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What can we learn from past nuclear accidents? A comparative assessment of emergency response to accidents at the Three Mile Island, Chernobyl, and Fukushima Nuclear Power Plants

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Abstract

Although nuclear power is still one of the most reliable and environmentally friendly energy sources, it has a strong public opposition, often because of concerns about its safety. These concerns are sparked by memories of the three major Nuclear Power Plant accidents, the consequences of which go beyond the radiation borders. A controversial issue in this domain is the effectiveness of emergency management. Therefore, we reviewed the emergency response to three Nuclear Power Plant accidents: Three Mile Island (1979), Chernobyl (1986), and Fukushima (2011). The aim of our research was to identify major problems that remain unresolved in nuclear emergency planning. We argue that not the accident itself, but rather how it was managed resulted in serious health consequences. We emphasize the need for increased attention to educating residents about the nuclear safety measures, as well as key aspects of the response. Our findings also suggest that it is necessary to focus on the shelter location selection considering the potential hazards from natural disasters specific to a particular country. Finally, the government and local authorities should be aware of possible economic losses in the event of an accident and take into account potential mass relocation in land management.

1. Introduction

When someone mentions nuclear power, generally, the first thing that comes to mind is a nuclear disaster. People's perception of safety is largely determined by three accidents: The Three Mile Island (TMI) in USA (1979), Chernobyl in Ukraine (1986), and Fukushima in Japan (2011). The last two, Chernobyl and Fukushima, were the most tragic events in terms of environmental pollution and mental health consequences, respectively.

The TMI accident took place at the American Nuclear Power Plant (NPP) located near Harrisburg, Pennsylvania on March 28, 1979 [1]. This accident received a Level 5 classification on the International Nuclear and Radiological Event Scale (INES), which means "accident with greater effects" [2]. The INES was originally proposed by the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA) in 1990. Then this scale was adopted in the world to explain the safety significance of nuclear accidents. Events in this scale are rated at seven levels according to the severity in terms of impact on people and environment. The highest level of radiation is indicated as Level 7 [2]. Although a series of mechanical and human errors at the station resulted in a reactor core meltdown in part, no considerable amounts of radioactive material were released into the atmosphere. Several studies carried out in the years after the accident confirmed the absence of adverse effects of radiation on human health [3]. However, there were clear signs of psychological distress following the accident and evacuation [3]. Nearly 144,000 inhabitants living within a 20-mile (approximately 32 km) radius area of the NPP have voluntarily left their homes. According to a health program run by the Pennsylvania Department of Health, people suffering from stress believed their health was worse than it was [4]. Nevertheless, 98% of evacuees had returned to their homes within a few weeks.

The Level 7 accident at the Chernobyl NPP in 1986 is still regarded as the deadliest catastrophe in the history of nuclear energy [5]. The Chernobyl nuclear power station was constructed at the Pripyat town of the former Soviet Union, 104 km north of Kyiv, the capital of Ukraine, and just 7 km south of the Ukrainian-Belarusian border. The disaster happened at night on April 25-26, when a technical error occurred during the experiment. Several powerful explosions caused a huge fireball and blew up one of the four reactors, which was completely destroyed. Consequently, the reactor's graphite core emitted a large number of radioactive materials into the atmosphere, from where they were carried out by air over long distances [6]. This led to a mass evacuation of nearby areas and the subsequent establishment of an exclusion zone that remains closed to this day. As a result, about 350,000 people were compulsorily resettled in the years after the accident, leaving a mark on public health. A huge number of non-radiation health effects have been reported since the accident including stress, mental disorders, depression, and even suicide [2].

A double natural disaster, the great earthquake in east Japan and the resulting tsunami were compounded by another worst nuclear catastrophe in the world's history since the Chernobyl. A 15-meter tsunami cut off power and cooling to three of the four Fukushima Dai-ichi NPP's reactors, leading to the nuclear accident that occured on March 11, 2011 [7]. Due to high radioactive release, the accident was rated Level 7 on the INES as a "major accident". Fortunately, most atmospheric emissions were blown east towards the Pacific Ocean, and a relatively small part of these emissions settled on the land [8]. However, this could not help to avoid evacuation. More than 160,000 people were forced to evacuate, of which about 40,000 still cannot return home due to restrictions. The evacuation of 11 districts was carried out in a hurry manner and led to the immediate death of elderly patients from nursing care centers. Over the next ten years, the total death toll from the psychological stress of evacuation and relocation rose to 2,000 [2].

Obviously, these nuclear accidents bear the imprint of risk perception and make people afraid of nuclear power. A number of studies have pointed to the fear of nuclear disasters and its consequences [9-12]. Many studies revealed that Chernobyl evacuees showed high concerns about the absorbed radiation dose [13-15]. Moreover, they had erroneous prejudices concerning the chronic radiation exposure, and many of these patients repeatedly sought medical attention, despite medical personnel reassuring them that it was safe for health. According to Japanese survey data, the total doses received by the general population, especially by the children, were quite low [16-17]. The effective doses received by the almost 23,000 workers engaged in the Fukushima emergency activities were below Japan's occupational dosage limit [18]. However, regardless of the actual dose of radiation received, many people had concerns about the possible development of cancer [19-20]. Reliable evidence that ionizing radiation poses a relatively low health risk is in stark contrast to popular fears. Moreover, as shown in Figure 1, when comparing the results of mortality rates from nuclear energy with other sources, it can be seen that it is one of the safest [21].

