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Historical analysis and effects of radiation accidents

Abstract

With the advent of radiation use, both its beneficial applications and detrimental effects have become evident. Radiation is now extensively employed across the nuclear industry, medicine, and scientific research. However, numerous radiation-related accidents have occurred globally, with long-term adverse consequences observed for human health and the environment.

This study provides a historical analysis of radiation accidents reported between 1957 and 2024. Data was collected from national and international academic sources, technical reports, and organizational publications. Supplementary information was retrieved from the IAEA and LAKA archives for undocumented cases. Radiation incidents were categorized and statistically evaluated by year, geographic region, INES level, and occupational environment. Analytical tools used included Google Sheets and Google Looker Studio.

A total of 1054 radiation events were identified, of which only 1.3% were classified as accidents. The 23 most significant incidents were analyzed in detail. It was noted that comprehensive INES classification became feasible only after 1990 due to improved data availability. Following the Fukushima Daiichi disaster in 2011 (INES Level 7), only event-level cases were documented. Although the majority of radiation incidents (600 cases, 57%) occurred at nuclear power facilities, only 6 of these were classified as accidents.

Key contributing factors to accidents included human error, safety system failures, and technical malfunctions. These findings underscore the need for continuous improvement in radiation safety and incident prevention strategies.

Keywords: radiation, radiation accidents, radiation protection, INES

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Introduction

The use of ionizing radiation has revolutionized multiple sectors, enabling significant advancements in nuclear power generation, medical diagnostics and treatment, industrial quality assurance, and agricultural applications. However, these advancements have not been without substantial risks, as history has witnessed multiple radiation-related incidents with varying degrees of severity.

Three major accidents-Chernobyl,[1,2] Fukushima,[3] and Kyshtym[4]-marked pivotal moments in the evolution of global nuclear safety regulations. These events contributed to international awareness, influencing the adoption of robust safety protocols and standardized risk assessment frameworks.

The International Nuclear and Radiological Event Scale (INES),[5,6] introduced in 1990, serves as a globally recognized framework for communicating the safety significance of nuclear and radiological events.

Figure 1 schematically illustrates the INES rating descriptions, which range from Level 0 (a deviation with no safety significance) to Level 7 (a major accident). The scale provides a standardized approach for classifying events involving radiation sources based on their safety impact. It encompasses incidents resulting in the release of radioactive material into the environment, exposure of workers or the public, and those that reveal failures in safety systems despite having no immediate consequences. The scale also applies to the loss, theft, or discovery of uncontrolled radioactive sources, such as those found in scrap metal. However, INES is not used to classify events involving deliberate exposure for medical treatment purposes. Intended solely for non-military applications, the scale focuses exclusively on the safety-related aspects of such events and has significantly contributed to improved reporting and transparency in radiation protection practices worldwide.

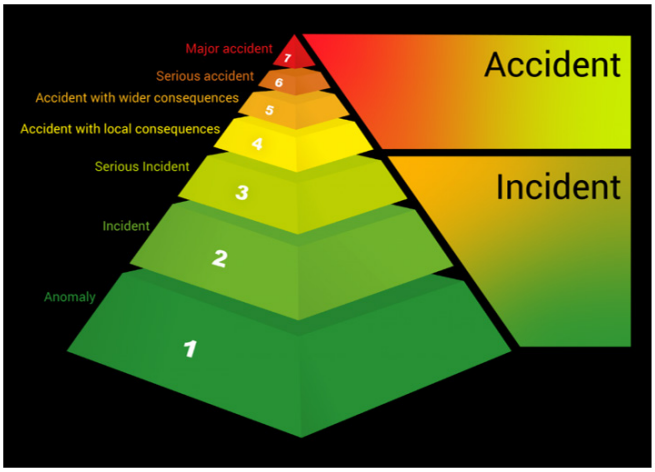

Figure 1 The International Nuclear and Radiological Event Scale (https://www.iaea.org/resources/databases/international-nuclear-and-radiological-event-scale)[6]

Materials and Methods

This research was based on a systematic compilation and analysis of radiation incidents occurring worldwide between 1957 and 2024. Incidents were selected based on criteria including publicly available documentation, severity level, and classification compatibility with the INES scale.

