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# Climate change and safety at work with ionizing radiations

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**Abstract**
The accident at Tokyo Electric Power Company's (TEPCO's) Fukushima Daiichi nuclear power plant (NPP) has been one of the dominant topic in nuclear safety and it has brought new attention on the matter of accidents in NPPs due to external events related to natural causes. Climate change has risen new risks and the growing probability of extreme external events has increased exposure and vulnerability of workers in the nuclear sector. However extreme natural events are a threat not only to NPPs but to all facilities dealing with radioactive material and in an emergency scenario they can affect the effectiveness and implementation of safety devices and procedures and also prevent communications, causing delays in the readiness of response. It is clear that adaptation strategies are necessary to cope with emerging changes in climate and a new nuclear safety culture is growing, that addresses accidents initiated not only by internal but also by external events.

**Key words**
- climate change
- occupational health
- safety management
- Fukushima nuclear accident
- emergencies

## INTRODUCTION

### *The Fukushima accident and the awareness towards climate change*

There is a great number of existing definitions of nuclear safety culture; IAEA International Nuclear Safety Group (INSAG) says that "safety culture is that assembly of characteristics and attitudes in organisations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance". In line with this approach, in her first talk to the staff in January 2016, Fabiola Gianotti, who just began her mandate as CERN Director General, started her presentation with a discussion on safety. In the last decades one of the major issues of discussion in the field of nuclear safety has been extreme (and rare) external events due to climate change (CC), which have proven to be some of the most serious initiators of degradation of defense-in-depth [1].

As a matter of fact, CC is not *per-se* a greater threat for workers with ionizing radiations (IRs) than for workers in other fields, but it could have a severe impact on safety directly or indirectly causing accident conditions, and the higher frequency and gravity of extreme weather events (EWEs) could lead to highly increased risks of exposure to IRs for workers.

The potential effects of EWEs on a nuclear power plant (NPP) were seen on March 11, 2011, when a major nuclear accident occurred at Tokyo Electric Power Company's (TEPCO's) Fukushima Dai-ichi NPP in Japan as a consequence of a huge tsunami that followed a massive earthquake: the combined effect caused the loss of off-site and on-site electrical power, so essential safety functions were lost at the plant, leading to core damage in three units and subsequently to considerable radioactive releases.

It was the worst emergency at a NPP since the Chernobyl disaster in 1986, but, unlike the Three Mile Island (1979) and the Chernobyl accidents, the chain of failures that led to disaster at Fukushima was triggered by an extreme external event beyond design basis. Therefore initially it was not a nuclear accident, but instead a NPP "under attack", and the accident was in fact recognized as the failure to prevent an accident that should have been addressed by appropriate safety measures.

Worldwide events have already shown that natural hazards can exceed the design basis for a NPP, but the Fukushima Dai-ichi accident has been an abrupt break in the overall trend towards higher safety in the sector of work with IRs, as it showed exposure and vulnerability to external events, in particular to flooding. Insufficient

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attention to external events and subsequent inadequacy of operating procedures caused complete loss of power, and then the lack of information on relevant safety parameters due to the unavailability of the necessary instruments and the loss of control devices. This means the impossibility to provide the fourth level of defense-in-depth, that is prevention of the progression of severe accidents and mitigation of their consequences.

The Fukushima accident showed that natural hazards are fundamentally different from internal hazards, as external hazards may simultaneously affect the whole facility, including back up safety systems and human intervention, and so it has brought new awareness of hazards due to EWEs and of the importance of proper implementation of defense-in-depth principle.

On the other hand, according to the Intergovernmental Panel on Climate Change, climate warming is unequivocal, and severity of effects depends on exposure and vulnerability of the systems. In particular the CC in the Mediterranean area will make it a region of high exposure and vulnerability.

As nuclear and radiation safety is the synergetic sum of several factors, there is an urgent need to undertake a comprehensive analysis of all external hazards as part of the design process and safety requirements for all facilities working with IRs, providing adequate protection against extreme weather conditions in the light of lessons learned to date from the accident at Fukushima. This article will then evaluate the risks for workers with IRs arising from CC impacts, bringing the conclusions also beyond the world of NPPs – to realities apparently more safe such as the hospitals, which, however, show a certain degree of vulnerability.

## IMPACTS OF CLIMATE CHANGE ON SAFETY AT WORK WITH IONIZING RADIATIONS

Changes in many extreme weather and climate events have been observed since about 1950 [2], and globally the number of weather-related natural disasters have more than tripled since the 1960s [3]. CC actually increases the risk of events like storms, droughts and floods, cyclical changes in precipitation, or long-term changes in temperature and sea levels [4], also modifying the frequency, intensity, duration, timing and spatial extent of extreme events. CC then could act as a significant "risk multiplier", and impacts of CC on safe operations of NPPs have been recognized by the International Atomic Energy Agency (IAEA) [5].

As a matter of fact, in the last decade EWEs have proven to be a real threat to the three fundamental safety functions in nuclear and radiological facilities, which are the control of reactivity in the nuclear fuel, the removal of heat from the reactor core and spent fuel pool, and the confinement of radioactive material, by both affecting the availability of water resources and causing deep damages to key buildings (*e.g.* those housing instrumentation and equipment) and control systems. Moreover, the impact of EWEs on the surroundings of the facilities can also impair emergency preparedness and response, which are critical issues in handling nuclear or radiological emergencies.