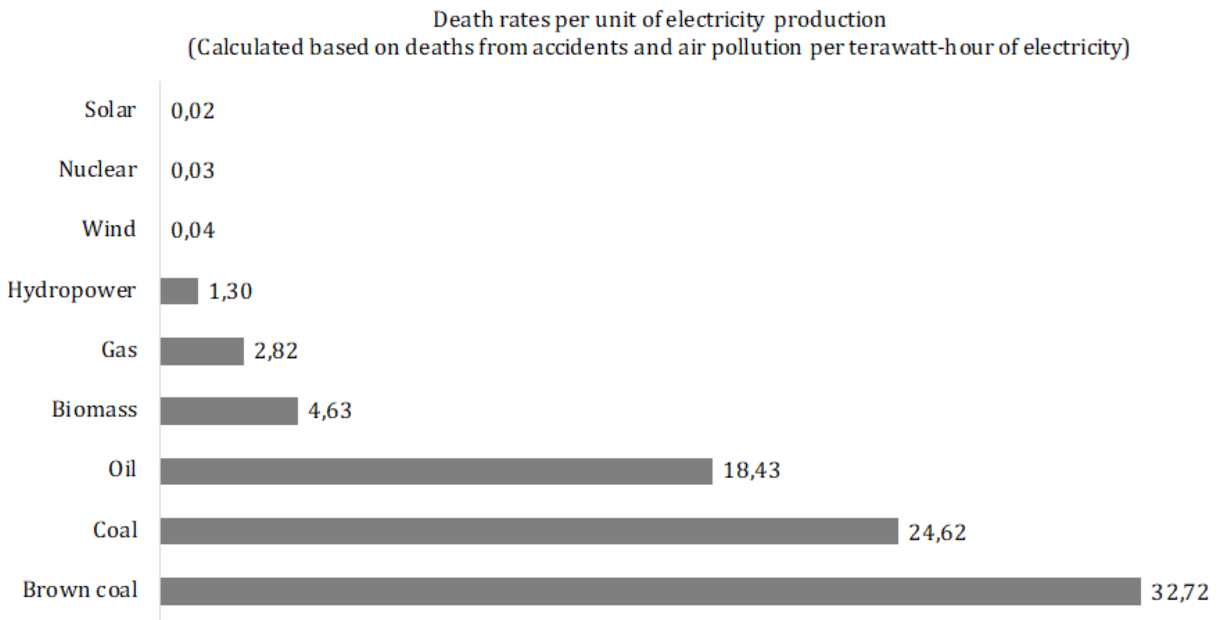


Figure 1. Death rates per unit of electricity production (data is taken from [21]).

The death toll from nuclear accidents is negligible compared to the millions that die in coal mine accidents and from air pollution due to fossil fuels. Nobody died directly from the accident at TMI and Fukushima NPPs; less than 50 people died from acute radiation syndrome after the accident at the Chernobyl NPP. How, then, did everyone come to see nuclear accident as so catastrophic? What exactly should we be afraid of – a release of radiation or insufficient preparedness for a disaster? In order to address the questions outlined above, we report here on the main issues that remain unresolved in nuclear emergency planning. Our main objectives are as follows:

1. To review and analyze emergency response in past NPP accidents such as TMI, Chernobyl and Fukushima.
2. To derive lessons learned from these accidents and to identify problematic uncertainties that remain unresolved.
3. To indicate needed developments to fill the scientific gap.

2. Background on emergency preparedness at NPPs

Since the first major accident at an NPP, all countries of the world have begun to plan for emergency situations. In 2019, the Nuclear Regulatory Authority (NRA) together with the Disaster and Emergency Management Authority (DEMA) of Turkish Republic developed the National Radiation Emergency Plan (NREP) which identifies all the responsible authorities and organizations as well as their main responsibilities in the event of an accident. The NREP was prepared in accordance with the requirements of the IAEA and is currently the main document explaining emergency planning and preparedness aimed at protecting citizens. According to the NREP, areas to be controlled are divided into special emergency planning zones which are explained in Table 1 [22].

Table 1. Emergency planning zones.

Name of zone	Distance from the NPP	Description
Precautionary action zone	5-km radius zone	Residents of this zone must be unconditionally evacuated in the event of a serious accident
Emergency planning zone	8- to 10-km radius zone	Measures such as evacuation and radiation monitoring to be taken
Urgent protective action planning zone	30-km radius zone	Residents must be evacuated if radioactive materials exceed certain levels
Plume protection planning zone	50-km radius zone	Residents may stay indoors or in shelters and iodine tablets to be distributed
Food sampling zone	100-km radius zone	Sampling of crops, cattle, water and other food sources must be monitored

These emergency planning zones can be resized to accommodate topographical features, rivers, highways, human settlements, etc., so that the emergency workers and local population can easily understand them and carry out the protective actions effectively. Therefore, the development, planning, and management of urban lands should be carried out in accordance with preparation plans and emergency zones.

