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Paper

Probability of Nuclear Power Plant Accidents with respect to Radioactive Fallout

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Summary

Traditionally, nuclear industry used the Probabilistic Risk Assessment (PRA) identifying the risks of spreading radioactive material to environment. Unfortunately, PRA failed to give us higher frequency of severe damage to the core. Optimistic figures mislead the society.
In the last decade, many natural and man-made phenomena such as magnitude of earthquake, frequency of use of words, net wealth of people were found to follow power-law distribution. After Fukushima-daiichi accidents in 2011, We have made a brief survey to find whether nuclear accident follow power-law distribution and found it follows.
If cumulative distribution function of the probability of accidents vs. radioactive fallout of nuclear accidents follows power-law distribution, we can disregards false prediction by PRA. We have collected past accidents record and plotted probability against radioactive fallout. And found out that the plot follows power-law distribution. It was also found out that Three Mile Island does not align with regression equation for power-law distribution. Preliminary considerations were given on the cause of the difference among the type of reactors. It is speculated that containment of PWR has superior containment capability than BWR.
Finnaly we had concluded that PRA is not suitable for predicting cumulative frequency of the nuclear plant accidents.

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Introduction

Traditionally, nuclear industry used Probabilistic Risk Assessment (PRA) identifying the risks of spreading radioactive material to environment. Historically, The Reactor Safety Study WASH-1400 (also known as the Rasmussen Report) evaluated the probability of a number of accident sequences that might lead to melting of the fuel in the reactor, by introducing the fault tree technique. A review report known as the Lewis Report (NUREG/CR-0400) followed. System failures are identified and quantified by system models like Fault Trees. At the lowest level, the Basic Events of the fault trees are assigned probability distributions. These probability distributions are propagated up through the tree logic to reach a probability distribution of the top event. The response of the plant itself to each group of Initiating Events is usually modelled by the use of Event Trees. They provide sequences that, depending on successes or failures of relevant systems, lead either to a safe or to a core damage state. This methodology is known as the fault tree methodology. Unfortunately, PRA failed to predict realistic probability of severe damage to the core. Optimistic figures mislead the society.

In the last decade, many natural and man-made phenomena such as magnitude of earthquake, frequency of use of words, net wealth of people were found to follow power-law distribution. [2 to 4] Newman et al. pointed out many reasons such as random walks of component failures, phase transition and critical phenomena, self-organized criticality or emergence are the cause of power-law distribution (Pareto distribution).[5] These phenomena had been referred as “black swan” or “dragon kings”.[37]

After Fukushima-daiichi accidents in 2011, We have made a brief survey to find whether nuclear accident follow power-law distribution and found 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".[1] Although Paul Scherrer Institute does not call F-N curve as power-law distribution, but it exactly looks like power-law distribution. Fatality of nuclear accidents is low soon after an accident but cost of losing large land area by radioactive contamination is far more critical for local society. As area of the land lost has a close relation to radiation fallout quantity, it is important to use radiation fallout quantity as the measure of consequence of the accidents instead of fatalities.

This is the reason why we started our project to find what it looks like the probability vs. radioactive fallout curve. It is easily anticipated that the curve will follow power law distribution. As probability vs. radioactive fallout curve is an actual plot of real accidents, it will give us more accurate prediction of future nuclear accidents.

1.Record of Accidents

We have decided to collect past accidents record and evaluate magnitude of accidents with respect to radioactive fallout and to find out cumulative distribution function of radioactive fallout. If we can find power-law distribution, we can say that nuclear accidents are not insurable because there is no average value. And we can also say that long tail of the distribution would surely bring to our civilization a disastrous tragedy bigger than Chernobyl accidents even though probability is low.

