Master Thesis

Safety of Nuclear Energy:
Analysis of Events at Commercial Nuclear Power Plants

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List of abbreviations

ATWS	Anticipated transient without scram
BWR	Boiling water reactor
CANDU	Canada deuterium uranium
CRDM	Control rod driving mechanism
IAEA	International atomic energy agency
IGSCC	Intergranular stress corrosion cracking
INES	International nuclear event scale
KNIS	Korea institute of nuclear safety
LCOE	Levelized cost of electricity
LER	Licensee event report
LOCA	Loss-of-coolant accident
LOOP	Loss of offsite power
LWR	Light water reactor
NEA	(OECD) Nuclear energy agency
NPP	Nuclear power plant
NRC	(US) Nuclear regulatory commission
OPIS	Operational performance information system
PSA	Probabilistic safety assessment
PRIS	Power reactor information system
PWR	Pressurized water reactor
PWSCC	Primary water stress corrosion cracking
RPV	Reactor pressure vessel
SG	Steam generator
TMI	Three-mile island
WNA	World nuclear association

Abstract & Structure of thesis

An open, comprehensive database of events in the civilian nuclear sector has been constructed through a team effort at the Chair of Entrepreneurial Risks, with the goal of deeper learning from operating experience and better understanding of risk in nuclear power. This thesis contributed to the completion of this database which captured both the safety and cost aspects of over 900 events, especially focusing on the estimation of costs of events. Analysis of events in the database yielded the following key insights:

1. Risk in nuclear power, when viewed from a cost perspective, is heavy tailed.
2. The historical accident externality of nuclear energy, i.e. cost of experienced events averaged over historical nuclear electricity production, is estimated to be around one USD cents/kWh, which is several times smaller than the emission externality of fossil fuels, and would not significantly change the economics of nuclear energy.
3. Deep-diving into costly events, several common themes have been identified. Besides major accidents with offsite impacts, events with widespread industry impact – including generic defects and some precursor events – have resulted in substantial costs. Furthermore, deficiencies in operational management / safety culture often led to increasing regulatory pressure, prolonged outages, and/or extensive modifications, all of which can be very expensive.
4. The safety- and cost- centric views of event significance do not always agree. An integrative view would be much more informative.

This report is only one of the deliverables of this thesis. Other key deliverables, including the database and accompanying files/resources, are listed in Appendix.

This report is organized as follows:

In the introductory chapter, the motivation behind this project is explained. Existing nuclear event databases and literature related to cost estimation are reviewed. Our database is then introduced, in terms of information and event coverage.

Next, the methodology of cost estimation is described in detail, motivated by the intention to share the knowledge and experience accumulated in this work.

In results and discussion, distributions of included events over facility types, geographical regions, and degrees of safety relevance (as indicated by INES score) are presented. The discussion is then centered on more than a dozen costly events, organized around four common themes. Based on the estimated full cost of experienced events, the historical accident externality of nuclear power is calculated on a per kWh electricity generated basis. The total cost is then broken down by event and cost type, revealing heavy-tailed distributions. Lastly, the cost and safety measures of risk in nuclear power are contrasted and illustrated through several examples.

At last, this thesis report ends with summaries of key learnings, limitations, and suggested future research areas.

1. Introduction

1.1. Motivation

The need for an open, comprehensive database

As a reliable source of base load electricity, nuclear generation accounted for around 10% of the electricity consumed globally in 2014 [1]. Although the negative externality of carbon emission is mostly absent from nuclear power, the dire consequences of major historical accidents serve as a good reminder of the unique accident externality in nuclear power. Hence, understanding and improving safety are paramount to the nuclear sector, and to society in general. Quoting the International Atomic Energy Association (IAEA), “nuclear safety requires a continuing quest for excellence'', supported by the technical principle of learning fully from safety research and operating experience [2].

The first grid-connected nuclear power plant, USSR's Obninsk reactor, started producing commercial electricity in 1954 [3]. As of 1 September 2017, there are 447 operable nuclear power plants worldwide, with a combined electric output close to 400 Gigawatt [4]. Over the six plus decades, more than 17,500 reactor-years of operating experience has been accumulated within the civil nuclear power sector [5]. Many lessons can be expected to be learnt from the past, through analyzing individual events and/or aggregate statistics.

Further motivated by the lack of open comprehensive information on this subject (see 1.2. Related work & Literature review), our team set out to construct a comprehensive, multi-purpose database of events (anomalies, incidents, accidents) at civilian-use nuclear facilities. Access will be granted to the scientific community and interested members of the public. It is envisioned that this work could add tremendous value by supporting scientific study and learning from experience, as well as bringing much-needed transparency and facilitating discussion about nuclear energy.

The importance of study of costs

From the perspective of the civil nuclear sector, adequate quantification of consequences of accidents is important because the costs of accidents are actually the potential benefits of safety investments [6]. Cost-benefit determination of safety investments – for example, the value-impact analysis of the ATWS rule done by the US NRC [7] – is one application of this principle. Probabilistic safety assessment (PSA), a systematic and comprehensive technique for assessing risks associated with complex systems [8], has become the primary framework for studying and regulating safety within the nuclear community. PSA is used during both the design and the operating stages of a nuclear power plant (NPP) to evaluate conceivable initiating triggers, sequences, and consequences of events. Specifically, Level 1 PSA characterizes the theoretical probability of reactor core damage [9]; Predicated on a core damage, Level 2 PSA analyzes the likelihood of containment failure and radiological release to the environment [10]; Given a release, Level 3 PSA is concerned with the impact on public health and the environment, as well as direct costs [11]. Unfortunately, Level 3 PSA – the study of consequences – is not legally required [9], and has only been done on relatively few occasions by academics.

Taking a more “big-picture” view, there is a need for simple and direct quantification of the absolute risk level in nuclear power, in order to support decision making within the public and corporate sector. Conducted on a site and plant specific basis, and in great detail, PSA has facilitated technical exchanges on safety matters between the nuclear industry and its regulators, among peers, and between plant designers and operators. However, its local focus and daunting complexity likely discourage non-experts, who would benefit more from high-level order-of-magnitude assessments of risk in the nuclear sector. Complimenting PSA with statistical experience, which our work aims to accomplish, could help fill this gap.

Understanding the cost of nuclear accidents is also important for the balancing of the energy portfolio. All relevant costs of different energy sources must be accounted for, which implies that the external costs (accident externality of nuclear power, emission externality of fossil fuels, etc.) should be considered [12]. Serious nuclear accidents are rare but costly, which probably contributed to the popular belief that the inclusion of accident externality in the price of electricity would make nuclear power economically unfeasible. One of the objectives of this thesis is to investigate this opinion through analysis of pooled operating experience.

1.2. Related work & Literature review

On events in the civil nuclear sector, large amount of technical information exists in diverse sources, with varying degree of accessibility. A summary is given in *Table 1*. This fragmented information landscape makes it impossible to conduct systematic analysis without exerting exceptional effort. Moreover, the searchable information about event significance is limited, with the INES[1] score usually being the only measure of severity.

Table 1. Some exiting sources of technical information about events in the nuclear industry. * 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.