Flood hazards in particular have been recognized as one of the most threatening disasters, firstly because they are related to several extreme meteorological phenomena, such as local extreme rainfall, off-site precipitation with waters routed to the site (besides models show an intensification of heavy precipitations in the future [6]), obstruction of a river channel by landslides, logs or debris, tornadoes, hurricanes and storm surges on the coasts, etc. Secondly, their repercussions at the site of a plant can be severe, as water collecting on rooftops or in low lying plant areas is a common cause of failure for safety related systems, and masses of water and accompanying debris can damage buildings and cause electrical shorts (with the subsequent disruption of other systems).

Furthermore, as it has been outlined, the flooding may involve also external infrastructures, causing power outages and affecting communication and transport networks around the plant site, eventually hampering emergency response and procedures. In the case of tornadoes, besides the other flood hazards it has also to be considered the risk of the striking of a missiles, *i.e.* flying objects transported by the tornado, among the potential hazards for the vulnerable critical areas of a plant.

Many NPPs as well as many radiological facilities (*e.g.* hospitals) in the world are also exposed to the above mentioned risks related to hurricanes and storm surges as the former can be located in low-lying coastal areas and the latter in coastal towns.

As an illustrative example of flood's impact, the chain of events of the accident at Fukushima Daiichi NPP on March 2011 can be shortly illustrated. The flooding, in this case resulting from the tsunami, was the cause of failure of the emergency power supply system, which, added to the previous loss of off-site electrical power, led to the station blackout and the subsequent near complete loss of systems providing DC power to measuring and control devices, and the destruction of the structures and components providing seawater cooling for the plant. This lack of cooling resulted in explosions and partial meltdowns at the plant facility, with problems at all six reactor units and the central spent fuel pools, and then in the release, over a prolonged period, of large amounts of radioactive material into the environment. The only emergency diesel generator unaffected by the flooding was that of Unit 6, located on the first floor of a separate diesel generator building at higher elevation with respect to the others, where generators were at ground floor.

Impacts on the surroundings are not less important: at Fukushima, backup power supplies (batteries or generators) from different locations could not be transported to the plant, since the roads that had not been damaged were jammed with cars fleeing the disaster sites – workers had to use their car batteries and plug them into the instrument panels in the control room. The same situation happened for instance in Florida in 1992: during the hurricane, access roads around the Turkey Point NPP were blocked and, even though emergency diesel generators maintained the plant during the loss of power, helicopters had to be used for fuel [1]. Moreover, the effects of such EWEs can create difficulties for the emergency response personnel to get to the plant site, as it happened during the flood in 1999 at Blayais NPP.

These risks however are not limited to NPPs, but involve all facilities working with IRs, also in those countries that do not exploit nuclear energy.

In many hospitals the nuclear medicine units (NMU) and the brachytherapy units (BU) are located in underground areas, extremely vulnerable to incoming water in case of flooding. In NMUs large amounts of unsealed radioactive sources are stored both for diagnosis ($^{99m}$Tc, $^{67}$Ga, $^{201}$Tl, $^{123}$I, etc.) and metabolic radiation therapy ($^{131}$I, $^{90}$Y, $^{177}$Lu, $^{186}$Re). In BUs sealed high activity sources are present for radiation therapy ($^{192}$Ir, $^{103}$Pd, $^{125}$I, $^{106}$Ru, etc.). Moreover, the presence of a commercial blood irradiator with a source of $^{137}$Cs could be one of the potential causes of exposure of workers, as the Cs source is contained in a case made of lead, and if the room is flooded the case could capsize and disperse the radioactive source into the environment. The same could occur for example with $^{63}$Ni sources for gas chromatography and especially with $^{192}$Ir portable sources used in industry for gamma radiography to locate flaws in metal components, as due to a flooding the source could end up submerged in mud and debris or dragged away. This may result in an undue exposure either during search operations or for a casual finding after the accidental event, as it happened for example in Egypt in 2000 when a lost $^{192}$Ir source caused serious exposure of more than one hundred people in a village [7].

In particular, areas for the storage of radioactive waste from diagnostic and therapeutic NMUs are often in detached underground areas. If the area containing the tanks for liquid waste and Imhoff tanks is inundated with water from a flooding or infiltrations from the roof (not always with an adequate impermeabilization), there is the risk of overflow of waste from the tanks and dispersion of radioactive material in the environment. The safety system would detect the presence of water on the floor as an accident due to an overflow of waste from one of the tanks, and then the content of the full tank would be discharged in the empty ones; however, there could be a malfunction of the automatic safety system due to water in close proximity to switchboards and electrical cables, so workers should manually intervene and activate the safety systems, as long as the switchboards and control panels are still attainable. It could also happen that, if the tanks are not fixed to the ground and the room is flooded, the tanks may float in the water, pouring out the liquid waste and spreading radioactive contamination.

Since NMUs are located within hospital complexes, the potential dispersion of contamination would affect workers and population of the entire hospital, and, in case of flooding, the radioactive waste could be carried away because of streams of water forming along streets.

Moreover, even in hospitals emergency diesel generators are often housed in underground rooms, exposed to the risks of flooding, with all the already mentioned consequences for the safety systems and automatic controls in the NMUs, as it happened in some hospitals during hurricane Katrina in 2005.

Another effect of CC to be taken into account is that the length and frequency of warm spells, including heat waves, have increased since the middle of the 20th century in large parts of Europe, Asia, and Australia and many simulation models anticipate an increase in their duration, intensity and spatial extent. Frequency and intensity of drought has also increased in the Mediterranean during recent decades [8].

Heat waves, high temperatures and eventually drought may cause higher river water temperatures and lower water level in rivers during summer, finally resulting in water scarcity and a lack in water supply. Water however is a basic resource for NPPs, as they need large amount of water in order to ensure both cooling of the reactor core and operativeness of the safety systems, and this requirement for long term core cooling is the reason why NPPs are always placed near consistent water sources as oceans, lakes or rivers.

