Distribution of doses to residents evacuated after the Fukushima Nuclear Power Station accident

Shigeru KUMAZAWA*

Formerly, Japan Nuclear Energy Safety Organization, 4-1-28, Toranomon, Minato-ku, Tokyo 105-0001, Japan
*shuen85@jcom.home.ne.jp

This paper presents a feasible analysis of the distribution of doses to residents evacuated after the Fukushima NPP accident. Data for analysis are obtained from the reports of the Fukushima Health Management Survey. The hybrid lognormal distribution, which is a skewed lognormal including the parameter of protection feedback, best describes the dose distribution. The distribution of doses to residents in Fukushima Prefecture is also provided for comparison with that of the evacuated residents; this comparison is made by examining the dose distributions based on the monitoring data obtained for Fukushima. The paper also shows a method for improving data homogeneity in the relevant analysis.

Key Words: *dose distribution, resident evacuation, protection feedback, hybrid lognormal, homogeneity*

1. Introduction

Statistical analysis is essential not only for an adequate interpretation of radiological data measured in environment but also for comprehensive dose assessment in such various exposure situations because there are many sources of uncertainty that can lead to biased conclusions. Radiological data are often analyzed using the lognormal (LN) distribution[1)] because the quantities involved vary over several orders of magnitude. However, as protection measures reduce doses more to residents evacuated from highly contaminated area than to those evacuated from low contaminated area, such countermeasures might distort the lognormality of doses more to residents protected from higher doses than to those protected from lower doses.

The hybrid lognormal (HLN) distribution[2)] may be applicable for the variation in doses to residents who were evacuated to avoid higher exposure. The UNSCEAR report of 1982[3)] states that "*the control of doses approaching the dose limits leads to a normal distribution; this presumption can be used to carry out analysis as a hybrid normal/lognormal distribution*." Our paper presents an interpretation of the distortion in terms of statistical variation and it shows the skewed lognormal distributions of doses to evacuated residents and other data relevant to the accident that occurred in TEPCO's Fukushima Daiichi Nuclear Power Station. The paper also includes a method for improving data homogeneity.

2. Method

(1) Distribution Analysis

In general radiation protection is to explore a good chance of exposure to get a net benefit over the radiological practice; at the same time, radiation protection must provide good control in dose reduction to avoid higher exposure. Thus the effectiveness of radiation protection practice causes the dose variations among exposed persons with uncertainty in two factors, such as acceleration and braking of exposure associated with a beneficial activity.

The law of proportionate effect is ubiquitous in natural and social phenomena, which often brings about a change over different orders of magnitude in stochastic processes such as the LN distribution. The negative feedback mechanism is also ubiquitous in natural and social phenomena, and negative feedback generally causes change within the same order of magnitude, as in the normal distribution. The former can be considered as a function of accelleration, causing a geometrical increase in the involved quantities, while the latter can be considered as a function of braking or slowing down, thereby preventing excessive increase in the quantities involved by acting as a "control mechanism."

The annual radiation doses to workers subject to radiation have often been analyzed via the LN distribution since Gale's study[4 - 6]. In annex B of ICRP Pub.101a[1], the genesis of the LN distribution is presented in order to define the representative of persons exposed to radiation using the classical central limiting theory instead of the Martingale central limiting theory[7]. For workers and residents exposed to radiation, the system of radiological protection involves gradually strengthening the control of exposure by weighing the net benefit against excess levels while preventing the dose from approaching the dose limits or the reference levels. This control depends on the excess of exposure required for the relevant benefit.

To analyze the variation in doses to evacuated residents, we should weigh the effect of protection measures such as occupational exposure under an "as low as reasonably achievable" (ALARA) program. In cases of accidents, protection measures taken are not always reasonable because of limited information and limited options available; therefore, the dose distribution model should account for stochastic nature in factors of acceleration, i.e. dose-increasing stimuli, and braking, i.e. protection feedback.

The HLN model reflects the stochastic process of dose increment as $\Delta X = \varepsilon X/(1 + \rho X)$ (mSv) where ε denotes the random variable corresponding to exposure stimuli and ρ denotes the average protection feedback (mSv^{-1}) depending on the perceived severity of exposure. According to the Martingale central limiting theory, this stochastic process generates the HLN distribution of doses to persons exposed in a given period[7]. When the average feedback factor ρ is insignificant, the HLN distribution is the same as the LN distribution.