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. Those are Fukushima 1, 2 & 3, Chernobyl 4, Three Mile Island 2, Enrico Fermi N0. 1 FBR, Idaho Falls reactor SL-1, Santa Susana Field Laboratory, Windscale (Sellafield) Pile No.1 & 2 and Chalk River Canada CANDU NRX. Selected accidents are listed in Table-1 Summary of published data with reference number. Accidents of nuclear reactors for military purpose were not considered because data are not available. Also accidents of fuel reprocessing plant are not considered because system is completely different and the number of such plant is very limited.

	Date of Start up	Date of Accidents	Power Output (GW)	Xenon (tBq)	Iodine (tBq)	Cesium (tBq)	Fallout (tBq)	Ref. No.
Fukushima1	March 1971	March 2011	0.4600	3,400,000	12,000	590		10
							130,000	8
Fukushima2	July 1974	March 2011	0.7840	3,500,000	140,000	14,000		10
							360,000	8
Fukushima3	March 1976	March 2011	0.7840	4,400,000	7,000	710		10
							320,000	8
Fukushima unknown							110,000	8
Fukushima total							900,000	8
		March 2011	2.0280		160,000	15,000		11
					-	35,800		12
					130,000	6,100		13
					150,000	12,000		14
					150,000	13,000		15
Chernobyl 4	1983	April 1986	1.0000		1,760,000	85,000		16
				6,500,000	1,760,000	85,000		17,18
					1,800,000	85,000		19
					7,000,000Ci	-	80,000,000Ci	20
Three Mile Island 2	Jan. 1979	March 1979	0.9600	480,000	0.555	0		21,22
					17Ci	0		23
					17Ci			20
Enrico Fermi N0. 1	1966	Oct. 1966	0.2000		20,000Ci	-		24,25
Idaho Falls SL-1	1958	Jan. 1961	0.0006	1,100Ci	80Ci	-		26,20
							10,000Ci	27
Santa Susana Field	1956	July 1959	0.0065				7,800Ci	28
					13,000Ci	2,600Ci		29
					4,000Ci	400Ci		30
					20,000Ci	600Ci		31
Windscale Pile1 & 2	1950	Oct. 1957	0.1800		20000Ci			20,32
Chalk River CANDU	July 1947	Dec. 1952	0.0420		-	-	10,000Ci	33
					-	-	10,000Ci	34

Table-1 Summary of published data with reference number

GW is giga watt, tBq is tera Bequrell

2.Radioactive Fallout

For this study, it was decided to use radiological equivalence to 131-I for releases to the atmosphere defined by The International Nuclear and Radiological Event Scale (INES) of IAEA and OECD/NEA. Total fallout is defined as the sum of representative isotopes converted to 131-Iodine. Radiological equivalences to Iodine are 40 for Cesium and negligible for Xenon.[6 to 7] When Cesium release quantity of accidents is not available, fallout quantity was assumed by multiplying 4 to 131-I. Calculated radioactive fallout of each accident were summarized in Table-2. Figures in boxes are the selected figures for the research. TEPCO figures were selected for Fukushima, because they are the latest estimate of fallout.[8] For other accidents, largest figures have been selected.

Accidents	Iodine (tBq)	40*Cesium (tBq)	Fallout (tBq)	Fallout (Ci)
Fukushima1	12,000	23,600	35,600	962,162
			130,000	3,513,514
Fukushima2	140,000	560,000	700,000	18,918,919
			360,000	9,729,730
Fukushima3	7,000	28,400	35,400	956,757
			320,000	8,648,649
Fukushima unknown			110,000	2,972,973
Fukushima total			900,000	24,324,324
	160,000	600,000	760,000	20,540,541
	-	1,432,000	-	-
	130,000	244,000	374,000	10,108,108
	150,000	480,000	630,000	17,027,027
	150,000	520,000	670,000	18,108,108
Chernobyl 4	1,760,000	3,400,000	5,160,000	139,459,459
	1,760,000	3,400,000	5,160,000	139,459,459
	1,800,000	3,400,000	5,200,000	140,540,541
	7,000,000Ci	-	-	80,000,000
Three Mile Island 2	0.555	0	0.555	15
	17Ci	0	0.629	17
	17Ci		0.629	17
Enrico Fermi N0. 1	20,000Ci	-	2,960	80,000
Idaho Falls SL-1	80Ci	-	11.84	320
				10,000
Santa Susana Field				7,800
	13,000Ci	3,848	4,329	117,000
	4,000Ci	592	740	20,000
	20,000Ci	888	1,628	44,000
Windscale Pile1 & 2	20000Ci			80,000
Chalk River CANDU	-	-	-	10,000
	-	-	-	10,000