In the last ten years, for example during dry summers of 2003, 2006 and 2009, reactors in several countries had to be shut down or reduce energy production due to the limited availability of cooling water. In summer of 2003 more than 30 NPPs in Europe had to operate at reduced capability because of water supply shortages, however some plants got exemptions from legal requirements to be able to continue their operating activities [9], with all the ensuing consequences for the safety of workers and also increased risk for the surrounding population and environment as well.

Moreover, drought may trigger wildfires: for instance, in the Western United States, since 1986, longer, warmer summers have resulted in a fourfold increase of major wildfires and a sixfold increase in the area of forest burned, compared with the period from 1970 to 1986 [10]. An indirect impact on all radiological and nuclear facilities is that smoke from wildfires can be blown to the site, damaging sensitive equipment and ventilation systems, and making access to the site extremely difficult for supply deliveries and critical personnel such as emergency response workers, as it happened at Cadarache Laboratories in France in 1989 [1].

Furthermore, the potential impact on different safety-related systems of a fire reaching a plant can be envisaged on the basis of the events following the cable-tray fire at Browns Ferry Unit One nuclear reactor in 1975, which caused multiple-system failures: the fire damaged many of the control cables, so that, despite redundancies, the emergency core cooling system was lost and normal cooling to the reactor fuel hampered, even though some cooling systems remained operative allowing to avoid core meltdown [11].

As concluding remarks it has to be considered that the lifetime of an NPP, including the decommissioning time, is more than 100 years, so NPPs and radioactive waste repositories are potentially vulnerable not only to occasional EWEs but also to slow and gradual CC impacts, such as sea level rise (which can affect NPPs located in coastal regions), coastal erosion or geomorphic changes like river course alterations. In particular for repositories it is extremely difficult to develop a credible safety assessment for a specific site because of the impacts of CC on the water cycle, for example designing the protection of repositories on the basis of the pace of sea-level rise or modelling how water could infiltrate a deep geological repository.

Most of the above mentioned risks are present in Italy because, even if civilian use of the nuclear energy for production of electricity was banned in 1987, Italy is the most "nuclear" of the "non-nuclear" countries, with, among other installations, four NPPs under decommissioning, a planned radioactive waste repository and several thousands of workers exposed to the risks of IRs in many different radiological facilities. Besides, while on the Italian territory nuclear accidents involving NPPs are not possible, as the few existing NPPs are currently dismissing, countries like France, Switzerland and Slovenia are equipped with NPPs, some of them close to the Italian borders. Therefore hypothetical nuclear accidents involving these facilities may require emergency actions and delayed remediation activities also on the Italian territory and potentially involving emergency workers even from Italy. Moreover, Italy has a high grade of exposure to CC, as it is located in the Mediterranean basin, which has been identified as a "hotspot" for CC where environmental impacts are more relevant than in other regions in the world [12].

## HAZARDS TO WORKERS

Extreme weather events due to CC can substantially increase the risk of exposure for workers with IRs, with their potential to cause emergency conditions and then harsh and critical environments with which workers have to cope.

Even though EWEs have a very low probability of occurrence they can result in significant consequences. The correlated risk, defined as the probability of occurrence of an event multiplied by the size of the damage ($R = P \cdot D$), could be similar to that of common events in the working routine of NPPs characterized by high probability of occurrence and limited size of the damage.

The Fukushima Daiichi accident demonstrated what could be the potential impact of extreme natural hazards on NPPs and facilities dealing with IRs, showing in particular vulnerability of safety systems to flooding. A systematic identification and assessment of external hazards and robust protection against them needs therefore to consider the lessons learned after that accident.

### *Exposure to radionuclides*

In the early phase of a nuclear or radiological accident the most significant contributor to the exposure of workers involved in emergency operations are external and internal exposure from radionuclides in the plume and deposited on the ground, the greatest source of intake of radionuclides being the inhalation.

At Fukushima, the noble gases $^{85}$Kr and $^{133}$Xe contributed to external exposure from the plume, the longer lived $^{134}$Cs and $^{137}$Cs to both external and internal exposure, while the intake of $^{131}$I, despite its short half-life, can give rise to relatively high equivalent doses to the thyroid gland. These are the same radionuclides released from the reactor that mainly caused exposure of individuals after the accident at the Chernobyl nuclear reactor, occurred on 26 April 1986.

So in the short term $^{137}$Cs and $^{131}$I, together with $^{134}$Cs, give by far the largest contribution to the exposure of workers, while in the long term the most important contributor is the external radiation from the deposited $^{137}$Cs. In particular, 50% of inhaled $^{131}$I is exhaled, and the rest quickly reaches the bloodstream; then 30% is absorbed by the thyroid gland in a day and 70% is excreted in the same time. Due to the short time it is critical to provide medical care to the exposed workers, and the use of stable iodine for thyroid blocking within the first 24 hours is often needed.

In order to deal with the emergency at Fukushima, immediately after the accident an effective dose reference level of 100 mSv was adopted by the government for the workers involved, and it was raised to 250 mSv on 14 March 2011 due to the particular circumstances. These constraints are in line with the internationally recommended reference levels by the International Commission on Radiological Protection (ICRP) and the requirements in the IAEA safety standards, which suggest a guidance value of 500 mSv for persons engaged in emergency activities aimed at preventing further worsening of a nuclear accident.

### *Harsh environmental conditions and related occupational health and safety (OHS) risks*

Apart from the radioactive release, EWEs may cause widespread destruction of many buildings, roads, and other infrastructures around the plant site, so workers involved in emergency operations may face a complete and prolonged loss of electrical power, instrumentation, reactor control, and communications systems both within and outside the site.