Source	**Provider**	**Accessibility**	**Information coverage**
IRS database	IAEA	Regulators / Research Institutions	~ 4,000 events, 400 with INES score (none above INES 2)
INES news website	IAEA	Public	Small number INES scores for recent radiological events
Operating experience database	WANO	Consenting member utilities	Several thousand reports per year, worldwide, including minor events; high quality / degree of detail
Clearinghouse on Operating Experience	EU JRC	Available upon request	~ 600 events drawn from reports from US and EU national regulators since 2006; safety lessons learned
LER database	US NRC	Public	Tens of thousands of reports since 1980, but unfortunately there is no searchable severity measure
Accident Sequence Precursor (ASP) Program reports	US NRC	Public	Quantifications of CCDP for hundreds of core damage accident precursors
OPIS Nuclear Event Evaluation Database	Korea KNIS	Public	Hundreds of events, mostly INES 0 / below scale; Easily searchable
Annual reports from national regulators	National regulators*	Usually available online, with a limited history	Typically contains INES scores for events above some threshold in that year

In contrast to technical information, cost-related information is scarce. Early efforts by *Sovacool* in constructing a cost-focused database are noted [13]. Our work made substantial improvements on both quantity of events and quality of information, through rigorous and systematic assessment, as well as expert reviews.

Concerning estimation of accident costs, there is no consensus on what cost categories to include, and how to quantify them. Nevertheless, the NRC regulatory analysis guidelines [14], and the 2013 OECD/NEA workshop [15], provide useful guidelines. The methodology employed in this thesis was largely based on these guidelines.

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[1] INES is the official scale for event severity [16], 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.

1.3. Description of our database

This open database on events in nuclear power has been built with the intention to serve both the scientific community and the general public. We have strived to make the database comprehensive, in terms of information provided as well as events covered.

The following information can be found in the database:

- Basic event information: event date, site location, source of information, references
- Site & reactor metadata: site location, industry, facility type, reactor power, reactor type, reactor capacity, current operational status
- Event description: a sound yet brief description covering the trigger, chain and consequences of the event.
- Event annotation (ongoing work): more in-depth characterization of events by
    - Operating mode: full power, transitory, shut down
    - Activity: Fuel loading, testing, maintenance, etc.
    - Trigger origin: “nuclear island”, “secondary” part (generator, turbine hall, power supply and substation, auxiliary cooling), and “external” (incl. natural hazards, LOOP, and events (fires, explosions, etc.) at auxiliary buildings)
    - Failure mode: human and/or mechanical
    - Event occurrence: actual and/or potential
    - Significance: fore-runners, common-cause failures / generic issues, and precursors.
- Safety-related information: INES rating (from the IAEA when available, otherwise specified according to the INES user manual [16]), number of fatalities, conditional core damage probability (CCDP) and condition duration for events covered by the US NRC Accident Sequence Precursor (ASP) Program [17]
- Cost-related information: costs estimated using methods outlined in chapter 2.

The database has thus far included more than 900 events (anomalies, incidents, accidents), covering all types of facilities in the life-cycle of commercial nuclear power. Event date goes back to as far as the 1950s. With regard to geographic coverage, the database will be more complete for some countries than others. This disparity is more pronounced for less significant events, that is, those with INES scores less than 2. Countries that instituted open and comprehensive event reporting include, to name a few, United States, Germany, Switzerland, South Korea, Sweden, and Finland. In comparison, nuclear regulatory systems in Russia, China, Japan and India are relatively less transparent.

While populating the database, priorities were given to events with safety significance above a certain threshold (we aimed for completeness/representativeness over events with INES score 2 and above), and costly events with at least some safety relevance.

To facilitate easy access of source information, more than 1500 reference files have been related to the database, including annual reports from national regulators, INES event notifications, other official documents, academic publications, and news articles found through internet search. Where applicable, we consulted open-access databases, such as the Licensee Event Report (LER) search tool for US events [18], the Operational Performance Information System (OPIS) for Korean NPPs [19], and the INES directory [20]. For more than 90% of the events, official sources have been identified. If the available information was not sufficient to allow a reasonable high-level understanding of an event – as assessed by an expert on nuclear technology – the event would be excluded.

2. Methodology of rough full cost estimation

Regarding estimation of costs of incidents/accidents at nuclear facilities, there is still disagreement over methodological issues. Adding further to the challenge, the availability of information also varies considerably from one country to another, and from one period to the next. For example, the transparency/openness of nuclear industries in the Soviet Union has been historically poor. And as to be expected, less information is available on events which took place before the Internet era.

In this work, emphasis has been placed on defining and implementing a methodology that is: (a) comprehensive enough to capture all relevant costs, so as to not underestimate the cost of incidents/accidents and correspondingly the value of prevention [6]; (b) flexible enough to allow consistent application in a wide range of events of varying natures.

Moreover, it must be stressed that we do not aim for precise cost figures for individual events, but rather order-of-magnitude estimates that allow for aggregate statistics. This is supported by the extreme nature of risks in nuclear power, whereby a selected few major events overshadow the rest in economic consequences.

With the above objectives and limitations in mind, the following types of costs have been included in our estimates, largely following the cost categories and methods defined within the US NRC regulatory analysis handbook [14], and guidelines suggested in the OECD/NEA workshop [15].

2.1. Costs related to production interruption

Temporary shutdown

The losses due to interrupted production are approximated by the value of foregone electricity generation, in other words, the amount of electricity the plant could have supplied in the duration of the plant outage, under normal conditions. Unless data on lost electricity output is directly available, downtime cost is calculated as

$$Downtime\ cost\ (million\ \$) = Annual\ output\ (GWh/year) * Downtime\ (years) * \$0.08 - 0.1/kWh$$

The main advantage of this approach is that it can be conveniently and consistently applied in most events. We assume that the result is close to, at least in order-of-magnitude, the sum of cost of purchasing replacement power, capital depreciation, and Operation & Maintenance (O&M) cost during plant outage. Whenever available or can be estimated, these three aforementioned sub-types of downtime cost are also provided. The few events where this is the case (see *event #160, 380, 398, 476*) support this assumption, which however can only be considered as anecdotal evidence.

Annual output is taken as representative/typical amount of electricity supplied yearly in preceding years, judging from the plant's operating history (as found in PRIS database [21]). If a plant's output fluctuated significantly from year to year, the average of outputs in the previous five years is usually taken. When operating history is unavailable, output is estimated based on the electricity generating capacity of the reactor, and by further assuming a Load/Operation Factor of 75%.

For NPPs in certain countries, duration and nature of outages can be found in databases and reports provided by regulators:

- In the United States, NRC provides daily Power Reactor Status Reports for all operational reactors, dating back to 1999 [22]. Useful information includes operational status (in terms of power percentage), starting date of outage (if there is any), and reason for outage. Should there be any abnormal occurrence, the status report would additionally point to the corresponding event notification, which contains technical descriptions of the event [23]. For events after 1980, Licensee Event Report (LER) could provide detailed information on the event and subsequent restoration process. To check whether relevant LER exists, search by the 3-digit plant docket number and event year in the LER search portal [18].
- In South Korea, KNIS provides a Nuclear Event Evaluation Database, in which date of event and date of restart (where applicable) are specified [19].
- In Sweden, annual reports on Operating Experience from Swedish Nuclear Power Plants are available for some years [24]. Details of significant outages can often be found in these reports.
- In recent years, IAEA published reports on Operating Experience with Nuclear Power Stations in Member States, which contain summary statistics of length and cause of outages at individual reactors [25]. Although outages caused by specific events cannot be track down through these reports, upper limits can nevertheless be inferred.

