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# Comparison of severity scales of human-made accidents of nuclear and chemical industries

Wasin Vechgama

*Nuclear and Radiation Safety Research Section, Thailand Institute of Nuclear Technology (TINT), Thailand. E-mail: wasin@tint.or.th*

Kampanart Silva

*National Energy Technology Center (ENTEC), National Science and Technology Development Agency (NSTDA), Thailand. E-mail: kampanart.sil@entec.or.th*

Severe accidents of Nuclear Power Plants (NPPs) caused radioactive material release into the people and the environment. Nuclear impact worldwide heightens public concern about the use of nuclear energy, both in countries that operate NPPs and those that do not. In the chemical industry, particularly oil and gas sectors, many severe accidents have also occurred, resulting in long-lasting environmental impacts. Both the nuclear and chemical industries rely on socio-technical systems to enhance safety, optimize operations, and minimize losses. Although both nuclear and chemical accidents affected similar losses, the chemical industries reveal less negative perception compared to nuclear energy. This work aims to recommend the standard of comparing severity scales on human-made accidents in nuclear and chemical industries using the levels of severity from the International Nuclear and Radiological Event Scale (INES) and Standard Operating Procedure (SOP). The similarities and differences of nuclear and chemical accidents' severity scales are examined to indicate the position of the chemical industry in the scheme of nuclear accidents. The finding of this work is expected to recommend the standard to explain the severity of nuclear and chemical accidents in the same approach to support public understanding of nuclear energy.

*Keywords*: Nuclear accident, Chemical accident, Oil & gas industries, International Nuclear and Radiological Event Scale (INES), Standard Operating Procedure (SOP).

## 1. Introduction

Past severe accidents at nuclear power plants (NPPs) such as Fukushima and Chernobyl accidents have led to the release of radioactive materials into the environment, exposing people to harmful radiation (Woo et al. 2024). These consequences have heightened global public concern about the safety of existing nuclear energy infrastructure and apprehensiveness toward its future expansion in both countries that operate NPPs and those that do not (Kosai & Yamasue 2019). Public communication is a crucial matter that requires attention from governments and regulatory bodies. It is imperative for these entities to develop proper communication standards and disseminate accurate information to the public to ensure a comprehensive understanding of the current state of nuclear incidents (Kim et al. 2024).

Basically, nuclear safety goals for probabilistic safety assessment (PSA) or probabilistic risk assessment (PRA) will be determined for different accident progression to support deciding severe accident management and communicating to the public (Sornette et al. 2013). According to PSA standards, core damage frequency (CDF) in level 1 PSA, large early release frequency (LERF) in level 2 PSA, and public dose exposure in level 3 PSA are important safety goals. Nevertheless, the PSA concept is difficult to answer some issues due to the unique release magnitude of specific core inventories and the different release timing of the site emergency plan for the evacuation strategy of the local population in many countries (Vitázková & Cazzoli 2013). Quantitative safety goals criteria have not been sufficiently justified with a technical discussion, particularly for LERF, which addresses thresholds of consequences concerning public doses. Many nuclear safety documents published by the International Atomic Energy Agency (IAEA) recommend establishing uniform safety standards to protect the health of workers and the general public because a serious accident in one location can affect public perception of nuclear power globally, not just in that specific area.

Based on the risk concept from WASH 1400, nuclear risks were compared with non-nuclear risks to make a realistic estimate. This comparison aims to provide perspectives on future reliance by society on nuclear power as an electricity source and suggests that potential accidents in nuclear power plants pose relatively small risks to the public (U.S. NRC 1975). Fig 1 shows the likelihood and number of fatalities from both nuclear and non-nuclear man-made accidents before 1980. Statistical data indicates that non-nuclear events are approximately 10,000 times more likely to result in many fatalities compared to 100 operating nuclear power plants (NPPs).

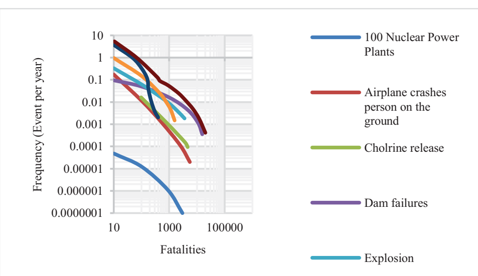


Fig. 1. Likelihood and fatalities of nuclear vs. non-nuclear accidents before 1980 (reproduced from WASH-1400) (U.S. NRC 1975).