In these extreme working conditions, operators in the early phase of the accident (days to few weeks) have to mitigate the radiological consequences and further progression of the accident, for example restoring the cooling system by reestablishing electrical power, and then take care of reactor stabilization and water decontamination. Afterwards, materials affected by the accident – *i.e.* debris, sludge from the water and sewage treatments, incinerated ash, trees, plants and soil resulting from decontamination activities – have to be disposed of.

Moreover, if a nuclear accident affects the environment surrounding the facility, after the management of the acute phase, remediation activities may require the employment of potentially large numbers of workers for long periods (weeks, months or even tens of years). These outdoor workers are not only exposed to radiation but also to a potentially increased levels of environmental agents, such as solar UV radiation or organic pollutants, with an increased risk for health outcomes arising from combined exposure to radiation and other chemical or physical agents, if an adequate personal protection and a proper medical surveillance are lacking.

Personal protection is imperative in the case of remediation activities with exposure to IRs as medical surveillance is. However, a more challenging thermal environment due to CC may alter the compliance with personal protective devices, impairing the optimization of radiation protection as well as the effective protection against other pollutants.

In the case of Fukushima, by the end of October 2012 24 832 workers had been involved in mitigation and other activities at the NPP site; about 15% of them were employed directly by the plant operator (TEPCO), while the rest were employed by contractors or subcontractors. In addition, a few hundred workers from the emergency services were deployed for on-site and off-site operations, including fire-fighters, police and personnel of the Self-Defense Force.

Implementation of the arrangements for ensuring the protection of workers against radiation exposure was severely affected by the extreme conditions at the site. Following the external EWE, operators had to work exceptionally long hours exposed to traditional OHS risks including heat, stress, explosion and fire as well as radiation. They had to secure the safety of the reactors and the nuclear fuel storage pools coping with loss of almost all power supplies, lack of proper equipment, loss of all safety systems including instrumentation and control. Additionally, many emergency workers came from different professions, but not all of them had been designated before the emergency nor had been trained to work in conditions of a nuclear emergency. As a matter of fact, in the early phase of the accident the main contributor to effective doses was internal exposure due to the intake of radionuclides, which may be attributed not only to the extreme working conditions but also to the inadequate implementation of protective measures, primarily attributable to the inadequacy of training [13].

Because of food and water shortages workers were provided with minimal nutrition and medical management; in addition the provision of personal protective equipment was severely affected.

Workers were exposed to radionuclides, predominantly in the form of airborne activity as a result of the hydrogen explosions and the continuing releases of radioactive material from the damaged reactors, so many of them had to work outdoors wearing double-layer Tyvek protective overalls and full-face respirators, causing heat exposure to become a supplementary important hazard.

***Loss of radiological monitoring***

Notwithstanding the high radiation levels, the capabilities for monitoring radiological conditions effectively, both on-site and off-site, may be severely hampered by EWEs: flooding may cause the loss of personal dosimeters, computer systems for recording dose from these devices, and portable survey instruments, while installed radiation monitors may be down due to the loss of electrical power, so it is not possible to gather information on controlled areas or on personal doses. Consequently emergency operations can be impaired as airborne and surface contaminations cannot be detected and workers cannot evaluate risks correlated to possible remedy actions.

At Fukushima, between 12 March and 1 April 2011 emergency operators had to share electronic personal dosimeters, with only one worker in a team wearing a dosimeter, and workers logging their individual doses manually, until after 1 April when personal dosimeters were provided to each worker.

The lack of information due to the unavailability of the necessary instruments because of the flooding is a critical issue for safety management: first of all, it hampers the prompt quantification and characterization of the amount and composition of the radioactive release and impairs the protective actions to be implemented and continuously modified in response to developing plant conditions or monitoring results.

Moreover the failure of a proper monitoring of exposure makes it difficult to draw health consequences for workers involved. Early and continued direct measurements of the radiation exposure and the levels of radionuclides incorporated are necessary for estimating radiation risks and potential health effects and for optimizing protection. In particular, while the assessment of external exposure is possible on the basis of information provided by electronic personal dosimeters, even using a single personal dosimeter per group of emergency workers expected to operate in similar conditions, internal exposure assessments rely on the assumed exposure scenario as well as on the use of complex models and software, thus giving rise to a greater uncertainty in the case of EWEs.

In the emergency conditions of the Fukushima Daiichi accident, *in vivo* measurements were possible only with a mobile whole-body counter at Onahama, 55 km south of the NPP site, with all the difficulties due to the large number of workers to be monitored and the relatively high environmental background. Results were reported only for $^{131}$I, $^{134}$Cs and $^{137}$Cs; for some workers with higher effective doses results were also reported for $^{136}$Cs and $^{129m}$Te. For most of the workers *in vivo* monitoring of $^{131}$I in the thyroid did not start until mid- to late-May: this delay in starting monitoring increases the uncertainty in dose assessments.

According to the records [14], the average effective dose of the about 25 000 workers over the first 19 months after the accident (between 11 March 2011 and 31 October 2012) was about 12 mSv. About 35% received total doses greater than 10 mSv, while 0.7% of the workforce (174 individuals, mainly TEPCO workers) received doses greater than 100 mSv. Six TEPCO workers received cumulative doses greater than 250 mSv. For comparison, average effective doses to those persons most affected by the accident at the Chernobyl nuclear reactor were assessed to be about 120 mSv for 530 000 recovery operation workers, with maximum recorded worker doses of more than 1000 mSv and 85% of recorded doses between 20 and 500 mSv [15].