As a less preferred source, media reports often contain information about outage duration, or equivalently, date of restart. An internet search for combination of site name and event year is usually a good way to start. This works particularly well for more recent events.

In absence of any concrete information on outage duration, the plant's operating history can help rule out extended outage. If the electricity supplied in the event year – sometimes the following year as well, if the event took place at year end – was above/similar to the average level in preceding years, it can be deduced that no extended outage resulted from said event. However, if there was a significant decrease in electricity supplied or Annual Time Online, the drop cannot be readily attributed to a single event, as there could be other contributing factors. In these cases, the decrease in output can only help gauge the upper bound of downtime impact.

It is worth noting that when facing a lengthy restoration process following an event, a plant may opt to enter refueling outage earlier than planned (see *event # 115* for an example) Under such circumstances, only the initial forced/maintenance outage is counted as downtime. When an event forced the reactor to run at reduced capacity for a long period of time, the equivalent outage duration is calculated on a pro rata basis.

In a few cases where there were widespread, extended outages among a company's NPP fleet, efforts would be made to check its annual reports, which may provide figures and explanations on decrease in nuclear generation (examples: *event # 160, 592*). If so, the downtime impact can be directly calculated, using the same electricity price as assumed above.

Early permanent shutdown

According to World Nuclear Association (WNA), the following three factors could lead to early permanent closure of a plant: extensive damages caused by an accident or serious incident, political decision/consideration, and economic reasons [26]. At times there could be a combination of factors leading to the shutdown decision. In our estimation, judgment is exercised to determine whether an event was the main contributing factor (rather than economic/political reasons), and accordingly how the costs should be attributed. The possible treatments are illustrated through the following two examples.

First example (event #559): Reactor unit 2 at Chernobyl NPP, which started commercial operation in 1979, suffered damage beyond repair during a turbine hall fire in 1991. Political environment also played a non-trivial role in its permanent shutdown, as the Ukrainian Parliament had already planned to halt operation of the remaining three Chernobyl reactors by 1995. Nonetheless, this incident is considered to be the main reason for premature closure.

To calculate the loss of initial capital investment (CAPEX loss), the estimated plant construction cost[2] is converted to 2016 USD first, and then straight-line depreciated over its licensed/intended lifespan. Specifically, CAPEX loss = 4 years (remaining life) / 16 years (intended life span) * $1.2 billion (estimated construction cost) = $300 million

Alternatively, the plant loss can be evaluated the way as in the case of temporary shutdown. That is, plant loss = 4 years (remaining life) *6000 GWh/year* $0.08/kWh=$1920 million. Results from the two methods are combined to form the range estimate of plant loss.

More on CAPEX loss:

- Depreciation in this context does not attempt to emulate the accounting practice adopted by the plant owner.
- When the remaining life of a plant is unknown, a nominal lifespan of 40 years is assumed.
- If the construction cost of a specific plant is unknown, general cost experience from the same country/region and preferably similar historical period is consulted.

Second example (event #586): In July 2009, the Krümmel NPP in Germany experienced an electrical transformer fire, which led to prolonged shutdown. A plan was made to replace

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[2] Directly relevant data on construction cost has not been found, cost experience from modern era Russia was consulted.

the transformers in 2010. However, the political environment changed after the Fukushima nuclear accident in 2011. In August 2011, the 13th amendment of the Atomic Energy Act came into force and resulted in the immediate/gradual closure of 17 NPPs. Given the circumstances, plant loss was not accounted for when estimating costs of the 2009 fire incident. Instead, only downtime cost associated with the 25-month outage (Jul 2009 – Aug 2011) was considered.

2.2. Costs of onsite restoration

This category is meant to capture the damages to the facility or repair costs, and costs necessary to bring the plant to a satisfactory state (e.g. back-fit/upgrade, cleanup). In contrast to downtime impact, information related to restoration costs is much scarcer. Besides relevant figures (on repair cost, capital investment/addition, increase in O&M expenses, etc.) reported by the plant, experiences of other plants which faced similar situation can give a good idea about the order of magnitude of likely costs. This is particularly applicable to generic issues such as replacement of transformer, steam generator, or reactor pressure vessel head.

In other cases, it is necessary to settle for a best-effort guess based on available information. Firstly, the scope of corrective actions should matter. Secondly, the time lapsed before the plant went back online should give some indication on the extent of corrective actions involved. Extended outage often signals major repairs/overhauls, with the exception of those caused by issues related mostly to poor management or safety culture.

When an event led to permanent shutdown, decommissioning cost is considered only if the event significantly increased the cost of decommissioning. In those cases, only the portion exceeding the budgeted amount is included in the costs of the event.

2.3. Industry impact

If an event had widespread industry impact, the costs to a single reactor in terms of downtime cost and costs of back fits/upgrades are estimated as if it were an isolated incident. The estimated range is then multiplied by the number of reactors affected nationally or globally. The industry impact of the Barsebäck Strainer clogging event (see section 3.2.3) was estimated in this manner.

Official reports produced by regulatory bodies can be a valuable source of information on industry impact of well-known issues. For instance, US NRC calculated the impact of the ATWS rule to the American nuclear industry in its value-impact analysis (see section 3.2.3). Other unofficial studies may also provide rough estimates of industry impact, the Browns Ferry cable fire event being one such example (see section 3.2.3).

When multiple related events exist in the database, industry impact is not attributed to any individual event but considered globally, in order to avoid double counting. The generic defects discussed in section 3.2.2 belong to this category.

2.4. Impact on employee health

Fatality: If an event conclusively resulted in deaths, a conventional value of a full human life of $6 million is assigned [27].

Radiation exposure: For the sake of simplicity, a range estimate of 0 to $1 million is used for any exposure level below 1000 mSv (or 100 rem). Since the magnitude of downtime and restoration costs at commercial NPPs can easily reach millions, this simplification is expected to have inconsequential impact on the total cost.

Other types of injuries (burn, trauma, etc.): In many instances, the injured person was able to return to work after recovery, in which case a range estimate of $0-1 million per injury is used. If the injury resulted in permanent disability / physical impairment, long period of hospitalization, or long-term health complications, the range is widened to $0-2 million.

2.5. Miscellaneous issues

Regulatory fines are included only when there is concrete evidence. Judging from events in the database, regulatory fines are miniscule when compared with other costs.

Currency conversion and inflation adjustments: Cost figures in foreign currencies are first converted to US dollars in the same year, then inflation-adjusted to equivalent dollar amounts in 2016. Historical exchange rates from 1953 onwards are provided by an independent data provider [28]. Inflation adjustments are done with the aid of an online inflation calculator [29], which is based on official Consumer Price Index (CPI) data.

The most theoretically sound way to convert an historical amount in currencies other than USD to 2016 USD is subject to discussion but should not be a focus of this project. The above approach was adopted mostly for pragmatic reason. Equivalent dollar amounts are often quoted in news articles. Then the straightforward thing to do would be simply adjusting for inflation in US dollars.

Highly uncertain cases: In cases where the available information is not good enough for estimation of concrete types of costs (e.g. downtime cost, repair), a rough range estimate of total cost is provided, without breaking down into individual types of costs. The estimates in these cases are more conservative, usually in the range of $0-1 million or $1-10 million, depending on specific circumstances.

