Extremes risks and dragon-kings in nuclear energy and cyber-risks
Power laws:

- Many (natural and social) phenomena have power law statistics.
- Extreme Value Theory, provides the Fréchet class (power law tail).
- For crises and extremes, power laws are the "normal" case.
- Scale-invariance -> inherent unpredictability of size.

Dragon-Kings (DK):

- Def: A double metaphor for an event that is both extremely large in size or impact (a "king") and born of unique origins (a "dragon") relative to its peers (from the same system).
- Generated by / correspond to mechanisms such as positive feedback, tipping points, bifurcations, and phase transitions, that tend to occur in nonlinear and complex systems.
- DK amplified to extreme/outlying levels
- Higher predictability
Examples of significant DK-outliers

- Crashes in financial markets (panic feeds panic, flash crashes), Urban agglomeration sizes (king-effect), Epidemic fatalities (special mechanisms), etc.
- Consequences for risk management. Relying on EVT to extrapolate tail behaviour not reliable
- EVT → generality of testing for outliers w.r.t exponential tails (For $X \sim \text{Pareto}$, $\ln(X) \sim \text{Exp}$)
- DK need not be outliers in Pareto/power law samples, but this is a classic setting

Outlier testing: procedures, swamping, and masking

Different testing procedures:

- Ordered sample: \( x_1 > x_2 > \cdots > x_{n-1} > x_n \)

Unique properties:

- Test statistics:

  - Proposed outliers
    - Proposed outliers (SWAMPING?)
    - Non-outliers: \( r < m + 1 < n \)

  - Max to robust-sum statistic:
    - \( T_{r,m}^{\text{MRS}} = \frac{x_r}{x_{m+1} + \cdots + x_n} \)
    - Compare with neighbor. E.g., Gates not outlying wrt Buffett → MASKING!

  - Likelihood ratio
    - Detects "inliers"
    - Specify mixture component
      - Powerful for clusters


*Some of these test statistics can be used in more than one procedure. We have derived the distribution of the SRS statistic.
Risk in nuclear energy: a case study of extreme risk analysis
Energy strategy & the nuclear question

- Superior living standard by accumulating new energy sources (OECD ~200 "energy slaves"/person)
- Consumption grows as global pop. "catch up"
- Want sustainability: decarbonize? wind/solar sufficient?
- Urbanization requires dense energy sources
- Nuclear is proven reliable, but is it too risky? (Costly?)

1 man-day = 35 Watt for 8 hrs = 1 Mega Joule
OECD citizens use 0.2 Giga Joule per capita per year = 4.7 tons of oil equivalent

→ 178 "energy slave" man-days per OECD citizen per day

Quality of life and energy consumption rate. Includes water access, income, electricity access, education, etc. [Pasten2012]
Incomparably energy-dense source; cheap and abundant fissionable fuel; low carbon; >80% capacity factor!

Generates heat and radioactive products: destructive potentials.

About >440 units operating globally, mostly >30 yr old LWR.

Providing 11% of global electricity (30% in CH, formerly in Japan; 70% in France).

Dominant risk: core damage accident --> failure of containment --> large off-site release.

Three major accidents triggered crises of confidence

1) Three Mile Island-2, USA, 1979 (industry inflection point)
2) Chernobyl-4 RBMK, USSR, 1987 (severe human radiological consequences)
3) Fukushima Daiichi-1,2,3+, Japan, 2011 (costly/multiple impacts)

Clearly an extreme risk, with rare events. What can be known about this risk?
Nuclear community approach: Probabilistic Safety Assessment (PSA)

- Nuclear sector has pioneered and has mature safety analysis methods, namely PSA:
  "PSA comprises a huge model of the plant, in which all safety relevant systems, involving thousands of components, are modelled in terms of their reliability and are logically linked together to determine to overall likelihood of core melt accidents, large off-site releases, and certain consequences."
  – O. Nusbaumer, NPP Leibstadt

- Relies on model being complete and realistic, incl. response to external disasters (e.g., flooding) as well as human behaviour.
  - At Fukushima, risk of tsunami was not done on a site-specific basis!

- A key quantitative output: CDF (core damage frequency)

- Global regulation maximum acceptable: CDF < 10^{-4} per reactor-year
  - ~ 1 core damage accident per decade (likely not to entail a large release) for the 400-unit global fleet, if at regulatory limit

- Can we compare these “theoretical” CDF with statistical experience?
A statistical approach & limited open risk information

Statistical approach: Limited open risk info.