3. Occurrence of nuclear accidents and emergency response to them

The accident at TMI developed over several hours, and the main reasons were equipment failure, followed by a misinterpretation of the course of the accident by personnel. At the second power unit of the TMI NPP, a leak occurred in the coolant system of the nuclear installation. The station staff did not notice this in time, and the nuclear fuel became dangerously overheated. Until the process could be stopped, up to 50% of the reactor core had melted [23]. The fact that the consequences of the accident at TMI turned out to be insignificant for the environment was largely due to the design of its reactor. It was a pressurized reactor vessel (PRV), that is, the core is located in a strong sealed vessel, which to some extent prevents nuclear fuel from being released to the outside [24]. In the Union of Soviet Socialist Republics (USSR), another type of reactor was actively developed – a nuclear power reactor with a graphite moderator (The RBMK – *Reaktor Bolshoy Moshchnosti Kanalnyy*, "High-power channel-type reactor") [25]. There are many differences in the design of these two reactors, but there are two key ones. Firstly, due to the enormous dimensions of the RBMK, it is impossible to "pack" it into a sealed vessel that would protect the environment in the event of the reactor explosion. Secondly, in contrast to PRV, where water is used either as a moderator or as heat exchange, in RBMK-type reactors water is utilized only for heat transfer and graphite acts as a moderator, i.e., it helps slow down the neutrons formed during fission to support the chain reaction. The Chernobyl experiment aimed to determine how long the turbines would power pumps when the main power source was turned off. Such an experiment was carried out earlier at the Chernobyl NPP and it was noticed that the power from the turbine drops very quickly. Thus, in this experiment, it was planned to test a new voltage regulator. As power was increased, contact of the hot nuclear fuel rods with the cooling water caused them to burst and pressurize as a result of excessive steam production. Consequently, immoderate steam formation covered the entire core and caused a steam explosion, which in its turn led to the release of fission products into the atmosphere. Several seconds later, the second explosion caused graphite release, which worsened the situation worse [26]. When an anomaly occurs in a NPP with water-moderated and water-cooled reactors, the high temperature will make the water boil up and then turn it into steam. While water is considered to be a good moderator, steam is not. Therefore, when the neutron slows down (because some or all of the water becomes steam), the neutrons can no longer continue the fission reaction and the reactor stops. In case of the Chernobyl accident, a strong power wave caused the cooling water to boil and because the reactor was not water-moderated, it led to sparks inside the graphite blocks, causing even more heating and subsequent damage.

The fact that the presence of a sealed vessel does not always save one from the serious consequences of accidents at NPPs is proved by the example of Fukushima. A strong earthquake of magnitude 9 hit the Pacific Ocean, causing an automatic shutdown of reactors at the NPP in Fukushima [27]. High-voltage power lines were destroyed, and the station's external power was turned off, but emergency generators immediately started working – it seemed that the danger had passed. However, several minutes after, a 14-15 meters-high tsunami wave raised by the earthquake reached the station. The protective dam was designed for only 5.5 meters [28]. The water flooded critical equipment that cooled the reactors, in particular seawater pumps. Batteries and diesel generators were flooded. The station remained de-energized, and its employees had no information about the state of the reactors. Subsequently, the nuclear fuel of three of the six power units melted. At the same time, hydrogen accumulated, which led to a series of explosions and releases of radioactive elements into the atmosphere [29].

The primary goal of an emergency response to a radiation crisis is to reduce the initial risk and prevent radiation poisoning of the public [30]. Immediate actions may include shelter-in-place, evacuation, the distribution of iodine tablets, as well as monitoring of food and water. In addition, long-term actions such as relocation and resettlement of affected populations may be also further undertaken [31]. The following sections describe the emergency response taken to past accidents at NPPs.

3.1. The TMI NPP accident

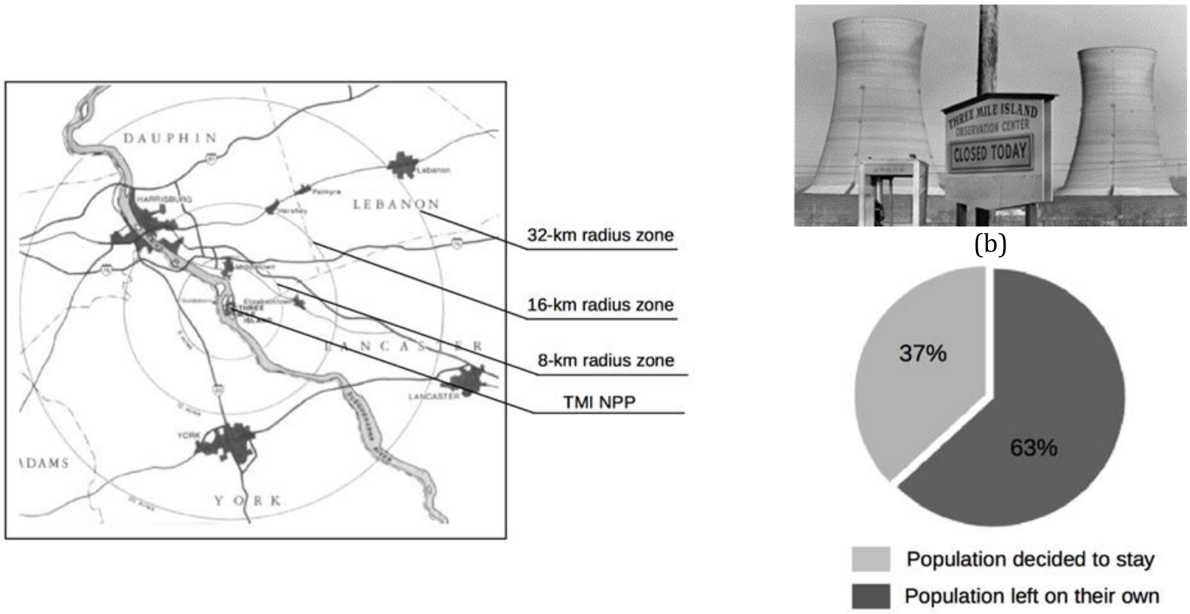
Due to the small release of radioactive materials without any impact on the environment and public health, the emergency response to TMI accidents included advisory evacuation, shelter-in-place, and voluntary evacuation [32]. Table 2 shows the steps in emergency response decisions made by the authorities.

Table 2. Emergency response decisions followed by accident at TMI.