Offsite impact: Only relevant for the few accidents that resulted in releases to offsite; cost estimates are taken from official reports and scientific studies.

3. Results and discussion

3.1. Data summary

After exclusion of events with insufficient information, there are 887 events left in the database. 17 of these events were at military/weapon related facilities (all but 3 took place before 1970). They have been temporarily excluded from consideration, as these facilities were designed and operated under radically different conditions and oversight, and with a different purpose. The breakdown of the remaining 870 events at civilian-use facilities by site type, and further by reactor type, is shown below.

Civilian-use facilities: 870 events

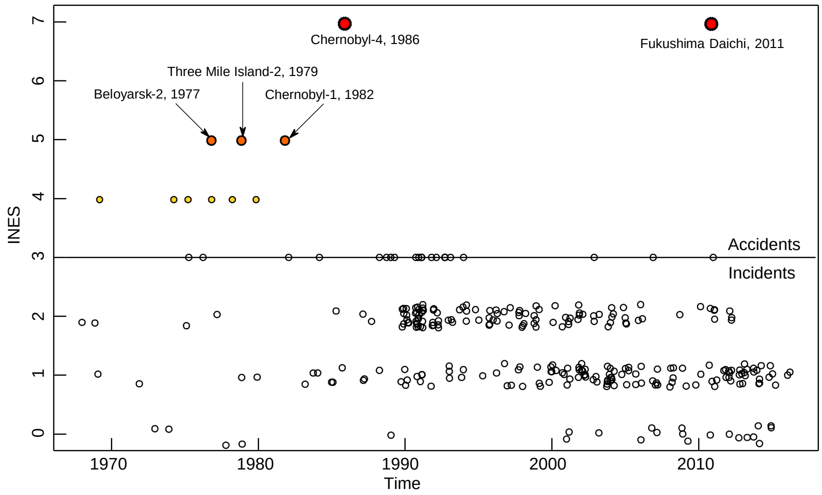
- Power plants: 787
- Reprocessing: 43
- Demo/Experimental/Research: 24
- Fuel Fabrication/Preparation/Recovery: 10
- Uranium Mine/Processing: 5
- Waste Disposal: 1

Power plants: 787 events

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

Further assessment of the 787 events at commercial NPPs identified 571 events with core safety relevance (i.e. can potentially lead to core damage), distributed over the following regions: North America (55%), Northern and Western Europe (23%), Asia (13%), and Eastern Europe (9%). The INES scores of these core safety relevant events are plotted in *Figure 1*. Two interesting trends can be observed at a glance: firstly, the number of accidents (INES score > 3) has decreased over time. Secondly, there are significantly more events with INES score after 1990, the year when INES was introduced.

Figure 1. INES scores for events at commercial NPPs[3], and deemed to have core-safety relevance. The data points are spread around their INES values for visibility. The INES 4 events include: St Laurent-1 (1969), Leningrad-1 (1974 & 1975), Bohnice-1 (1977), Beloyarsk (1978, INES = 3-4), and St Laurent-2 (1980). *[Credit: S. Wheatley]*



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[3] Excluding events at facilities other than commercial power plants, such as: fuel preparation site (e.g. Tokai-mura, 1999), experimental reactors (e.g. Luzern, 1969).

3.2. Thematic overview of costly events

Disclaimer: *In the following discussions involving specific events, references have been included as part of the database and cited in corresponding cost estimation notes (see Appendix). To avoid an excessively long bibliography list, only the few most important sources are cited in this report.*

Deep-diving into costly events in the database, at least four common themes can be identified:

1) The three major accidents, namely TMI (1979), Chernobyl (1986), and Fukushima Dai-ichi (2011), are most costly by far, due to significant offsite and industry impact.

2) Then there were generic defects found in certain types of reactors, which led to wide-scale replacement/repair actions. The following three issues have been investigated:
    - (PWR) RPV head leakage due to PWSCC of CRDM nozzles
    - (PWR) SG tube degradation due to PWSCC
    - (BWR) recirculation piping cracking due to IGSCC

    Note: due to the widespread nature of these defects, and the minor safety significance of many of the related events, only some of the major events have been included in the database.

3) Some precursor events can also result in expensive back-fits across the industry. Well-known incidents include:
    - Cable fire at Browns Ferry (US, 1975)
    - ATWS events at Salem & Browns Ferry (US, 1980 & 1983)
    - Strainer clogging incident at Barsebäck (Sweden, 1992)

4) Another distinct type of costly events rooted from unsatisfactory human (as opposed to technical) performance, such as imprudent management, weak safety culture, information concealment[4], etc. Although often (but not always) minor from a safety perspective, these events are usually reasons for increasing scrutiny/pressure from the regulators. The plants may be shut down for a long period of time to address deficiencies. There are many such events in the database. A few examples are discussed here:
    - Pickering A – Bruce A saga (Canada, 1997)
    - Falsification of safety inspection records at TEPCO (Japan, 2002)
    - Mismanagement of SG replacement at Crystal River (USA, 2009)
    - Programmatic weaknesses at Browns Ferry & Sequoyah (USA, 1984)

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[4] What's particularly alarming about information concealment is that it has contributed to many major industrial/natural disasters [50], including but not limited to those in the nuclear sector.

3.2.1. Major accidents

Given the well-publicized nature of the three major incidents, they are not described here. Their consequences and costs, which were compiled from official and scientific reports [30], are presented in *Table 2.*

A few comments on significant cost categories:

- **TMI**: led to increased safety requirements worldwide. It can be argued that the costs of retrofits may have been offset by the benefits they brought.
- **Chernobyl**: significant offsite release, largely due to a design flaw that is absent from modern reactors.
- **Fukushima Dai-ichi**: disruption of nuclear generation in Japan until the present day.

Table 2. Estimated rough full cost of experienced major nuclear accidents. The interval in the approximate total is the sum of the upper and lower bounds of the individual costs. Comparatively large costs are highlighted in bold. Life and health impacts include deterministic and projected radiological fatalities, and evacuation/displacement 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, for instance, costs and potential benefits relating to impacts on energy policy, which are too uncertain to quantify. *[Credit: S. Wheatley]*

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

3.2.2. Generic defects

(PWR) RPV head leakage due to PWSCC of CRDM nozzles

Event # 243, 358, 596, 651, 656, 734, 742, 755, 763, 771, 827, 830, 837

Stress corrosion of components (in the primary system) that are made of Alloy 600 material, known as primary water stress corrosion cracking (PWSCC), was the cause of many well-known issues affecting PWRs, including steam generator (SG) tube degradation and reactor pressure vessel (RPV) head leakage [31]. Leakage caused by PWSCC was first observed in 1991, when a leakage in one control rod drive mechanism (CRDM) head penetration was discovered at the Bugey-3 reactor in France. Repair solutions and non-destructive examination techniques were developed accordingly. Then a decision was made in 1994 to replace the RPV heads at all 900 MW(e) and 1300 MW(e) reactor in France. A total of 54 vessel heads were to be replaced with new ones made of materials insensitive to stress corrosion in the primary circuit.