However, it is not easy to explain straightforward the risk concept in public communication to understand the current situation (Boholm 2019, IAEA 2013). The complicated risk concept can affect the overall understanding of risk, whether generally or in specific issues. This problem is associated with both internal faults within the agency and deficiencies in the recipient of the communication.

The International Nuclear and Radiological Event Scale (INES), established by the IAEA and the Organization for Economic Co-operation and Development's Nuclear Energy Agency (OECD/NEA) in 1990, serves as a standardized tool for communicating the safety significance of events related to industrial applications such as radiography, medical use of radiation sources, operations at NPPs and nuclear research reactors (NRRs), activities related to spent nuclear fuel (SNF) and radioactive waste management facilities, and the transport of radioactive materials (IAEA 2014, Kermisch & Labeau 2013). However, the use of INES has some limitations associated with the unclear multiple criteria for assigning INES rating, especially in level 7 of the INES scale in taking differences in severity between disasters involving multiple initiators into account in the long term (Kermisch & Labeau 2013).

Since the INES level is additionally assessed mainly through the estimation of the doses received from an environmental release corresponding to a quantity of radioactivity equivalent to a release to the atmosphere of Iodine-131 (I-131) and the ambiguous number of people exposed, it is difficult to use the INES level to directly compare nuclear accident consequences with those of non-nuclear accidents to communicate with the public, especially newcomer countries, looking for NPPs as new electricity source to support their chemical or heavy industries, particularly oil and gas production. Hence, this work aims to suggest the comparative severity scales on human-made accidents between nuclear and chemical industries using the levels of severity of the INES from nuclear accidents (IAEA 2013) and Standard Operating Procedure (SOP) from chemical accidents (Louisiana State University 2011) to indicate the similarities and differences between them in the same severity scale for enhancing public understanding and reducing misconceptions about nuclear energy.

## 2. Methodology

In order to compare the severity of nuclear and chemical accidents on a unified scale, a comparative analysis was conducted between the INES from nuclear accidents (IAEA 2013, IAEA 2014) and SOP from chemical accidents (Louisiana State University 2011) to identify their similarities and differences.

The comparative results will be able to help inform the establishment of new severity standards applicable to both nuclear and chemical accidents, enhancing public understanding. This study primarily focuses on the severity scales of INES and SOP concerning their impact on people and the environment, for proposing new severity standards. The basic severity scale of INES and SOP are described in the subsections below.

### 2.1. INES: Nuclear Consequences to People and the Environment (IAEA 2013, IAEA 2014)

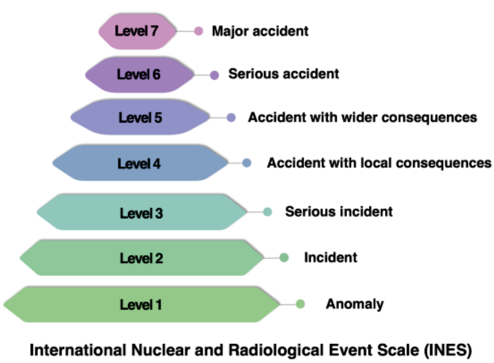


Fig. 2. INES scale for nuclear consequences to people and the environment.

Fig. 2 shows the INES scale for nuclear consequences to people and the environment. The INES scale, established by the IAEA and the OECD/NEA in 1990, is a tool identifying the safety significance of an event based on a technical basis for communicating to the public. INES covers events where there are near misses or failures in processes, systems, and safety management that do and do not result in actual consequences. The INES rating of events having an impact on people and the environment considers the actual radiological dose of workers, the public, and the amount of radioactive material released into the environment. An incident is used to describe events without death, that are less severe than accidents, the maximum level for incidents is Level 3. If the radiation levels are sufficiently high to cause deterministic effects or death, the event will be rated to the potential consequences of accidents starting at Level 4 in INES. INES scale for nuclear consequences to people and the environment based on the hierarchy in Fig. 2 can be classified as follows;

- **Major accident (Level 7):** Major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures;
- **Serious accident (Level 6):** Significant release of radioactive material likely to require implementation of planned countermeasures.
- **Accident with wider consequences (Level 5):** Limited release of radioactive material likely to require implementation of some planned countermeasures with several deaths from radiation.
- **Accident with local consequences (Level 4):** Minor release of radioactive material unlikely to result in implementation of planned countermeasures other than local food controls with at least one death from radiation.
- **Serious incident (Level 3):** Exposure in excess of ten times the statutory annual limit for workers with non-lethal deterministic health effects from radiation.
- **Incident (Level 2):** Exposure of a member of the public in excess of 10 mSv and exposure of a worker in excess of the statutory annual limits.
- **Anomaly (Level 1):** Overexposure of a member of the public in excess of statutory annual limits.

