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Probability Distribution of Radioactive Fallout in the Nuclear Power Plant Accidents

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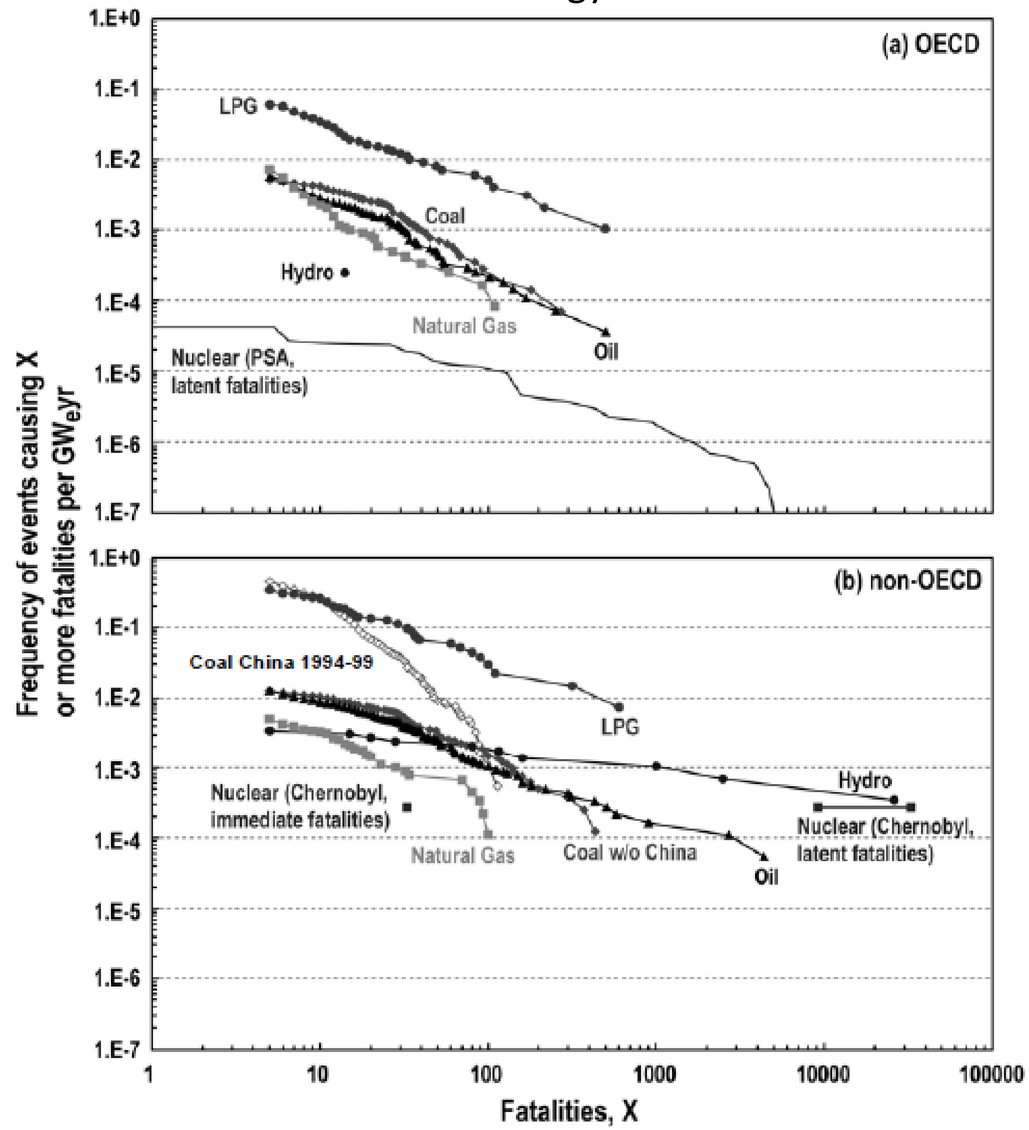
1. Introduction

- Normally, consequence of an accident of energy industry is expressed in terms of fatalities.
- Typical examples are Frequency-consequence curves (F-N curve) made by Paul Scherrer Institute for OECD2010/NEA6861 report "Comparing Nuclear Accident Risks with Those from Other Energy Sources".
- In this F-N curve, consequence was expressed in terms of fatalities.

OECD 2010 NEA No.6861

"Comparing Nuclear Accident Risks with Those from Other Energy Sources



Introduction continued

- Fatality of nuclear accidents is low soon after an accident but cost of losing large land area by radioactive fallout is far more critical for local society.
- Therefore, it is important to use radiation fallout quantity as a measure of consequence of the accidents instead of fatalities.
- In the last decade, many natural and man-made phenomena such as magnitude of earthquake, war, net wealth of people and bubble economy were found to follow power-law distribution.
- Although Paul Scherrer Institute does not call F-N curve as power-law distribution, but it exactly looks like power-law distribution. Then the question arise what it looks like the cumulative occurrence probability of nuclear reactor accidents as a function of radioactive fallout per cumulative power generated.

