Supplemental Material to: Reassessing the Safety of Nuclear Power

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The following supplemental material on methods is largely extracted from, and a summary of Ref. [7].

1 Methods 1: Defining and documenting nuclear energy accidents and incidents

We define an "event" as an incident or accident within the nuclear energy system that had material relevance to safety, caused property damage, or resulted in human harm. The nuclear energy system includes nuclear power plants, as well as the facilities used in its fuel cycle (uranium mines, transportation by truck or pipeline, enrichment facilities, manufacturing plants, disposal facilities, etc.). Events are defined to be independent in the sense that one event does not trigger another one. For instance, three reactors melted down at Fukushima in 2011, however we define this as a single accident due to the fact that the occurrences at the individual reactors were part of a dependent sequence, and linked to a common cause. Statistical changes due to industry responses to past accidents are controlled for in the modeling. With this definition, we compiled an original database of as many events as possible over the period 1950 to 2014. To be included in the database, an accident had to be verified by a published source, some of them reported in the peer-reviewed literature, but others coming from press releases, project documents, public utility commission filings, reports, and newspaper articles.

The dataset includes three different measures of accident severity: the industry standard measure, INES; a logarithmic measure of radiation release, NAMS (Nuclear Accident Magnitude Scale) [5]; and the consequences of accidents measured in 2013 US Dollars (USD). The industry standard measure is the discrete seven point INES, defined as [3]: level 0: events without safety significance, level 1: anomaly, level 2: incident, level 3: serious incident, level 4: accident with local consequences, level 5: accident with wider consequences, level 6: serious accident, and level 7: major accident. Levels 1-3 are considered to be "incidents", and levels 4-7 "accidents". The distinction between incidents and accidents is not clear and thus somewhat arbitrary (e.g., see page 152 of [3]). Incidents tend to concern degradation of safety systems, and may extend to include events where radiation was released and people were impacted. However, when the damage and impact to people and the environment becomes large enough, then the event is deemed an "accident". But, there are rules about how many fatalities, or how much radiation release, is necessary to qualify for a specific INES level.

The second measure, NAMS, was proposed as an objective and continuous alternative to INES [5]. The NAMS magnitude is $M = \log_{10}(20R)$ where R is the amount of radiation released in terabecquerels. The constant 20 makes NAMS approximately match INES in terms of its radiation level definitions.

Finally, the main measure used here is the USD consequences/costs due to an event. This cost measure is intended to encompass total economic losses, such as destruction of property, emergency response, environmental remediation, evacuation, lost product, fines, court and insurance claims, etc.

In the case where there was a loss of life, we added a lost "value of statistical life" of 6 MM USD per death. The 6 MM USD figure is chosen as a lower bound of the value of statistical life reported by various US agencies (e.g., the Environmental Protection Agency, Food and Drug Administration, Transportation Department, etc.) [1].

Table 1 presents the 15 costliest incidents since 1960, where the full dataset is available at `https://tasmania.ethz.ch/index.php/Nuclear_events_database`, where the public is encouraged to contribute to the continuous improvement of this open dataset.

Table 1: The 15 largest cost events since 1960 are provided with the date, location, cost in MM 2013USD, INES value, and NAMS value. Unknown values are indicated with a dash.

Date	Location	Cost (MM USD)	INES	NAMS
1986-04-26	Chernobyl, Ukraine	259'336	7	8.0
2011-03-11	Fukushima, Japan	166'089	7	7.5
1995-12-08	Tsuruga, Japan	15'500	-	-
1979-03-28	TMI, Pennsylvania, United States	10'910	5	7.9
1977-01-01	Beloyarsk, USSR	3'500	5	-
1969-10-12	Sellafield, UK	2'500	4	2.3
1985-03-09	Athens, Alabama, United States	2'114	-	-
1977-02-22	Jaslovske Bohunice, Czechoslovakia	1'965	4	-
1968-05-01	Sellafield, UK	1'900	4	4.0
1971-03-19	Sellafield, UK	1'330	3	3.2
1986-04-11	Plymouth, Massachusetts, United States	1'157	-	-
1967-05-01	Chapelcross, UK	1'100	4	-
1982-09-09	Chernobyl, Ukraine	1'100	5	-
1983-08-01	Pickering, Canada	1'000	-	-
1973-09-26	Sellafield, UK	990	4	2.0