Evacuation decision	0-8 km radius zone	>8-16 km radius zone	>16-32 km radius zone
I decision (1. day of the accident)	Advisory evacuation	Indoor sheltering	
II decision (2. day of the accident)		Voluntary evacuation	
III decision (3. day of the accident)			Voluntary evacuation

On the first day of the accident, an advisory evacuation was announced for people living within 0-8 km radius zone from the NPP and simultaneously with this, indoor sheltering was declared for the population living within an 8-16 km radius zone (Figure 2a). Figure 2b shows a sign announces the closure of the TMI NPP after the accident. Although only pregnant women and children of pre-school age were recommended to evacuate the 0-8 area, almost all residents immediately fled [33]. The same behavior was observed during the sheltering and voluntary evacuation announced on the second and third days of the accident. Sheltering was recommended after radioactive gas was found in the atmosphere. Schools in these areas were immediately closed and authorities warned residents to stay inside with their windows closed. However, most people had no intention to stay. As the result, the total evacuation amounted to more than 50% (Figure 2c) [34]. Post-accident surveys and questionnaire-based studies have revealed that the main reason for citizens to evacuate was caused by communication failure [35]. At first, authorities assured people that the situation was under control and there was nothing to worry about, however, in a few hours later, this statement was changed explaining the situation as been much complex. It is not surprising that inability to assess the risk of danger caused fear and panic among the population. Other factors influencing the decision to evacuate were the close proximity to the NPP, safety of children, anxiety and uncertainty [36]. The spatial distribution of evacuation spread over the long distances. According to some estimates, most of the evacuees moved to a distance of 120 and 150 kilometers from the reactor [37]. Among those who chose to evacuate were pregnant women, families with small children, and young and wealthy people.

This accident had a huge impact on the attitude of Americans towards nuclear energy. Almost all residents returned to their homes a few months after the evacuation, as the exclusion zone had not been established. Numerous studies investigating the TMI accident revealed that more than 60% of public statements about nuclear power's viability were unfavorable [38].



(a) (b) (c)

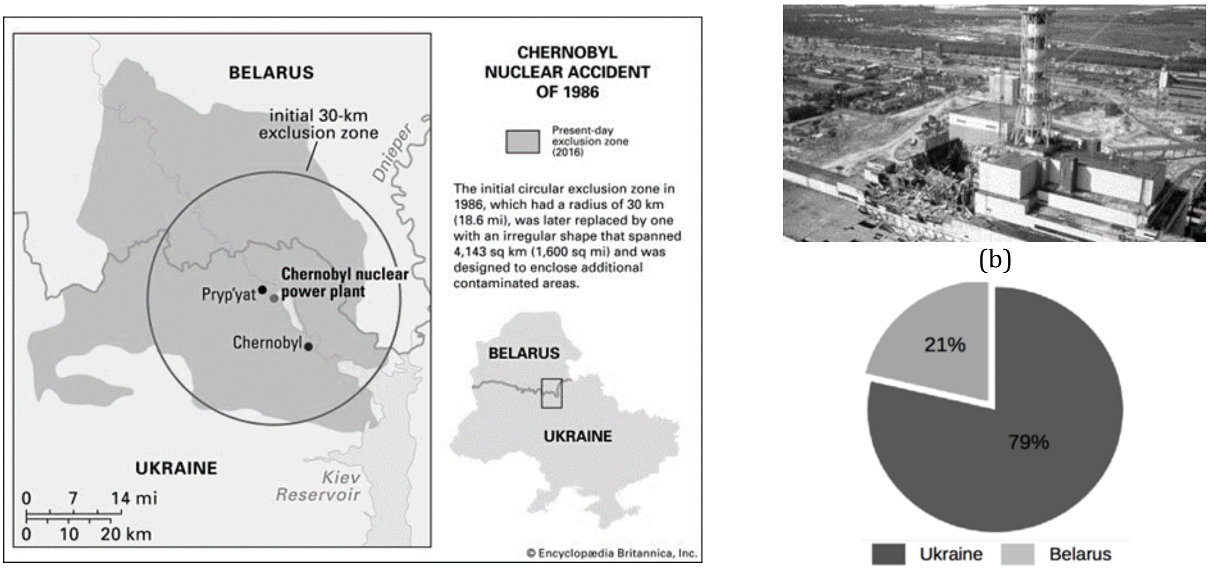
Figure 2. Emergency response to TMI accident: (a) Evacuation zones [32]; (b) TMI NPP after the accident [39]; (c) Percent distribution of evacuated and stayed population.

3.2. Chernobyl NPP accident

Because of reactor's explosion, the initial response to Chernobyl accident was aimed on the extinguishing the fire to prevent the additional nuclear reactions [40]. Furthermore, it was feared that the melted uranium could sink into the ground and infect the ground waters and follow-up actions was therefore directed towards digging a tunnel under the reactor's building to create a heat exchanger space to prevent possible contamination of groundwater [41]. These were the hardest-to-control aspects of the disaster response, which caused the evacuation to be delayed by nearly 36 hours [42]. Even when officials announced the evacuation, it was said it would be temporary and implemented only as a protective measure in the event of sudden hazard. However, by that time, all population living in the immediate vicinity of the NPP had already received the highest doses of radiation. Table 3 provides the timeline of evacuation-related orders and sequences. Evacuation was carried out as obligatory and under the strict control of the government. About 45,000 people, who were mostly employees at the NPP and their families, were evacuated on the early stages of evacuation from the 3-km radius zone [41]. Then, evacuation was extended to 10-km, and later to 30-km zone, as it is shown in Figure 3a. Due to destructive power of an accident (Figure 3b), active evacuation lasted almost a half a year and involved about 116,000 people, mostly from Ukraine and Belarus (Figure 3c). Following the disaster, a 30-km circle-shaped exclusion zone was set up around the NPP, and later expanded to include other contiguous areas that were subsequently found to be heavily irradiated. In total, more than 350,000 people were evacuated outside the most contaminated areas. Although their radiation exposure has decreased, many of them have experienced severe stress as a result. The psychological discomfort of the accident and its consequences affected not only the behaviors of people, but also the behaviors of entire communities [2, 42].