2. Objective of the present study

- Objective of the present study is to prove that cumulative occurrence probability of nuclear reactor accidents is a function of radioactive fallout per cumulative power generated.
- If the function constitute the power-law distribution, we can say that nuclear accidents has a long tail and has no average value.
- This means that nuclear technologies are not insurable and long tail of the distribution would surely bring to our civilization a disastrous tragedy bigger than Chernobyl accidents even though probability is low.
- As this function is an actual plot of real accidents, it will give us more accurate prediction of future than other mathematical model using Gaussian distribution for component failure.

3.Method for analysis

- After searching historical record of many nuclear power plant accidents, 10 accidents had been selected as major accidents which accompanied meltdown of core and killed operator or contaminated surrounding area with radioactive fallout and forced people to evacuate temporary or permanently.
- Then we have evaluated magnitude of accidents with respect to radioactive fallout X per cumulative power generated and to find out cumulative occurrence probability P(X) of the accidents.
- Radioactive fallout per power generated, X is obtained by dividing total fallout quantity in Curie (Ci) by total power generated in giga Watt year (GWy).
- Total power generated is calculated from power output multiplied by operating years from start-up to the time of accidents. Thus unit of X becomes Ci/GWy.
- Cumulative Distribution Function will be obtained by plotting fallout per power generated X on horizontal axis and frequency of the accidents P causing X on vertical axis. Cumulative distribution function of accidents is written as

$$P(X)=CX^{-\alpha}$$

- Here, the parameter α is scaling exponent and C is a constant. Those parameters could be obtained by plotting data on logarithmic scales, and when we see the characteristic straight-line, it would mean that nuclear accidents follow the power-law distribution.

