerosols through ventilation stock. The Commission of the nuclear industry concluded that radioactivity detected offsite was not significant. The reactor likely restarted 10 days later. Total cost of this accident is estimated to be $10-100 million: $10-20 million downtime cost, cost of repairs, irradiation of workers during repair (extent unknown), and impact on environment.

And second, selected incidents with high costs are:

2007, KASHIWAZAKI KARIWA, 7 BWR units (Kashiwazaki, Japan), INES=0. A 6.6 offshore earthquake, beyond design basis, initiated a complete shutdown. Generous site-specific safety margin credited for strength of plant response. After repairs and seismic upgrades, reactors successively restarted in 2009 and 2010. Decrease in nuclear generation between FY2007 to FY2009 totaled 125 billion KWh. Total estimated cost: $12.6-16.1 billion.

1975, Browns Ferry (Decatur, United States), INES=3. A fire was started when a worker inside the containment, using a candle to search for air leaks, ignited a combustible seal. The fire spread on the reactor building side wall, burned for seven hours and damaged cables, disabling safety-grade systems related to the control of unit 1 and 2; meltdown was averted. This led to an 18-month outage of both reactors and widespread industry impact, with cost of retrofitting US stations estimated in 1976 to be $7-12 billion in 1976 dollars. Total estimated cost: $32-54 billion.

1997, COOK (Bridgman, United States), INES=1. Both units shut down for three years due to design-related concerns about ice condenser (containment). Total estimated cost: $3.6-5 billion. And similarly: PICKERING (Pickering, Canada), 1997, INES 1. Small LOCA (2-meter-long split), led to extended outage for re-tubing. Total estimated cost: $3.3-5 billion.

4. COST OF EVENTS: PREDOMINANCE OF MAJOR ACCIDENTS

4.1 The Three Major Accidents

Considering full cost, the three most costly events, and a hypothetical event (by the French IRSN [19]), are given in Table 1. This rough accounting indicates that a major accident can cost hundreds of billions of USD to the nuclear sector and society. Perhaps most notably:

- In terms of public and on-site impacts, TMI cost on the order of USD 10 billion. It had a major measurable influence, costing ten times more, through the increased safety requirements worldwide – and is hence has substantial benefit associated with it [20-21]
- Chernobyl showed the potential of massive public economic costs, claimed to have exceeded even the major toll on life and health due to exposure to widely spread ionizing radiation [22].
- Fukushima Dai-ichi gave insight into the non-radiological trauma caused by evacuation and continued displacement. Perhaps most costly is the disruption of nuclear power generation, which continues to cost Japan dearly as natural gas is imported to replace the lost nuclear electricity production [23].
- The IRSN hypothetical estimate is similar to the estimated costs of Chernobyl and Fukushima.

Although the toll on life and health of a major accident are severe, they form a minority of the full costs: For both the IRSN study, and Fukushima, it is less than 10% of the total; and for Chernobyl – a unit with design weaknesses that do not exist in modern units – it is likely to be less than 25% of the total, especially as this relies on the Linear-No-Threshold model for long-term low doses.

Table 1. Approximate estimated full cost of major nuclear accidents. Given in Billions of 2017 USD, including the French hypothetical major accident. The interval in the approximate total is the sum of the upper and lower bounds of the individual costs. Comparatively large costs given in bold. Life and health impacts include deterministic and projected radiological fatalities, and evacuation related trauma. Replacement is the incremental cost of replacement power. The "beyond" category identifies potential costs that are outside of the scope of the estimation. Arguably the TMI retrofit costs could be excluded on the basis that they were beneficial. Deeply uncertain costs and potential benefits relating to impacts on energy policy are not quantified.

Cost (USD Bil.)	**ISRN, 2011**	**TMI, 1979**	**Chernobyl, 1986**	**Fukushima Dai-ichi, 2011**
On-site	10	5-10	**25-35**	**20-30**
Life & Health + Public-Economic	< 60 + 110	 0.1	26-33 + **150-250**	14-15 **+** 50-100
Replacement + Retrofits	110	5-15 + **100-200**	10-30 + 2-8	**100-150** + 60-120
Beyond...	200 "reputation"	**Sector inflection point.**	**Political instability?**	**German nuclear exit, etc.**
Approx. Total	< 500	110-225	213-356	244-415

4.2 Other Events

Following guidelines from the NRC and materials from the OECD/NEA workshop [14]**,** the rough full cost to both the nuclear sector and society were estimated for all events in the database [27]. We focus on comparing the cost of the "Big 3" (Chernobyl, Fukushima, and TMI) major civilian nuclear accidents to other costly incidents and accidents[‡‡]. In Table 2, the big 3 account for about 80% of the total historical cost, including events at all types of commercial nuclear facilities. This emphasizes the heavy-tailed nature of consequences of incidents and accidents. Concerning Sellafield[§§], whose cost was excluded from the above, about 2/3 of the estimated cleanup and decommissioning costs of 170 Bil. USD are attributed to civilian use [24], which included a number of incidents [25]. This event is

[‡‡] Some industry impacts of generic defects are excluded as they are often not attributable to any single event. Notably replacement of RPVH and SG in PWRs and recirculation piping in BWRs are estimated to have cost tens of billions [27]. Furthermore, some costly events with very limited safety relevance have not been included in the database.