Table-2 Calculated radioactive

Ci is Curie. Cesium was converted to iodine using radiological equivalence defined by IAEA and OECD/NEA. Figures in boxes are the selected figures for the research.

Cumulative operation time and power output are shown in Table-3. Radioactive fallout x could simply be radioactive fallout per accidents. But considering different size and different length of operating time of the nuclear plant, it was decided that x shall be radioactive fallout per total power generated. Therefore, radioactive fallout per power generated, x is obtained by dividing total fallout quantity in Curie (Ci) by total power generated in giga Watt-year (GW-y). Total power generated is calculated from power output multiplied by operating years from startup to the time of accidents. Thus unit of x becomes Ci/GW-y.

Accidents	Cumulative Operation (y)	Power Output (GW)	Fallout (tBq)	Fallout (Ci)	Fallout per power generated x (Ci/GW-y)
Fukushima 1	40	0.460000	130,000	3,513,514	190,952
Fukushima 2	37	0.784000	360,000	9,729,730	335,415
Fukushima 3	35	0.784000	320,000	8,648,649	315,184
Chernobyl 4	3	1.000000	5,200,000	140,540,541	46,846,847
Three Mile Island 2	1	0.960000	0.629	17	18
Enrico Fermi N0. 1 FBR	1	0.200000	2,960	80,000	400,000
Idaho Falls reactor SL-1	3	0.000600	370	10,000	5,555,556
Santa Susana Field Laboratory	3	0.006500	4,329	117,000	6,000,000
Windscale Pile No.1 & 2	7	0.180000	2,960	80,000	63,492
Chalk River Canada CANDU NRX	5	0.042000	370	10,000	47,619

Table-3 Radioactive fallout per power generated

x is obtained by dividing fallout in Curie (Ci) by total power generated in giga watt-year (GW-y)

3.Rank-Plot Method

Frequency of the accidents causing x fallouts or cumulative probability P(x) will be calculated by rank-plot method proposed by George Kingsley Zipf.[5] 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.[9] Calculation results are summarized in Table-4

Accidents	Fallout per power generated x (Ci/GW-y)	Rank number	Actual frequency of accidents P (1/GW-y)	log x	log P
Fukushima 1	190,952	7	0.000483	5.281	-3.32
Fukushima 2	335,415	5	0.000345	5.526	-3.46
Fukushima 3	315,184	6	0.000414	5.499	-3.38
Chernobyl 4	46,846,847	1	0.000069	7.671	-4.16
Three Mile Island 2	18	10	0.000690	1.248	-3.16
Enrico Fermi N0. 1 FBR	400,000	4	0.000276	5.602	-3.56
Idaho Falls reactor SL-1	5,555,556	3	0.000207	6.745	-3.68
Santa Susana Field Laboratory	6,000,000	2	0.000138	6.778	-3.86
Windscale Pile No.1 & 2	63,492	8	0.000552	4.803	-3.26
Chalk River Canada CANDU NRX	47,619	9	0.000621	4.678	-3.21

Table-4 Fallouts per power generated and frequency of the accidents

Frequency of the accidents P = (Rank number)/(world cumulative reactor-year)

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4.Cumulative Distribution Function

Cumulative Distribution Function (cumulative frequency) of power-law will be obtained by plotting fallout per power generated x on horizontal axis and frequency of the accidents P causing x on vertical axis. Both x and P are on logarithmic scale. Cumulative distribution function of power-law 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.