4. Result of the analysis

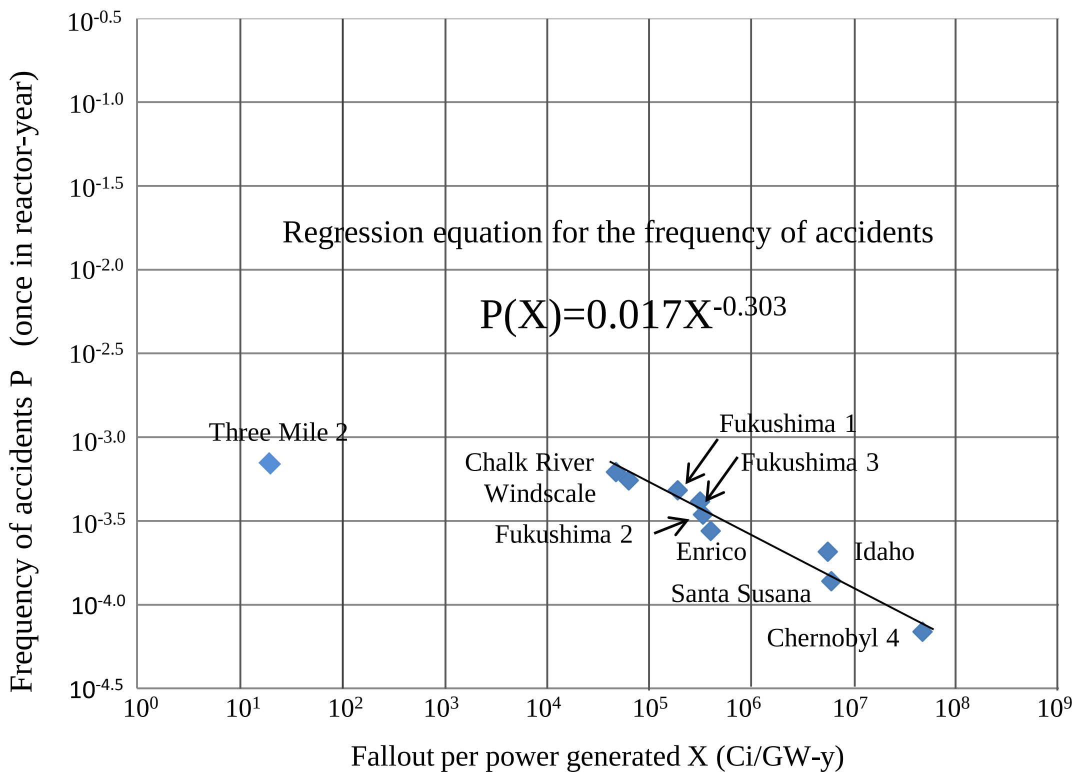
Table-1 P(X) and X

Accidents	P(X) (once in reactor-year)	Fallout (tBq)	Fallout (Ci)	Fallout per power generated X (Ci/GWy)
Fukushima 1	7/14,500	130,000	3,513,514	190,952
Fukushima 2	5/14,500	360,000	9,729,730	335,415
Fukushima 3	6/14,500	320,000	8,648,649	315,184
Chernobyl 4	1/14,500	5,200,000	140,540,541	46,846,847
Three Mile Island 2	10/14,500	0.629	17	18
Enrico Fermi N0. 1 FBR	4/14,500	2,960	80,000	400,000
Idaho Falls reactor SL-1	3/14,500	370	10,000	5,555,556
Santa Susana Field Laboratory	2/14,500	4,329	117,000	6,000,000
Windscale Pile No.1 & 2	8/14,500	2,960	80,000	63,492
Chalk River Canada CANDU NRX	9/14,500	370	10,000	47,619

- Frequency of the accidents causing X fallouts or cumulative probability P(X) will be calculated by rank-plot method proposed by George Kingsley Zipf.
- What all we need to do is sort the accidents in decreasing order of X, number them starting from 1, and then divide those rank numbers by world cumulative reactor–year.
- It is reported that world cumulative reactor-year is 14,500 at the time of Fukushima Daiichi accident.

4. Result of the analysis continued

- We have plotted fallout per power generated X and frequency of the accidents P causing X as shown in Figure-1.



- Here, we see straight line.
- From this fact, we can say that cumulative distribution function of radioactive fallout per power generated of nuclear accidents follows power-law distribution.
- Only exception is Three Mile Island accident which does not align on straight line.
- From the straight line plot excluding Three Mile Island accidents, we get $\alpha = 0.303$ and C=0.017

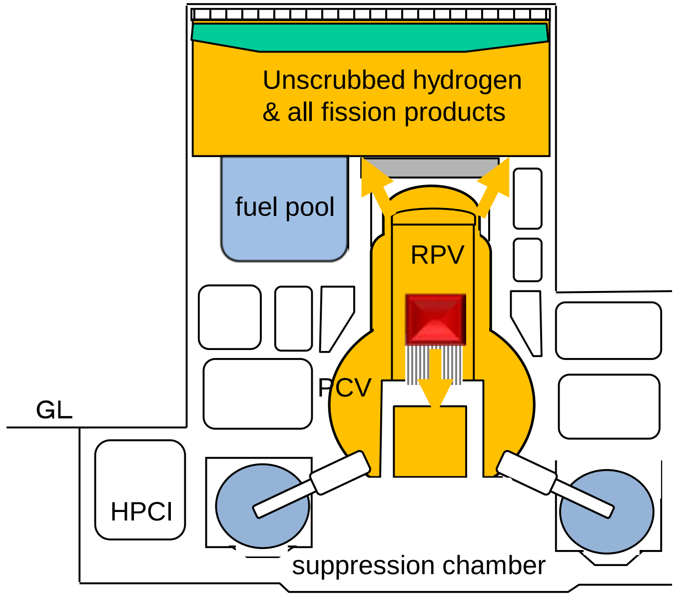
5. Discussion

As already pointed out, only exception of cumulative distribution function is Three Mile Island accidents. The fallout per cumulative power generated is extremely low compared to other accidents. Among them, only Three Mile Island plant is using pressurized reactor (PWR) and others are various type. Fukushima Daiichi had been second worst accidents. Type of the reactor is boiling water type (BWR). Followings are the main difference between BWR and PWR.

Probably, we might find cumulative distribution function of PWR runs along with that of other types with lower X values.

Accidents	Type of Reactor	Coolant	Reactor Pressure Vessel	Control rod penetration	Primary Containment Vessel
Fukushima 1	BWR	water	cylindrical	bottom	small w/ suppression
Fukushima 2	BWR	water	cylindrical	bottom	small w/ suppression
Fukushima 3	BWR	water	cylindrical	bottom	small w/ suppression
Chernobyl 4	RBMK	water	tubular	top	none
Three Mile Island 2	PWR	water	cylindrical	top	large dry
Enrico Fermi N0. 1 FBR	FBR	sodium	none	top	none
Idaho Falls reactor SL-1	BWR	water	cylindrical	bottom	none
Santa Susana Field Laboratory	FBR	sodium	none	top	none
Windscale Pile No.1 & 2	AGR	air	none	-	none
Chalk River Canada CANDU NRX	CANDU	water	none	top	large w/ water spray

