ELVIRA ROMERA • ALEJANDRO NÚÑEZ
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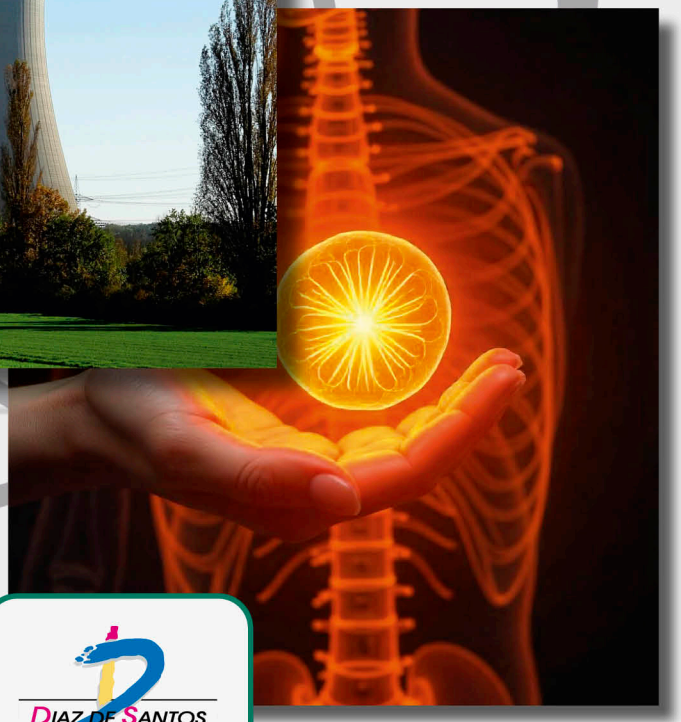
Editors

ARTIFICIAL INTELLIGENCE IN NUCLEAR SAFETY AND RADIATION PROTECTION



DIAZ DE SANTOS

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■ INTRODUCTION

Artificial intelligence (AI) has emerged as a transformative technology in various fields. These include the disciplines of protection against ionizing radiation and safety and security of radiation nuclear installations, which will be hereinafter termed *radiation and nuclear safety*. This book explores some potential applications, challenges, and implications of AI in radiation and nuclear safety, particularly in ensuring the safe operation of radiation and nuclear facilities, the detection and management of radiation hazards, and the overall security of nuclear materials and installations.

With its capabilities for advanced data processing, pattern recognition, and decision-making, AI offers significant potential to enhance protection and safety on one hand, and efficiency and reliability of radiation and nuclear operations on the other hand. The book focuses on some key areas, such as monitoring, predictive maintenance, incident response, and radiation protection, but also discuss the ethical, regulatory, and technical challenges associated with the deployment of AI in these critical areas.

The book contains chapters that describe general topics about different radiation and nuclear safety applications of AI technology in radiation and nuclear endevours and facilities, as follows: (i) ethical aspects of radiation and nuclear safety, and their relationship with AI, (ii) AI and radiation protection, (iii) AI and the challenges to nuclear safety; as well as a set of more specific chapters (iv) Artificial intelligence and radiation protection in medical applications (diagnosis and therapy), (v) AI for radiation protection in the decommissioning of radiation and nuclear facilities, and (vi) innovation in the role of AI for regulatory document management.

Radiation and nuclear safety is a critical concern for ensuring the protection of public health and the environment. Nuclear power plants, research reactors, ra-

diation installations, radiological devices, the transportation of nuclear materials, among other endeavors, require strict safety protocols to prevent accidents, unacceptable radiation exposure, or various misuses. Traditional safety systems often rely on human operators and conventional automated systems, which, although effective, may have limitations in handling large-scale data or identifying complex patterns that indicate potential threats. AI, particularly machine learning (ML) and deep learning, has the potential to revolutionize the approach to radiation and nuclear safety by enhancing detection, decision-making, and real-time responsiveness to radiation risks.

AI can play in the realm of radiation and nuclear safety, providing both opportunities and challenges for stakeholders in the radiation and nuclear industries, including regulatory bodies, safety operators, and researchers.