The HLN distribution is the probability distribution of a positive variate X so that $Y = \rho X + \ln(\rho X)$ is distributed normally with the mean μ and variance σ^2 of Y where $\rho X + \ln(\rho X) \sim N(\mu, \sigma^2)$ or $X \sim \Omega(\rho, \mu, \sigma^2)$. Defining the hybrid function $\mathrm{hyb}(x) = x + \ln(x)$ and its inverse function $\mathrm{cyb}(s)$ where $s = \mathrm{hyb}(x)$, the HLN distribution is $\mathrm{hyb}(\rho X) \sim N(\mu, \sigma^2)$ and the median is $\mathrm{cyb}(\mu)/\rho$. When the randomness of X appears in the range above a (>0) or from a to b, the HLN distribution is defined as $\mathrm{hyb}[\rho(X - a)]$ or $\mathrm{hyb}[\rho(X - a)/(b - X)] \sim N(\mu, \sigma^2)$. The latter is called the hybrid S_B distribution, following the Johnson's S_B (JSB) distribution defined as $\ln[(X - a)/(b - X)] \sim N(\mu, \sigma^2)$. The former is denoted as the HLN4 model. The LN3 model is expressed as $\ln(X - a) \sim N(\mu, \sigma^2)$.

In accident situations, like such as Chernobyl NPP, the extreme-value distribution should be considered to describe the radiation exposure in extreme variation with the longer upper tail of distribution. Using the hybrid function transformation to obtain flexibility of distributions, the extreme-value type I (EVI) or Gumbel (maximum) distribution is also defined as $\mathrm{hyb}(\rho X)$, $\mathrm{hyb}[\rho(X - a)]$ or $\mathrm{hyb}[\rho(X - a)/(b - X)] \sim \mathrm{EVI}(\mu, \eta)$ where μ is the location parameter and η is the scale parameter. These probability distributions are considered in order to analyze data of the doses to evacuated residents and other individuals in the vicinity of accident site.

(2) Homogeneity of acquired data

The homogeneity of data is important for an adequate dose assessment. To confirm data homogeneity, the best linearity should be identified between the horizontal and vertical variables after they are properly subgrouped. The hybrid function affords extended linear relationships

Fig.1 Example of hybrid scale x, scale values of which are marked on the linear scale of s with the relationship s=hyb(x).

Table 1 Nine types of linear relationships obtained with hybrid scales for x and y. (Center: the hybrid-hybrid section paper)

Linear–Log $y = \alpha + \beta\,\mathbf{ln}(x)$	Linear–Hybrid $y = \alpha + \beta\,\mathbf{hyb}(x)$	Linear–Linear $y = \alpha + \beta x$
Hybrid–Log $\mathbf{hyb}(y) = \alpha + \beta\,\mathbf{ln}(x)$	Hybrid–Hybrid $\mathbf{hyb}(y) = \alpha + \beta\,\mathbf{hyb}(x)$	Hybrid– Linear $\mathbf{hyb}(y) = \alpha + \beta x$
Log–Log $\mathbf{ln}(y) = \alpha + \beta\,\mathbf{ln}(x)$	Log–Hybrid $\mathbf{ln}(y) = \alpha + \beta\,\mathbf{hyb}(x)$	Log– Linear $\mathbf{ln}(y) = \alpha + \beta x$

because the hybrid function consists of three typical regions as a hybrid scale: logarithmic, hybrid and linear regions (see Fig.1).

To apply the hybrid scale to both x and y axes provides nine types of section papers (see Table 1). The hybrid–hybrid section paper unifies four types of popular section papers (normal, two types of semilog and log–log). It can often provide an adequate plot of data with the same variance over the whole range where the data varies in different orders of magnitude and at a time in the same order of magnitude.

(3) Data for analysis

The Fukushima Health Management Survey (FHMS)[8] has reported the effective radiation doses to 14,753 residents estimated by August 31, 2012, excluding radiation workers among 56.0% of respondents from the 29,044 subjects evacuated from Kawamata (Yamakiya), Namie, and Iidate (see Table 2). The FHMS also examined 22.4% of respondents from 2,027,950 subjects in Fukushima, and it has reported the effective doses to 104,697 respondents estimated by August 31,2012, excluding radiation workers.

