Nuclear and radiation safety and security

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Abstract. All applications of nuclear materials as well as of any sources of ionizing radiation are accompanied by a risk of radioactive contamination of the environment or unnecessary overexposure of workers and the general public. Such an incident may result from malfunctioning of devices (radiation sources, shields, monitoring systems etc.) or a diversion from accepted procedures; it may be also intentional (sabotage or terrorist actions). All such incidents may be harmful for the victims, but they also may ruin the image of a given technology, irrespectively of the country or institution where it has occurred. Safe, secure, peaceful and efficient use of nuclear energy as well as of any source of ionizing radiation requires sustainable tools, including infrastructure that provides legal, regulatory, technological, human and industrial support for that programme. Therefore, the measures assuring radiation and nuclear safety and security, including physical protection of nuclear materials and radioactive sources, originate from internationally established and controlled principles on which obligatory national regulations are based. Evolution of technologies and changes of global or regional political situation may lead to new threats which creates a need to introduce new legal and institutional instruments, both national and international. Poland seems to be well situated in the present nuclear and radiation safety and security system.

Key words: nuclear safety • nuclear security • radiation protection • safety and security culture • safeguards

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Received: 3 November 2008

Introduction

Radiation can be harmful to humans and to the environment. All applications of any sources of ionizing radiation and especially of nuclear materials may cause a risk of incidents leading to overexposure of workers and general public, the most serious being of course a nuclear explosion. Radiation incidents may result from malfunctioning of the instrumentation (radiation sources, shields, monitoring systems etc.) or a diversion from accepted procedures; it may be also intentional (sabotage or terrorist actions). One has to realize that any nuclear or radiation incident even not serious from the point of view of its real consequences may ruin the image of a given technology, irrespectively of the country or institution where it has occurred. That means that all applications of radiation have to be safe, where "safety" is the achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards. The measures assuring radiation and nuclear safety and security, including physical protection of nuclear materials and radioactive sources, are being negotiated and agreed globally and national regulations originate from internationally established and controlled principles. That is achieved by more or less universal legal system of international conventions and treaties, commonly accepted standards and international institutions with proper mechanisms (legal and instrumental) to verify compliance with that system. The system has to be continuously modified due to changing technologies and new threats.

Radiation safety and radiation protection

Radiation safety involves prevention or reduction of potential exposure and other risks (for the minimization of danger). Radiation protection involves prevention or reduction of (existing) radiation exposure (for the protection of health). Protection and safety are closely related: protection is much simpler if the source in question is kept under control, so safety necessarily contributes towards protection.

The primary aim of radiation protection is to provide an appropriate standard of protection for man without unduly limiting the beneficial actions giving rise to radiation exposure. The field of radiation protection (and radiation safety) has been evolving for more than 100 years and remains an excellent example of the interactions among science, technology, professional responsibility, public concern and government. Discoverers of radioactive substances and first users of radioactive sources and X-ray tubes have not realized that ionizing radiation may provide any harm to the living organisms. However, the need for guidelines to protect individuals against the harmful effects of ionizing radiation was realized already in the early years of the 20th century when the diagnostic and therapeutic potential of X-rays and radioactivity began to be exploited in medicine which also brought to light the adverse biological effects of overexposures; by 1922 more than 100 radiologists died of radiation lesions working without any protection.

Around 1920 several national regulations were established, however, there was no international consensus. First attempts to universalize the standards in radiological protection were made in 1925 at the First International Congress of Radiology in London, which created International Commission of Radiological Units or ICRU (now known as International Commission of Radiological Units and Measurements). In 1928, during the Second International Congress of Radiology in Stockholm the International Society of Radiology (ISR), the professional society of radiologist physicians, founded the International Commission of Radiological Protection, or ICRP, then called the "International X-ray and Radium Committee" [13].

The ICRP is a body which offers its recommendations to regulatory and advisory agencies and provides advice intended to be of help to management and professional staff with responsibilities for radiological protection. It has no formal power to impose its proposals on anyone; however, legislation in most countries adheres closely to ICRP recommendations. Therefore, the ICRP deserves a particular mention: this is the oldest international organization in this field which is still going strong. Its protection recommendations are applicable to all sources and to individuals exposed to ionizing radiation (existing, planned and emergency exposure situations) and all categories of exposure (occupational exposure, public exposure and medical exposure of patients).