One of the main challenges faced by the AI is its governance, namely the actions or manners of governing its development and use. Good governance require a commonly shared protective framework for both people and the environment. Such framework ought to be based on shared ethical principles. Governance following these principles would be able to contribute to the development of AI for the common good. It is to be noted that any governance system is based on a social order established mainly by three mechanisms: own interests, legitimacy and coercion [1]. There are numerous theoretical studies and thoughts regarding governance of AI (see for example [2,3,4,5]).

Currently there are a number of governance initiatives for AI technology. For instance, the European Union approved a law in June 2024 to regulate AI [6], dedicating a significant portion to specific rules for AI systems that pose a high risk to health, safety, or the fundamental rights of individuals. This legislation also proposes the creation of a European Artificial Intelligence Committee, which, among other functions, would provide guidance on the implementation of the regulation. In addition, each EU Member State is required to designate national competent authorities (namely, a notifying authority and at least one market surveillance authority related to the AI regulation), which must exercise its powers independently, impartially, and without bias. An EU 'White Paper' highlights the need for human oversight as a safeguard, from the design phase throughout the entire lifecycle of AI products and systems [7]. The Organization for Economic Co-operation and Development (OECD) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) have also issue governance suggestions mainly based on ethical principles. Other government-led initiatives also stand out, including those from the US government and the Chinese government (China's White Paper on AI Standardization).

The need for a wide governance to regulate radiation and nuclear safety became evident almost immediately after the discovery of ionizing radiation and the perception of its potential detrimental effects. The International Commission on Radiological Protection (ICRP), a non-governmental charity of scientist providing

recommendations, was created in 1928, and since then an extraordinarily prudent radiation protection paradigm was developed over the years and used globally [8, 9,10]. This paradigm provides the basis of radiation protection and include an internationally applied set of limits on the radiation exposure, as well as requirements for justification of activities involving radiation exposure and for optimizing the protection options, all based on solid ethical principles.

Following the devastating atomic explosions in Nagasaki and Hiroshima at the end of World War II the preoccupations on radiation and nuclear safety took a big momentum. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), was established in 1955 by Resolution 913 (X) of the UN General Assembly in response to widespread concerns about the effects of radiation on human health and the environment. In accordance with its mandate given by the General Assembly, the Committee undertakes scientific evaluations of sources of radiation and of the associated exposures, effects and risks to human health and to the environment; and provides independent, objective and up-to-date scientific basis for radiation safety. The Committee regularly reports on its evaluations to the UN General Assembly, which are then published for use by the scientific community, national and international organizations, regulatory bodies and the general public. Over the decades, UNSCEAR has become the world authority on radiation science and estimation of global levels and effects of exposure to radiation. Governments and organizations throughout the world rely on the Committee's estimates as the scientific basis for evaluating radiation risk and for establishing protective measures.

Moreover, the events in Japan also led to an immediate analysis of the ethical aspects related to this new technology. Although the ethical aspects of radiation and nuclear safety, as well as their relationship with AI, will be addressed in detail in the second chapter of this book, it is worth mentioning here that, after the atomic bombing of the Japanese cities, ethical considerations in nuclear technology focused on non-proliferation, and the need to ensure nuclear safety and radiation protection for people and the environment, and, significantly, intergenerational justice, were considered. These ethical reflections were particularly relevant when considering the peaceful uses of nuclear technology and the management of the radioactive waste generated by these applications.

The most significant step toward establishing governance for nuclear technology developments in general and for radiation and nuclear safety in particular came after President Eisenhower's "Atoms for Peace" initiative, with the creation of the International Atomic Energy Agency (IAEA) in Vienna in 1957. It is also worth mentioning the establishment of another important agency, initially created as a European agency and later, in 1972, transformed into an international agency: the Nuclear Energy Agency (NEA). Specifically, in 1958, the European Nuclear Energy Agency (ENEA) was established under the Organization for European Economic Co-operation (OECD), which in 1972 became the Nuclear Energy Agency

(NEA-OECD) following the transformation of the OEEC into the OECD. Additionally, each country with uses of radiation or nuclear activities had to establish its own radiation and nuclear safety regulatory body, with competencies and particularities that vary by country but have to respect the legally binding obligations undertaken by countries through international conventions and are generally aligned with the safety standards agreed upon by the IAEA.