Table 3. A timeline of the evacuation-related orders and sequences due to Chernobyl accident.

Date and local time	Description
April 26, 1986 01:23	The accident occurred.
April 27, 1986 11:00	Evacuation buses arrived in the city of Pripyat.
April 27, 1986 14:00	Evacuation of Pripyat began.
April 27, 1986 17:00	Evacuation of Pripyat was completed. Nearly 45,000 residents were evacuated.
April 28, 1986 21:00	The first official announcement about the accident was done in the local news.
April 30 – May 03, 1986	10,000 residents were evacuated from 10-km zone south.
May 03 – May 07, 1986	28,000 residents of Ukraine and more than 11,000 residents of Belarus living within the 30-km zone were evacuated.
May – September, 1986	3,500 people from Ukraine, more than 14,000 people from Belarus, and 186 residents from the Russian city named Bryansk were evacuated. These were territories outside the 30-km zone.
1986 – 2000	The total number of permanently resettled people from the most contaminated areas were about 350,000.



(a) (c)

Figure 3. Emergency response to Chernobyl accident: (a) 30-km evacuation zone [43]; (b) Chernobyl NPP after the accident [43]; (c) Percent distribution of evacuated population from Ukraine and Belarus.

3.3. Fukushima Dai-ichi NPP accident

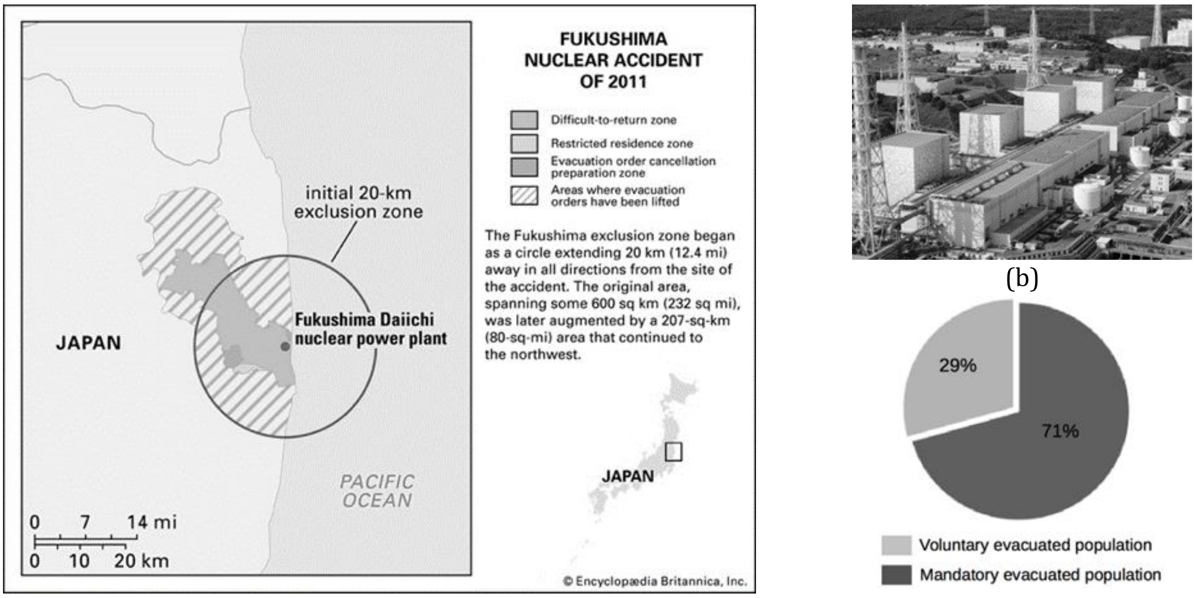
The initial measures to protect the population included evacuation, sheltering, restrictions on food and water consumption, and then relocation. Several hours after the accident, the Japanese government responded to the accident and issued various evacuation orders [44]. Table 4 gives the chronology of issued instructions.

Table 4. A timeline of the response-related orders due to the Fukushima accident.

Date and local time	Region	Decision
11 March 14:46	A Mw 9.0 earthquake struck Japan's Tohoku area 72 km to the east	
11 March 15:27	The first wave of tsunami hit the Fukushima Dai-ichi NPP	
11 March 20:50	0-2 km	Forced evacuation
11 March 21:23	2-3 km	Forced evacuation
11 March 21:23	3-10 km	Indoor shelter
12 March 05;44	3-10 km	Forced evacuation
12 March 18:25	10-20 km	Forced evacuation
15 March	10-20 km	Forced evacuation
15 March	20-30 km	Indoor shelter
25 March	10-20 km	Forced evacuation
25 March	20-30 km	Permission to evacuate voluntary
22 April	0-20 km	Area designated as a restricted zone
22 April	20-30 km	Prepared evacuation area in case of increased radiation
22 April	20-55 km north-west part	Intentional evacuation area
30 June	20-55 km north-west part	Detection of specific places recommended for evacuation