In the early years, the emphasis was on the protection of the radiation workers and the focus was on non--transmissible consequences of radiation exposures. The ICRP published its initially general recommendation for radiological protection already in 1928, advising limitation of the doses from "tolerance" (10 rad/day or 0.1 Gy/day) to "permissible" levels, well below the initiation thresholds of any deterministic effects. The Commission recommended also the use of protective shielding, limitation of working hours and introduction of some special procedures in handling the radioactive substances. The values of then introduced "maximum permissible doses" have evolved from 1000 mSv/y (100 rem/y) in 1934, through 600 mSv/y in 1950 to 150 mSv/y in 1956 [13]. The protection of general public was not an issue. However, the mutagenic effects of X-irradiation in Drosophila germ cells discovered in the late 1920s extended to other kinds of ionizing radiation and other biological systems in the years that followed introduced a new dimension to the concern about radiation risk. The radioactive fallout resulting from the detonation of atomic bombs over Hiroshima and Nagasaki as well as from the later atomic bomb tests sparked worldwide concern over adverse health effects of exposures of large number of people to low levels of radiation. As a consequence of such understanding the genetic effects were assumed to be the main determinant for recommending limits of radiation exposure of people. The "maximum permissible doses" to radiation workers (5 rem in a year), to individual members of the public (0.5 rem/year) and the population at large (5 rem over a 30 year period or 170 mrem/year) recommended in ICRP Publication 1 published in 1959 [11], although not based on actual observations of radiation-induced genetic effects in humans, reflected this point of view. By the early 1960s it was clear that cancer risks were much more important quantitatively than genetic risks. Over the following years there was a gradual shift in perspective which led to the development of a risk-based protection system introduced in ICRP Publication 26 in 1977. The three key principles underscored in that document – justification of a practice, optimization of protection and individual "recommended dose limits" (not any more "maximum permissible doses"), as well as the general ALARA principle – "As Low As Reasonable Achievable, economic and social factors being taken into account", have remained valid since that time. In the new system rate estimates for cancer and hereditary effects were taken one step further by incorporating a measure of impact called detriment – mortality in case of cancers and severity in case of genetic effects. No change in dose limits to the workers or to the members of the public was deemed necessary and dose limits for population were not considered necessary anymore.

By the time of the 1990 ICRP Publication 60 [12], more data on cancers and revision of genetic risk estimates were available. The dose limits to workers were lowered to 20 mSv/y (from 50 mSv/y in 1959) averaged over 5 years. For members of the public, it was lowered to 1 mSv/y (from 5 mSv/y). The "radiation dose limits" (expressed as effective doses, the "weighting factors” for different tissues being determined) were defined as such values which “will not cause observable deterministic health effects in individuals or have any effect on pre-existing medical conditions, and that risk of stochastic effects can be kept under a level which is deemed acceptable”.

As it was stated in the 1990 ICRP Recommendations, “the primary aim of radiological protection is to provide an appropriate standard of protection for man without unduly limiting the beneficial actions giving rise to radiation exposure. This aim cannot be achieved on the basis of scientific concepts alone. All those concerned with radiological protection have to make value judgments about the relative importance of different kinds of risk and about the balancing of risks and benefits. In this, they are no different from those working in other fields concerned with the control of hazards” [8].

Radiation safety systems should be prepared for three types of exposures – planned, emergency and existing. There is a distinction between what is called “practice” and “intervention”. Practices have to be controlled so that additional doses are appropriately restricted, while interventions are the actions against radiation exposures that already exist for the purpose of reducing the exposures, but both practices and interventions have to be justified so they will cause more good than harm. The decision to intervene is made on the basis of the dose that can be averted.

The ICRP Publication 60 recommendations were taken into account in preparation of two fundamental radiation safety documents, namely the 1996 International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources [8] and the 1996 EU Directive No 96/29/Euratom, laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation [2]. (Poland has based its radiation safety legal system contained in the parliamentary act – Atomic Law of 29 November 2000 (amended, [1]) on both mentioned above documents).