In 2002, significant RPV head degradation was found at the Davis-Besse plant in the US. Cracks in the welds of five CRDM nozzles penetrating the RPV head were identified during an inspection [32]. Further examinations discovered a football-sized cavity next to one of the nozzles, caused by accumulation of reactor coolant leaked through the cracks. Only a thin layer of stainless steel remained between the reactor coolant and the containment atmosphere. The damaged RPV head was replaced with an unused, similar one from an aborted plant, and the Davis-Besse plant restarted after a 2-year outage. The replacement was intended as a temporary measure until a new head with improved design (consist of Alloy 690 material) can be manufactured. However, similar cracks were again found during a refueling outage in 2010. The second RPV head replacement was carried out several years ahead of schedule.

The 2002 discovery at Davis-Besse intensified the NRC's focus on the stress corrosion issue, leading to industry-wide actions. As of 2011, new RPV heads had been installed at 37 out of 69 PWRs (incl. Davis-Besse) in the United States. Internationally, RPV head replacement took place at 23 plants in 5 countries (excl. US & France) between 1993 and 2005, according to a list compiled by the IAEA [31]. The countries (with the number of plants in parenthesis) are: Japan (12), Spain (5), Sweden (3), China (2), and Belgium (1).

Across the nuclear industry, different replacement costs have been reported: \$60 million estimated average cost for each replaced head in the US, \$20 million at Oconee (2001), \$55-75 million at Davis-Besse (2002), \$22 million at Cook (2006), \$115 million at Davis-Besse (2010), \$150 million at Callaway (2014), \$18 million at Beznau in Switzerland (2014).

Cost of RPV head replacement (per head): \$18 million – \$150 million

Number of RPV heads replaced: >115

Industry impact (only considering capital and labor costs for RPV head replacement): \$2 – 17 billion

Note: This is an extremely conservative estimate, as cost of downtime/replacement power has not been considered. Furthermore, the above list of replacements carried out is neither exhaustive nor up-to-date. Replacements in more recent times, and/or in countries other than those mentioned, can be considered.

(PWR) SG tube degradation due to PWSCC

Event #: Too many to enumerate (more than 20 events)

Another widespread issue caused by stress corrosion of Alloy 600 was degradation of SG tubes, which could potentially lead to primary system to secondary system leakage.

Plugging or sleeving of the degraded SG tubes was commonly employed as the first remedy. However, this is usually a temporary fix. Performance of the SG deteriorates after several operation cycles using this strategy, and outage duration and maintenance costs often increase. Under such circumstances, it is often more economical to replace the SGs. At Rancho Seco (1989), San Onofre (1992), and Trojan (1992), SG tube degradation even contributed to early permanent shutdown.

The PWR SG replacement history (1979-2005) provided by the IAEA [31] shows that SG replacement had been carried out at 83 plants in the following countries (with the number of plants in parenthesis) during this period: USA (41), France (14), Japan (11), Belgium (6), Spain (4), Switzerland (2), Sweden (2), Germany (1), Korea (1), and Slovenia (1). Other sources reported that SG replacement had taken place at around 50 American plants.

SG replacement cost per plant (excl. cost of replacement power): $55-230 million

Number of plants that replaced SGs: around 90 (of which ~50 in the US)

Industry impact (only considering capital and labor costs for SG replacement): <u>$5 – 21 billion</u>

Note: estimation was done at plant level, as opposed to number of SGs replaced; downtime costs have not been considered; SG tube plugging/sleeving costs have not been considered.

(BWR) recirculation piping cracking due to IGSCC

Event # 414, 416, 421, 430

In 1982, cracks were found at nozzle-to-safe end welds of two 711 mm reactor recirculation outlet nozzles of Nine Mile Point-1 [31]. The plant was shut down for 15 months to conduct recirculation piping replacement, at a reported cost of $65 million ($170 million in 2016 USD). Lessons learned from this incident also prompted improvement of the examination technique and development of corrective measures. According to an IAEA report [31], piping of reactor recirculation and residual heat removal systems were replaced with high IGSCC resistant materials at 12 BWR plants in the US through 1999. In lieu of piping replacement, weld overlay was applied in over 20 BWR plants in the same period.

Four cases of recirculation piping replacement have been included in the database: Nine Mile Point (1982), Browns Ferry (1983), Pilgrim (1983), and Peach Bottom (1985). They all took roughly one year. Assuming a load factor of 75%, the 600-1400 MW(e) capacity of BWRs in the US would translate into an annual output of $4000-9000 GWh. Then downtime cost associated with an one-year outage would be $400-900 million.

Estimated cost per plant (downtime + piping replacement): $500 million – $1 billion

Number of plants that carried out piping replacement: no less than 12 plants in the US

Industry impact (only considering the US): $6 – 12 billion

Note: International experience (e.g. Germany, Japan) not considered; In the US, the costs to over 20 BWR plants which chose weld overlay over piping replacement not included.

3.2.3. Precursor-driven

Cable fire at Browns Ferry (USA, 1975)

Event # 476

In March 1975, A fire was started when a worker, 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 systems related to the control of unit 1 and 2; meltdown was averted. This incident led to an 18-month outage of both reactors and widespread industry impact. All commercial NPPs in the US were required to enhance fire protection through extensive plant modifications. The cost of retrofitting US plants was estimated in 1976 by one observer to be $7-12 billion in 1976 dollars [33]. Given there were around a hundred nuclear reactors in the US, this would translate into a cost of roughly $100 million (approximately $400 million in 2016 USD) per unit.

Total cost of this incident is estimated to be $32-54 billion, including $1.4-1.8 billion downtime cost, $0.9-2.1 billion repair cost, $30-50 billion industry impact (in 2016 USD).

ATWS events at Salem & Browns Ferry (USA, 1980 & 1983)

Event # 552, 576, 577

Anticipated transient without scram (ATWS) is a type of reactor event whereby the reactor trip portion of the protection system (the scram system) fails to properly shut down the reactor during an anticipated transient. An ATWS event is one of the “worst case” accidents with significant impact on reactor core safety. Therefore, ATWS has been the subject of a considerable amount of regulatory scrutiny.

In 1973, an ATWS event took place at the KAHL experimental reactor in Germany [34]. Due to a change in manufacturing process, the protective coating on the trip relays became sticky during operation and caused the relays to remain closed when they were required to open. There was little actual safety- or cost- related consequence, as the anomalies were fortunately discovered during testing.

On 28 June 1980, another precursor ATWS event happened at Browns Ferry Unit 3, a PWR plant. While preparing for a scheduled shutdown for feedwater system maintenance, 76 of the 185 control rods failed to fully insert. After three manual scrams and an automatic scram over a span of 15 minutes, all remaining control rods were finally in place. There was no damage to the plant or equipment. The scram failure was attributed to a reduction in scram discharge volume due to retention of water in the east side header.

In late February 1983, two ATWS events occurred at Salem unit 1, this time a PWR plant. In both instances, the reactor was manually scrammed within thirty seconds. Subsequent analysis identified failure of circuit breakers in the automatic shutdown system, which was caused by inadequate maintenance and supervisory practices. A 3-month outage ensued. The plant paid a then-record $850,000 fine and carried out significant and costly corrective actions. According to our cost estimation methodology, the total costs were between $400 million and $600 million.

Following the precursor ATWS events at Browns Ferry and Salem, the NRC conducted a regulatory analysis of ATWS [35], and subsequently issued a rule mandating hardware modification to improve NPP's capability to prevent an ATWS and mitigate its consequences. PWR plants were asked to implement diverse means to trip the turbine and initiate auxiliary feedwater. At BWR plants, diverse recirculation pump trip, alternate rod insertion circuitry, and upgraded emergency operating procedures were required. Alternatively, high capacity standby liquid control systems must be installed.