We have plotted fallout per power generated x and frequency of the accidents P causing x shown in Table-3 on horizontal logarithmic axis and on vertical logarithmic axis. Figure-1 is the results. 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.

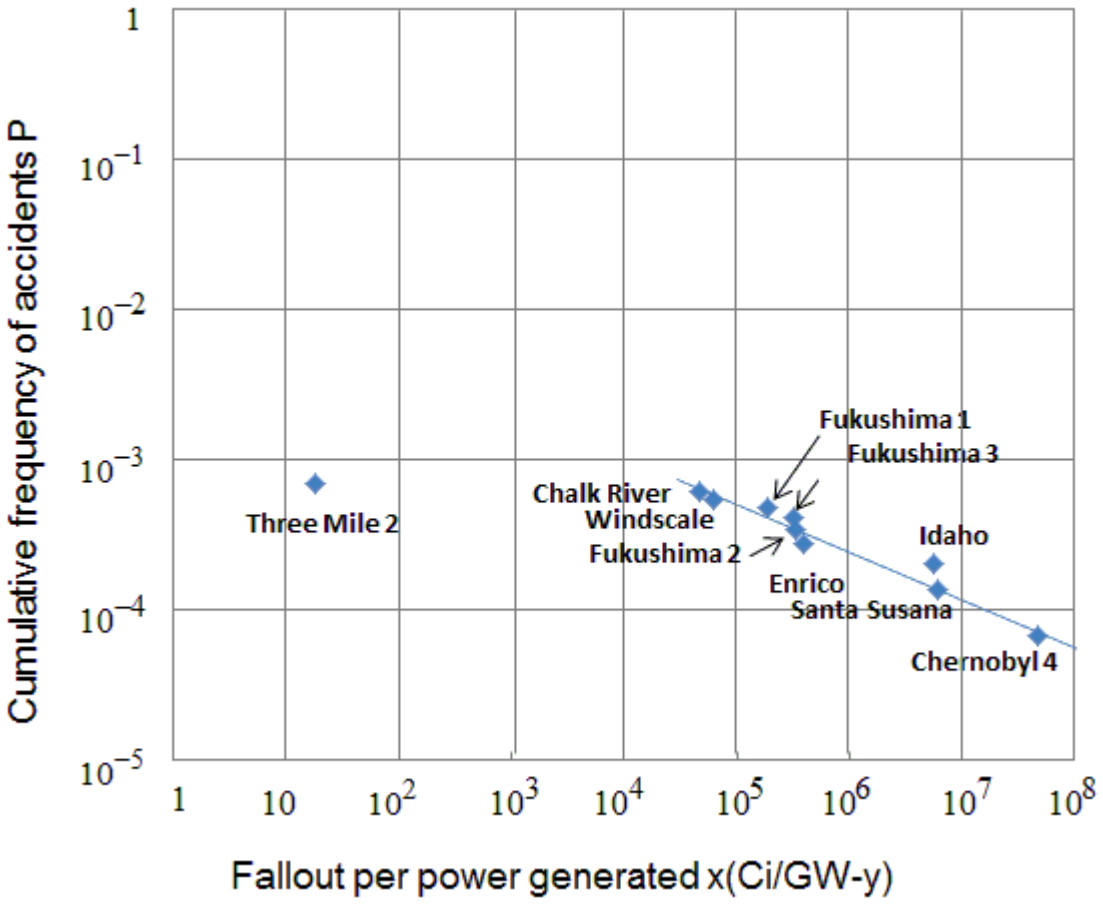

Figure-1 Cumulative distribution function of power-law

unit of frequency of P is once in reactor-year

From the straight line plot excluding Three Mile Island accidents, we get

$$\text{Log } P = -0.3034 \log x - 1.7709$$

This means $\alpha = 0.303$、and $C = 10^{-1.7709} = 0.017$ of

$$P(x) = Cx^{-\alpha}$$

Thus distribution function becomes;

$$P(x) = 0.017x^{-0.303}$$

5.Type of Reactor on Probability

As already pointed out, only exception of cumulative distribution function is Three Mile Island accidents. The fallout per power generated of Three Mile Island accidents is extremely low compared to other accidents. It seems that Three Mile Island plant behaved differently from other accidents. Probability of meltdown of Three Mile Island might be in the same order like other reactors. This suggests that the consequence x of Three Mile Island is extremely low compared to other case due to better containment capability.