- Public data on events effectively limited to INES scores
- Introduced by the IAEA, in 1990, for public communication of risk information
- Discrete scale intended to correspond to orders of magnitude of safety relevance
- Of limited use for coherent assessment of risk and consequences
- Surprisingly, no authoritative historical database provided!

- We have compiled the largest open scientific database of incidents and accidents in nuclear power, also considering consequences in terms of cost.

- Simple statistics: Commercial international fleet with 5 core damages across 3 sites in 15k reactor-years:

  → Historical CDF of $3.3 \times 10^{-4}$ with 95% conf. interval ($10^{-4}$, $10^{-3}$)

- Problem: highly uncertain, ignores improvement over time.

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Wheatley, Kröger, & Sornette, “Open Comprehensive Nuclear Events Database”, Probabilistic Safety Assessment and Management PSAM 14, September 2018, Los Angeles, CA
We provide a comprehensive open database on events in nuclear power that is useful for both scientific study and for the public. It 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 nearly one thousand 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.
- 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.

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 power facilities; and
3) The total consequences of events must be studied to understand the true value of safety investments.

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).
Selected incidents with high costs:

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 a 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.

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.
Learning from experience: Precursors/near-misses

Fukushima-Daini: four-unit site, neighbor to Daiichi, where the 2011 earthquake and tsunami also caused major flooding. Unlike at Daiichi, 1/4 external power lines remained, allowing some control information. Due to outstanding accident management, core damage accident avoided. A true near-miss.

What is the probability of core damage in such a case? This quantity, the Conditional Core Damage Probability, can be quantified using PSA models (see table below).

Many events, allowing to differentiate risk over time, design, etc.

! Many precursors experienced not fully captured by PSA models!


date

<table>
<thead>
<tr>
<th>Site and unit</th>
<th>CCDF</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>28/3/79 Three Mile Island-2</td>
<td>1</td>
<td>Loss of feedwater; pressure operated relief valve failed open; operator errors led to major core damage.</td>
</tr>
<tr>
<td>22/3/75 Browns Ferry-1</td>
<td>0.2</td>
<td>Cable fire disabling systems related to the control of unit 1 (and 2).</td>
</tr>
<tr>
<td>20/3/78 Rancho Seco</td>
<td>0.1</td>
<td>Failure of non-nuclear instrumentation and steam generator dry-out.</td>
</tr>
<tr>
<td>24.09.77 Davis Besse</td>
<td>0.07</td>
<td>Stuck open pressure operated relief valve caused reduced water level in steam generator.</td>
</tr>
<tr>
<td>01(&gt;30) Point Beach-1-2</td>
<td>0.042</td>
<td>Design deficiency in air-operated minimum-flow recirculation valves of the EFW pumps (not modeled in PSA).</td>
</tr>
<tr>
<td>01(&gt;30) Oconee-1-3</td>
<td>0.036</td>
<td>Potential failure of Jocassee Dam would likely cause accident.</td>
</tr>
<tr>
<td>05/74 Turkey Point-3</td>
<td>0.02</td>
<td>Failure of three emergency feedwater pumps to start during test.</td>
</tr>
<tr>
<td>20/7/76 Millstone-2</td>
<td>0.01</td>
<td>Loss of offsite power from grid disturbance; errors in emergency diesel generators loading, and failure of the emergency core cooling systems.</td>
</tr>
<tr>
<td>20/4/75 Brunswick-2</td>
<td>0.009</td>
<td>Multiple valve failures; reactor core isolation cooling inoperable as a result of stuck-open safety valve.</td>
</tr>
<tr>
<td>07/04/74 Point Beach-1</td>
<td>0.005</td>
<td>Inoperable auxiliary feed water pumps during shutdown.</td>
</tr>
<tr>
<td>05/5/75 Kewaunee</td>
<td>0.005</td>
<td>Inoperable EFW pumps during startup as a result of leaks from demineralizer into the condensate storage tank.</td>
</tr>
<tr>
<td>09/5/74 Kewaunee</td>
<td>0.0015</td>
<td>Design deficiency could cause unavailability of safety-related equipment during postulated internal flooding.</td>
</tr>
<tr>
<td>09/5/74 St. Lucie-1</td>
<td>0.0015</td>
<td>Air intrusion into component cooling water system causes pump cavitation.</td>
</tr>
<tr>
<td>04/11 Palisades-1-3</td>
<td>0.0013</td>
<td>Containment sump recirculation potentially inoperable.</td>
</tr>
<tr>
<td>12/7/71 Point Beach-1</td>
<td>0.001</td>
<td>Failure of containment sump valves.</td>
</tr>
<tr>
<td>27/2/02 Davis Besse</td>
<td>0.006</td>
<td>Cracking of CRDM nozzles, RPV head degradation, potential clogging of the emergency sump, and potential degradation of the RPV pumps.</td>
</tr>
<tr>
<td>07/12/86 Surry-2</td>
<td>INES 3</td>
<td>Catastrophic rupture of feedwater pipe due to corrosion, resulted in 8 workers injuries, four died later; the event cascaded from the non-nuclear part across safety-grade systems causing accident management problems. Appears to be omitted from 1986 NRC analysis.</td>
</tr>
<tr>
<td>26/12/85 Rancho Seco</td>
<td>INES 3</td>
<td>Following loss of the integrated control system (ICS), the unit tripped and an overcooling transient occurred due excessive feedwater flow. Finally, the operator attempted to close the manual isolation valve but it could not be moved because of lack of any maintenance on that valve during life of the plant. Restoration of power within 26 min.</td>
</tr>
</tbody>
</table>

