Estimation of occupational compensation based on a linear-quadratic methodology for the nuclear industry

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Highlights

- Potential health damage caused by low doses of ionizing radiation is assessed.
- A Linear-Quadratic function is proposed instead the LNT relation for low doses.
- The new Linear-Quadratic methodology (LQM) results in significantly higher charges for higher doses.
- Also it results in lower charges for low exposure levels and even zeros payment for environmental doses.
- This LQM provides motivation for nuclear facilities to improve health & safety measures.

Abstract

Production of nuclear electricity is under scrutiny because of health issues connected with operation of nuclear facilities. National and international regulatory institutions aim to have regulations that ensure that any radiation dose received by the workers are kept as minimal as possible to reduce any risk on human health. Under these circumstances when a controlled nuclear facility is operating in standard conditions the possibility to have direct injuries connected by non-stochastic effects of ionizing radiation will happen only if regulations are violated. In addition, the stochastic effect of radiation may cause cancer. Nuclear power plants calculate the cost of potential health damage caused by ionizing radiation based on the Linear No-Threshold Relationship (LNT) between the dose and cancer risk. However, recent radiological research questions the validity of the LNT relationship for low and very low doses. In this paper, a new methodology based on a linear-quadratic function is proposed for the cost estimation of health risks induced by ionizing radiation, this new methodology results in significantly higher monetary cost for higher doses. At the same time the new methodology also results in lower monetary cost for low exposure levels and even zeros payment for environmental doses because they cannot be avoided. By adopting this new methodology it could provide motivation for nuclear facilities to improve health & safety measures.

1. INTRODUCTION

Electricity generation by using nuclear power reactors produces low greenhouse gases (GHG) emission in the whole life cycle, which substantiates nuclear energy as a clean electricity source (Nian, 2015; Hong, 2015; Alonso and del Valle, 2013). On the other hand, use of nuclear power requires regulatory structures that will provide very strict mechanisms of safety to reduce any possible risk due to ionizing radiation (Strupczewski, 2013). In addition, nuclear energy production is the one of the electricity generation technologies that has low external costs (Thopil and Poris, 2015; Vujic et al, 2012) during the generation phase though it requires higher investment costs for deployment than other base-load electricity sources (Hultman and Koomey, 2007; Joskow, 2011).

Any accident or incident, changes the public perception of safe operation in any electricity power plant, and this public perception increases if the source is a nuclear reactor, as it was the case of Fukushima disaster (Niam and Chou, 2014; Srinivasan and Rethinaraj, 2013; Poortinga et al, 2013). For these reasons, it has always been mandatory in the nuclear industry to evaluate the radiation doses to which personnel are exposed in any nuclear power plant.

A regulatory body continuously monitors the operations of nuclear power plants, which means keeping as low as possible the ionizing radiation dose to the personnel working at the power plants.

To meet this regulation there is an economic evaluation for collective dosage which is quantified in monetary terms and there will is a cost that must be paid by the nuclear utility to the regulatory body if the collective dosage is over a certain value. Currently, the mechanism used to calculate the collective radiation dosage is based on the Linear Non-Threshold model.

The Linear Non-Threshold (LNT) model overestimates the health risk induced by radiation because it uses a conservative approach. In particular at low doses there is insufficient relevant data to create a more precise model.

Since the LNT model is not adequate at low radiation doses, it will be important to find new relationships between radiation dose and health risk, thereby enabling in reducing negative perceptions within the general public about very low doses of ionizing radiation produced by the nuclear industry.

To substantiate this fact, several radiological studies consider as very low or non-existent the risk induced by very low doses of ionizing radiation (Tubiana et al, 209). In particular the threshold for very low doses is stated in the document “Effects of ionizing radiation Report to the General Assembly” (UNSCEAR, 2013a) at 50 mSv while Preston et al (2004, 2007) states the threshold in the range of 40-200 mSv.

In addition, Hooker et al (2004), Zeng et al (2006) and Loucas et al (2004) consider as safe dose, a limit of 100 mSv, as long as no intra-chromosomal inversions and deletions are observed. All of these dose values are higher than 20 mSv which is the standard accepted annual maximal occupational average dose in a nuclear facility.

In this paper a new methodology to assess very low doses of ionizing radiation is proposed. This very low radiation dose corresponds to the one that occupational personnel in a nuclear facility might be exposed to. As an example, the Nuclear Regulatory Commission of United

States of America sets a dose limit of 50 mSv per year for occupational personnel (NRC, 2015)

Using the new methodology which is based on a linear-quadratic function, the monetary health cost of health risks induced by ionizing radiation is calculated. This new methodology results in significantly higher monetary costs for higher doses. At the same time the new methodology also results in lower monetary cost for low exposure levels and even zeros payment for environmental doses which cannot be avoided.