The IAEA's statutory main objective is as follows [11]: "The Agency shall seek to accelerate and enlarge the contribution of atomic energy to peace, health, and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or under its supervision or control is not used in such a way as to further any military purpose." Significantly, a relevant statutory function of the IAEA is to establish standards for the protection of health '*in collaboration with the competent organs of the United Nations and with the specialized agencies concerned*'. These *Standards* are founded on the findings of UNSCEAR, and take account of the recommendations of ICRP. Moreover, since the end of the last century they are widely cosponsored by relevant international organizations [12]. Over time widely cosponsored Fundamental Safety Principles [13] where established to head the *Standards*. The current edition of the Standards [14] is cosponsored by the following relevant international organizations: the European Atomic Energy Community (Euratom), the Food and Agriculture Organization of the United Nations (FAO), the International Labour Organization (ILO), the IAEA, the International Maritime Organization (IMO), the OECD Nuclear Energy Agency (OECD/NEA), the Pan American Health Organization (PAHO), the United Nations Environment Programme (UNEP) and the World Health Organization (WHO). It is to be noted that in addition to its statutory function ef establishing the standards, the IAEA shall also provide for their application at the request of any State.

In the radiation and nuclear context, the IAEA's functions encourages the establishment of a regulatory framework in each country that is independent and unbiased, ensuring the safety of nuclear and radiation facilities throughout their lifecycle. This is achieved by setting safety standards, codes of conduct, requirements, and international recommendations for radiation and nuclear safety including security. Moreover, the IAEA has important functions for ensure the safeguards of nuclear materials preventing their military use.

Notably, in addition to the IAEA functions, States have undertook legally binding obligation in radiation and nuclear safety, including, the Convention on Early Notification of a Nuclear Accident, the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, the Convention on Nuclear Safety, and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. These conventions establish legally binding obligations for signatory parties and serve as international legal instruments.

Another essential element of governance is solidarity and justice, also emphasized in the IAEA's statute [11], which states: "Allocate its resources in such a

manner as to secure efficient utilization and the greatest possible general benefit in all areas of the world, bearing in mind the special needs of the under-developed areas of the world." To fulfill this goal, the IAEA has a Technical Cooperation Department.

Some aspects of these global governance approaches for radiation and nuclear safety could likewise serve as a reference and inspiration for the governance of AI.

Among the different applications of AI in radiation and nuclear safety is the monitoring and surveillance with AI technologies, especially machine learning algorithms, which have shown promise in improving the monitoring of radiation and nuclear facilities including radiation environments. Traditional safety systems rely on a limited set of sensors and alarms, but AI can aggregate data from diverse sources, including multiple sensors, satellite images, and real-time monitoring equipment, to provide a more comprehensive view of operations. For instance, AI systems can detect anomalies in radiation levels, pressure, temperature, and other critical parameters, predicting and mitigating risks before they escalate into dangerous events [17].

AI systems can analyze data from radiation detectors placed around radiation and nuclear facilities. By continuously comparing real-time data with historical trends, AI can identify deviations in radiation patterns that human operators might miss. The AI system could then raise an alert for an early intervention, potentially preventing serious accidents.

Other important application could be the predictive maintenance and system reliability. AI-driven predictive maintenance systems can enhance the safety of e.g. nuclear reactors and radiation facilities by identifying wear-and-tear or potential failures before they occur. Using machine learning algorithms, AI can continuously analyze sensor data from various equipment components. By recognizing patterns in the data, AI can predict when equipment is likely to fail, allowing for proactive maintenance or replacement before critical components break down.