Table of initiators and failure probabilities given presence of initiator

*LOCA: loss-of-coolant accident

Table of selected major precursors in the US, from US NRC.
Precursor CCDP can be summed to estimate CDF:

\[
E[CD] = E\left(\sum_{i=1}^{N} X_i\right) = \sum_{i=1}^{N} \Pr(X_i = 1) = \sum_{i=1}^{N} \text{CCDP}_i \Pr(C_i = 1) \approx \sum_{i \in S} \text{CCDP}_i,
\]

where \(S\) is the set of observed precursors. One can then divide this by the number of reactor-years of operating experience to obtain an estimated CDF.

Result for fleet of ~100 US reactors:

Major improvement in CDF, from unacceptably high level, to likely below the regulatory limit, on average. Largely due to costly improvements following Three Mile Island, 1979.

Western European plants are found to have a similar post-TMI risk level, despite no accidents having occurred.

In some plants, with post-Fukushima improvements, without major seismic/flood risks, CDF around \(10^{-5}\) are possible. But why be exceptionally safe, when one unsafe plant leads to costly sanctions to the global fleet? (Incentive/regulatory problem).

Next generation designs put a radical emphasis on safety and are claimed to achieve CDF \(10^{-6}\) -- projecting one accident per 1000 years for a fleet of 1000 reactors. Without experience, we cannot test these claims statistically.
Surprisingly assessment of cost of accidents is not required by regulators

- We have estimated the approximate cost of historical incidents and accidents, in our database
- The three major accidents, with costs reaching hundreds of billions of USD, dominate the cost of the hundreds of other incidents studied (none of which caused significant offsite costs – mostly downtime, and higher electricity prices).
- TMI, with no major release, led to costly reforms, increasing the price of electricity (but also increasing safety). Fukushima led to substantial economic costs, with costs due to exposure to radiation being relatively low.
- Chernobyl: 4'000-16'000 eventual radiological fatalities (expected shortening of life)
- Fukushima: 2'000 (elderly relocation), up to 1’000 eventual radiological.

Other energy production:
- Human activities related to energy production already lead to the annual premature death of more than 100’000 people worldwide. (WHO)
- Vajont Dam (Italy, 1963): Landslide caused tsunami killing 1’917 people

Industrial accident:
- Bhopal pesticide gas leak (India, 1984): killing 3’787 directly and causing 3’900 permanently disabling injuries

Other:
- 1.25 million road traffic deaths globally in 2013. (WHO)
- Elevators and escalators kill about 30 and seriously injure about 17’000 people each year in the United States (CPRW, 2013)
Externalities of a range of energy sources [PSI, ExternE 2005]. Nuclear (PWR and LWR) omits accident externality.

Nuclear accident externality (2017USD cents per kWh) with figure adapted from NEA. Our estimate given by the X, based on CDF $10^{-4}$, and average accident cost of $100$Bil. Externality $0.1$ cents/kWh, for a unit with annual generation of $10$TWh/reactor-year.

Nuclear accident externality has been underestimated, but is still small relative to externalities of other energy sources. In particular, the health impacts of burning coal.

Alternative characterization: major accidents with current global fleet:
CDF $10^{-4}$:
Pr[#large releases per century=0,1,2] = 0.5, 0.35, 0.12

CDF $10^{-5}$:
= 0.93, 0.07, 0.002

With dropping CDF, accidents highly unlikely, but not impossible. Acceptable?