The aim of this new methodology is to provide an economic motivation for nuclear facilities to improve health & safety measures in order to reduce collective radiation dosage. The rest of the paper is organized as follows: Section 2 presents a discussion about the LNT method and provides arguments about the inadequacy at very low doses of ionizing radiation.

Section 3 shows the current methodology based on the LNT model which is used to calculate the monetary cost for radiation exposure in a nuclear facility; Section 4 states the new methodology based on a linear-quadratic model; Section 5 discuss about the economic implication of its use in a specific case of study and the last section shows the conclusions of this work.

2. LINEAR NON-THRESHOLD MODEL

Collective effective dose must not be used for epidemiological studies; it can be used as an instrument for optimization and for comparing radiological technologies and protection procedures, and it is inappropriate to use it in risk projections. The *International Commission* *on Radiological Protection (ICRP)* (2007) recommends avoiding the usage of collective effective dose to compute cancer deaths because it conceals large biological and statistical uncertainties.

The linear non-threshold (LNT) dose-response model has been presented in its historical context by Kathren (1996); it was considered initially to assess radiation protection. The epidemiologic data used for the first time to build the LNT model comes from the atomic bombing survivors from Hiroshima and Nagasaki (Preston et al, 2007; Shimizu et al, 1989). There are evidences that LNT might be imprecise or even incorrect at low and very low doses, as it is the case of health risk of leukaemia, which follows a linear-quadratic function at low doses (Bast et al, 2000). The UNSCEAR report annex B (2013) from the United Nations confirm this fact. However, LNT model is still valid according to ICRP (Wrixon, 2008; National Research Council, 2006) and it is used by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2006; UNSCEAR, 2013a; UNSCEAR, 2013b), and there are also new publications that follows the LNT model (Zablotska, 2013).

The radiation hormesis model states that low dose radiation stimulates intrinsic cellular defence mechanisms that protect the organism against the development of cancer. This was initially proposed in the late 1950s and is gaining increasing support (Tubiana et al, 2009; Scott, 2014; Doss, 2013). The well-known effects of cell/tissue damage and cancer development are produced only by higher radiation doses.

The defense mechanisms stated in the hormesis model remains from the very early stages of evolution when the developing organisms were exposed to harsh environmental radiation

(Jaworowski, 1999). To prevent the cell damage or death, one of this mechanisms produce antioxidants which decrease levels of reactive oxygen species (Kataoka, 2013).

Microhomology-mediated end joining, homologous recombination and non-homologous end joining mechanisms repair the damaged double strand breaks (DSB) of DNA (Scott, 2014). These are error free except non-homologous end joining mechanism which is error prone. As stated by Tubiana et al (2009) “The magnitude of the mutagenic effect (per unit dose) varies with dose rate, reaching a minimum in the range of 1–10 mGy/min, which corresponds approximately to the rate of reactive oxygen species–inducing DNA damage during oxidative stress”. The probability of error during the repair of DSBs is low when DSBs are widely separated in space or time but increases drastically when multiple breaks are present simultaneously.

To remove the damaged cells the apoptosis (programmed cell death) is induced (Collis et al, 2004). The ‘adaptive response’ and ‘bystander effects’ is a mechanism that prevents harm from higher dose irradiation because of the exposure to low dose radiation (Tubiana et al, 2009; Scott, 2014). There is a more detailed description in the literature of the defense mechanisms stimulated by low dose radiation (Tubiana et al, 2009; Scott, 2014; Doss, 2013) but it is beyond the scope of this study.

Currently the radiation hormesis has been recognized by the French Academy of Sciences — National Academy of Medicine (Aurengo et al, 2005) and there are more studies favoring this hypothesis (Lehrer et al, 2015). The argument is that LNT ignores the intrinsic and archaic defense mechanisms stated in the hormesis model (Scott, 2014). This implies that there must be a threshold where the LNT model is not valid and the relationship between health risk and dose is different. In conclusion, there evidence showing that LNT model is not adequate at low doses.

3. LNT METHODOLOGY

The economic evaluation for collective dosage is quantified in monetary terms and it is denoted as alpha (α) and is expressed in USD/man-Sv. The sum of all personal dosages in the group is the collective dosage and its units are man-Sv. The economic evaluation is then expressed in USD.

There is no standard regulation among nuclear countries to set the alpha (α) values. Each regulatory body has set different fees to account for high personal doses (ISOE, 2012). The Information System of Occupational Exposure (ISOE, 2012; ISOE, 2015) provides the valuation data for occupational dosage for different countries. The ISOE is a database maintained by the OECD Nuclear Energy Agency and the IAEA; it conducts annual surveys among nuclear regulators and utilities to determine use of alpha (α) values.

The economic evaluation (EE) of the occupational dosage is calculated in USD based on the LNT model according to the formula:

$$EE = \alpha \times S \tag{1}$$

where:

EE- economic evaluation of dose (USD),

α – alpha value (USD/man-Sv),

S- collective effective dose (man-Sv).