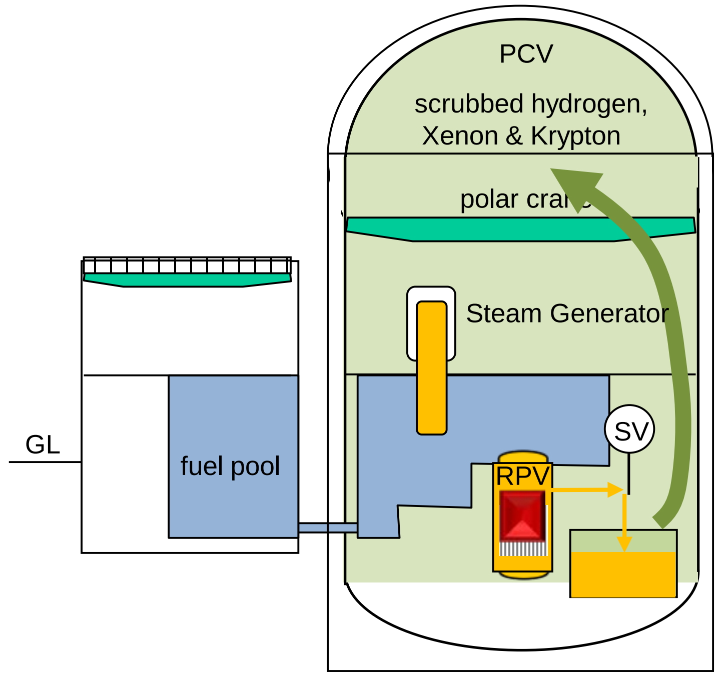
5.1 Boiling Water Reactor



BWR

- In-core monitor housing is not sealed outside reactor, thus core melt down results in gas leakage through this monitoring housing without cooling and scrubbing fission products.
- When high temperature hydrogen gas is flowing through this housing tube, water remaining in bottom part of reactor was evaporated. Thus, more chemical reaction heat was added.
- Small relative volume between primary containment vessel and reactor pressure vessel does not gives operator ample time for saving the plant.
- Due to close clearance between reactor pressure vessel and primary containment vessel, big flange at the top of primary containment is heated by meltdown heat and start leaking un-scrubbed gas through it.
- Spent fuel pool is located at the top of the building and subject to loss of cooling water

5.2 Pressurized Water Reactor



PWR

- No leakage occur from reactor in the event of core melt down, as thimble tubes for Neutron monitors selector are sealed outside reactor.
- Released gas from reactor pressure vessel via SV is cooled and scrubbed through water and most of fission products are removed except Xenon and Krypton.
- Water is supplied from steam generator through connecting piping as required, and protect bottom plate of the reactor.
- There is no big flange at the top of primary containment vessel
- Large relative volume between primary containment vessel and reactor pressure vessel gives operator ample time for controlling situation.
- Spent fuel pool is sitting on the ground

5.3 Meaning of the distribution function

Compensation=Cumulative frequency of accidents P(X) x Loss of accidents

Loss of accidents ∝ SQRT(Fallout)

X = Fallout/(cumulative power generated)

When parameter α of P is 0.303, compensation becomes;

Compensation $\propto X^{0.197}$

	unit	Three Mile Class	Fukushima Class	Chernobyl Class
Power output	GW	0.96	0.784	1
Cumulative operation	year	1	37	3
Fallout	tBq	0.629	360,000	5,200,000
Fallout per power generated X	tBq/(GWy)	0.655	12,410	1,733,333
Cumulative frequency of accidents P(X)	1/(reactor-y)	0.000690	0.000345	0.000069
reactor year	reactor-year	1,449	2,900	14,500
Loss of accidents=proportional to SQRT(fall out)	tera yen/accidents	0.067	9.2	109
Compensation for loss of accidents	yen/kWh	0.05	3.17	7.50

- For reference, maximum holdup of fission products in a reactor is 4,000kg/reactor, while maximum quantity of fission products in Atomic bomb is only 8kg.
- Cumulative frequency of Fukushima Daiichi accident is once in 2,900 reactor-year and cumulative frequency of accidents of Chernobyl 4 is once in 14,500reactor-year. If there are 500 reactors in the world, another Chernobyl class accidents might happen once in every 29years.

6. Conclusion

- This study proved that cumulative occurrence probability of nuclear reactor accidents is a function of radioactive fallout per cumulative power generated. And the function follows the power-law distribution.
- Power law distribution function has no mean figure and have long tail. Accidents of Three Mile Island does not align with regression equation for power- law distribution. It is speculated that containment of PWR has superior containment capability than BWR.
- Operating companies having poor containment provisions like BWR, have to be prepared for the mega loss exceeding maximum liability of insurance of 0.2trillion yen.
- Nature and man-made system generally follow power-law distribution, but our brain is designed to recognize nature and man-made system only through Gaussian distribution and tends to repeat the same decision mistakes on the future of nuclear power and repeat disaster like bubble economy and war.