[§§] A unique and complex site with reprocessing and storage facilities as well as the two Windscale Piles, Calder Hall, and the AGCR prototype – was hastily constructed for military weapons use, and has accumulated large amounts of concentrated high level radioactive waste.

largely a relic of the past, but emphasizes the importance of excellence in design and operation across the full nuclear fuel cycle and life.

Table 2: Approximate cost of events at civilian-use nuclear facilities, in USD Billions, excluding Sellafield, industry impacts of generic defects, events with very limited safety relevance, etc.

Category	**All-inclusive costs**
"Big 3": Chernobyl, Fukushima, TMI	567 – 996
Other events at NPP (excl. big 3 events): 784 events in total	153 – 280
Events at other types of civilian-use nuclear facilities: 83 events in total	4 – 8
Grand total: 870 events in total	**724 – 1284**

To understand these costs in further detail, some of the costliest events at NPP other than the big 3 (totaled in row 2 of Table 2) are summarized in Table 3, and the cost types broken down for all events at NPP (row 1 and 2 of Table 2) in Table 4. This clearly indicates the absence of substantial off-site impacts, but the potential for significant on-site costs (incl. retrofits and downtime) due to incidents – for which the Browns Ferry fire in 1975, an alarming precursor, provides a good example.

The "event" at Browns Ferry & Sequoyah in 1984 emphasizes the sometimes tenuous link between safety and cost relevance[***]. Further, there are multiple events with costs around $1 billion, related to minor incidents, and due to mismanagement and increasing regulatory pressure, leading to costly periods of downtime, retrofitting and even plant shutdown. Such costs should be reflected in the capacity factor, and therefore already considered in the standard cost of production. In this sense the grand total estimate in Table 2 is conservative (on the high side), and the cost of accidents likely further predominant than the 80% mentioned above.

Table 3: Breakdown of costs, excluding "Big 3". In USD Billions, only for events at NPP.

Events	**Costs**	**Significant cost components**
Browns Ferry fire in 1975	32.3 – 53.9	30 – 50 industry impact
Kashiwazaki earthquake in 2007	12.6 – 16.1	10 – 13.5 downtime, 2.6 repair
Browns Ferry & Sequoyah programmatic weaknesses in 1984	8.8 – 10. 2	4.5 – 5.5 downtime, 4.3 – 4.7 repair
Between 1-5 Bil. costs: 34 events	66.2 – 124.3	
Less than 1 Bil. costs: 747 events	32.6 – 75.5	
Subtotal of NPP events (excl. big 3)	**153 - 280**	

Table 4: Breakdown of cost by type, in USD Billions, only for events at NPP, excluding Sellafield, industry impacts of generic defects, events with very limited safety relevance, etc. * of which $30-50 billion is from the Browns Ferry fire incident (1975). ** mostly impact on the health of employees/contractors.

Cost Types	**Chernobyl, Fukushima, TMI**	**All other events**	**Row total**
Downtime / Replacement	115 – 195	94 – 156	209 – 351
Industry impact / retrofits	162 – 328	39 – 70*	201 – 398
Public Economic	200 – 350	~0	200 – 350
Life & Health	40 – 48	<1**	40 – 49
On-site	50 – 75	20 – 53	70 – 128
Column total	567 – 996	153 – 280	**720 - 1276**

5. CONCLUSIONS

[***] "A series of investigations by the N.R.C. and other agencies, including the FBI, uncovered significant weaknesses in the design, management and operation of Browns Ferry and its sister, the Sequoyah nuclear plant […] coupled with higher operating costs and the public uneasiness prompted by TMI, […] Browns Ferry and Sequoyah were closed. The adventure in nuclear power cost the T.V.A. at least $20 billion [...]" [26].

We have constructed a comprehensive open database with about 900 incidents and accidents in civilian nuclear power, of unique value for scientific analysis and public use. Essential value is added due to review by a nuclear technology expert and use of official sources. This was justified given the lack of accessible open information. In addition to measuring safety relevance of events with INES scores, it is emphasized that a cost measure of consequences is also important. In particular, the full cost to both the nuclear sector as well as society should be accounted for to assure a full appreciation of the value of safety. With estimated costs, it is shown that the total cost of the major three historical accidents heavily dominate the cost of all other events -- although potential costs due to poorly managed fuel reprocessing and storage cannot be excluded. This database provides the basis for future scientific studies and improvement of safety. For instance, in [7], a risk assessment was done, with frequency of accidents based on incidents and accidents – in particular precursors – and the cost of experienced accidents informing potential severity of accidents.