### 2.2. *SOP: Consequences of Chemical Spill (Louisiana State University 2011)*

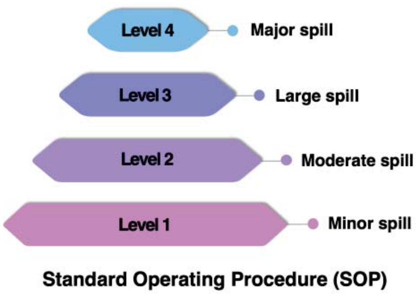


Fig. 3. Severity scale of SOP for consequences of chemical spill.

Fig. 3 shows the severity scale of SOP for consequences of chemical spill. Generally, the use of SOP is a mandatory item in industry and private research based on Standards - 29 CFR of the Occupational Safety and Health Administration (OSHA). SOP of consequences of chemical spill or release is used to guide the user in preparing for and responding to chemical spills, to minimize the severity of such incidents and accidents. Chemical spills can impact people and the environment thus it is necessary to report the severity of the situation and related actions of such incidents and accidents to regulatory authorities. The level of severity is summarized and classified into four levels based on the hierarchy in Fig.3 in the following;

- **Major spill (Level 4):** Accidents of large spills, fires, or explosions that occur in the workplace that require evacuation with a threat to the public and the environment and can trigger other incidents or accidents with serious injuries and fatalities, respectively. Local police officers need to notify the public to evacuate and manage the impact of major hazardous materials with other related agencies.

- **Large spill (Level 3):** Accidents of large spills, fires, or explosions that occur in the workplace that require evacuation without a threat to the public. Emergency assistance from the security section and local police officers is to control the release of hazardous material in an amount that exceeds the regulated quantity and injury with hospitalization or a fatality, respectively.

- **Moderate spill (Level 2):** Incident of debris or chemical spills in large working areas that cannot be controlled and cleaned up by workers. Emergency assistance from the security section and local police officers are to perform gross cleanup and take care of nonserious injuries, respectively.

- **Minor spill (Level 1):** Incident of a minor chemical spill in a workplace that can be controlled and cleaned up by workers with no response from environmental health and safety authorities or law enforcement.

## 3. Results and Discussion

### 3.1. Comparative Analysis

Basically, the INES scale is not applicable to events without safety relevance with respect to radiation or nuclear safety. Chemical hazards resulting from the release of non-radioactive materials, which lead to worker injury, death, or environmental consequences, would not be classified using the INES scale (IAEA 2013). On the other hand, the severity scale of SOP is designed to assist users in preparing for and responding to chemical accidents to minimize the impact of such incidents. SOP does not address radioactive materials (Louisiana State University 2011). Even though the severity scales of INES and SOP have distinct objectives in managing accidents in the nuclear and chemical industries, they can potentially lead to public misunderstanding and confusion in public-to-public and government-to-public communication, particularly in industrial areas where nuclear energy is shared with heavy and chemical industries. Thus, the similarity of these two scales is suggested to generalize to standard to support public communication. Regarding consequences to people and the environment, considering only released hazardous materials without distinguishing radioactive and non-radioactive materials of these two scales, the number of injuries or deaths and consequence boundary inside and outside plants can be used to simply compare the similarity of INES and SOP severity scales. However, economic impacts and specific consequences based on distance are challenging to compare when evaluating the similarity between INES and SOP. This difficulty arises due to varying compensation policies in different countries and the unique meteorological conditions of each accident (Sovacool 2018, Planas et al. 2006).