The highest reported effective dose was 679 mSv for the TEPCO worker who also had received the highest reported committed effective dose due to internal exposure (590 mSv). The highest reported effective dose due to external exposure was 199 mSv for a contractor's worker who had a total reported effective dose of 238 mSv. Female workers were not allowed to enter the plant after the accident. None of the firefighters, police and Self-Defense Force personnel involved in on-site emergency activities received effective doses in excess of 100 mSv, the majority receiving effective doses of less than 10 mSv.

The available information indicates zero confirmed fatalities from radiation exposure so far and that no individual received a dose at or above the threshold levels for acute radiation effects; however, thirteen workers were estimated to have received absorbed doses to the thyroid in the range of 2 to 12 Gy from inhalation of $^{131}I$, with an average dose of about 5 Gy.

Among the group of workers who received effective doses over 100 mSv, an increased risk of cancer would be expected in the future. However, "any increased incidence of cancer in this group is expected to be indiscernible because of the difficulty of confirming such a small incidence against the normal statistical fluctuations in cancer incidence" [16].

### *Health risks from exposure to low levels of ionizing radiations*

The system of radiological protection is based on three leading principles: justification, optimization and dose limitation. In the formulation of ICRP they are defined as follow [17].

- *Justification*: "Any decision that alters the radiation exposure situation should do more good than harm", that is the benefits obtained by the use of IR or in situation implying the exposure to IR have to be greater than the risk to health and environment due to radiation exposure.
- *Optimisation of protection*: "The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors". This is not a mere minimization approach, but a principle aimed at reducing the overall exposure to IR harmonized with other individual, social and economic needs.
- *Application of dose limits*: "The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits specified by the Commission".

These principles, the last two in particular, are based on the so-called linear non threshold model (LNT) applied to stochastic effects of radiation: cancer and transmissible deleterious mutations. For doses below 100-200 mSv the model states that the risk is linearly correlated to the dose without a threshold, *i.e.* a small dose has a little but finite probability to induce the effect, being the risk equal to that of background when the dose approaches zero.

For higher doses deterministic (or non stochastic) effects, the so-called tissue reactions, may start to take place. They are threshold effects, but their occurrence is unlikely also in overexposure situations (for instance during emergencies) up to effective doses of 500 mSv (with the possible exception of the cataract, see below), and then are not expected in the occupational and environmental exposure conditions discussed in this paper.

The LNT assumption is adopted by the ICRP and other international and national bodies sharing the ICRP approach (including the European Union). Its utility is intended only for the scopes of radiological protection, as any application of the LNT hypothesis for individual risk predictions or epidemiological purposes is improper. The LNT model derives risk estimates (*i.e.* detrimental coefficients for each organ/site involved in radiation-induced cancer) extrapolating, from medium-high to low doses, epidemiological data largely acquired by the follow up of the Japanese atomic bomb survivors (Life Span Study) [17], adjusting for acute *vs* protracted exposure and for populations different from the Japanese one. The overall risk coefficient for cancer induction in adults is 5 x $10^{-2}$ $Sv^{-1}$, while for children is three fold higher. Epidemiological data from atomic bomb survivors are unable to detect any increase in cancer risk at doses lower than 100 mSv.

A recently published study on a cohort of over 300 000 radiation-monitored workers in US, France and UK (pooled data) with a total follow up of 8.22 million person-years [18] shows a substantial risk increase for leukemia (excluding chronic lymphocytic leukemia) for cumulative bone marrow doses above 200 mGy (external penetrating radiation, primarily $\gamma$ rays), with a linear trend in all dose ranges and an estimated excess relative risk (ERR) of mortality caused by leukemia of 2.96 per Gy (90% CI 1.17-5.21), similar to that of the atomic bomb survivors (ERR = 2.63 at 1 Sv, 90% CI 1.50-4.27). Therefore, a risk increase due to chronic radiation exposure quantitatively similar to that obtained from atomic bomb survivors acutely exposed to radiation was established, at least for leukemia. This study displayed a stronger and more precise association between protracted radiation exposure and risk of leukemia occurrence, except for chronic lymphocytic leukemia, with respect to a previous large study conducted in 15 countries on workers chronically exposed to radiation [19]. However, at cumulative doses below 100 mGy the observed risk increase as a function of the increasing dose is not significant, given wider confidence intervals. The same cohort was also analysed with regard to overall cancer mortality and mortality for solid cancers [20]. Data have shown an increased risk of cancer, quantified in an excess relative rate of 0.48 (90% CI 0.20-0.79) per Gy of cumulative colon dose (external exposure to high energy photons) for overall cancer deaths, an estimate larger but statistically compatible with that one obtained in the Japanese atomic bomb survivors. Estimates are similar when the analyses were conducted excluding the smoking induced cancers (primarily the lung cancer) and the asbestos induced cancers (lung and pleura), as well as when data are disaggregated by country and when the cohort is stratified with regard to the suspected or known exposure to radionuclides or neutrons. A linear dose-response relationship provides a reasonable description of data, but in correspondence of 100, 150 and 200 mGy of cumulative dose (ranges involving the vast majority of the over 19 000 cases of cancer deaths reported at the end of the follow up) the estimates are less precise, although a linear trend in risk increase with dose is recognizable.