The effective dose reported is estimated for the period from March 12 to July 11, 2011 (subsequently, the dosage was negligibly small), subtracting the background radiation level given as 0.04 (mGy/h) × 0.75 (Sv/Gy) = 0.03 μSv/h (the same as in Fukushima city). The FHMS also provided a method to estimate the annual effective dose to residents as a sum of four-month doses (3/12 - 7/11, 2011) and eight-month doses based on the average dose rate, obtained in Fukushima city from October 11 to November 11, 2011.

The residents of interest (Table 2) were evacuated over the interval between March 12 and 31, while a few of them were evacuated in late May or early June. Table 2 summaries the four-month effective dose (3/12 - 7/11, 2011).

For residents who were not evacuated, their doses were similar to the ones based on the dose rates at their locations. The Ministry of education, culture, sports, science and technology (MEXT)[9] periodically reported the integrated doses at given monitoring points in planned evacuation areas, restricted areas and other areas. Upon matching the area (Kawamata, Namie, and Iidate) and the four-month period (3/12/2011 - 7/11/2011), the distribution of doses to residents, who were assumed not to have evacuated, may be similar to the distribution of integrated doses obtained considering 8-h outdoor and 16-h indoor exposure with a shielding factor of 0.4 (as evaluated by the MEXT) for the same period at locations relevant to residents of interest (Table 2).

These data are used for the following analyses mentioned in the following section.

Table 2. Effective doses to residents of Kawamata, Namie, and Iidate (August 31, 2012)
http://www.pref.fukushima.jp/imu/kenkoukanri/240911siryou1.pdf

mSv	1	2	3	4	5	6	7	8	
residents	8414	3175	1193	577	476	378	212	101	
mSv	9	10	11	12	13	14	15	>15	Total
residents	74	37	40	28	16	10	10	12	14753

3. Results

(1) Distribution Analysis

The analysis of the data of doses (mSv) integrated at measured points in Kawamata, Namie, and Iidate by the MEXT[9], shows an LN distribution for the specific four months (3/12 - 7/11, 2011) or the year (3/12, 2011 to 3/11, 2012), as shown in Fig.2. The lower distribution boundary is estimated to be $a \approx 0.6$ mSv via the LN analysis.

Analysis of the data of effective doses (mSv) to residents who were evacuated from Kawamata, Namie, and Iidate by using the middle and upper bounds of the dose cells with weight of the number of data, provides the HLN distribution with the lower boundary close to 0.1 mSv (a=0.099), thereby showing the stronger effect of reducing the higher dose above approximately 4.5 mSv, which leads to a departure from the straight LN trend (see Fig.3).

The data plots in green are not used for curve fitting, where the highest and the second highest values are the

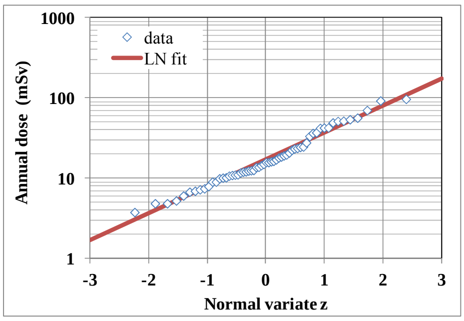

Fig.2 Log probability plot of integrated doses (3/12 - 7/11, 2011)[9] at measured points in Kawamata, Namie, and Iidate.

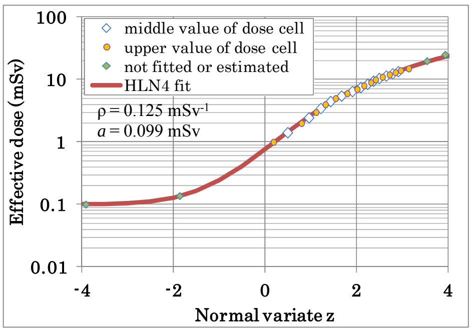

Fig.3 Log probability plot of resident doses reported in Table 2. (effective dose for the specific period: 3/12 - 7/11, 2011)

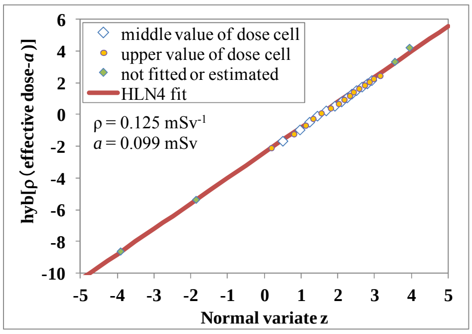

Fig.4 Hybrid probability plot of the same data plotted in Fig.3. (HLN4 model: hyb[0.125(x - 0.099)] ~ N[-2.412, 1.598^2])

reported maximum of 25 mSv and the middle of the dose cell (>15 mSv) on the hybrid scale, the lowest and second lowest estimated values are the minimum and the middle of dose cell (<1 mSv) estimated. These plots are account for by the straight line of the HLN4 fit, as shown in Fig.4. The extrapolation below 1mSv is made to account for the exposure situation (above the background radiation level) of 57% of residents, despite large uncertainty of such an extrapolation.