The economic evaluation is a function of the collective dose such as **EE** = f(**S**). In addition, the collective effective dose is calculated as:

$$S = \sum_{i=1}^{n} H_{e_i} \tag{2}$$

where:

H_e – effective dose for a single person (Sv),

n= size of the group (man),

Here, substituting equation (2) in (1) and rearranging will produce equation (3) as

$$EE = \alpha \times S = \alpha \times \sum_{i=1}^{n} H_{e_i} = \sum_{i=1}^{n} \alpha \times H_{e_i} \tag{3}$$

In this way, Equation (3) represents the economic evaluation of dose as a sum of all individual dose economic evaluations according to individual effective dose (H_{ei}) .

Ionizing radiation has different effects depending on the part of the body that are acting, the type and source of radiation and the specific characteristics of the individual (OECD, 2011).

Four types of radiation are considered, α, β, γ, and neutrons, they interact with human cells in different way and produce different damage that it is directly related with a different weight factor Q. Each human cell has a different sensitivity to ionizing radiation and also the source radiation location produces different effects. It can be inside (internal) or outside (external) the human body.

Internal radiation can be produced by ingestion or inhalation and it can cause bigger cell damage therefore the limits, in food and drinks, of radioactive elements are very strict. Some authors have proved that some health effects can be seen even for low doses of ^{137}Cs when the exposure is given for long time period (years) (Jelin et al, 2016; Lindgren et al, 2015).

There are some methods available (Li et al, 2009) to assess internal exposure but it is beyond the scope of this work, however the focus here will be given to external exposure that is responsible for occupational exposure that happens in a nuclear power plant.

Radiation produces more damage in infants, young children and older people and for people with weaker immune system (UNSCEAR, 2012b). To account for how likely the cell is to be damaged by radiation is given by the radiosensitivity giving by different N factors. Human organs have different radio-sensitivity; depending on the exposed tissue volume the probability of damage will vary, if the volume is smaller the cancer probability increases. If a radiation dose is received in a shorter time the probability of damage increases, on the contrary if the same radiation dose is received in a longer time the probability decreases.

To account for the received dose, in other words the amount of radiation received, the following equation is used:

$$D = \frac{dE}{dm} \tag{4}$$

where

D- dose, unit : Gray (Gy),

E – released energy in the volume expressed in Joule,

m- weight of the volume expressed in kg

Here, it is important to measure the health risk induced by ionizing radiation to the human body, which is given by the effective dose H_e it is measured in Sievert (Sv). It is calculated as follows:

$$H_e = \sum_t w_t \times H_t \tag{5}$$

where:

$$H_t = \sum_k D_k \times Q_k \times N_k \tag{6}$$

where:

t = number of different tissues – approximate to number of exposed organs in body,

k – number of different types of radiation.

The total effective dose, provided by equation (5) is the sum of effective doses for each organ in the human body; here the radio-sensitivity weight factor W will be given for each organ. The effective dose on the particular organ considered is given by equation (6). It represents the sum of doses absorbed by the organ originating from all radiation types and sources with different factors **Q** and **N**.

The effective dose is only an approximation of real health effects because it uses statistical data to account for organ dose D and several other empirical defined weight factors (ICRP, 2007). In a nuclear plant, the general monitoring is performed by the use of a personal dosimeter which cannot measure the exact value of effective dose but rather provides an approximation.

In particular, depending on the type of work executed by the exposed operational workers, additional monitoring is performed in agreement with their work. Therefore occupational exposure is more precisely monitored than general public exposure due to likelihood of radiation exposure that could cause health damage under normal power plant operation.

4. LINEAR-QUADRATIC METHODOLOGY

The proposed methodology of economic evaluation for dosage is based on the linear-quadratic function because this function has been used and accepted in some health impact studies of low radioactive dose (UNSCEAR, 2006; UNSCEAR, 2013a; UNSCEAR, 2013b); Zablotska et al, 2013). The aim of this study is to avoid usage of the LNT model at low doses, and also to use average occupational dose **(S/i)** instead of the collective dose **S**.

Here, the proposed linear- quadratic function **EE/i** replaces the LNT function **EE**:

$$\frac{EE}{i} = a \times \left(\frac{S}{i}\right)^2 + b \times \left(\frac{S}{i}\right) + c \qquad (7)$$

where:

a,b,c are coefficients which must be calculated. ***i,***

EE,S – have the same meaning as in the previous equations,

(***S/i***) represents average effective occupational dose and,

(EE/i) represents the average payment per person in the nuclear facility.

In a nuclear facility by regulation, the upper limit of maximal allowed occupational dose is about 20 – 25 mSv. This value is below the limits considered in the studies done by Tubiana et al (2009; 2011) for lower doses where the LNT model is not valid, making the health effect in a nuclear facility negligible or non-existent. Therefore, the function of radioactive dose economic evaluation from Equation 7, **(EE/i)** and its coefficients **a,b,c** must be determined according to specific conditions.