Linear extrapolations to the low dose range (< 100 mSv) are not supported by sound scientific evidence. On the opposite, in the last decades radiobiological studies *in vitro* but also *in vivo* display the existence of nonlinear responses at low doses *(Figure 1)*, such as those characterizing non targeted effects (the so-called bystander effect), genomic instability or adaptive responses [16, 21-23], all biological effects involving additional action mechanisms with respect to the induced gene mutations, in the frame of a complex and only partially elucidated scenario of reactive oxygen species (ROS) production, mithocondrial-nuclear interplay, epigenetic alterations, synthesis and release of cytochines etc. From an epidemiological point of view several studies (see for instance the recent analysis of [24]) on populations resident in geographical areas characterized by high levels of background natural radiation (up to doses of some hundreds mSv per years) did not show an increase in cancer risk proportional to the dose on the basis of LNT model, but seem to suggest an adaptive response to these high levels of IR, with even a reduction in the background risk of cancer. Similar conclusions are proposed by some authors (for instance [25]) examining in detail the shape of the dose-response relationship for leukemia and solid cancers in the low dose range in Japanese atomic bomb survivors.

In any case, the definition of the shape of dose-response relationship at low doses (see for instance [26]) as well as at low dose rates in subjects chronically exposed to radiation (but, by extension, to environmental or occupational mutagenic and carcinogenic agents) and the difficulties of epidemiological investigations to assess small excess in cancer risk (typically relative risks below 1.2-1.3) has been repeatedly recognized, also in relation to the follow up of populations involved in fatalities such as nuclear accidents (see for instance [27] with regard to the Fukushima accident).

However, a case of risk quantification and definition of a clear dose-response relationship at low dose rates is the lung cancer with regard to prolonged exposure to indoor radon. A collaborative analysis of 13 case-control studies conducted in European countries [28] has shown that the risk of lung cancer for radon exposure in dwellings increases of 16% every 100 Bq/m$^3$ of mean exposure to indoor radon and its progeny in the year (ERR = 0.16; 95% CI 0.05-0.31), with a linear dose-response relationship. These results are similar to those obtained by a combined analysis of North American case-control studies on residential radon and lung cancer (ERR = 0.18; 95% CI 002-0.43 at 100 Bq/m$^3$) [29] and by the analysis of two Chinese case-control studies (OR = 1.32; 95% CI 1.07-1.91 at 100 Bq/m$^3$ for subjects resident in the current home for 30 years or more) [30]. The advantages of residential studies (which also included a detailed assessment of the effects of smoking on radon cancer risk estimates) is the lack of confounding factors potentially affecting studies on lung cancer in miners exposed to radon. The conversion of an activity concentration (in Bq/m$^3$) into an effective dose to the lung (in Sv) is affected by uncertainties, depending on the dosimetric model (for instance the application of the human respiratory tract model) and the exposure conditions [31]. However, the order of magnitude of the effective dose corresponding to 100 Bq/m$^3$ is in the range of few mSv, so falling in the typical low dose range of exposure.

A case where an increased cancer risk has been observed in the dose range < 100 mSv is the childhood cancer in relation to diagnostic prenatal exposure to IR (X rays). The Oxford Survey of Childhood Cancer (OSCC) and other studies conducted in the past decades and reviewed by the publication 90 of the ICRP [32] indicate a significant increase in the risk of leukaemia and other neoplasms in children whose mothers were exposed to diagnostic X rays during pregnancy. These studies have a number of methodological limitations, including the largest one (the OSCC study), and dose estimates are often uncertain, especially for exposures occurred in the farthest decades which the studies referred to. However, the risk was significantly increased for both childhood leukaemia and solid cancers when the OSCC study is considered alone or in combination with the other ones or when the other studies are taken together excluding the OSCC study. Medical doses used in radiodiagnostic

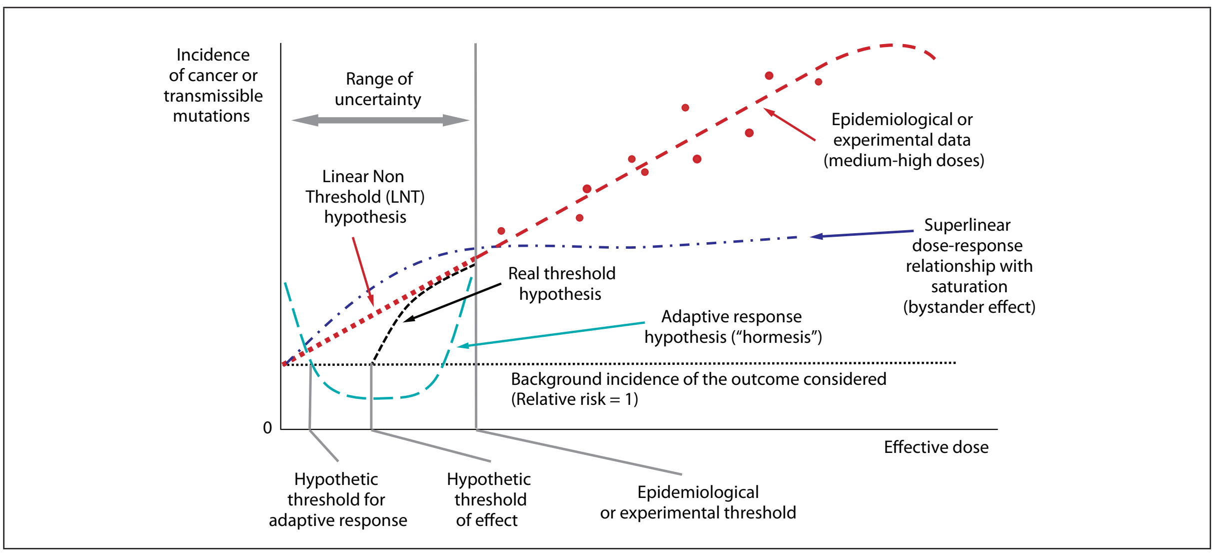


**Figure 1**
Possible dose-response relationships at low doses for biological and health effects of ionizing radiation.

practices are constantly decreased over time, but they were likely to be less than 100 mSv, even in the case of repeated examinations during pregnancy and accounting for the marginal involvement of the abdominal and pelvic regions in radiation exposure during extra-abdominal radiograms in the past.