2 Methods 2: Modelling the frequency of events

We observe $N_t = 0, 1, 2, \ldots, 102$ events, above the threshold of 20MM USD, each year for the v_t nuclear plants in operation for years $t = 1960, 1961, \ldots, 2014$, taken from [2]. The *annual observed frequencies* of events (incidents and accidents) per operating facility are $\widehat{\lambda}_t = \frac{N_t}{v_t}$. The annual count N_t is assumed to follow a Poisson process. Thus the standard error of the annual observed frequency is $(\lambda_t/v_t)^0.5$. The running rate estimate,

$$\widehat{\lambda}^{\text{RUN}}_{t_0,t_1} = \frac{\sum_{t=t_0}^{t_1} N_t}{\sum_{t=t_0}^{t_1} v_t} = \sum_{t=t_0}^{t_1} v_t \widehat{\lambda}^{\text{RUN}}_{t,t} \ , \tag{1}$$

can be used to estimate the rate on intervals. In Panel I of Fig. 1 it is calculated on 5 year windows. In Panel II it is taken running backwards ($t_1 < t_0 = 1986$) and forwards ($t_1 > t_0 = 1987$) from Chernobyl. The frequency fluctuates around 0.012 before Chernobyl and drops to around 0.004 after. The null hypothesis that these two rates are the same versus the one-sided alternative that the post-Chernobyl rate is lower is tested with the uniformly most powerful exact test (see R-programming:poisson.test): testing the observed frequency from the pre-Chernobyl interval from 1975 to 1986, and the post-Chernobyl inverval from 1987 to 2010 yields a p-value of 0.0008. Thus the drop in rate is highly significant.

3 Methods 3: Modelling the distribution of historical damage

Costs (measured in million (MM) 2013USD) are considered to be i.i.d random variables $X_i,\ i = 1, 2, \ldots, n$ with an unknown distribution function F. The independence of events is a reasonable assumption as the damage caused by one event should not influence the damage of another event. In a scatterplot of cost over time, there was an apparent change in regime centered around the Three Mile Island (TMI) event (1979). To study this the empirical Cumulative Distribution Function (CDF),

$$F_n(x) = \frac{1}{n}\sum_{1} 1\{x_i \leq x\} \ , \tag{2}$$

was plotted in Panel (III) of Fig. 1 for the pre and post TMI periods. The two distributions are clearly different. To confirm that the changepoint coincides with the TMI event, the data was partitioned for a range of points, and the two partitions are tested with the null hypothesis of having identical distributions using the well known Kolmogorov Smirnov (KS) test. The smallest p-value (≈ 0.01) occurs at 1979, identifying Chernobyl as a change-point in distribution. No other clear changepoints were detected. For instance, we considered that there could have been a change point after Chernobyl. However, the empirical CDFs for intervals 1980-1989 and 1990-2014 were qualitatively similar, and the KS test for equivalence of these two samples gave a p-value of 0.98. Thus, the damage size distribution has remained quite stable since 1980.

The pre-1979 data, having median damage size of 283 MM USD, has a higher central tendency than the post-1979 data, having a median damage size of 77 MM USD. However, the post-1979 distribution has a heavier tail, whereas the pre-1979 distribution decays exponentially. Focusing on the apparently stationary post-1979 period, we consider the Pareto df,

$$F_P(x; u_1) = 1 - (x/u_1)^{-\alpha},\ x > u_1 > 0\ ,\ \alpha > 0\ . \tag{3}$$

Further, a distribution may be restricted to a truncated support as,

$$F(x|u_1 \leq X \leq u_2) = \frac{F(x) - F(u_1)}{F(u_2) - F(u_1)},\ 0 < u_1 < u_2\ , \tag{4}$$

where u_1 and u_2 are lower and upper truncation points that define the smallest and largest observations allowed under the model. Extending further, truncated distributions may be joined together to model different layers of magnitude,

$$F_{2P}(x|u_1 \leq X) = F_P(x|u_1 \leq X \leq u_2)\Pr\{u_1 \leq X \leq u_2\} + F_P(x|u_2 \leq X)\Pr\{u_2 \leq X\}. \tag{5}$$

MLE of eq. 3, for damage values above 20MM USD, for a range of lower thresholds u_1, indicates that α is in the range of $0.5 - 0.6$.

4 Methods 4: Identifying dragon kings

Identifying dragon kings (DKs) is an exercise in statistical outlier detection. For NAMS, there is a cluster of four apparently outlying points, visible in Panel (III) of Fig. 1. Further, the top 15 or so points appear to follow an Exponential distribution (with the exception of the outliers). Thus, we assess the outliers by estimating a mixture of an Exponential and a Normal density,

$$f_{\text{NAMS}}(x|x > 3.5) = \pi\alpha\text{exp}\{-\alpha x\} + (1 - \pi)\phi(x; \mu, \sigma) \ , \ \ \alpha, \sigma > 0 \ , \tag{6}$$

to the top 15 points, where the Gaussian density $\phi(x; \mu, \sigma)$ provides the outlier regime, and $0 \leq \pi \leq 1$ is a weight. This model is estimated using an EM algorithm. The estimates of this (alternative) model are $(\widehat{\pi} = 0.8, \widehat{\alpha} = 0.78, \widehat{\mu} = 7.8, \widehat{\sigma} = 0.21)$. We also consider a null model with no DK regime ($\pi = 1$). For this the MLE is $\widehat{\alpha} = 0.66$. The alternative model has a significantly superior log-Likelihood (the p-value of the likelihood ratio test is 0.04). Thus there is a statistically significant DK regime relative to the Exponential, with $(1 - \hat{\pi}) \cdot 14 \approx 3$ outliers expected.