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

Table-5 Characteristics of each nuclear plant

Original data were collected from reference No.10 to 36.

Regarding Three Mile Island accident, it seems that there is no big difference on frequency of melt down. The difference is rather attributable to the difference of containment capability. As shown in Table-5, Three Mile Island plant used pressurized water reactor (PWR). In the case of PWR equipped

with large containment vessel of which design pressure can withstand hydrogen explosion, almost all Cesium had been contained in containment vessel by bubbling up pressure relief gas through water in pressure relief tank. It has no big opening at the top of primary containment vessel as fuel is changed inside containment vessel. In addition, capacity of primary containment vessel is large enough for operator do necessary save actions. As the control rod penetration is at the top side of reactor pressure vessel, chance of corium penetration is also low. We can even say that PWR has lower probability of meltdown, because we can use directly connected steam generator as natural circulation cooling devise as if it works an isolation condenser of BWR.

On the other hand, Fukushima plants had been using boiling water reactor (BWR). BWR has small primary containment vessel. Smaller volume of containment vessel means that operator is given short time to do something to save the plant. It also has a large flange at the top of primary containment vessel for spent fuel change using crane placed above containment vessel. In addition, reactor pressure vessel is located just below of this large flange. This design is needed because spent fuel has to be changed with new fuel under water to avoid superheating of the spent fuel and for protecting operator from fatal radiation. Therefore, when reactor pressure vessel is heated up by decay heat, top flange of containment vessel would be heated by convection and radiation from hot reactor pressure vessel. Biological shield surrounding reactor pressure vessel worsen the situation by cutting heat loss from reactor vessel and send all heat up ward to the top flange of containment vessel. Thus the top flange of containment vessel starts leaking. As the BWR reactor vessel has many control rod penetrations through the bottom wall of reactor pressure vessel, molten corium of BWR easily penetrate through bottom holes of control rod drive of BWR without scrubbing through pool of water in suppression chamber. Radioactive material accumulated in the containment vessel eventually leaked out without cleanup of Cesium etc. Once leakage occurs, it may result in large release of fallout like the case of Fukushima.

The characteristic of nuclear technology is an unavailability of improvement by trial-and-error process common to other technology. Therefore, it is a very slow and unethical process to improve the technology. You might be able to find a better distribution by testing various reactor designs by computer simulation using agent based model etc. But you would not be able to eliminate long tail completely.

6.Meaning of the power-law distribution

Compensation/cumulative power is expressed in the following equation.

$$\text{Compensation/Cumulative Power} = P(x) \times \text{Loss of accidents}$$

Where P(x) is cumulative frequency of accidents.

When we assume that the Loss of accidents is proportional to a square of fallout. As compensation is only required for the linear area where people live and cultivate. along valley and flat land.

$$\text{Loss of accidents} = (\text{Fallout})^{0.5}$$

Here,

$$\text{Fallout} = x\ (\text{Cumulative Power})$$

When parameter α of P is 0.303, compensation for loss of accidents/cumulative power becomes;

$$\text{Compensation/cumulative Power} \propto x^{0.197}$$

It is reported that the compensation liability of Fukushima-daiichi is almost 10 trillion yen. From this figure, it is easily predicted that liability of Chernobyl class accident would reach 100 trillion yen as shown in Table-6. Cumulative frequency of Fukushima-daiichi accident is once in 2,900reactor-year and cumulative frequency of accidents of Chernobyl 4 is once in 14,500reactor-year.