Equation 7 must be set to zero if (***S/i***) is below the environmental background in the area where the nuclear facility is allocated. To meet this requirement the function must be explicitly defined to be zero if (***S/i***) < $\boldsymbol{R_e}$. Since the function is continuous, the linear-quadratic function from Eq.7 is set to zero only for (***S/i***) = $\boldsymbol{R_e}$. Substituting Re by (***S/i***) in Eq.7 and setting to zero then Equation 8 is set as:

$$0 = R_e^2 a + R_e b + c \tag{8}$$

Local nuclear authorities monitor the environmental background radiation on a regular basis. Therefore the values of average annual environmental annual dose $\boldsymbol{R_e}$ received by the population is known and is usually between 0.5-2 mSv (Slovak Republic, 2006; Bezuidenhout, 2014).

In addition, Equation 7 must provide positive value for any doses considered. To meet this requirement the resulting function must be convex which is fulfilled if a > 0. To ensure this requirement the discriminant from Eq.7 must be zero. This assumption guarantees only one non-trivial solution. Therefore this condition is then defined as:

$$\mathrm{a} > 0$$

$$0 = b^2 - 4ac \tag{9}$$

To set the last condition, the 20 mSv dose is considered as the upper limit, the LNT economic evaluation EE should be multiplied by at least a factor of ten to produce the same economic evaluation when the linear quadratic model is used for a 20 mSv dosage. The factor of 10 can be adjusted for each country according to the local regulations.

Using the above assumptions in equation 7, it is produced equation (10).

$$10(\alpha \times S) = 400a + 20b + c$$

then:

$$200\alpha = 400a + 20b + c \tag{10}$$

Eq.7 is valid only up to a certain upper limit dose for nuclear personnel; however this limit might slightly vary among countries; as mentioned it could vary between 20-25 mSv in average. In many countries using nuclear energy, this average limit is 20 mSv per year. In addition, in some countries the nuclear workers can be classified in different groups and some of them could receive higher doses. For example in Slovakia a group of classified workers could receive up to 50 mSv by year, however the integrated dose in any consecutive 5 years cannot be above 100 mSv (Slovak Republic, 2006). In this study the dose upper limit is 20 mSv ($S/i < 20$ mSv), which means that if the average occupational dose is close to 20mSv the health effect on the workers will be considered negligible or non-existent (Preston et al, 2007;

Loucas et al, 2004). However the nuclear facility will be charged accordingly because the dose is in the upper limit.

It is an international and national requirement to report to the International Atomic Energy Agency any incident or accident where employees have received doses above the upper limit. By regulation according to the received dose, these employees can be banned from any further work in ionizing radiation environments to prevent further biological damage and their health risk cases will be processed using another individual economic evaluation dose. However, their individual dose contribution still will be added to the economic evaluation dosage given by equation (8).

It is possible to receive higher average doses than the upper limit (20mSv) only in a case of an accident or as a consequence of serious violation of operational guidelines. These incidents are very rare and usually the numbers of cases are below 10 per annum worldwide (Turai and Veres, 2001).

Using MATLAB and equations (8), (9) and (10) the coefficients **a,b,c** are obtained, the solutions for these coefficients are:

$$a = \frac{200\alpha}{(R_e - 20)^2},\ b = -\frac{400R_e\alpha}{(R_e - 20)^2},\ c = \frac{200R_e^2\alpha}{R_e^2 - 40R_e + 400} \tag{11}$$

Using equation 7 and the coefficients given by equation 11, the economic evaluation dose for all the intervals considered is given as:

$$\frac{EE}{i} = \begin{cases} 0, & 0 \le \left(\frac{S}{i}\right) < R_e \\ \frac{200\alpha}{(R_e - 20)^2} \times \left(\frac{S}{i}\right)^2 - \frac{400R_e\alpha}{(R_e - 20)^2} \times \left(\frac{S}{i}\right) + \frac{200R_e^2\alpha}{R_e^2 - 40R_e + 400}, & R_e \le \left(\frac{S}{i}\right) \le 20mSv \\ must\ be\ calculated\ by\ another\ method, & \left(\frac{S}{i}\right) > 20mSv \end{cases} \tag{12}$$

Equation 12 provides the proposed linear-quadratic function set for the economic evaluation of dosage when **(EE/i)** at 20 mSv is 10 times higher compared to the LNT relationship. The next section shows the economic implication by using it.

5. ECONOMIC IMPLICATIONS

This new methodology has serious economic implications which are important to discuss. Taking into account the current methodology based on LNT, there is no universal standard fee among nuclear countries. Each regulatory body has set different fees to account for personal doses (ISOE, 2012). In addition to that there is no an exact report about the number of workers in each power plant. For example the Nuclear Energy Institute (2017) reports that in USA there are between 400 to 700 workers per unit reactor, on the other hand for example, the Netherlands and Mexico reports that there are 1000 workers per unit (ISOE, 2012).