As it is shown, a mandatory evacuation was started firstly for the area of 2 km radius from the damaged NPP and then, in less than 24 hours, was expanded to a 20 km radius zone. This region was then assigned as an exclusion zone with the subsequent prohibition on entry (Figure 4a). One hour after the first decision, authorities started to remove people living between 2 and 3 km zone and, ordered shelter-in-place for 3–10 km at the same time. Next day, mandatory evacuation was implemented for the area of 20 km. On the fifth day, government instructed residents living between 20-30 km to shelter-in-place, which continued for several days and finally, people were advised to evacuate voluntary. In June, almost four months after, authorities began to identify "hot spots" outside the 30-km zone where high radiation levels were detected, and more than 15,000 residents were removed from the contaminated area 20-55 km northwest of the plant. Because of these various decisions, taken one after other, all residents from children to elderly, were forced to repeatedly evacuate from place to place having no idea about prospects for the future [45]. Numerous studies revealed that the extend of the catastrophe and the radiation risk were not officially disclosed to evacuees [46]. This happened due to lack in communication system after the earthquake. As a result, many people evacuated on their own on the pile of fear and were exposed to high radiation levels after fleeing in a northwesterly direction. In addition, a huge traffic jams on the escape route became the reason for delayed evacuation, leaving the population significantly distressed [47]. More importantly, there were several hospitals and 17 nursing care homes inside the 20 km radius zone. It was estimated that about 2,000 elderly patients were still there when the evacuation of 20 km area was almost over. On March 13, evacuation of hospitals was arranged. But transportation was hurried, and patients were not accompanied by medical personnel or received any necessary support they needed. Consequently, 60 of them died either during the evacuation or soon after [32, 48]. There were no deaths related to the high radiation or acute radiation syndrome. No significant contamination was found in the evacuees from 20-km zone despite the fact that more than 40 hours had passed between the accident and their evacuation [49]. According to the WHO, those who were evacuated in the first days received doses up to 6 mSv, and those evacuated later were undergone up to 10 mSv [50]. At the same time, on average, a permanent Japanese resident receives about 4 mSv per year from natural sources [16]. This information suggests the danger of unprepared evacuation, which in a sense, killed more people than the accident itself or the risk of exposure. Figure 4b shows an aerial view of the damaged Fukushima NPP taken one year after the accident.

In the first year of accident, more than 160,000 people evacuated from the Fukushima prefecture [51]. They represent more than 45% of all evacuees including displayed because of earthquake and tsunami. As it is shown in Figure 4c, 71% of residents were mandatory evacuated, while 29% left on their own. As the result, 11 municipalities were included in evacuation process [52]. In the years since, large-scale clean-up operations allowed some residents to return, however, according to the several surveys it was found that the majority of evacuees no longer wanted to return because of fear and because they had already settled elsewhere [53].



(a) (c)

Figure 4. Emergency response to Fukushima accident: (a) Evacuation zone [43]; (b) Fukushima NPP before the accident [43]; (c) Percent distribution of evacuated population from Fukushima.

4. Discussion

Concerns about nuclear safety have long dominated discussions about the use of nuclear energy. TMI, Chernobyl, and Fukushima were the three biggest nuclear reactor disasters, and the responses from the government provided lessons about how to prevent and handle nuclear accidents. While there is no reliable plan for prevention or immediate response, past experience can and should guide future nuclear power regulations. A comparison of these three disasters shows that a strong safety culture and independent oversight are essential for rapid response, planned evacuation, relocation and resettlement, and effective communication to the local population before, during, and after an accident. Table 5 provides the main lessons derived from past NPP accidents.

4.1. Emergency response capabilities and unavoidable natural disasters

The accident at Fukushima-Daiichi NPP showed how vulnerable countries are when faced with global nuclear catastrophes in peacetime. The available disaster response capabilities of Japan were reduced due to conflicting earthquake and tsunami requirements [54]. These extreme natural disasters affecting wide areas have exceeded the procedures already in place for nuclear emergencies, resulting in widespread disruption of communications, electricity and other critical infrastructure for an extended period of time. Japan is known to be well prepared for various severity levels of natural hazards, however in this time the severity was beyond what the country was prepared for. Only the initial emergency response to natural disasters involves a complex interaction of rescue and safety equipment, but a major nuclear accident will require more efforts and cost, and therefore a comprehensive methodology for evaluation plant response is needed. The nuclear industry and organizations responsible for emergency management should evaluate their preparedness for catastrophic nuclear accidents associated with localized accidents. Given the fact that due to traffic congestion and destroyed infrastructure, it will be physically impossible to evacuate, therefore, plans should include preparations for all possible hazard to eliminate various threats and indicate when evacuation or shelter-in-place is appropriate.

Table 5. Lessons learned in light of accidents at the NPPs.

The TMI	Chernobyl	Fukushima
Advisory and voluntary evacuation: - Public overreaction to the accident. - Congestions on the road as the result of uncontrolled mass evacuation. - Public opposition to nuclear power has moved steadily.	Mandatory evacuation: - Population was not informed on the level of radiation and the development of an accident. - Misallocation of responsibilities among emergency response workers. - Delayed evacuation. Relocation: - Loss of home, work, social ties caused serious psychological distress and mental disorders including deep depression and suicide. - Impossibility of using the abandoned territories led to the national economic losses. - Transboundary impact (environmental contamination of other countries).	Mandatory evacuation: - Evacuation of hospitals was unplanned and insufficient, resulting in the death of 60 patients. In subsequent years, this number increased to 2,000. Voluntary evacuation: - Public overreaction to the accident. - Many people accidentally fled to much more contaminated areas during the evacuation. Sheltering: - People was forced to evacuate several times. - Those in the shelters were left without essential supplies such as food, water, medicine. Relocation: - Like in Chernobyl, relocation resulted in adverse mental health consequences.

4.2. Challenges in emergency response

Controlling radiation exposure and reducing risks to the public are the first objectives of a physical response strategy immediately after an NPP accident. Nuclear disaster emergency response involves such operations as evacuation, sheltering, iodine distribution, and rescue, which must be addressed to the greatest extend possible. The decisions on a particular response are often made quickly despite limited information, and it is still unknown how much damage could be done to a nuclear reactor and what areas of risk could arise. Each of the three major accidents at NPPs caused at least an immediate reaction to the situation at the reactor site, but larger physical reactions revealed different approaches.