In a nuclear power plant, AI algorithms can be employed to predict when a reactor's cooling pumps may fail based on data such as vibration levels, motor temperature, or flow rates. Such predictive capabilities can reduce the risk of unplanned outages or accidents that might compromise the safety of the facility.

In the event of a radiation incident, AI can assist emergency response teams by providing decision support tools. By processing large amounts of data from sensors, weather forecasts, and satellite images, AI can help emergency responders make quick, informed decisions on evacuation zones, resource allocation, and containment strategies. Furthermore, AI-driven simulation models can be used to predict the spread of radioactive materials, aiding in the development of effective containment and decontamination plans. The AI systems could simulate the behavior of radioactive clouds in real time, factoring in wind patterns, terrain, and radiation dispersion models. This data can help authorities determine which areas

to evacuate and which safety measures need to be prioritized, significantly reducing human error and response time.

On the other hand, AI has significant potential in improving radiation protection for occupationally exposed workers. Machine learning algorithms can process health monitoring data from workers in nuclear plants, detecting early signs of exceeding radiation exposure based on biomarkers, radiation levels, and environmental factors. AI systems can also optimize deployment of personal protective equipment and monitoring in order to ensure that workers are adequately protected from radiation [16]. AI-based systems can analyze data from wearable sensors that monitor the radiation exposure of workers in a nuclear plant. By using pattern recognition, the AI can detect when radiation exposure is approaching elevated levels, automatically alerting the worker and recommending specific actions to mitigate it.

Regarding the challenges and risks of AI in radiation protection and nuclear safety, one of the issues is that the effectiveness of AI is heavily dependent on the quality and availability of radiation and nuclear safety related data. Incomplete, inconsistent, or inaccurate data can lead to unreliable AI predictions and decisions. Furthermore, AI systems need access to diverse datasets from various sources (e.g., sensors, historical records, and maintenance logs), which may be difficult to integrate or standardize across different systems. Addressing data quality and integration challenges is crucial for the successful deployment of AI in radiation and nuclear safety, however the deep learning, are often seen as "black boxes" because their decision-making processes are not always transparent. In high-stakes environments like radiation and nuclear safety, the lack of explainability in AI decisions can undermine trust in the system. Stakeholders, including safety operators, regulatory bodies, and the public, need clear explanations of AI-driven decisions, especially in critical situations. Ensuring that AI systems can provide transparent and understandable reasoning is essential for their widespread adoption.

Other important issue is that the use of AI in radiation nuclear safety raises significant ethical challenges. Ethical concerns include firstly the coherence and consistency between the already available ethical basis of radiation and nuclear safety and the new ethical principles that are being developed for AI in general. The potential for AI systems to make decisions that may not align with human values, such as decisions that prioritize efficiency over protection or safety.

Another significant issue relate to regulatory challenges. The regulation of radiation and nuclear safety is very developed and sophisticated. But the regulatory landscape for AI is still evolving. Governments and supranational organizations are establishing frameworks for the responsible use of AI technologies. This includes developing standards for AI algorithms, ensuring proper oversight, and preventing potential misuse or errors in AI systems [20], Achieving coherence and consistency between the regulatory approaches for radiation and nuclear safety and AI will be a challenge.

Additionally, the AI systems, like all digital technologies, are susceptible to cybersecurity risks. In the context of radiation and nuclear safety, any breach or compromise of AI systems could have catastrophic consequences, including false alarm generation, system failure, or malicious manipulation of critical safety data. Robust cybersecurity measures, including encryption, authentication, and continuous monitoring, are essential to safeguarding AI systems from cyber threats [19]. This s specially critical in radiation and nuclear safety.

As a conclusion, the AI holds immense potential in enhancing radiation and nuclear safety, e.g., by improving monitoring capabilities, predictive maintenance, incident response, etc. As AI technologies evolve, their role in radiation and nuclear safety is likely to grow, providing operators and regulatory bodies with more accurate, real-time insights into the operation of radiation and nuclear facilities. However, addressing the challenges of data integration, transparency, ethics, and security is essential to ensure that AI systems can be trusted and deployed safely in these critical environments.