The ICRP has stated that its recommendations will be reviewed at least every 10–15 years. The 2005 ICRP Recommendations [14] are focused mainly on the concept of “dose constraint” as the most fundamental level of protection in the source-related restriction on individual dose. It is used to provide a level of protection for the most exposed “individuals”, from a “single source”. Except for the exposure of patients, these constraints should be regarded as basic levels of protection to be attained in normal situations, accidents and emergencies, and in case of controllable existing exposure. These constraints represent the level of dose where action to avert exposures and reduce doses is virtually certain to be justified. Four values of effective doses are proposed:

– 100 mSv/y in emergency situations, for workers, other than for saving life or preventing serious injury or preventing catastrophic circumstances, and for public evacuation and relocation; and for high levels of controllable existing exposures (there is neither individual nor societal benefit from levels of individual exposure above this constraint).
– 20 mSv/y for situations where there is direct or indirect benefit for exposed individuals who receive information and training, and monitoring or assessment; it applies into occupational exposure, for countermeasures such as sheltering, iodine prophylaxis in accidents, and for controllable existing exposures such as radon, and for comforters and carers to patients undergoing therapy with radionuclides.
– 1 mSv/y for situations having societal benefit, but without individual direct benefit, and there is no information, no training, and no individual assessment for the exposed individual.
– 0.01 mSv/y as a minimum value of any constraint.

In all situations the constraints are complemented by the requirement to optimize the level of protection achieved. The optimization principle requires that further, more stringent, measures should be considered for each individual source. The level of protection for an individual from all sources within a class of exposure, in normal situations only, is the “dose limit” as defined and determined in the 1990 Recommendations, ICRP Publication 60.

In the 2007 recommendations, while maintaining the individual dose limits for effective dose and equivalent dose from all regulated sources that represent the maximum dose that would be accepted in planned situation by regulatory authorities, the ICRP proposes to abandon the process based protection approach (using practices and interventions) moving to a situation based approach, applying the same source-related principles to all controllable exposure situations.

Nuclear safety and security

For 16 years since its discovery in 1939, the nuclear fission was used only in nuclear explosives. When the USA, the first nuclear weapon-state (first test in 1945) was joint in 1949 by the Soviet Union and in 1952 by Great Britain, the president of the United States Dwight Eisenhower in his famous speech “Atoms for peace” delivered on 8 December 1955 at the UN General Assembly said: …“The United States knows that if the fearful trend of atomic military build-up can be reversed, this greatest of destructive forces can be developed into a great boon, for the benefit of all mankind. The United States knows that peaceful power from atomic energy is no dream of the future. The capability, already proved, is here today. Who can doubt that, if the entire body of the world’s scientists and engineers had adequate amounts of fissionable material with which to test and develop their ideas, this capability would rapidly be transformed into universal, efficient and economic usage? ...**Experts would be mobilized to apply atomic energy to the needs of agriculture, medicine and other peaceful activities. A special purpose would be to provide abundant electrical energy in the power-starved areas of the world**…”. The President probably heard the statement of L. L. Srauss, Chairman of the US Atomic Energy Commission, who in 1954 said: “nuclear energy will provide electricity too cheap to meter” [3, 4].

The first nuclear power installations were built already in the late 1940s; on 20 December 1949 in Idaho

Falls, USA, the reactor EBR1 was put into operation demonstrating ability to "produce electricity". The first (still experimental) nuclear power 5 MWe plant was opened in 1954 in Obninsk, USSR, and the first industrial plant (50 MWe) in Calder Hall, UK, with the gas cooled graphite type GCGR reactor, was connected to the grid in 1956. As for September 2008, 439 nuclear power units of total net capacity equal to 371,684 MWe have been operated in 31 states and provided 15% of world electricity [6].

In order to keep any use of nuclear technologies restricted to peaceful applications, some international system of the control and verification had to be established. Dwight Eisenhower proposed: ..."The governments... should begin now and continue to make joint contributions from their stockpiles of normal uranium and fissionable materials to an international atomic energy agency. We would expect that such an agency would be set up under the aegis of the United Nations... The atomic energy agency could be made responsible for the impounding, storage and protection of the contributed fissionable and other materials… The more important responsibility of this agency would be to devise methods whereby this fissionable material would be allocated to serve the peaceful pursuits of mankind".

These ideas helped to create the International Atomic Energy Agency and to shape its Statute, which 81 nations unanimously approved in October 1956 (the IAEA was finally established in 1957). The Statute outlined the three pillars of the Agency's work: nuclear verification and security, nuclear and radiation safety and nuclear technology transfer. In 2007 the 50 years old IAEA had 144 Member States [3, 5].