This loss of accidents constitutes a long tail of distribution function and operating companies have to consider this mega loss exceeding maximum liability of insurance.

	unit	Three Mile Class	Fukushima-daiichi 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 (fall out)$^{0.5}$	tera yen/accidents	0.067	9.2	109
Compensation for loss of accidents/cumulative power	yen/kWh	0.05	3.17	7.50

Table-6 Compensation for loss of three major accidents

This means that compensation of accidents per power generated during its life time has no mean figure, and operator of the nuclear facility having poor containment provisions might face maximum environmental contamination greater than Chernobyl.

After we had made a presentation in NURIS 2015 held in Vienna about our findings, Spencer Wheatley et al published “Of Disasters and Dragon Kings: A Statistical Analysis of Nuclear Power Incidents and Accidents” in 2016 [37]. In Fig. 3 of this paper, the severity measures are plotted according to their empirical complementary

cumulative distribution functions (CCDFs) against cost, INES-1 scores, and NAMS scores. All showed straight line like power-law distribution. Hence their findings and our findings are equal.

The characteristic of nuclear technology is an unavailability of improvement by trial-and-error process common to other technology. Therefore, it is a very slow and unethical process to improve the technology. You might be able to find a better distribution by testing various reactor designs by computer simulation using agent based model etc. But you would not be able to eliminate long tail completely.

7.Cumulative distribution function v.s. density function

The derivative of cumulative distribution function of power-law is written as,

$$dP(x)/dx = p(x) = Cx^{-\alpha-1}$$

This is called probability density function of power-law. Figure-2 shows the p(x) when C=0.017 and α =0.303. Probability density function of power law range in 10^{-8} to 10^{-12} (1/GW-y). Whereas, as shown in Figure-1, cumulative distribution function of power-law range in $10^{-3.2}$ to $10^{-4.3}$(1/GW-y). This means that cumulative distribution function gives higher frequency than density function about an order of magnitude of 4.8 to 7.7.