In the coming years, continued research and collaboration between radiation and nuclear safety experts, AI researchers, and regulatory bodies will be crucial to realizing the full potential of AI in radiation and nuclear safety. Ultimately, AI has the power to transform the radiation and nuclear industries, providing more reliable, efficient, and safer solutions for managing many endeavors such as radiation applications in medical diagnosis and therapy and the generation of nuclear energy.

In summary, AI techniques are already being applied in some specific aspects in activities involving radiation and nuclear safety and the number of applications is likely to grow, some in a predictable way and also some in ways we are still unpredictable. This rapidly changing situations invites to explore relevant associated issues such as the ethical principle that should govern these developments and their governance. It is therefore expected that the growing use of AI will have an impact in the regulation of radiation and nuclear safety. It will also present a huge challenge in professional training for the adaptation of the regulatory system to the new demands, in order to ensure compliance with the obligations that must be accomplished by regulatory bodies. The application of AI in nuclear technology and industry presents significant regulatory challenges. Addressing these challenges and achieving effective solutions will require collaboration among all stakeholders.

Elvira Romera, Alejandro Núñez,
Francisco Herrera and Abel Julio González.

■ REFERENCES

1. Hurd, I. (1999). Legitimacy and authority in international politics. *International Organization, 53*(2), 379–408.
2. J. Turner (2019) *Robot Rules*, *Regulating Artificial Intelligence*, Palgrave Macmillan.
3. Angela Daly, Thilo Hagendorff, Li Hui, Monique Mann, Vidushi Marda, Ben Wagner, Wei Wang, Saskia. Witteborn (2019) *Artificial Intelligence Governance and Ethics: Global Perspectives*, arXiv: 1907.03848.
4. Gagan Deep Sharma, PhD, Anshita Yadav, Ritika Chopra, (2020) *Artificial intelligence and effective governance: A review, critique and research agenda* Sustainable Futures 2, 100004.
5. Karryl Kim Sagun-Trajano, *Artificial Intelligence Governance: Lessons from Decades of Nuclear Regulation,* RSIS Commentaries, 134-23.
6. Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence and amending Regulations (EC). *DOUE*, 1-144.
7. White Paper on Artificial Intelligence: a European approach to excellence and trust. *COM/2020/65 final/2*, 1-32.
8. ICRP, 1977. Recommendations of the ICRP. ICRP Publication 26. Ann. ICRP 1 (3).
9. ICRP, 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann. ICRP 21 (1-3).
10. ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4).
11. Estatuto del Organismo Internacional de la Energía Atómica. 29 de julio 1957.
12. Food and Agriculture Organization of the United Nations, International Atomic Energy Agency, International Labour Organisation, Nuclear Energy Agency of the, Organisation for Economic Co-operation and Development, Pan American Health Organization, World Health Organization. Safety series, ISSN 0074-1892; 115. Safety standards. STI/PUB/996. ISBN 92-0-104295-7. International Atomic Energy Agency, Vienna, 1996.
13. European Atomic Energy Community, Food And Agriculture Organization Of The United Nations, International Atomic Energy Agency, International Labour Organization, International Maritime Organization, OECD Nuclear Energy Agency, Pan American Health Organization, United Nations Environment Programme, and World Health Organization. *Fundamental Safety Principles: Safety Fundamental.* IAEA Safety Standards Series, ISSN 1020-525X; No. SF-1). STI/PUB/1273. ISBN 92–0–110706–4. International Atomic Energy Agency, Vienna, 2006.
14. European Commission, Food And Agriculture Organization Of The United Nations, International Atomic Energy Agency, International Labour Organization, OECD Nuclear Energy Agency, Pan American Health Organization, United Nations Environment Programme, and World Health Organization. *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards*. IAEA safety standards series, ISSN 1020–525X; no. GSR Part 3. STI/PUB/1578. ISBN 978–92–0–135310–8 Requirement 32**:** Vienna: International Atomic Energy Agency, 2014.