Nevertheless, after 1955 the nuclear arms race continued, France in 1963 and China in 1964 became the new nuclear weapon states. To limit the ability of the states to develop new weapons and to expand their nuclear military capabilities, different instruments were used: establishing "atom-free" zones, prohibiting nuclear tests and finally – freezing number of the members of the "nuclear club" through non-proliferation legislation and verification system, established by the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). The Treaty entered into force in 1970 for 25 years, but in 1995 was extended indefinitely. The NPT provides a collective security legal instrument by which the state-parties undertake reciprocal non-proliferation commitments to prevent the spread of nuclear weapons. The Treaty provides for its parties to pursue peaceful nuclear programmes, but mandates that their nuclear activities have to comply with the Treaty's non--proliferation obligations. It requires the application of the International Atomic Energy Agency safeguards to help to ensure that nuclear programmes for peaceful purposes are not diverted into other uses.

The IAEA safeguards are applied to nearly 1000 facilities in 162 NPT contracting Parties, out of which 75 have in force the "additional protocols" enabling the IAEA officers to inspect the sites and activities "undeclared" by the States on a short notice. In spite of creation of new nuclear weapon states (India, Pakistan, Israel, South Africa, North Korea), the IAEA role in fulfillment of its verification duties has obtained the highest appraisement. In 2005, the Nobel Peace Prize was awarded to the Agency and its Director General Dr Mohamed ElBaradei "for their efforts to prevent nuclear energy from being used for military purposes and to ensure that nuclear energy for peaceful purposes is used in the safest possible way".

The end of the Cold War was marked by a shift from a bi-polar structure of global security into a more complex and unpredictable configuration of world affairs. It also brought about new security challenges, i.e. an increased probability for low-density regional, national or sub-national conflicts with new and more dispersed threats emanating from a larger number of actors, including non-state actors: terrorists or criminals. After September 11, the new threat – the nuclear terrorism, has got a new dimension. That expression incorporates four distinct types of terrorist activity:

- theft and use of an intact nuclear device,
- theft or other acquisition of fissile material which would then be used to make a nuclear weapon,
- attacks on reactors or other nuclear facilities with the goal of causing radiological contamination of surrounding areas, and finally
- use of radiological material to make a radiological dispersal device (RDD), the so-called dirty bomb.

It is clear, especially since 9/11, that for the continued and expanded use of nuclear energy or radioactive materials, nuclear security is indispensable and an important prerequisite for successful and sustainable development. This means that one has to observe not only the nuclear/radiation safety principles, but also the nuclear security system, including physical protection of nuclear materials, radioactive substances and any facilities essential for the technology. Additionally to that, in case of nuclear materials safeguarding and accountancy principles and procedures have to be followed and maintained.

Nuclear safety is defined as actions related to the protection of people and property from the deleterious effects of radioactive contamination, exposure to ionizing radiation and criticality. In other words, nuclear safety means the actions taken to prevent nuclear and any other radiation accidents or to limit their consequences. This covers nuclear power plants and other nuclear facilities, the transportation, the use and storage of nuclear materials and radioactive sources for medical, power, industry, and military uses. Nuclear safety imposes strict demands on the containment of radioactive materials.

Nuclear reactors can fail in a variety of ways. Should the instability of the nuclear material generate unexpected behavior, it may result in an uncontrolled power excursion. Normally, the cooling system in a reactor is designed to be able to handle the excess heat it causes, however, should the reactor also experience a loss-of--coolant accident, then the fuel may melt, or cause the vessel it is contained in to overheat and melt. Such an event is called a nuclear meltdown. Because the heat generated can be tremendous, immense pressure can build up in the reactor vessel, resulting in a steam explosion such as happened at the Chernobyl NPP.

The mechanisms for assuring proper level of nuclear/radiation safety are as follows: well designed facilities and instrumentation, well designed and proven operating procedures and well trained and experienced personnel. This can be achieved only, if the national legal and regulatory system based on the international conventions is properly established, containing strong enough licensing and verification regime, and is fully independent (not dependent on any other body within the government or any non-governmental organization).

Nuclear security is defined as “the prevention and detection of, and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material, other radioactive substances or their associated facilities” [10]. These three nuclear/radiation security principles: prevention, detection and response mean, respectively:

- Prevention – to prevent unauthorized access to nuclear and other radioactive material. Prevention refers to an analysis of the threat and establishing a system of physical protection with an objective of averting the accomplishment of unauthorized acts that may lead to the theft or sabotage of nuclear and other radioactive material. The effective physical protection system has three components: detection of intrusion, delay and response to intrusion.
- Detection – to detect nuclear and other radioactive material; it refers to instrumentation and procedure enabling proper detection and identification of the material.
- Response – to respond to an alarm as well as to response to a nuclear or radiological incident that has been triggered by an alarm with the potential involvement of nuclear and other radioactive material. Response to the radiological consequences that might ensue is considered part of safety.