The FHMS initially reported a dose range 0.2 - 2 mSv for 20-km zone around the accident site and 0.8 - 19 mSv for the planned evacuation zone. Including the reported background level of 0.03 μSv/h, the four-month cumulative dose is about 0.086 mSv upon applying the calculation method used by the MEXT. Consequently the minimum dose to the residents might be of the order of about 0.1 mSv by as per HLN analysis.

When compared the fit line in Fig.2, the fit curve in Fig.3 is roughly in parallel with the fit line for z = 1 to 3; however, the curve gradually decreases and diverges to depart more from the line. Thus the higher doses in Fig.3 are distorted from the straight trend to reduce to smaller

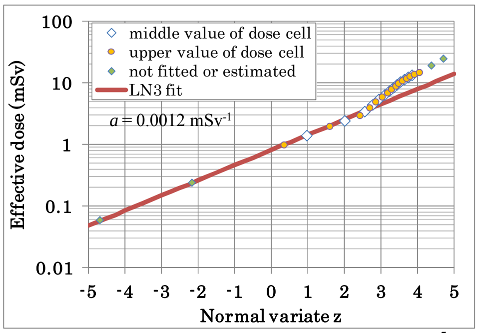

Fig.5 Log probability plot of doses to 4.6 × 10^5 respondents (excl. radiation workers), calculated from the dose statistics for 1.2 × 10^5 individuals among all respondents (4.7 × 10^5) [8].

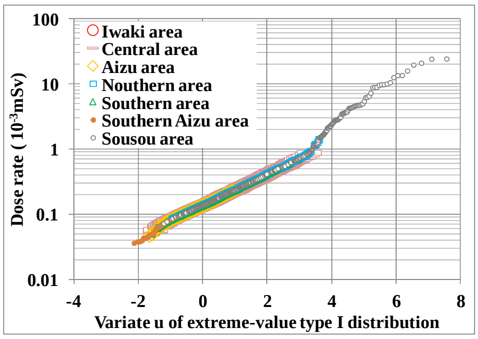

Fig.6 Extreme-value type I log probability plot of recent dose rates in eight areas of Fukushima. (data source: see text)

doses.

In order to obtain a rough distribution of doses to residents (excluding radiation workers) in Fukushima, we arrangd the statistics of doses to residents of interest (Table 1) and others reported by the FHMS for Northern, Central, Southern, Aizu, Southern Aizu, Sousou, and Iwaki areas according to the resident ratio for each subcategory and the estimation of integrated doses for Iwaki (not yet estimated). The doses to 4.6 × 10^5 respondents (excluding radiation workers) show an LN distribution (Fig.5) below 3 mSv with the lower boundary about 10^{-3} mSv; however, doses above 3 mSv are higher than the straight line. Almost data above 3 mSv corresponds to those in the Sousou area.

Analysis of the data concerning recent dose rates at 3,225 points in eight areas of Fukushima (data were down loaded from radioactivity.mext.go.jp/map/ja/), provides an extreme-value type I distribution below 10^{-3} mSv as shown in Fig.6. The departure pattern from the straight line is similar to that in Fig.5 because of both contribution from the Sousou area in both cases.

The FHMS process of estimating doses to residents in

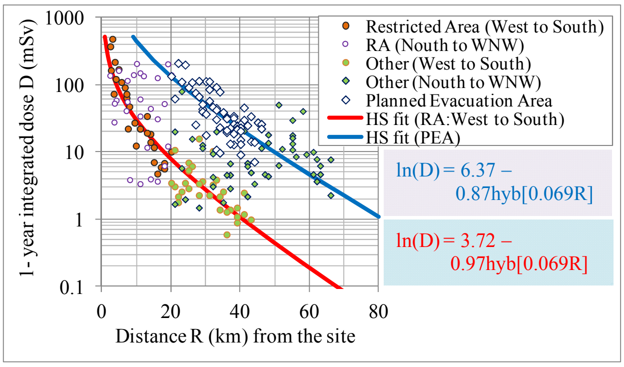

Fig.7 Basic trend of dose reduction over distance via the HS model.