There is no easily accessible data from most countries about the amount of people working in a nuclear power plant in order to calculate the average dose. Therefore three different scenarios of, 400, 700 or 1000 workers is used to calculate the average dose (S/i) from the information given in the ISOE country report (2012) for those countries where the regulatory bodies have set a fee for high personnel dose. Table I shows those average dose (S/i) for these scenarios. Table I shows the average dose by reactor type, where it can be seen that the higher dose is produced by the Boiling Water Reactor (BWR), followed by the Pressurized

Table I. Average annual dose by reactor type

Country	Average annual collective dose (man-mSv/unit)	S/i (400) mSv	S/i (700) mSv	S/i (1000) mSv	Reactor Type	Number of Reactors
Mexico	4833.51	12.08	6.91	4.83	BWR	2
Spain	2466.80	6.17	3.52	2.47	BWR	1
Switzerland	1234.00	3.09	1.76	1.23	BWR	2
United States	1222.39	3.06	1.75	1.22	BWR	34
Germany	1114.00	2.79	1.59	1.11	BWR	2
Sweden	835.00	2.09	1.19	0.84	BWR	7
Finland	376.24	0.94	0.54	0.38	BWR	2
Pakistan	1843.83	4.61	2.63	1.84	PHWR	1
Republic of Korea	585.15	1.46	0.84	0.59	PHWR	4
China	402.00	1.01	0.57	0.40	PHWR	2
South Africa	1028.16	2.57	1.47	1.03	PWR	2
Slovenia	790.00	1.98	1.13	0.79	PWR	1
France	710.00	1.78	1.01	0.71	PWR	58
Sweden	679.00	1.70	0.97	0.68	PWR	3
Pakistan	593.71	1.48	0.85	0.59	PWR	2
Switzerland	573.00	1.43	0.82	0.57	PWR	3
United States	440.50	1.10	0.63	0.44	PWR	65
Spain	430.25	1.08	0.61	0.43	PWR	6
China	395.00	0.99	0.56	0.40	PWR	23
Brazil	325.66	0.81	0.47	0.33	PWR	2
Belgium	320.00	0.80	0.46	0.32	PWR	7
Republic of Korea	310.52	0.78	0.44	0.31	PWR	21
The Netherlands	217.20	0.54	0.31	0.22	PWR	1
Germany	169.00	0.42	0.24	0.17	PWR	6
United Kingdom	50.91	0.13	0.07	0.05	PWR	1
Armenia	890.00	2.23	1.27	0.89	VVER	1
Ukraine	620.00	1.55	0.89	0.62	VVER	15
Russian Federation	559.60	1.40	0.80	0.56	VVER	18
Hungary	441.00	1.10	0.63	0.44	VVER	4
Bulgaria	377.00	0.94	0.54	0.38	VVER	2
China	260.00	0.65	0.37	0.26	VVER	2
Finland	258.43	0.65	0.37	0.26	VVER	2
Slovak Republic	163.41	0.41	0.23	0.16	VVER	4
Czech Republic	140.00	0.35	0.20	0.14	VVER	6
Canada	830.00	2.08	1.19	0.83	CANDU	19
Romania	194.00	0.49	0.28	0.19	CANDU	2
United Kingdom	66.58	0.17	0.10	0.07	CGCR	14

Heavy Water Reactors (PHWR), the Pressurized Water Reactor (PWR), the Pressurized Water Reactor Russian type (VVER), the Pressurized Heavy Water Reactor Canadian type (CANDU) and the Gas Cooled Reactor (GCR). In particular, BWR are the ones that present an average dose higher than 5 mSv and they have room for improvement.

Making a comparison between the linear and quadratic approximations:

$$\frac{EE}{i} = \alpha\frac{S}{i} \tag{3}$$

$$\frac{EE}{i} = \frac{200\alpha}{(R_e - 20)^2}\left(\frac{S}{i}\right)^2 - \frac{400R_e\alpha}{(R_e - 20)^2}\left(\frac{S}{i}\right) + \frac{200{R_e}^2\alpha}{(R_e - 20)^2} \tag{12}$$

It can be found that they have two crossing points at the following average dose points

$$\frac{S}{i} = \frac{\left({R_e}^2 + 360R_e + 400\right) \pm \sqrt{{R_e}^4 + 720{R_e}^3 - 29600{R_e}^2 + 288000R_e + 160000}}{400} \tag{13}$$

which are independent of the “alpha value”. The graphical plot of this function together with LNT function from Eq.(1) is shown in Fig. 1. The figure shows all the functions with coefficients **α**=1300 USD/man-mSv (ISOE, 2015) and $\mathbf{R_e}$=1.5 mSv. For illustration, the new formula with **α** = 308 USD/man-mSv is also shown.