Acknowledgements

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Appendix: SELECTED INTERESTING EVENTS

1975, Leningrad-1 (RBMK/LWGR), USSR: A fuel channel in Unit 1 suffered a loss of coolant, resulting in the degradation of a nuclear fuel assembly that led to a significant release of radiation lasting for one month; no notification of danger in the affected region.
- INES=4. Forerunner to Chernobyl.

1977, Davis-Besse-1 (PWR), USA: Reactor shut down because of a disruption in the feed-water system; this caused a pressure increase in the primary circuit and the opening of the pilot-operated relief valve (PORV) for the pressurizer which falsely stuck open.
- INES=3. Forerunner to TMI.

1999, Blayais-2 (PWR), France: Unexpected combination of tide and high winds partially flooded site with units 1,2, and 4 operating; all units lost 225 kV power supply and units 2 and 4 also lost 400kV power supply, leading to automatic shutdown after failure of self-supply, and triggered start of diesel backup generators; damage to safety related systems; inadequate emergency response: restoration of 400kV power supply after less than 3 hours; no damage to the reactors but the event raised concern about similar threats in other plants in France, and caused upgrades of design rules and protection.
- INES=2. Forerunner to Fukushima.

1982, Armenian-1 (PWR), former-USSR: Series of failures, short circuits, cable over-heatings and fires after switching of reserve service water (boron) pump to vital 6 kW bus ordered during maintenance of service water pump; later, control rods dropped, emergency protection system activated; 3 hrs later total plant blackout, 5 hrs later a high pressure injection pump became operational, and 6.5 hrs later fires liquidated and feed-water pump activated to fill steam generators and cool primary circuit.
- INES=3. Highly complex serious incident -- entailing all elements of complexity and human actions.

2011, North Anna-1-2 (PWR), USA: LOOP due to BDB earthquake, while Unit 1 AFW pump out-of-service for testing. Reactor automatically shut-down and four EDG started; one EDG failed but was replaced by a fifth; off-site power was restored same day.
- INES=2. Experienced beyond design basis (BDB) "accident" in USA.

2006, Forsmark-1,2 (BWR), Sweden: Work outside core building caused short circuit, led to loss of two of the four trains of the emergency power supply and house-load power. Cooling maintained by 4x50% design of the emergency and safety systems. Full power supply re-established after 22 minutes through manual switching. Reactor scram successful. Two valves in the pressure relief system opened because of unwarranted initiation of safety trains. The ECCS system in 2/4 trains sufficient, as there were no additional LOCA. Partial loss of control information throughout loss of power event.
- INES 2. Origin outside of nuclear island, due to human maintenance error.

2001, Rovno-2-4 (PWR), Ukraine: Dismounting crane fell on cables passing from 330/6kV transformers to unit 4 (under construction). Due to the resulting earth fault, outside 300kV transmission lines were cut off by electrical protection actuation lines; there was a loss of normal and emergency power supply leading to decreasing frequency of the power supply of the main coolant pumps and actuation of emergency protection including scramming of units 2 & 3. Because of overload the central alarm indication system was disabled that caused difficulties in the event management by the personnel. The earth fault caused high currents, burning of the cables, and the following fire spread to 6 kV distribution buses. The fire was extinguished after 1 1/2 hours; the plant was kept under hot standby condition and restarted after permission.
- INES=2. Human error outside of nuclear island, and multiple units at different operational states.

1995, Pickering-5 (PHWR), Canada. Two technicians carried out work on the wrong reactor (reactor 5 instead of reactor 6), disabling the second fast shutdown system on reactor 5, which was operating at full power at the time.
- INES=1. Potentially significant human error during maintenance.

1990, Vogtle-1-2 (PWR), USA. Truck backed into support column for the feeder line in the low voltage switchyard, supplying power to one the reserve auxiliary transformers (RAT), each of unit 1 and 2, resulting in loss of power. The unit 2 EDG started and loaded the de-energized vital bus. However due to another electrical fault the turbine and reactor were tripped. Both (cross-tied) vital buses of unit 1 were de-energized and the available EDG started but shut down automatically after 1.5 minutes; loss of all vital ac power for more than 15 minutes with subsequent shut down of operating reactor heat removal pump, while the standby pump could not be started. Reactor system coolant heat-up, core cooling was reestablished at after two hours.
- INES=2. Human error outside of nuclear island; complex behavior of dual cross tied plants at different plant states

1992, USA, TURKEY POINT-3,4 (PWR). Hurricane Andrew passed over station, causing 6 day LOOP; plant relied on EDGs. All offsite communications lost for 4-hours, site blocked by debris, fire protection system was rendered inoperable, compensated by pumping water from adjacent salt water lagoon. Reactor shutdown electrical cables on exterior of containment (rare design), damaged by winds and subject to potential fire, with risk worsened by wind blowing combustible fuel from adjacent oil-fired plants over the nuclear site and lagoon emergency water supply.
- INES=2. External hazard from neighboring non-nuclear site.