To assess outliers in cost, we consider the *sum-robust-sum* (SRS) test statistic,

$$T_r^{SRS} = \frac{\sum_{i=1}^{r} x_{(i)}}{\sum_{i=r+1}^{n} x_{(i)}}, \quad m \geq 1 \ , \tag{7}$$

for the ordered sample $x_{(1)} > x_{(2)} > ... > x_{(n)}$, which compares the sum of the outliers to the sum of the non-outliers [6]. This test was performed for $r = 2$ and $r = 3$ outliers for a range of upper samples – i.e., the sample in excess of a growing lower threshold. For $r = 2$, the p-value fluctuates between 0.05 and 0.1 for samples ranging from the ten to the forty largest points. For $r = 3$, the test fluctuates between 0.1 and 0.2. Thus, there is evidence that the two largest events are indeed outliers, both in terms of radiation and cost.

Due to this suggestive evidence of outliers in cost (and also NAMS), to avoid under-estimating significant extreme damage risks, we elect to consider a two layer model (eq. 5), called F_{DK}, where the upper layer is for the DK regime. The first layer, from $u_1 = 20$ MM\$ to $u_2 = 1100$ MM\$ (up to the 5th largest point) is Pareto with $\widehat{\alpha_1} = 0.55$ (0.15) estimated by MLE. The second layer, from $u_2 = 1100$ MM USD onwards, is also Pareto with heavier tail $\widehat{\alpha_2} = 0.4$, estimated on the 5 largest points.

5 Methods 5: Aggregate damage

Given the rate λ_t at year t and the damage distribution F, we here combine these models in a Compound Poisson Process (CPP) (for references, e.g., [8, 4]) to model the annual total damage,

$$Y_t = \sum_{i=1}^{N_t} X_{i,t} \sim \text{CompPois}(v_t \lambda_t, F) \ , \tag{8}$$

where for each year $t = 1980, 1981, \ldots, 2014$ there are a random number of events N_t, modeled by a Poisson process with annual rate $v_t\lambda_t$, and each event has a random size $X_{i,t} \overset{i.i.d.}{\sim} F,\ F(20) = 0,\ i = 1, \ldots, N_t$. We have already discussed and justified the models used for frequency and severity. The CPP provides the simplest way to bring frequency and severity together, and does so with the sound assumption that the size and number of accidents occuring in a year are independent. The *aggregate distribution* of Y_t is computed for the year 2014 by Monte-Carlo [8, 4].

For the computation of the 50 percent probability return periods, we show here the calculation for Fukushima. The rate of events greater than or equal to Fukushima ($x_{(1)}$) is,

$$\lambda_{X>x_{(1)}} = \lambda_t v_t Pr\{X > x_{(1)}\} \ , \tag{9}$$

and thus, with the Poisson model, the probability of such events can be computed. E.g., for the 0.5 probability return period may be calculated by solving the following equation for $t_1 - t_0$.

$$\begin{aligned} &Pr\{\text{At least 1 events} > x_{(1)} \text{ in period}(t_0, t_1)\} = Pr\{N_{X>x_{(1)}}(t_0, t_1) > 0\} = \\ &= \exp\{-(t_1 - t_0) \times \lambda_{X>x_{(1)}}\} = 0.5. \end{aligned} \tag{10}$$

References

[1] B. Appelbaum. As U.S. Agencies Put More Value on a Life, Businesses Fret. *The New York Times*, Feb 16, 2011.

[2] IAEA. Nuclear power reactors in the world 2010. *Reference data series no. 2. 2010 Edition*, 2010.

[3] IAEA. INES User Manual. `http://www-pub.iaea.org/MTCD/Publications/PDF/INES2013web.pdf`, 2013. accessed 01-12-2015.

[4] T. Mikosch. Non-Life Insurance Mathematics. 2nd printing. . *Springer*, 2006.

[5] D. Smythe. An objective nuclear accident magnitude scale for quantification of severe and catastrophic events. *Physics Today: Points of View*, 2011.

[6] S. Wheatley and D. Sornette. Multiple outlier detection in samples with exponential & pareto tails: Redeeming the inward approach & detecting dragon kings. *Submitted to Journal of Applied Statistics. arXiv preprint arXiv:1507.08689*, 2015.

[7] S. Wheatley, B. Sovacool, and D. Sornette. Of disasters and dragon kings: A statistical analysis of nuclear power incidents & accidents. *Risk Analysis (in press, 2016).*

[8] M. Wüthrich. Non-Life Insurance: Mathematics & Statistics. *SSRN Manuscript 2319328.*, 2014.