Safety Science 105 (2018) 1–8

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

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

Michal Chudy[a,b,*], George Alex Thopil[a], Gustavo Alonso[c,*], Johan F.M. Slabber[d]

[a] Department of Engineering and Technology Management, University of Pretoria, Lynnwood Road, Hatfield, Pretoria 0001, South Africa
[b] Institute of Power and Applied Electrical Engineering, Slovak University of Technology in Bratislava, Ilkovičova 3, 841 04 Bratislava, Slovak Republic
[c] Instituto Nacional de Investigaciones Nucleares, Carretera México-Toluca s/n, La Marquesa, Ocoyoacac, Estado de México 52750, Mexico
[d] Department of Mechanical and Aeronautical Engineering, University of Pretoria, Lynnwood Road, Hatfield, Pretoria 0001, South Africa

A B S T R A C T

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 et al., 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 Pouris, 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 (Nian 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

* Corresponding authors at: Institute of Power and Applied Electrical Engineering, Slovak University of Technology in Bratislava, Ilkovičova 3, 841 04 Bratislava, Slovak Republic (M. Chudy). Instituto Nacional de Investigaciones Nucleares, Department of Nuclear Systems, Carretera México-Toluca s/n, La Marquesa, Ocoyoacac, Estado de México C.P. 52750, Mexico (G. Alonso).

E-mail addresses: Michal.Chudy@stuba.sk (M. Chudy), george.alexthopil@up.ac.za (G.A. Thopil), gustavo.alonso@inin.gob.mx, gustavoalonso3@gmail.com (G. Alonso), johan.slabber@up.ac.za (J.F.M. Slabber).

https://doi.org/10.1016/j.ssci.2018.01.017
Received 5 December 2017; Received in revised form 19 January 2018; Accepted 25 January 2018
0925-7535/

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., 2009). 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 et al., 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 and Rosenzweig, 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).