When comparing the INES severity scale with the SOP severity scale in terms of incident effect within plant boundary, Levels 1 and 2 of INES correspond to the incident of a minor chemical spill of Level 1 in SOP. The consequence of hazardous material release in both nuclear and chemical plants can be controlled by operators and staff without injury or death. Only the exposure of significant amounts of hazardous material in excess of the statutory limit for workers is considered for the proper management of the operating teams' working periods to minimize their consequences. Level 3 of the INES scale indicates a low probability of significant public exposure, with exposure levels exceeding ten times the statutory annual limit for workers, yet without causing non-lethal deterministic health effects in operating areas. The consequences of a Level 3 incident on the INES scale are comparable to a moderate spill classified as Level 2 on the SOP scale. This is considering incidents involving debris or chemical spills in large working areas without resulting in serious injuries. Regarding accident consequences, the INES scale begins to account for at least one death caused by radioactive material released into the public and the environment outside the plants starting from Level 4. The scale assigns increasingly wider and more severe consequences with higher fatalities in Levels 5 and 6, respectively. The scope of Levels 4, 5, and 6 on the INES scale is equivalent to the large spill accident in Level 3 of the SOP which regulates injury and fatality. Finally, a major release of hazardous materials at Level 7 of the INES scale and Level 4 of the SOP scale are considered equivalent due to the impact triggering additional incidents or accidents, resulting in numerous serious injuries and fatalities.

### 3.2. *Standard Generalization*

Table 1 shows the recommended severity level standard for nuclear and chemical accidents. To standardize the severity criteria for both nuclear and chemical accidents for better public communication, the impact of injuries or deaths, along with consequence boundaries, is used to recommend classifying the severity scale of the SOP into 7 levels, similar to the INES scale. Additionally, criteria for the number of deaths in identifying the severity level have been developed to conveniently support users in evaluating the severity of accidents. In the recommended severity level standard, the number of deaths is approximated by the number of deaths from existing nuclear accidents in the past and deviation at ten times greater for each increase in level on the scale of INES scale. For example, in Table 1, Level 4 of the recommended severity scale begins to account for at least one death caused by the release of hazardous material, similar to the INES. Therefore, the recommended range for the number of deaths at Level 4 is from 0 to 10. At higher levels, the number of deaths increases tenfold progressively.

Table 1. Recommended severity level standard for nuclear and chemical accidents.

| Level | Recommended severity level |
|---|---|
| **7** | Major release of hazardous material with widespread health and environmental effects requiring implementation of planned and extended countermeasures with deaths from consequences of more than 1000 people. |

| Level | Recommended severity level |
|---|---|
| 6 | Significant release of hazardous material likely to require implementation of planned countermeasures with deaths from consequences of more than 100-1000 people. |
| 5 | Limited release of hazardous material likely to require implementation of some planned countermeasures with deaths from consequences of more than 10-100 people. |
| 4 | Minor release of hazardous material unlikely to result in implementation of planned countermeasures other than local food controls with only serious injuries or deaths from consequences of more than 1-10 people. |
| 3 | Exposure of significant hazardous material in excess of ten times the statutory limit for workers. |
| 2 | Exposure of significant hazardous material in excess of the statutory limit for workers. |
| 1 | Minor problems or abnormalities with critical components happened without significant effect to workers. |

### 3.3. *Demonstration*

Tables 2 and 3 in Appendix show the demonstration of recommended severity level standards for nuclear and chemical accidents, respectively. After generalizing the severity criteria for nuclear and chemical accidents, Table II reveals that the severity ratings of the INES (column 12) and the recommended scale (column 13) assign the same severity level scores to nuclear accidents such as the Tokaimura Criticality Accident and the Goiania Accident. This is the case even though the range of the number of deaths in the recommended severity level standard is more precisely defined. Nevertheless, in Table III, the chemical accidents of the Oppau explosion and the West Fertilizer Company explosion are rated at the highest level, or Level 4, for SOP (column 12). After classifying the severity scale into 7 levels on the recommended scale (column 13), the Oppau explosion is rated at Level 6, and the West Fertilizer Company explosion is rated at Level 5, respectively. The new recommended severity level standard not only helps classify the severity of chemical accidents but also explains the differences in consequences between nuclear and chemical accidents. This enhancement aims to facilitate easier public communication during emergency situations or public engagement activities in industrial areas.

## 4. Conclusions

The primary objective of the safety and operation of nuclear and chemical plants is to minimize losses to people and the environment. Although nuclear and chemical accidents result in similar losses, the chemical industry faces less negative perception compared to nuclear energy. This work aims to recommend new comparative severity scales for human-made accidents in the nuclear and chemical industries, using the levels of severity from the INES for nuclear accidents, to improve public communication.

The new recommended severity criteria for both nuclear and chemical accidents are classified into 7 levels, similar to the INES scale, with specifications for the number of deaths. The new recommended severity level standard not only aids in classifying the severity of chemical accidents but also clarifies the differences in consequences between nuclear and chemical accidents in order to facilitate easier public communication during emergency situations or public engagement activities in industrial areas.