In NRC's original ATWS regulatory analysis, the total impact of the ATWS rule on the nuclear industry (131 operating plants) was expected to be approximately $1.3 billion (in 2016 USD). In a report on Regulatory Effectiveness of the ATWS Rule published by NRC in 2003 [7], the value-impact of this rule was updated based on actual outcome. The costs of implementing the ATWS rule were determined to around $400 million for 102 plants.

Total costs (including industry impact): $800 million - $1.9 billion

Strainer clogging incident at Barsebäck (Sweden, 1992)

Event # 349

On 28 July 1992, Barsebäck unit 2 experienced clogging of the intake strainers for containment spray water and failure of related systems during restart after revision. Owing to very low reactor power at the time of the incident, core damage was avoided. The clogging was caused by mineral wools carried by water leaked from the primary cooling circuit. In early August, the reactor restarted and operated for 6 weeks. Then the Swedish Nuclear Power Inspectorate (SKI) halted operations at the five oldest BWR units in Sweden (Barsebäck 1 & 2, Ringhals, Oskarshamn 1 & 2), as the Barsebäck strainer incident revealed serious deficiencies in the emergency cooling systems at these plants. The affected utilities were required to adequately address these deficiencies before taking their reactors into operation. The two reactors at Barsebäck were allowed to restart in January 1993, while the other three reactors remained offline. The downtime impact on Barsebäck is estimated to be approximately $200 million. For the other two plants, total downtime costs could easily reach $300 million.

Prior to the Barsebäck event, safety issues related to strainer clogging had been considered as resolved. The Barsebäck strainer incident reignited the interests of regulators worldwide.

After a period of active development and testing, new strainer designs were implemented. The NEA reviewed modifications of the Emergency Core Cooling System (ECCS) and/or Containment Spray System (CSS) suction strainers carried out in 15 countries [36]. As of 2001, strainer modifications had been performed / were to be performed at 38 PWR units and 53 BWR units in these countries. None of the 58 PWR units in France were modified at that time. However, Electricité de France (EdF) announced in 2004 its plan to replace existing sump screens at all 58 of its PWR units, at a cost of about \$2.2 million per unit [37]. Cost studies performed by the US nuclear industry put the cost of plant modifications at \$3 million to \$5 million per unit. To account for possible cost disparities in different countries, we assume the strainer modification would cost \$1 million to \$ 10 million. Thus, the industry impact is likely in the range of \$150 million to \$1.5 billion.

Total costs (including industry impact): <u>\$650 million - \$2 billion</u>

3.2.4. Management/culture issues

Pickering A – Bruce A saga (Canada, 1997)

Not included in the database

At the end of 1997 and the beginning of 1998, Ontario Hydro (now Ontario Power Generation – OPG) shut down seven of its oldest reactors, namely unit 1, 2, 3, 4 at Pickering A and unit 1, 3, 4 at Bruce A (unit 2 had been shut down in October 1995 due to a maintenance accident). The shutdown was necessary to reverse the downward trend in performance and safety. After very expensive upgrades/refurbishments, 5 of the 7 reactors returned to service several years later. Unit 2 and 3 at Pickering A were eventually retired, as refurbishment was not economically justifiable.

From early 1980s until the mid 1990s, the Pickering generating station experienced several significant events (see *event # 422, 384, 371, 348, 318, 305*), including the most serious one at a Canadian commercial nuclear station – a major loss of coolant accident (LOCA) on December 10, 1994 [38]. Furthermore, the station was unable to meet the deadline for a key safety improvement. Unlike later CANDU reactors, which all have a second fast shutdown system, the four reactors at Pickering A were originally equipped with a fast-acting shutdown system and a slow-acting system. In 1993, the Canadian federal regulatory body ordered that a redundant fast shutdown system be added by the end of 1997, as a license condition. By 1997, the regulator grew increasingly concerned about Pickering's deteriorating performance and shortened the term of its operating license.

In 1997, a team of experts were brought in from the US to review Ontario Hydro's nuclear operations and recommend improvement plans. The review findings were highly critical of nearly all aspects of its management and operational performance. The company was found to had developed a "production-dominated" culture and deviated from a strong safety culture. In fact, many of the deficiencies discovered amounted to departures from the "defense-in-depth" concept, a cornerstone of the nuclear industry [38]. The Pickering station received a minimally acceptable rating, which was substantially below industry standards and suggested that drastic measures must be taken immediately. The safety and management problems unveiled by the review prompted Ontario Hydro's then-president to resign, as well as the launch of its phased improvement plan. Operations at the aforementioned 7 reactors were suspended to free up resources for improvements at the other 12 then-operating reactors at Bruce B, Pickering B and Darlington.

After a refurbishment project that went both over time and over budget (which led to the firing of senior executives at OPG), Pickering A unit 4 was brought back to service in 2003. Unit 1 followed in 2005. Unit 2 and 3 were given up, as the estimated repair bill (more than $2 billion) was deemed too high. At Bruce A, Unit 3 and 4 restarted in January 2004 and October 2003, respectively. Subsequently, refurbishments of unit 1 and 2 were carried out and completed in 2012.

The Pickering A – Bruce A saga is estimated to have costed between $18 billion and $24 billion (in 2016 USD), roughly equally distributed between the two generating stations. This figure does not include the around $7 billion (in 2016 USD) cost for refurbishing the other 12 reactors that were kept in service [39]. Hence, the all-inclusive cost could reach as high as $30 billion.

Falsification of safety inspection records at TEPCO (Japan, 2002)

Event # 580

In August 2002 TEPCO, Japan's largest power company, admitted that it had concealed several minor safety findings from the regulator. Instead of reporting and properly documenting minor cracking found at several of its plants from the late 80s until the early 90s, the company falsified data on safety inspections. Although plant safety was never comprised, this blunder resulted in damage to TEPCO's reputation and credibility, resignation of its senior executives, and shutdown of all 17 of its reactors for full safety checks. According to the utility's estimation [40], the shutdown of its NPPs costed around $3.5 billion (in 2016 USD).

The scandal at TEPCO reflected weak safety culture in the Japanese nuclear power industry at the time, as well as flaws in the system of NPP safety regulation and reporting in Japan [41]. As a result, both the regulator and the industry took this wake-up call and began to actively look into measures to address these issues.

Mismanagement of SG replacement at Crystal River (USA, 2009)

Event # 568

In 2009, the Crystal River NPP was taken offline to conduct replacement of its steam generators. Its then-owner, Process Energy, made the unprecedented choice of managing the replacement project itself, in an attempt to save $15 million [42]. In contrast, 34 other US plants had successfully replaced their steam generators with the help of experienced contractors. Crystal River's self-managed SG replacement project caused the plant's containment dome to crack. After two failed attempts at repairs, the new owner, Duke Energy, decided in 2013 to permanently shut down the plant. Before the failure of the project, the plant was expected to obtain regulatory approval to extend its operating life by another 20 years. Thus, the botched SG replacement project shortened the plant's operating life by as much as 27 years.

The utility's ill-advised "Do-It-Yourself" approach to steam generator replacement is estimated to cost between $3.7 billion and $5.5 billion (in 2016 USD), including downtime cost, site repairs and plant loss. With the benefit of hindsight, the risk undertook clearly far exceeded the intended benefit, diagnosing unsound decision-making.