There is not an exact distinction between the general terms “safety” and “security”. Safety measures and security measures must be designed and implemented in an integrated manner, so the security measures do not compromise safety and safety measures do not compromise security. Safety matters are intrinsic to activities, and transparent and probabilistic safety analysis is used. Security matters concern malicious actions and are confidential, and threat-based judgment is used.

Safety/security culture is defined, as “the assembly of characteristics, attitudes and behavior of individuals, organizations and institutions which serves as a means to support and enhance nuclear safety/security” [10]. This means that a proper attention is paid to organization’s values and behaviors – modeled by its leaders and internalized by its members that serve to make safety (security) overriding priority, and safety (security) issues receive the attention warranted by their significance. Lessons learned from accidents which have occurred in facilities similar to those used in the organization help to improve the nuclear safety culture, especially from the staff attitude factor. E.g. the following accidents in industrial irradiation facilities with fatal consequences or with severe radiation injuries have been thoroughly analyzed: Illinois, USA, 1965 (Co-60), Stimons, Italy, 1975 (Co-60), Kjeller, Norway, 1982 (Co-60), San Salvador, El Salvador, 1989 (Co-60), SorVan, Israel, 1990 (Co-60), Maryland, USA, 1991 (accelerator), Hanoi, Vietnam, 1991 (accelerator), Nesvezh, Belarus, 1991 (accelerator), Toulouse, France, 2008 (accelerator) [7]. The list of accidents in medical irradiation facilities is much longer. The analysis of the attacks on nuclear facilities, published in open sources, may improve the nuclear security culture.

Safety/security culture is an amalgamation of values, standards, morals and norms of acceptable behavior. They are aimed at maintaining a self-disciplined approach to the enhancement of safety/security beyond legislative and regulatory requirements. Safety/security culture has to be inherent in thoughts and actions of all the individuals in any contact with radioactive substances and at every level in an organization. An important safety/security indicator is such a situation, when operation and maintenance are performed according to approved procedures and the staff follows established plans or seeks a proper approval before deviating from planned duties and activities.

Implementation

As it was stated at the beginning of this paper, any deviation from nuclear/radiation safety/security principles and procedures, that is – the violation of safety/security culture, may cause a situation leading to an incident which may be harmful not only for the victims, but may also damage the image of a given technology, irrespectively of the country or institution where it has occurred. Therefore, the measures assuring nuclear and radiation safety and security are being negotiated and agreed globally and national regulations are laid down based on internationally established and controlled principles. That is achieved by a system of international conventions and treaties and commonly accepted standards as well as by an international close mutual co-operation, assistance and peer reviews and, finally, by a verification mechanism accepted by all the stakeholders.

Among the international treaties and conventions the following are the most important:

- The Non-Proliferation Treaty (NPT) and the verification system of that treaty: the bilateral (IAEA – Member State) Safeguards Agreements and Additional Protocols,
- Convention on the Physical Protection of Nuclear Material,
- Convention on Early Notification of a Nuclear Accident,
- Convention on Assistance in the Case of a Nuclear Accident and of Radiological Emergency,
- Vienna (and Paris) Convention on Civil Liability for Nuclear Damage,
- Convention on Nuclear Safety,
- Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management,
- Convention on the Physical Protection of Nuclear Material and Nuclear Facilities.

That list has to be supplemented by some of recommendations or generally accepted but legally not biding documents, like mentioned already International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (and binding the European Union Member States – the EU Directive No 96/29/Euratom laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation), as well as IAEA Code of Conduct on the Safety and Security of Radioactive Sources [9]. The national legislation system, containing not only regulations on a safe and secure use of nuclear and other radioactive materials, but also licensing and regulatory procedures, has to implement all those international acts (once the country is a Contracting Party to the given convention; that is the case of Poland). The regulatory authority issuing the license has to check whether the rules of conduct and operational procedures contained in the motion for that license demonstrate that the nuclear (or radiation) safety and security culture will be introduced. This should be a prerequisite for licensing and fulfillment of that condition should be checked during every regulatory inspection of the organization.

A growing use of nuclear power worldwide as well as rapidly growing use of radiation in industry and medicine are evidence of the important role of nuclear technologies in a sustainable development. A need of keeping proper standards in nuclear safety and radiation protection is usually well understood both by workers and the general public. However, for the continued and expanded use of nuclear energy or radioactive materials, nuclear security is indispensable and an important prerequisite for any activity.

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