Fig. 1: Comparison of of cost evaluation according to LNT and the new methodology

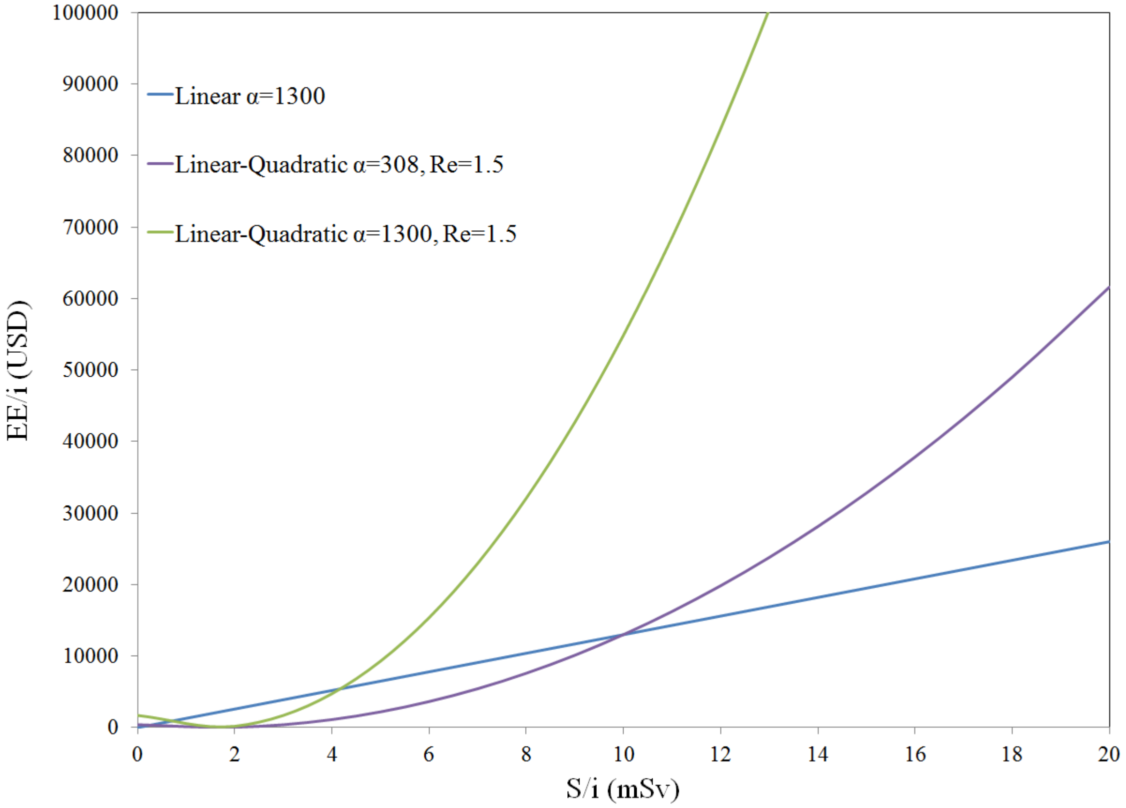
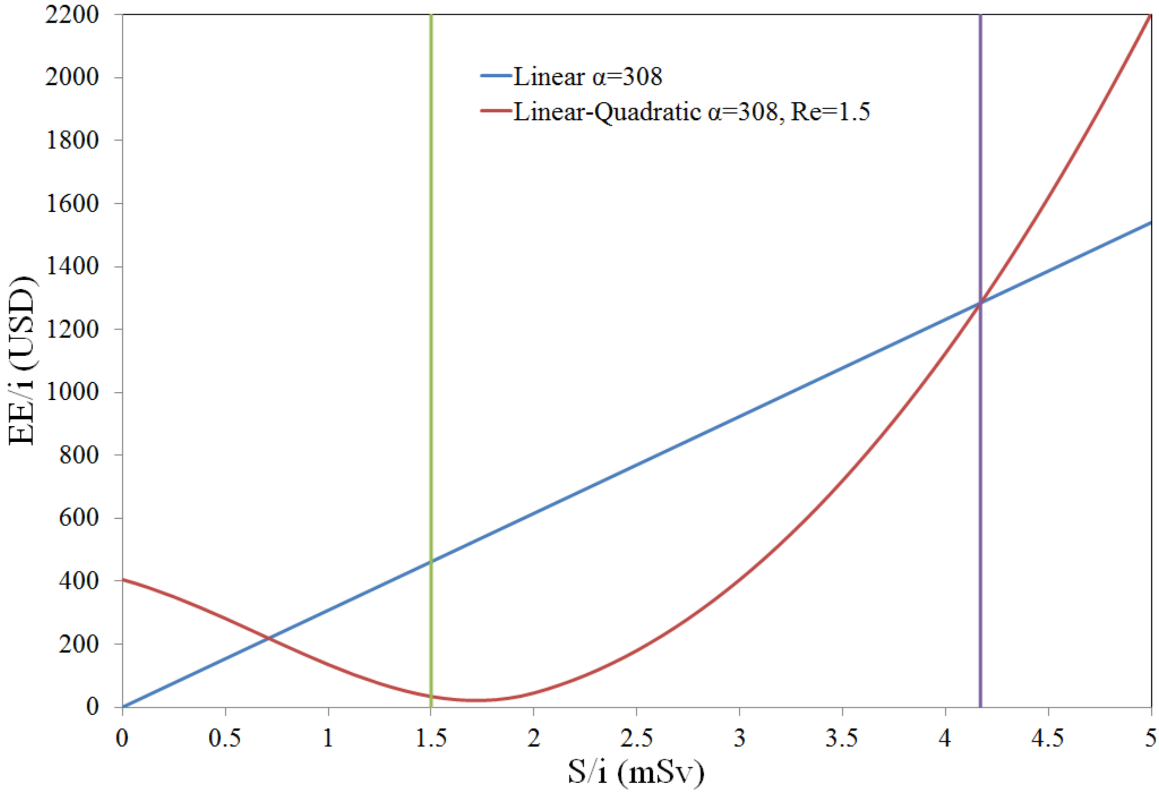