Programmatic weaknesses at Browns Ferry & Sequoyah (USA, 1984)

Event # 410

Due to deficiencies caused by programmatic weaknesses, unqualified personnel, non-compliance with fire protection regulations, operation of the three units at Browns Ferry NPP were suspended for 20, 5, and 10 years, respectively. Both units at Sequoyah generating station were also shut down. Sequoyah-2 restarted in early 1988 after independent evaluations and repairs. Sequoyah-1 followed in late 1988.

Estimated total cost: $8.8 - 10.2 billion (conservative estimate, as cost of replacement power were heavily discounted after the first three years of outage).

3.3. Summary of event costs

The rough full cost of events in the database, excluding those that took place at military facilities, are tabulated in *Table 3*. The "big 3" account for nearly 80% of the total historical costs of incidents and accidents at civilian use facilities, signaling a heavy-tailed distribution. However, it must be emphasized that *Table 3* does not fully capture the unexpected costs of civil nuclear power to society. The industry impacts of generic defects discussed in section 3.2.2 (estimated to cost $13-50 billion) are not attributable to any single event, and thus not reflected in the total. The cost of environmental restoration at Sellafield[5] was also excluded. The UK Nuclear Decommissioning Authority (NDA) estimated that at least one third of the 120 billion GBP (around 160 billion in 2016 USD) decommissioning & cleanup cost at Sellafield could be attributed to the site's military objectives, with the remaining proportion associated with the civil energy program [43]. Lastly, costs of political events, for instance, phasing out of nuclear power, have not been taken into account.

Table 3: Estimated costs of events at civilian-use nuclear facilities, in USD billions, excluding Sellafield, industry impact of generic defects, political events etc.

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

To put things into perspective, the estimated cost of historical events in civilian nuclear power can be converted to a per unit electricity produced basis. According to the BP Statistical Review of World Energy 2017 [44], total nuclear generation worldwide from 1965 to 2016 amounted to approximately 85,000 TWh. Our rough estimate of total cost of experienced events (highlighted in bold in *Table 3*) can then be normalized to 0.9-1.5 USD cents per kWh of historical nuclear electricity production. For a point of reference, the NEA puts the levelized cost of electricity (LCOE[6]) of nuclear generation at 6-9 USD cents/kWh, comprising 4-6 USD cents/kWh capital cost, about 1 USD cent/kWh O&M cost, less than 1 USD cents/kWh fuel cost, and around 1 USD cents/kWh variation resulted from different choices of discount rate for the longer-term back end of the fuel cycle [45].

Perhaps due to the extreme nature of nuclear accidents, it is widely assumed that including the external cost of nuclear accidents in the price of electricity would make nuclear energy economically unfeasible. However, the above calculation of historical externality suggests that it should not materially alter the cost-competitiveness of nuclear energy. Furthermore, it is several times smaller than the externality of fossil fuels (coal, oil, gas), which the Paul

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[5] A densely packed site where highly hazardous materials are stored. On this 6 km^2 site, several facilities were built in the 1940s for weapon-related purposes. Other facilities, such as nuclear fuel fabrication plants, nuclear fuel reprocessing plants, and nuclear waste storage facilities, were used for both military and civil purposes.

[6] The average cost over the full lifecycle of an energy source, per unit of energy produced. It is intended to capture the full cost of production, but in practice tends to omit external costs / externalities.

Scherrer Institute (PSI) and the ExternE-Pol project put at 2-9 USD cents/kWh (when converted to 2016 USD) [46]-- on the basis of health impacts from emissions alone, and more-so when the potential of anthropogenic climate change is considered.

Table 4 summarizes the costs of events at commercial nuclear power plants, other than the "big 3" (totaled in row 2 of *Table 3*). It becomes obvious that most events are relatively minor from the cost perspective.

Table 4: Cost of events at commercial NPPs, other than the "big 3", in USD Billions

Events at commercial NPPs (excl. big 3 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	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 for 784 events	**153 - 280**	

Table 5 breaks down the costs of all events at commercial nuclear power plants, i.e. row 1 and 2 of *table 3*, by cost type. Nearly all the off-site impacts were due to the "big 3", while other events can potentially cause significant on-site costs (incl. retrofits and downtime).

Table 5: Breakdown of cost of events at commercial NPPs by cost type, in USD Billions. * of which $30-50 billion is from the Browns Ferry fire (1975). The $13-50 billion costs of generic defects discussed in section 3.2.2, which are not attributable to any single event, have not been included. ** Mostly impact on health of employees/contractors.

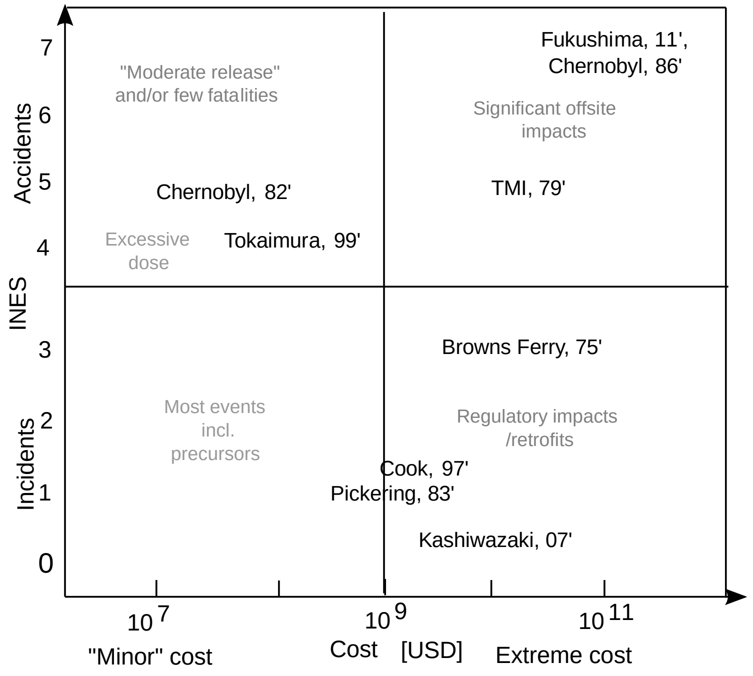
Cost Types	**Chernobyl, Fukushima, TMI**	**Other 784 events**	*Row total*
Downtime / Replacement	115 – 195	94 – 156	*209 – 351*
Industry impact / retrofits	162 – 328	39 – 70*	*201 – 398*
Public Economic	200 – 350	~ 0	*200 – 350*
Life & Health	40 – 48	< 1**	*40 – 49*
On-site	50 – 75	20 – 53	*70 – 128*
Column total	*567 – 996*	*153 – 280*	***720 – 1276***

3.4. Cost and safety

Since our database provides both safety and cost related information, the estimated full costs of events and their safety relevance can be compared. This is important to the discussion of risks in civil nuclear power, which can be viewed either from a safety perspective or from an economic perspective.

Using INES score as a measure of safety relevance, events can be placed in one of the four quadrants in *Figure 2*. Accidents with large offsite release are obviously severe in terms of both cost and safety. The three best-known events, namely TMI (1979), Chernobyl (1986), and Fukushima (2011), have been covered in section 3.2.1 and thus not further discussed here. Most events in the database are minor by either measure. Given the huge number of such events and their low significances, no specific examples are provided here.