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## Appendix

Table 2. Demonstration of recommended severity level standard for nuclear accidents.

| No. | Event | Basic information | | | Root causes | | | Consequences | | | Severity rating | | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Continent | Country | Date | Nuclear-related issues | Operation-related problems | Human errors | No. of fatality | Human injuries | Environmental injuries | INES | Recommend scale | |
| **1** | Tokaimura Criticality Accident | Asia | Tokaimura, Japan | 1999-09-30 | A stolen radiotherapy source (cesium-137) led to widespread contamination. | A highly radioactive cesium-137 source that was abandoned in a disused radiotherapy machine. When the machine was dismantled and its contents were inadvertently spread -> led to the incident. | The Insituto Goiano de Radioterapia (IGR) left the obsolete (cobalt-70 had become the standard for such units at the time) without notifying the government or Brazil's regulatory body for nuclear energy, the Comissão Nacional de Energia Nuclear (CNEN). | Four people died | 28 people suffered radiation burns. | Cesium-137, in the form of a highly soluble powder, was dispersed across multiple locations in the city, including scrap yards, homes, and streets. | 5 | 5 | World Nuclear Association 2020 |
| **2** | Goiania Accident | Europe | Goiania, Brazil | 1987-09-13 | Soviet-designed RBMK (reaktor bolshoy moshchnosty kanalny, high-power channel reactor) has the shortcomings: | The reactor's fuel burn-up, control rod configuration, and power level led to a positive void coefficient large enough to overwhelm all other influences on the power coefficient. | Shut down the power and safety control system. | About 112,000 people were examined for radioactive contamination and 249 of them were found to have been contaminated | Cesium-137, in the form of a highly soluble powder, was dispersed across multiple locations in the city, including scrap yards, homes, and streets. | Soil, walls, and other materials absorbed the radioactive substance, rendering several areas uninhabitable. | 7 | **7** | Mascarenhas et al. 2018, NCT CBNW 2014, 17. Offic e of Scientific and Technical Information 2014 |

Table 3. Demonstration of recommended severity level standard for chemical accidents.

| No. | Event | Basic information | | | Root causes | | | Consequences | | | Severity rating | | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Continent | Country | Date | Chemical-related issues | Operation-related problems | Human errors | No. of fatality | Human injuries | Environmental injuries | SOP | Recommend scale | |
| 1 | Oppau explosion | Europe | Germany | 1921-09-21 | Approximately 4,500 tonnes of a mixture of ammonium sulfate and ammonium nitrate fertilizer stored in a tower silo exploded at a BASF plant in Oppau.<br><br>The explosibility of the 50-50 mixture in highly confined conditions and a relatively low density, the explosion is limited to the region around where the explosives are placed. | NA | Lack of safety training related to the storage limit. | 561 | 1952 injured 7500 people left homeless | a large crater in the ground, widespread destruction of buildings in the surrounding area, significant air pollution from released noxious gases like nitrogen oxides and ammonia, and potential long-term soil contamination due to the dispersed chemical residue from the explosion, primarily from the ammonium nitrate fertilizer. | 4 | 6 | Ministère de la Transition écologique et de la Cohésion des territoires 2018 |
| 2 | West Fertilizer Company explosion | USA | Texas | 2013-04-17 | Ammonium nitrate exploded | N/A | Overlimit storage (According to its last filing with the EPA in late 2012, the company stated that it stored 540,000 pounds (270 short tons; 240 t) of ammonium nitrate and 110,000 pounds (55 short tons; 50 t) of anhydrous ammonia on the site.) | 15 | 160 cases | Releasing 46.8 million tons of greenhouse gases in 2021 – as much as nine million gas-powered passenger vehicles driving for a year.<br><br>Emitting 16,146 tons of nitrogen | 4 | 5 | Ministère de la Transition écologique et de la Cohésion des territoires 2018, Environmental Emergencies Centre 2021 |

| No. | Event | Basic information | | | Root causes | | | Consequences | | | Severity rating | | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Continent | Country | Date | Chemical-related issues | Operation-related problems | Human errors | No. of fatality | Human injuries | Environmental injuries | SOP | Recommend scale | |
| | | | | | | | | | | oxide air pollution, as well as 12,491 tons of ammonia, 5,227 tons of sulfur dioxide, and 3,981 tons of volatile organic compounds (all of which contribute to smog); 1,929 tons of particulate matter (which can trigger asthma and heart attacks); and 12 tons of benzene (a known carcinogen). | | | |