Externalities of a range of energy sources [PSI, ExternE 2005]. Nuclear (PWR and LWR) omits accident externality.
Didier Sornette, Wolfgang Kröger, Spencer Wheatley

New Ways and Needs for Exploiting Nuclear Energy

The history of mankind is a story of ascent to unprecedented levels of comfort, productivity, and consumption, enabled by the increased mastery of the basic reserves and flows of energy. This miraculous trajectory is confronted by the consensus that anthropogenic emissions are harmful and must decrease, requiring de-carbonization of the energy system.

The mature field of indicator-based sustainability assessment provides a rigorous systematic framework to balance the pros and cons of the various existing energy technologies using lifecycle assessments and weighting criteria covering the environment, economy, and society, as the three pillars of sustainability. In such a framework, nuclear power is ranked favorably, but since emphasis is often placed on radioactive wastes and risk aversion, renewables are usually ranked top. However, quantifying the severity of the consequences of nuclear accidents on a rough integral cost basis and balancing severity with low-core damage accident probabilities indicates that the average external cost of such accidents is similar to that of modern renewables, and far less than carbon-based energy.

This book formulates the overall goal and associated unprecedented demanding criteria of taming nuclear risks by excluding mechanisms that lead to serious accidents and avoiding extremely long stewardship times as far as possible, by design. It reviews the key design features of nuclear power generation, paving the way for the exploration of radically new combinations of technologies to come up with "revolutionary" or even "exotic" system designs. The book also provides scores for the selected designs and discusses the high potential for far-reaching improvements, with small modular lines of the best versions as being most attractive.

Given the ambition and challenges, the authors call for an urgent increase in funding of at least two orders of magnitude for a broad international civilian "super-Apollo" program on nuclear energy systems. Experience indicates that such investments in fundamental technologies enable otherwise unattainable revolutionary innovations with massive beneficial spillovers to the private sector and the public for the next generations.
New Ways & Needs For Exploiting Nuclear Energy
D. Sornette, W. Kröger, S. Wheatley

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      1.1.1 History of energy and human development
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      1.1.3 “The electricity God”
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   7.1 Paradox of human societies and irreversibility
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Cyber risk: a case study on data breaches and privacy
A **personal data breach** is: “a breach of security leading to the accidental or unlawful destruction, loss, alteration, unauthorized disclosure of, or access to, **personal data** transmitted, stored or otherwise processed in connection with the provision of a public electronic communications service”.

**Personal data:** Name, credit card, SSN, passwords, medical data, private communications, etc.

“ #1 risk facing businesses today ”; causing fraud, disruption, loss of reputation, credit,

- Stolen identities used for large scale fake comments online to “hack consensus” in important political issues (Hackernoon)
- Ashley Madison, 2015. 37 Mil members.
- Yahoo, 2013-2014: 1.5 Bil user accounts compromised.
- Equifax, 2017. 151 Mil people with SSN and CCN exposed
- Sony Pictures, 2014. “Cost up to 1 Bil USD”. Uber, Ebay, JPMorgan, …
• Growing exposure: The 3rd and 4th industrial revolutions have brought rapid coupling of the physical and digital (i.e., cyber) worlds. More people and data online.

• Hazard: Day-zero vulnerabilities are sold; black markets collect and distribute breached info; easy money; complex social engineering attacks

• Vulnerability: Proliferation of mobile devices, hardware and software with bugs. State actors? Intel bug? MS bug? Concentration of data on the cloud?

Rapidly evolving and without standards, what can be known?
A frequent, extreme, & costly risk

- USA: 1'713 breaches > 10’000 ids, since 01/2005.
- Total USA breach 1.4 x 10^{10} ids; The largest: 3 x10^9, 30% of total !
- If > 10^4 then 10% chance > 10^6, and 1% chance > 10^8 !
- Range of estimates indicate global losses > one hundred billion USD per year[1] – i.e., a nuclear accident every year!
- Cost types are many over time. Lack of standards, data, and true consequences difficult to know

Business disruption, ID fraud, IT repairs, loss of credit, lost IP, reputational damage,…


Big hack-type events are getting bigger/more frequent

As expected, the risk is getting worse! (1/2)

Breach sizes over years, by type (HACK black, DISC red, INSD blue, HW green). Trend quantified by the log-linear regression of the 0.9 quantile.

- Hack events: significant increase quantified by a log-linear negative binomial regression.
- Annual growth ranges from 8 percent for breaches in excess of $10^4$ up to 19 percent per year for breaches larger than $10^6$, having significantly faster growth for larger breaches.