Figure 2. Comparing cost and safety severity (as measured by INES score) of events experienced at nuclear facilities



What's particularly interesting are events for which cost and safety measure of significance conflict. They suggest that neither INES nor cost alone can fully capture risks in nuclear power. Some events are minor from a safety perspective but can be rather costly. Although they did not result in offsite radiological impact, the public can be indirectly affected, in that they often shoulder the cost burden through paying higher rate for electricity. Notable examples include:

- **Browns Ferry cable fires** (USA, 1975): see section 3.2.3
  Event # 476; INES = 3

- **Kashiwazaki Kariwa earthquake** (Japan, 2007)
  Event # 160; INES = 0
  A 6.6 offshore earthquake, with a shock beyond design basis, initiated a complete shutdown of the world's largest nuclear power plant. Largely thanks to a generous safety margin at the plant, disastrous outcomes were avoided. After repairs and seismic upgrades, reactors successively restarted in 2009 and 2010. Decrease in nuclear generation from FY2007 to FY2009 totaled 125 billion kWh. The official INES score for events that took place during the earth quake – including leaks of nuclear fuel rod cooling water, a burning transformer and other problems – has yet to rise above INES level 0.
  Estimated total cost: <u>$12.6-16.1 billion</u> (incl. $10-13.5 billion cost of replacement power, and $2.6 billion restoration expenses)

- **Pressure tube rupture at Pickering** (Canada, 1983)
  Event # 422; INES = 1
  A small LOCA, caused by a two-meter-long split of a pressure tube, led to extended outage for re-tubing (4 years at unit 1, 5 years at unit 2).
  Estimated total cost: $3.3-5 billion

- **Design-related concerns at Cook** (USA, 1997)
  Event # 289; INES = 1
  Both units were shut down for approximately three years to address design-related concerns about its ice condenser containment.
  Estimated total cost: $3.6-5 billion

Examples of high INES score but not so costly events include those that resulted in moderate release (to offsite), and/or a small number of fatalities, such as:

- **Criticality accident at Tokai-Mura** (Japan, 1999)
  Event # 274; INES = 4
  Human error and violation of safety principles led to a criticality accident at this small fuel preparation plant. The criticality exposed three operators to excessive doses (two proved fatal) and 116 others to doses below permissible limits. The amount of radioactive materials released was not significant. The plant operator was nevertheless required to pay 15.3 billion-yen compensation for direct damages inside Ibaraki Prefecture.
  Total cost of this accident is estimated to be between $200 million to $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.

- **Minor release from Chernobyl-1 (**USSR/Ukraine, 1982**)**
  Event # 426; INES = 5
  Rupture of pressure pipes led to contamination of the reactor building of Chernobyl-1 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.

4. Conclusions

With the goal of providing a comprehensive resource for scientific learning from the history of nuclear power, a database of events experienced in the civil nuclear sector has been constructed, capturing both the safety and cost aspects of nearly 900 events. This thesis contributed to the partial completion of this database, in particular to the estimation of rough full costs of events.

Bearing in mind that the cost of accidents translates into the value of safety investments, focus of this thesis has centered on cost. Important lessons learned include:

- The total cost of the three major accidents heavily dominate that of all other events at commercial NPPs.
- The historical accident externality of nuclear energy is estimated to be around one USD cent per kWh of electricity produced, the inclusion of which would not dramatically change the LCOE of nuclear power generation.
- Aside from technical deficiencies, unsatisfactory human performances – such as imprudent decision-making, poor management, not adhering to rules/regulations, etc. – often led to expensive outcomes. A strong safety culture should never be underappreciated.
- With regard to the significance of events, INES score alone may not tell the whole truth. Some events with low INES score, i.e. considered minor from the safety perspective, have costed dearly. Therefore, a combined view is recommended.

As a closing remark, I would like to emphasize that the analysis conducted within this thesis has only unlocked a fraction of the full potential of this database. It can also provide the basis for more sophisticated studies, for instance, the risk assessment done in [47]. Thus, continuous update/improvement of the database is definitely warranted. Some ideas are suggested in the next chapter.

5. Limitations & future research

As a living ongoing project, the usefulness of this database depends on continuous update. Improvements can be made on quantity of events, and on quality of information.

In constructing this database, we have strived for completeness/representativeness for events above a certain safety threshold, which we defined as an INES score of 2. It is expected that a huge number of lower level events (INES < 2) have been left out. For instance, the five INES 1 events at the Olkiluoto NPP (Finland) in 2008 have not been included [48]. Since the reporting requirement is much less stringent for low level events [49], aiming for full inclusion would be too ambitious. Nonetheless, addition of the more interesting ones (e.g. cost relevant, or core damage precursors) to the database would be meaningful in future research.

One of the main valuable contributions of our work is the in-depth characterization of both safety and cost aspects of events. The evaluation of cost has been completed within this thesis. As for annotation of events, some domain knowledge is required. However, relatively simple tasks such as identification of core safety relevance, failure mode and trigger origin (see section 1.3) can likely be attempted.

Concerning the generic defects described in section 3.2.2, only hardware replacements carried out in a selected few countries over certain time periods have been accounted for. The cost estimates can be improved through looking into more countries, longer time periods, or additionally considering repairs (e.g. SG tube plugging/sleeving) and downtime costs.

Analysis conducted in this thesis has mostly emphasized events at commercial nuclear power plants. Significant events in other stages of the nuclear fuel cycle, e.g. waste and spent fuel management (see Sellafield in section 3.3), could also be relevant to discussion of unexpected costs of nuclear power. However, they are expected to be minor relative to the accident externality. Additionally, costly political events may be explored. The phasing out of nuclear power in some European countries is one such example.

6. Appendix: key thesis deliverables

1) **Thesis report**

2) **Main dataset:** stored as one flat table in a XLSX file. Each row in the table contains all the information described in section 1.3 on a single event. Each event has been assigned with a unique event number. Events from the NRC ASP program are additionally identified by precursor IDs that start with the letter "P", followed by numeric digits.

3) **Reference files:** PDF files collected from:
    a. NRC website: almost 300 files[7], including:
        i. Licensee Event Reports: file name in the format of "LER xxx-xx-xxx", where x stands for numeric digit. The first three digits are plant docket numbers. The next two digits represent event year in short form. The last three digits are sequential numbers.
        ii. Inspection Reports: file name in the format of "IR xxx-xx-xxx". The numeric digits follow the same convention as those in the LERs.
        iii. Escalated Enforcement Action reports: file name in the format of "EA--xx-xxx", in which the first two digits designate the year when the report was issued.
    b. Other diverse sources: around 1200 files with file names beginning with "[xxxx]", which is the assigned reference number (length can vary from 1 to 4 digits). The URLs of sources, where applicable, are tabulated in a separate XLSX file.

4) **Cost estimation notes:** DOCX files that contain key information extracted from references, as well as descriptions of cost calculation (more succinct versions are also provided in the main dataset). These notes are organized as follows:
    a. For events with assigned event numbers: The combination of event number and site name has been formatted as header for quick navigation.
    b. For those without event numbers (generic issues, excluded events…): individual DOCX files were created and named in an easily identifiable way.

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[7] Currently this collection is not yet exhaustive. However, these files are freely accessible from NRC website.

7. References

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