Unlike Fukushima, where accident developed gradually, the Chernobyl disaster occurred in a matter of seconds due to the reactor's explosion. It was one of the reasons why Soviet Government did not announce an urgent evacuation. While residents must be immediately removed from the contaminated area, the authorities threw all their forces into putting out the fire after the explosion to prevent the release of even more radiation. It was difficult to take early safety measures due to government efforts to cover up the extent of the damage and the widespread politically motivated belief that the reactor used in Chernobyl was fundamentally fail-safe. Due to postponed evacuation, in the nearest radius from the NPP, thousands of people including children received an incurable disease – thyroid cancer [55-56]. Obviously, in this situation, finding a safe place indoors and staying there until an evacuation order is issued would be an effective emergency response measure. However, indoor sheltering should be also pre-planned and organized. In the context of Japan's Fukushima NPP accident, on the fourth day after the disaster, local government issued an order for shelter-in-place within the area of 20-30 km radius. Following this instruction, the delivery of emergency supplies to the region was stopped due to concerns about radiation exposure. The 20-30 km region, therefore, became fully isolated from any required and essential goods. For the nursing homes located in this zone, evacuation was inevitable due to lack of staff and care equipment, such as medicines, life-saving drugs, and breathing apparatus, not even mention food and water supply. Despite great efforts, operations to evacuate elderly people were unplanned and overcrowded, eventually resulting to a significant increase in post-evacuation deaths. Despite dangerous radioactive dispersion, there were no radiation-related deaths or injuries at Fukushima, thanks to an evacuation that was immediately put into place. However, more than 2,000 deaths have been recorded and occurred as a result of compliance with evacuation procedures, proving that the very measures taken to prevent radiation exposure can have a much more adverse impact on public health. In contrast, some medical facilities that chose not to evacuate their patients despite lacking staff and medical resource were lucky enough to get help from volunteers, and that meant that they could wait with sufficient resources.

On the other hand, although TMI's reaction was also swift, the evacuation procedure was not organized. Low radiation levels have not stopped locals from leaving on their own due to conflicting governmental and media reports. Also, in Fukushima, many residents left the area voluntary with private cars, owing to inadequate information sharing, which caused huge traffic disruptions and car accidents. Moreover, many people were forced to move from one evacuation point to another three or more times since orders on evacuation and sheltering were constantly changing. In addition, under the influence of fear and panic, some residents fled their homes despite the authorities have suggested to stay in shelters. In the Chernobyl, on the contrary, evacuation was completely implemented under government control and was done using public transport, however, the absence of a follow-up national plan of action for the period after the evacuation led to the disrupted families and other societal chaos. Thus, many pre- and school-age children were evacuated to the summer camps being separated from their parents for several months.

There is still debate about how to effectively balance the risk of radiation with the risk of evacuation, relocation and resettlement. After the initial evacuations, there was no significant radioactive leak at TMI, so radioactive exposure was not a big concern. The 30-km radius zone around Chernobyl was evacuated due to the severity of the spill and is still completely uninhabited. However, at Fukushima, the need for evacuation was determined using a radiation threshold of 20 millisieverts per year. This threshold is generally considered safe given the known public health costs of evacuation and relocation but has been controversial because some people feel it is too conservative to be used in catastrophic circumstances. As a result, in addition to the hazards associated with evacuation, relocation and resettlement, careful study of radiation issues is required to determine the best course of action to public health.

The three accidents demonstrated a variety of long-term strategies for prevention and recovery of population. Careful resettlement was hampered by the lingering contamination of Chernobyl and Fukushima, but the minimal release of TMI radiation allowed the population to recover quickly. The continuous release of radioactive materials and health risks forced nearly all 350,000 residents to permanently move out of Chernobyl. Finally, in the case of Fukushima, a significant evacuation of over 160,000 people was required due to the huge radiation leak and associated health risks. More than 80,000 evacuated individuals still require shelter, and efforts to rehouse these displaced populations have been put off. The success of the initial evacuation can partly explain the fact that there were no radiation-related deaths at Fukushima. The fact of mortality as a result of evacuation illustrates the complex balance between the danger of evacuation and the need to ensure radiation safety.

4.3. The importance of communication and public trust

As learned from the experience of these three disasters, during the emergency response there was lack of a sufficient information such as on protective measures or evacuation routes available to residents. When available, details were often found incorrect or completely hidden. In Chernobyl, people learned rumors about the accident. For political considerations, Soviet authorities engaged in disinformation to cover up the accident, putting millions of lives in danger. When other countries started discovering the environmental effects caused by the explosion at the Chernobyl NPP, even then, the Soviet government did not immediately disclose the severity of the accident saying that the situation was under the control. Unfortunately, not only in other countries, but also in Ukraine itself, people were not aware of how critical the situation was. After the evacuation order was issued, resident was told to take only the bare essentials they might need within a few days and that evacuation was only the matter of days. However, till this announcement neither shelter-in-place nor iodine distribution were implemented, and a half of residents including pre-school children have been already exposed to the high radiation levels. The government's attempt to resolve the situation caused great damage to the country from the political, economic, material and spiritual points of view. Only an equal, diverse, and open dialogue without any prejudice can help all countries to overcome the global security crisis and prevent nuclear catastrophe. In Fukushima, risk communication was also faced with challenges, such as emergency management failure to communicate with the public at the initial stages of the accident (evacuation, sheltering, and potassium iodine distribution; failure to deal with public's fear), and failure to communicate with public at the subsequent stages (lack of information related to radioactive release and its spatial spread; failure to encourage public to return to evacuated areas). In both, the Chernobyl and the Fukushima accidents, many residents from non-evacuated areas were very much worried about the effects of radiation on their health. It revealed that prior to the disaster, people had not been taught any knowledge about the radiation protection measures what actually triggered the surge of fear. All this ultimately led to social disintegration. Thus, internally displaced residents experienced negative impact from local communities owning a fear of getting contaminated by radiation. Communication faults very much contributed to residents' anxiety, as well as distrust not only in government, nuclear safety regulations, or emergency management, but also in nuclear industry worldwide.