Fig. 2: Intersection between linear and linear-quadratic models



Here, for a background radiation of Re = 1.5 mSv and **α** = 308 USD/man-mSv, the crossing points will be at 0.54 mSv and 4.17 mSv, the first one is below the range of validity of the quadratic approximation that is above 1.5 mSv (see Fig. 2).

With this information, it is clear that the application of this particular quadratic approximation (which is strongly dependent on economic condition and alpha value) will produce higher penalty for average dose above 4.17 mSv and lower penalties if the average dose is below this value in comparison with the linear approximation.

From the information of Table I, the only type of reactor that has room for improvement is the Boiling Water Reactor (BWR), the other ones will benefit from the use of the quadratic approximation with lower penalties because they are below 4.17 mSv even if the amount of personnel is as low as 400 people.

Higher dose in a power plant mostly comes from maintenance activities and refueling outages, which are scheduled to last less than one month. Therefore, it is possible that some extra personnel could be hired for specific activities to reduce higher dose and get benefits from the use of the quadratic approximation. LNT behaves the other way around and motivates nuclear facilities to hire as few personnel as possible.

Fig. 3: The case of Mexico, using the linear and linear-quadratic models

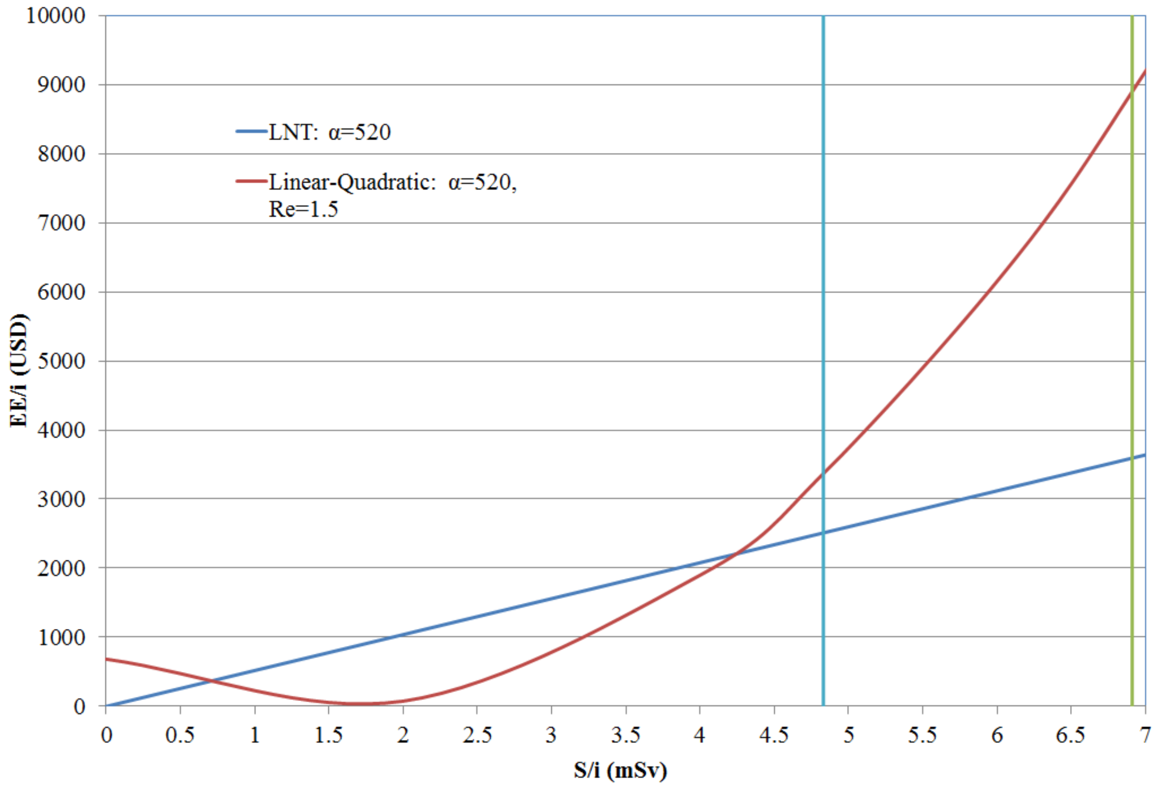


Table II. Monetary cost estimation in the Mexico case.