Regardless epidemiological indications the conservative approach characterizing the LNT model is likely to continue to be the basis of the international system of radiological protection. It focuses on the optimization of exposure, after a given practice involving the exposure to IR is justified.

***Co-exposures***

Any exposures or potential exposures of workers and emergency workers during a nuclear or radiological emergency should be assessed, taking into account also the possible development of hazardous conditions [33].

The possibility of individual co-exposures to mutagenic and carcinogenic agents other than IR as well as to agents responsible of adverse effects other than cancer and transmissible mutations but also inducible by IR (*e.g.* cataract) is an important reason enforcing the need to apply the optimization principle in all exposure situations, including the emergencies, but is not adequately addressed in the scientific literature.

For instance, the lung is one of the most important site of radiation induced cancer, both for external ($\gamma$-rays and neutron) and internal (radon) exposure, but it is also the main target of other occupational, environmental and life style related carcinogens, such as tobacco smoke, asbestos, silica, polycyclic aromatic hydrocarbons (PAH), arsenic etc. In addition or in alternative to the direct mutagenicity, some of them share mechanisms of carcinogenic action such as ROS synthesis and epigenetic modifications [34]. Many of the aforementioned studies on indoor radon and lung cancer show clearly a synergistic action between radon exposure and tobacco smoke in lung cancer induction [28, 29]. A synergistic effect is also predictable for co-exposure to two or more lung carcinogens, so the carcinogenic action of a given level of exposure to a given carcinogenic agent is strengthened with respect to the same level of the same agent taken alone.

Skin is a site of radiation induced cancer, although IR are recognized to be a carcinogen almost exclusively in relation to non melanoma skin cancer (basal cell carcinoma and squamous cell carcinoma).

Skin cancer is also inducible by other exposures, being UV radiation the most important recognized skin carcinogen [35]. Both UVB and UVA have carcinogenic action and share, although to a different extent, the same action mechanisms (direct mutations, ROS synthesis and epigenetic modifications), but UVB is much more effective based on the Erythemal action spectrum. Dose-response relationship is not fully defined, but squamous cell carcinoma is mostly related to UV cumulative exposure while basal cell carcinoma and cutaneous melanoma are more likely associated to intense and sunburning exposures, especially during infancy and young ages. Outdoor workers are at higher risk of skin cancer due to chronic exposure to solar UV radiation. Other recognized skin carcinogens are PAH and arsenic [36].

Lens of the eye is a biological target of IR, an agent known to induce cataract, especially cortical and posterior subcapsular cataract. On the basis of new epidemiological data (including data from the Chernobyl accident) and reanalysis of existing data (reviewed by the ICRP in the publication 118 devoted to the assessment of tissue reactions [37]) dose limits for the lens have been consistently lowered, approaching those aimed at reducing at an acceptable level the risk of stochastic effects for occupational exposure. In fact, the Council Directive 2013/59/EURATOM [38] states the following dose limits for the lens:

- 20 mSv/year or 100 mSv in five years, in terms of equivalent dose, with a maximum dose of 50 mSv in one year;
- 15 mSv/y for workers and students aged 16-18 as well as for the general public, in terms of equivalent dose.

Therefore, the risk of radiation-induced cataract seems to be higher than expected in the past. Radiation is not the only cataractogenic agent in occupational and environmental settings. UV radiation is known to induce cortical and possibly nuclear cataract, being the cataractogenic action mainly attributed to UVB band, with no exclusion of the UVA (the last one being maximally absorbed by the lens) [39, 40]. Outdoor worker are at risk of cataract occurrence due to prolonged exposure to solar radiation without an adequate eye protection. The dose-response relationship is not well defined, but the risk is likely to be a function of cumulative exposure.

## DISCUSSION AND CONCLUSIONS

***A new safety culture: adaptation after Fukushima***

CC may affect workers' exposure to a lot of environmental agents, including organic pollutants (among which PAH) and solar UV radiation. Furthermore, as discussed above, a changing climate may challenge nuclear safety, for instance increasing the likelihood of a nuclear accident and emergency or amplifying the magnitude of the consequences.

IAEA states that the external events that could arise for a facility or activity have to be addressed in the safety assessment, and it has to be determined whether an adequate level of protection against their consequences is provided [41].

In Europe, in 2011 the European Commission requested that the safety of all EU NPPs should be reviewed on the basis of "stress tests" developed by the European Nuclear Safety Regulators Group (ENSREG). At a worldwide level, the 2nd Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety (CNS) was held in 2012 to review and discuss lessons learned from the accident at Fukushima Dai-ichi NPP.

However, in the framework of the radiation protection practice, the combination of a nuclear or radiological accident with the consequences of CC may challenge primarily the principle of the optimization of protection and safety, according to which exposures must be maintained at the lowest possible levels consistent with the economic and social conditions. An increase in costs due to the issues described may limit the effectiveness of radiation protection (as in the case of the Fukushima accident) and eventually question the nuclear power as a means of adaptation/mitigation of CC [42].

A lot has been written on this topic since 2011 regarding the safety culture in NPPs. Some considerations are presented here, valid not only for NPPs but for all facilities working with IRs, based on the assumption that safety culture means to invest on prevention rather than intervention in the emergency phase. This can be accomplished by means of "soft" (organizational and procedural methods) and "hard" (design and technical methods) measures [43].

The first organizational measure is that licensees of nuclear and also radiological facilities now take into account low probability EWEs due to CC among the potential accidents and regulatory systems and control organisms address extreme external natural events adequately, including their periodic review, and ensure that clarity of roles and responsibilities are preserved [33].