The primary data were extracted from national regulatory authority publications, peer-reviewed scientific reports, IAEA releases,[7] UNSCEAR databases,[1] and archives such as LAKA.[8]

While the 2013 INES publication provides access to IAEA assessments up to the year 2008, the IAEA's official website

contains data only for the most recent year. Therefore, to obtain comprehensive archival data covering all years, the LAKA database (LAndelijk Kernenergie Archief – National Nuclear Energy Archive), a Netherlands-based national nuclear energy archive, was also utilized via its official website (https://www.laka.org/).[8]

In cases where INES classification was not initially provided, best approximations were made based on reported consequences and technical parameters.

Google Sheets was utilized for raw data organization, while Google Looker Studio facilitated the generation of visual representations such as heatmaps and bar charts. These tools allowed for real-time filtering and longitudinal trend observation. To enhance data reliability, all entries were cross-verified using at least two independent sources whenever possible.

Results and Discussion

To systematically classify and communicate the severity of such incidents, the International Nuclear and Radiological Event Scale (INES) was introduced by the IAEA and OECD/NEA in 1990. Since then, efforts to track and evaluate radiation-related incidents have improved.

Temporal trends

Figure 2 illustrates the distribution of reported radiation events and accidents globally between 1957 and 2024. A significant increase in recorded cases can be observed post-1990, likely due to better documentation and the implementation of standardized reporting frameworks such as INES. As shown in Figure 2, a noticeable increase in reported incidents occurred after the implementation of INES, peaking during the early 1990s. While the number of events has declined in recent years, the historical record highlights the persistent occurrence of radiation-related incidents over the past seven decades.

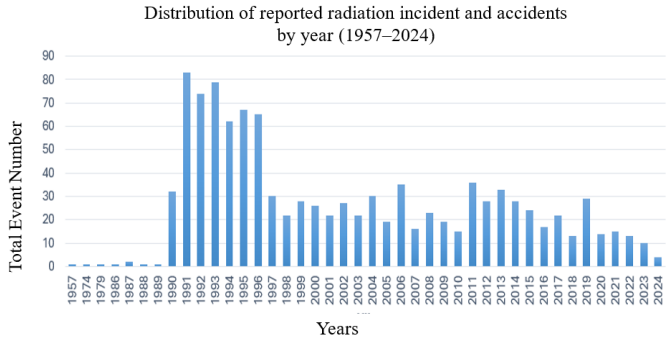

Figure 2 Distribution of reported radiation incidents and accidents by year (1957–2024).

Between 1957 and 2024, a total of 1,054 radiation-related events were identified and systematically classified based on their severity. The vast majority of these events, accounting for approximately 98.7%, were categorized as incidents, indicating that while they may have involved operational deviations or minor safety issues, they did not pose significant risks to public health or the environment. In contrast, only 1.3% of the recorded events were classified as accidents with an International Nuclear and Radiological Event Scale (INES) rating of Level 4 or higher, signifying more serious occurrences with potential or actual consequences at the national or international level. This distribution highlights the relative rarity of severe nuclear and radiological accidents in comparison to the broader category of reportable incidents over the examined time period.

A significant and dramatic increase in the number of reported radiation events was observed after 1990, a trend that closely coincides with the formal implementation of the International Nuclear and Radiological Event Scale (INES) by IAEA. The introduction of INES provided a standardized framework for assessing and communicating the severity of nuclear and radiological events, thereby encouraging more consistent reporting practices across member states. This period also marked a broader global shift toward enhanced transparency and accountability in the nuclear sector, which contributed to the more systematic documentation and dissemination of event data. Notably, following the Fukushima Daiichi nuclear disaster in 2011- an event classified as INES Level 7, the highest possible rating- there was a marked change in the pattern of reported cases. In the aftermath of Fukushima, international reporting practices appear to have become more conservative, with only event-level cases, often of lower severity, being made publicly available. This shift suggests both a heightened sensitivity in public and institutional responses to radiological events and possible changes in the criteria or thresholds for international disclosure.