- HACK: is any unauthorized exfiltration of ids by an outsider, typically including software media, and a range of attack strategies, excluding physical theft of devices.
- HW: is for all physical devices, i.e., hardware, either lost or stolen.
- DISC: is accidental disclosure via software media.
- INSD: is a HACK performed by an insider.
- NA: is not further specified, unknown, and/or does not fall into the above categories.

The breach size distribution is extremely heavy tailed

As expected, the risk is getting worse! (2/2)

• So heavy-tailed that breach of 10 Billion ids not an outlier!

• For hacks in the USA, estimated compound negative binomial model predicts:
  • Median of 0.5 Billion ids breached in final 6 months of 2018.
  • Heavy tail allows for more than 7 Billion ids to be breached with about a 5% chance – equal to the total data already breached due to all past hacks!

Main: Empirical survival distributions for the breach types for all time by color: DISC red, INSD blue, and HW green. HACK (black) is split into pre-2010 data and post-2014 data, being the heavier tailed of the two. Maximum likelihood fits to the post-2014 hack data plotted: Pareto with upper truncation (black solid), and Lognormal (red dashed). Inset: Estimated parameter $\alpha$ of the Pareto tail ($u=25'000$), from 2005 to Q4 2017 on a moving window of 50 points, for the HACK events, including one and two standard deviations of the maximum likelihood estimate.
Organization size provides a first step towards risk differentiation

An important risk factor: org. size → risk surface

- Considered the 4,950 firms publicly traded on the NYSE, AMEX, and NASDAQ, and used their market capitalisation as a measure of size.
- Only 10 percent of these firms have been victimised, but nine of the ten largest have been (multiple times)...

Risk surface: Both breach frequency and severity scale $\sim s^{2/3}$ with size
- The largest subunit in an org. scales in the same way!

WE ELABORATED MORE THAN 25 CASES OF LARGE-SCALE DISASTERS:

INDUSTRIAL SECTOR
- Vajont dam disaster (Italy, 1963)
- Three Mile Island nuclear accident (USA, 1979)
- Bhopal fertilizer plant gas leak (India, 1984)
- Challenger Space Shuttle disaster (USA, 1986)
- Chernobyl nuclear disaster (USSR, 1986)
- Exxon Valdez oil spill (USA, 1989)
- Ufa train disaster (USSR, 1989)
- Deepwater Horizon oil spill (USA, 2010)
- Raspadskaya coalmine burnout (Russia, 2010)
- Fukushima-Daiichi nuclear disaster (Japan, 2011)
- Minamata mercury poisoning (Japan, 1932-1968)
- Asbestos crisis (worldwide, 1970s)
- Sayano-Shushenskaya hydropower station accident (Russia, 2009)
- Shale energy production (USA, since 2005)

FINANCIAL SECTOR
- Barings bank collapse (Singapore-UK, 1995)
- Enron’s bankruptcy (USA, 2001)
- Subprime mortgage crisis (USA, 2007-2008)
- US total debt problem and hiding of liabilities (ongoing case)
- Falsification/manipulation of Chinese GDP and problems in banking sector (ongoing case)

MILITARY, SOCIAL AND NATURAL DISASTERS
- Unreadiness of the Soviet Red Army for invasion of the Nazi (1941)
- Great wildfires in the European part of Russia (Russia, 2010)
- Krymsk flooding (Russia, 2012)

RISK CONCEALMENT IN THE RETAIL PRODUCTION INDUSTRY
- Cost reduction rate and Toyota problems (USA-Japan, 2000s)
- Poly Implant Prothese fraud (France, 1993-2010)
- Cigarette industry (worldwide)
The research identified more than 30 repeated causes of failures within the cases considered, and confirmed that most of the factors which obstruct the free transmission of risk information have been consistently present across many major disasters, which have occurred throughout the world and in different historical periods according to quite similar scenarios.
The four quadrants of risk and resilience management regimes corresponding to the system’s degree of uncertainty/predictability and stress level within it.

- **AD HOC MANAGEMENT**
  - self-organization, decentralization, delegation

- **BLACK SWAN**
  - exogenous surprising disturbances

- **ADAPTIVE MANAGEMENT**
  - rigorous iterative learning and policy adjustment

- **DRAGON KING**
  - endogenous maturation, reduction of complexity close to a threshold

**Metrics**

- **Response mechanisms:**
  - negative feedback, adaptation and coevolution
  - positive feedback, avoidance or transformation

**Risk and resilience management instruments:**

- passive defense measures; margins, reserves, provisions; mitigation, contingency plan
- active interventions; model design and hypotheses testing; strategy adjustment