This implies a deterministic safety assessment (DSA) which predicts the response to postulated initiating events, considering also how to cope with those circumstances when multiple systems have been affected by an extreme event.

A classic example is the case of flooding, which could involve a total loss of power for a significant period of time, resulting in a loss of all active accident response capabilities. In response to this scenario an organizational measure is placing backup generators at different elevations, especially in areas prone to flooding. Then every nuclear and radiological facility should have at least one generator with a runtime of several hours, housed in a sealed room that is flood-safe, and the availability of remote generators on demand, in order to guarantee monitoring, safety systems and medical care for workers involved in an emergency.

In hospitals' NMUs the DSA has to consider all possible pathways of dispersion of contamination within and outside the hospital (sewers, flows of water due to flooding, etc) and ensure accessibility to local control points required for manual actions (for instance control panels in radioactive waste rooms). In nuclear facilities, the safety assessment has to take into account training of people potentially involved as emergency personnel and medical monitoring and assistance of contaminated and/or overexposed workers on site (which entails training of medical staff of hospitals near the facilities about the risks of IRs, radiation monitoring and decontamination measures) and eventually anticipate harsh working environment for workers and long duration emergency operations [33].

However a comprehensive safety analysis regarding CC impacts has to use both deterministic and probabilistic methods in a complementary manner, and the hazard analyst should also study the possible dependence between external events and treat multiple secondary events arising from a single external event, like, for example, a tornado that can produce concurrent flooding and missiles. Uncertainties in estimating risk of accidents caused by external events tend to be greater than those associated with other accident-initiating events and need to be further explored. Even if great confidence can be put on engineering judgment and experts' opinion for necessary actions of prevention, such as the radiation protection expert or the medical physics expert or the clinical engineer in hospitals, safety improvements depend on safety research giving novel techniques, like for instance calculation tools and other methods for advanced safety assessment.

In particular, a useful tool against flooding, whose effects have a major bearing on safety, can be the regional risk assessment methodology proposed by the Euro-Mediterranean Center on Climate Change [44] based on the concept of risk being function of hazard, exposure and vulnerability, which allows to identify areas at risk of being affected by floods and supports the development of prevention measures to minimize flood impacts.

The safety and risk assessments related to CC impacts should be included in the authorization documents not only of nuclear but also radiological facilities, and local authorities should accordingly draw up an emergency preparedness and response plan (in Italy the intervention plan in compliance with to LD 230/95, art 115 quarter [45]). Then the authorization documents could contain organizational and procedural measures against CC impacts, establishing the related organizational structure (for clear allocation of responsibilities) and the arrangements for coordinating activities and cooperating with external response agencies in a timely manner and throughout all phases of emergency.

For instance, unlike NPPs, hospitals' radioactive waste rooms are not provided with an emergency team available 24/7, which would be appropriate in order to limit possible radioactive contaminations of high frequented areas. Organizational and procedural measures could comprise a clarification of roles and responsibilities in an emergency due to an EWE, including qualified experts (such as a radiation protection expert) with established and recognized skilfulness in the field of nuclear or radiological emergency management. This personnel, in charge of making decisions to initiate protective actions and other response actions upon notification of an emergency, should be available on call to coordinate the emergency team (for example in the case of flood), having also the possibility of using an onsite emergency support center.

For new radiological facilities and hospitals, external hazards should be considered as an integral part of the design and the level of detail and analysis provided should be proportionate to the contribution to the overall risk, as well as the "hard" design and technical measures, like the monitoring system of water in the radioactive waste room or diesel generators able to face a power loss for several hours. In safety organization, when "hard" safety measures have to be planned, the importance of logistics is clear, meaning the right choice and storage of equipment: in radiological facilities, like in NPPs, implementation of mobile (*i.e.* with no power) monitoring equipment could be contemplated, so that it could be possible to replace failed equipment by portable equipment, properly stored in hardened buildings/

warehouses safe and secure even in case of an EWE significantly beyond the design basis. Likewise, the possibility of manual control of safety devices is essential (as for instance the control of tanks of radioactive waste in a NMU, when the storage area is flooded and the switchboards are out of order), together with procedures in the case of loss of power.

However, when CC impacts are involved, safety cannot be just a list of rules and procedures, but it is an endless process in continuous improvement and requiring periodic review, because it is impossible to address every concern and CC is a constantly evolving variable. Then periodic safety reviews are necessary at least for the following areas: natural external events, including flooding; extreme weather conditions and the related systematic monitoring of weather; the loss of safety functions and severe accident management.

Moreover, nuclear, and consequently radiological, safety culture currently focus on the minimization of prompt fatalities, but is this the appropriate metric? The approach to radiation protection in the definition of the constraints is optimization and determination of appropriate dose constraints: a reference level can be set, lower than the legal limit, in a situation of emergency exposure when adequate protection can be provided without causing disproportionate damage due to countermeasures implemented or excessive costs. A reference level is a level above which it is considered inappropriate to allow exposures to occur, although it is not a limit that cannot be exceeded. Such reference levels could be adopted as good practise objectives for radiological emergencies in hospitals and other radiological facilities, weighting costs/risks/benefits separately in each case.

Last but not least, an emergency classification system for nuclear or radiological emergencies should be developed, on the basis of objective and measurable criteria (emergency action levels) and a list of consequent protective actions, which therefore classifies accidents considering not only the impacts, like the INES scale, but also the countermeasures taken to contain the consequences.

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***Conflict of interest statement***

There are no potential conflicts of interest or any financial or personal relationships with other people or organizations that could inappropriately bias conduct and findings of this study.

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