Geographic distribution and severity

The geographical distribution of radiation incidents and accidents that occurred throughout history has been visualized cartographically using the "Google Looker Studio" software. The increase in the number of cases in each region is represented using shades of blue, with case density illustrated progressively from light blue to dark blue.

Figure 3 presents the global geographic distribution of reported radiation events between 1957 and 2024. The intensity of the blue color represents both the number of radiation events, and the total number of events recorded for each country. This figure reflects not only the extensive scale of nuclear activity within the country but also the robustness and transparency of its reporting mechanisms. Beyond the general distribution, a distinct clustering of high-severity events was shown by arrows indicate the highest INES level recorded in each country over the studied period, where red represents level 7 (major accident), orange level 5 (serious accident), and yellow level 4 (accident with local consequences). The spatial analysis reveals that North America and Asia reported the highest number of radiation events, with the United States alone accounting for 131 cases. However, the most severe incidents - those classified as INES Level 7 - occurred in countries like Russia, Japan, and France, regardless of their overall event count.

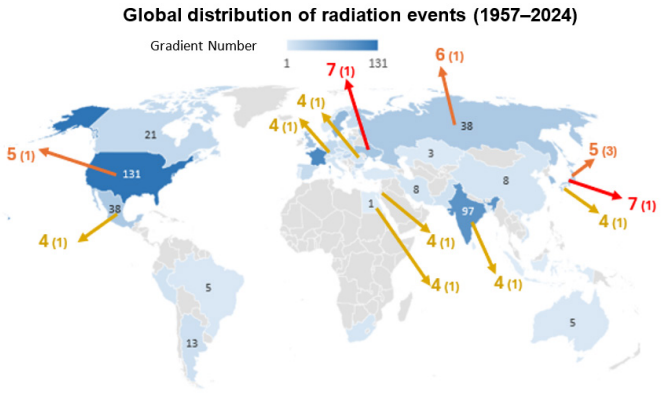

Figure 3 The global geographical distribution of radiation events (1957–2024).

This regional concentration suggests the influence of multiple interrelated factors, including historical legacies of nuclear

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development, geopolitical dynamics, varying levels of technological advancement, and disparities in safety culture and regulatory oversight. These patterns underscore the critical importance of strengthening international cooperation and harmonizing safety standards to reduce the occurrence and impact of severe nuclear and radiological incidents worldwide.

Combined with the temporal trend in Figure 2, this emphasizes the need for continued international coordination in radiation protection standards and incident tracking. This highlights that accident severity does not necessarily correlate with event frequency- countries with fewer total incidents may still experience high-severity failures. These disparities emphasize the importance of robust safety culture, not just frequency monitoring.

Root causes

Most events were linked to human error (e.g., mismanagement, unauthorized access), technical malfunction (e.g., equipment failure), and Inadequate safety culture and training. In terms of regional distribution, Eastern Europe, East Asia, and North America accounted for a significant proportion of radiation incidents. This is largely due to the high concentration of nuclear reactors, medical radiological use, and industrial irradiation facilities in these regions.

Analysis of accident types shows that medical misadministration and industrial radiography errors form the bulk of lower-level INES events, while reactor-related issues dominate Level 4 and above. Interestingly, 75% of INES Level 5–7 accidents involved reactor systems or fuel handling, suggesting that these remain the most vulnerable nodes in nuclear infrastructure.

Conclusion

This study provides a comprehensive historical overview of radiation-related events worldwide, using the INES scale as a classification tool. The concentration of severe accidents in early decades and their decline in recent years demonstrates progress in global radiation protection protocols.

However, the continued occurrence of low-level radiation incidents underlines ongoing vulnerabilities in human performance, safety culture, and system resilience. This study advocates for a global, interoperable incident reporting network, potentially overseen by the IAEA, that would allow nations to contribute to and access a centralized database of radiation events. Such an initiative would enable earlier trend detection and promote collective learning from past failures.

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Conflicts of interest

None.

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