Average radiation dose (mSv)	Monetary cost (US$)	
	LNT: α=520	Linear-Quadratic: α=520, Re=1.5
0.00	0.00	0.00
1.5	780.00	0.00
2.00	1,040.00	75.97
4.00	2,080.00	1,899.20
4.17	2,169.40	2,169.40
4.83	2,511.60	3,369.60
6.00	3,120.00	6,153.40
6.83	3,551.60	8,632.65
8.00	4,160.00	12,838.57
10.00	5,200.00	21,954.71
12.00	6,240.00	33,501.83
14.00	7,280.00	47,479.91
16.00	8,320.00	63,888.97
18.00	9,360.00	82,729.00
20.00	10,400.00	104,000.00

ISOE (2015) reports 1000 workers per BWR unit in the Mexican Nuclear Power Plant. With this information, the average dose for each BWR unit is slightly over the crossing point of the linear and the quadratic approximations. Fig. 3 shows both approximations using the corporate alpha value of 520 US$ reported at ISOE (2012) and Table II shows the monetary cost obtained by using both functions for the 0 to 20 mSv range.

From Table II, for the 4.83 mSv average dose, the linear approximation shows a penalty of 2,511.60 US$ against 3,369.60 US$ if the linear-quadratic approximation is used. In the crossing point at 4.17 mSv the penalty is 2,169.40 US$ and below this value the use of the linear-quadratic approximation will provide economic benefits to the power plant compared to the use of the linear approximation. In addition, above the crossing point the linear-quadratic approximation will give higher penalties than the use of the LNT approximation as it is shown in Table II.

One way to reduce radiation exposure time and consequently radiation collective dosage is though the construction of a safety culture to improve system safety and workers team performance (Morrow et al, 2014; Hwang et al, 2009; Mitropoulos and Cupido, 2009).

In this nuclear power plant in Mexico, specific task during refueling must be assessed and the corresponding working time must be optimized to reduce exposure time as a way to meet the ALARA (As Low As Reasonably Achievable) criteria. However, determining how much radiation collective dosage is reduced by the use of these practices is beyond the scope of this work.

In addition, another alternative could be the hiring of temporary personnel to reduce the higher dose in refueling outages periods. However, the analysis to explore this alternative depends on the availability of trained personnel and it is also beyond the scope of this study.

If this second alternative is pursued there must be a tracking mechanism of the personal radiation dose because these workers will be performing the same task in different power plants in the same year and they cannot overpass the radiation dose limit of 50 mSv per year and the integrated dose in any consecutive 5 years cannot be above 100 mSv.

In general the international regulatory framework considers the use of the LNT model as appropriate. The validity of the LNT model for low doses deserves at least a new expert discussion which evaluates current research findings from radiology. LNT emphasizes danger of health effect for very minimal doses, which may create futile stress for people receiving these doses and create economic penalties for nuclear facilities for health risks which are probably non-existent.

If this proposed new linear-quadratic model is accepted and applied for the regulatory framework worldwide, it will motivate the nuclear utilities to improve procedures and optimize working time in radiation environments to reduce radiation personal dose. This motivation is based on the fact that penalties increase by a factor of up to 20 in comparison with the LNT model for average radiation dosage of 20 mSv per year. Thus nuclear utilities will have to limit the average radiation dosage to less than 4.17 mSv which is the crossing point between LNT and linear-quadratic model.

6. CONCLUSIONS

Although this study challenged the LNT model, it is recommended that greater scrutiny which includes additional investigations that may yield similar results are required until LNT at low doses will be officially disproved and replaced.

This study proposes an alternative methodology for economic evaluation of occupational doses. The new formula takes into account the second most widely used relation which is the linear-quadratic function. The main attributes of this kind of function include stronger motivation for nuclear facilities to protect their personnel and avoid higher occupational doses thereby reducing penalties.

The new methodology rewards nuclear facilities with very low exposure levels with low or zero payments compared to the LNT model which requires payment even for doses at the level of environmental background radiation. In addition, new methodology motivates nuclear facility to reduce cost of occupational dosage charges by improving procedures and/or employing more personnel.

The latter could be benefit for the regions with higher unemployment but at the same time it can mean a problem to find qualified personnel. Another possible operational opportunity which arises for nuclear facilities as a result of the new methodology is that, nuclear facilities can employ personnel for refueling process or annual maintenance operations only.

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