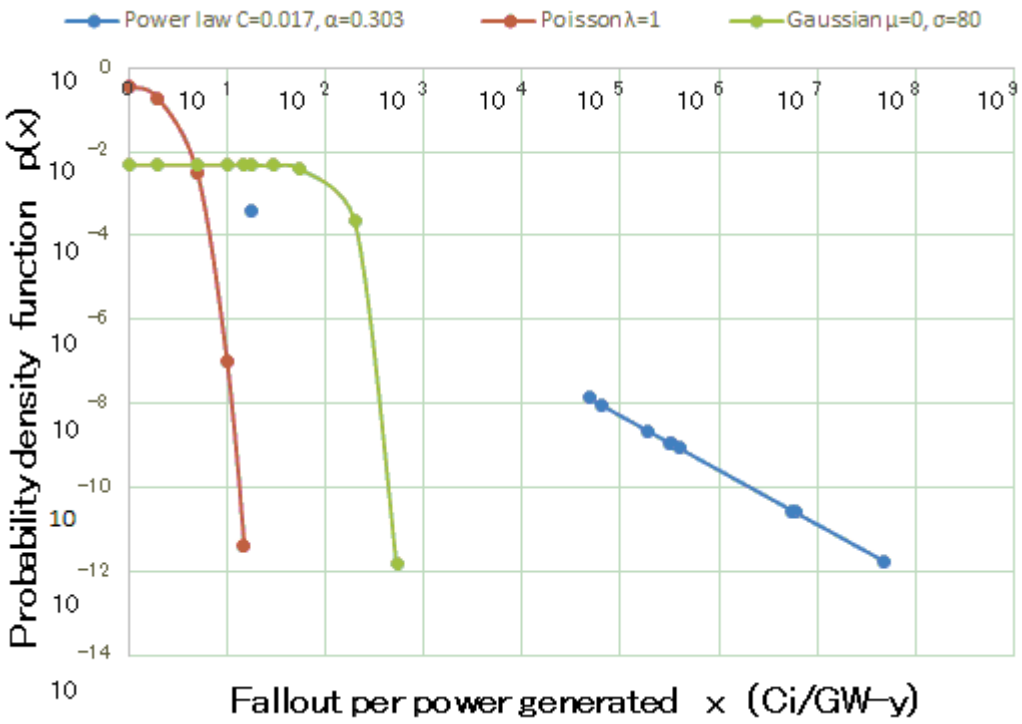

Figure-2 Probability density function

unit of frequency of p is once in reactor-year

PRA calculate top event frequency from component failure frequency using Boolean algebra. As component failure frequency is a density function of Poisson and/or Gaussian, top event frequency is still density function. Therefore, the density function has to be integrated to give cumulative distribution function. Otherwise, optimistic figure of PRA will mislead our society.

$$P(x) = \int_0^x p(x)dx$$

As shown in Figure-3 cumulative distribution of Poisson and Gaussian distribution approach 1 at larger x above 103(Ci/GW-y). This means that it is impossible to analyze cumulative operating data using those functions.

As shown in Figure-2, Probability density function of Poisson and Gaussian distribution could not handle long tail of nuclear plant properly. Here, the rate parameter of Poisson distribution λ =1. Gaussian distribution's mean μ = 0 and standard deviation σ = 80. Only power-law distribution could handle the long tail of nuclear accidents appropriately.

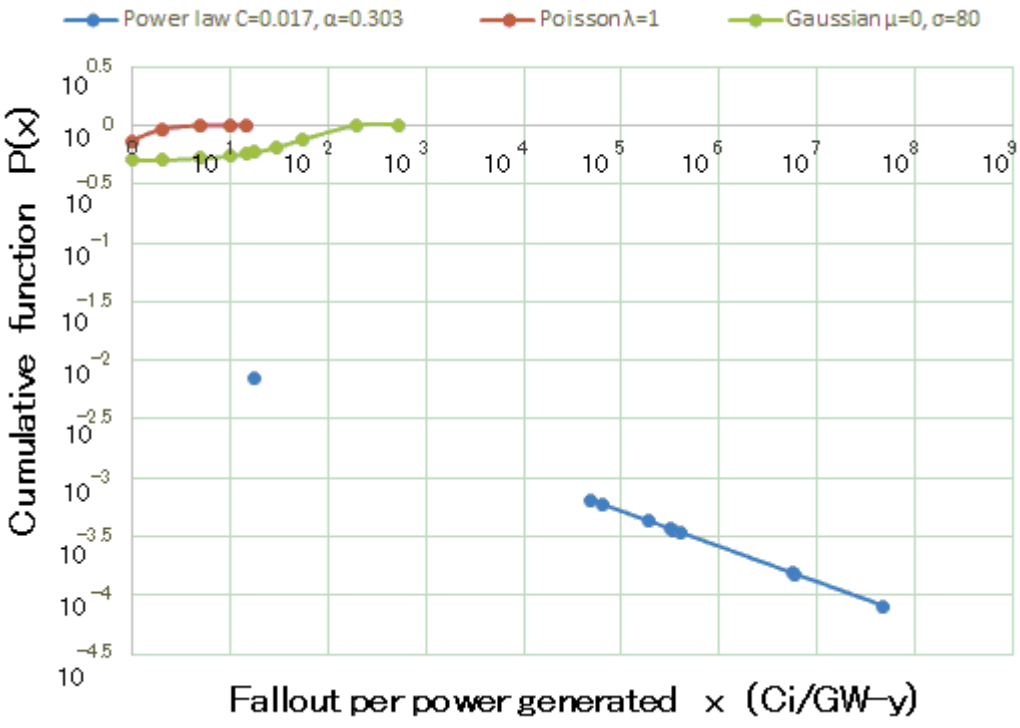

Figure-3 Probability density function

unit of frequency of p is once in reactor-year

8.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.

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.

PRA is not suitable in predicting cumulative frequencies of the nuclear plant accidents correctly.

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