Fukushima is still in an early stage. Therefore, it is too early to obtain accurate values of the dose distribution to the residents. However, as a preliminary analysis, Figs.2 ~ 6 may be useful in considering the effect of evacuation, on the statistical variation of resident doses, against excess radiation field in Fukushima, thereby supplementing the comprehensive dose maps for Fukushima.

(2) Homogeneity of acquired data

It is crucially important to understand the basic characteristics of dose trends in time and space. The Fukushima NPP accident reinforces the necessity of a comprehensive radioactivity map subsequent to the Chernobyl accident. However, it is useful to identify the underlying trend of dose reduction over distance.

The data concerning one-year integrated doses at a point[9] can be analyzed and fitted by the hybrid scale (HS) model as a straight line of the logarithm of dose vs. the hybrid transformation of distance (km) using the parameter ρ (km^{-1}) as shown in Fig.7. Thus the basic trend of dose reduction with normal residual errors can be obtained despite the complexity of radioactivity dispersion.

The time function of dose reduction is also expressed by the HS model in Table 2 because of the power law decay in the early stage and the exponential decay in the later stage, as shown in a predictive model of resuspension factor after deposition[10]: The HS model is expressed as $\mathrm{hyb}[\nu(S_f - a)] = \alpha + \beta\, \mathrm{hyb}(\tau\, t)$ where S_f : resuspension factor (m^{-1}), ν: 66,500 (m), a: 1.5×10^{-10} (m^{-1}), α: -8.36 (-), β: -1.40 (-), t: time (d) after deposition, and τ: 0.001 (d^{-1}).

For the dose assessment, the HS scale that depicts the evolution of the HLN distribution is useful for analyzing various relevant data with normalized residual errors in order to improve data homogeneity.

4. Conclusion

The study showed that the distribution of doses to residents evacuated from Kawamata, Namie, and Iidate is influenced by evacuation action by as per HLN analysis, while the integrated doses based on dose rates at a point are distributed lognormally for the planned evacuation area or in the extreme value type I distribution for the Fukushima Prefecture. To confirm the homogeneity of acquired data, the hybrid scale model (using a hybrid–hybrid section graph or nine types of section graphs) was proposed to use for the future analysis of various data relevant to the Fukushima NPP accident.

Reference

1) ICRP: "Assessing dose of the representative person for the purpose of radiation protection of the public," Annex B, Publication 101a, Ann. ICRP 36(3) (2006).
2) Kumazawa, S. and Numakunai, T.: "A new theoretical analysis of occupational dose distributions indicating the effect of dose limits," Health Phys. 41(3) 465-475(1981).
3) UNSCEAR: "Ionizing radiation: Sources and biological effects," Annex H (New York: United Nations) (1982).
4) Gale, H.J.: "The lognormal distribution and some examples of its application in the field of radiation protection," Report AERE-R4736 (1965).
5) UNSCEAR: "Sources and effects of ionizing radiation," Annex E (New York: United Nations) (1977).
6) ICRP: "Recommendations of the ICRP," ICRP Publication 26 Ann. ICRP 1(3) (1977).
7) Kumazawa, S. and Numakunai, T.: "Why do we need dose distribution models?," Radiat. Prot. Dosim. 36, 269-273 (1991).
8) Fukushima Health Management Survey: documents of the 5th and the 8th working committee, http://wwwcms.pref.fukushima.jp/pcp_portal/PortalServlet?DISPLAY_ID=DIRECT&NEXT_DISPLAY_ID=U000004&CONTENTS_ID=24809, in Japanese (2012).
9) MEXT: Integrated doses at a point of monitoring, http://radioactivity.mext.go.jp/en/contents/5000/4161

/24/1305904_0720.pdf(2011) or http://radioactivity.mext.go.jp/ja/contents/5000/4767/24/1750_032118r.pdf , in Japanese (2012).

10) Kumazawa, S.: "Reappraisal of predictive models for resuspension," ICRS-12 & RPSD-2012, Nara, 9/2-7, 2012, P3-55 (2012), to be published, Progress in Nucl. Sci. Tech.