4.4. Land use planning for reducing nuclear disaster risk

Urban land management should include knowledge of the potential consequences of a nuclear accident in terms of hazards so that the risk of an accident in the urban area can be addressed through measures such as policy development or public investment proposals related to hazard reduction. In order to effectively include the risk factors associated with an accident at an NPP in land use planning, it is necessary to implement the following activities:

- Multidisciplinary collaboration: work together with emergency response workers, civil engineers, hazard researchers, economists and land use specialists to identify potential risky and hazard zones as well as potential economic losses,
- Use knowledge about disaster risk: there is a need to "prepare" ahead a land to be used for mass relocation considering the specific needs of resettles including socio-economic characteristics, health characteristics and special dependence on natural recourses, land uses and other vital opportunities,
- Policy development: implement new policies that restrict residential construction in high-risk and environmentally sensitive areas, as well as restrict the development of new types of production, especially in agricultural areas.

5. Conclusion

Today, nuclear power is a reliable, acceptable, and, in certain countries, unavoidable source of energy. The vast majority of countries work on the development of nuclear energy, which indicates a general increase in the number of NPP in the near future. The most crucial concern in the development and use of nuclear energy is its safety, therefore, throughout the world, not only its regulatory safety requirements must be strictly observed and implemented, but also the requirements of nuclear disaster management which involves preparation and response to the accident.

This study was aimed at reviewing emergency response to major accidents at NPPs in the past, including accidents at TMI, Chernobyl, and Fukushima. A detailed analysis of these accidents shows that local authorities have reinforced the belief that the probability of an accident is very low and that they are quite capable of effectively responding to any emergency, but, as a result, were unarmed to overcome it. Unlike Chernobyl, where all residents were mandatory evacuated, during the response to TMI and Fukushima, people were advised to evacuate voluntary. As experience has shown, this evacuation turned out to be more of a chaotic and lengthy undertaking rather than an organized and well-oiled operation. The vast majority of residents were not familiar with evacuation routes. In Fukushima, the situation with medical facilities was so serious that it took deep roots in the lives of the elderly. Firstly, the unplanned evacuation of hospitals resulted in the deaths among evacuees. Secondly, the development of the accident forced people to evacuate several times from one shelter to another. And finally, those who decided to wait in the shelter were left without any essential and vital needs. The Chernobyl accident confirmed the importance of a quick response to a disaster. Despite the fact that all the residents were evacuated, unfortunately, this evacuation was very much delayed. As a result, most of inhabitants, including children, were exposed to radioactive fallout. In general, all three accidents resulted in serious mental health consequences. In the TMI, people were terrified of what was happening. In Chernobyl and Fukushima, the displaced people were forced to start life anew, losing all their property, jobs and habits. Based on the above, in order to help overcome the majority of issues, we offer several recommendations and suggestions, which are summarized below.

During the evacuation:

- Ensure timely and rapid evacuation giving prioritizing areas where high levels of radiation may occur in the coming hours/days.
- When evacuating a hospital, evacuate only those patients who can withstand it physically.

- When deciding on hospital evacuation, recruit staff correctly: decide who will assist the evacuees and who will stay.
- Keep and update evacuation records.
- Avoid repeatable evacuation.
- Control voluntary evacuation giving clear instruction on available routes and times.

During the sheltering:

- Keep a record of the number of people in the shelter, as well as the time of their stay in it.
- Interact with those in the shelter to monitor needs, and if necessary, to provide essential medical supplies and health services.
- To evacuate people as soon as possible.

Communication system:

- It is necessary to apply local and global cooperation for successful emergency management.
- It is necessary to ensure a prompt exchange of information including on-site conditions, radiation dose, primary protective measures between NPP officials, local authorities outside the NPP, and the public.
- Emergency workers must clearly know their responsibilities and duties, as well as be able to set a priority.
- Arrangements should be made to include in the response those emergency workers who were not assigned prior to the occurrence of the emergency, and people who volunteer to assist in the response to the emergency.

Nuclear accidents have also the most severe consequences on global scale. No country alone is able to eliminate the effects of a NPP accident in full and in the shortest possible time. It is therefore necessary to unite multiple forces and means of different countries for trouble proof operation of nuclear facilities. This requires the timely availability of important information as well as the development of a common vision of what constitutes sustainable nuclear governance. With the Fukushima disaster, for the third time since the TMI and Chernobyl, the nuclear industry faced threat of distrust from the world community. In order to win this trust again and restore the development of nuclear energy, it is necessary to carry out a lot of explanatory work among the population, which in turn requires a lot of time. One of the primary needs in disaster management science is preparation, adaptation, and recovery from the disaster drawing on multidisciplinary research. About one-thirds of the world's 400 NPP have more population living within the 30-km radius zone than 170,000 people who living inside this radius when the accident at the Fukushima-Daiichi occurred. More than 20 NPP in the World have population larger than 1 million and 6 plants have population larger than 3 million within the same radius. Only the KANUPP NPP in Pakistan, has 8 million residents living inside the 30-km zone. As of 2023, more than 50 nuclear reactors are being built in the world, and the first NPP in Turkey located within the provincial boundary of Mersin will start operating in the very near future. According to the Turkish Statistical Institute (TURKSTAT), the population of Mersin province has already reached almost 2 million people and it is expected to increase in the subsequent decades. All this once again stresses the need for realistic planning and further development of the approaches for assessing various natural hazards. As many nations rely on nuclear energy, the findings of our study will be useful for governmental policymakers and emergency decision-makers, considering the potential risks of nuclear accidents.

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Author contributions

Maryna Batur: Conceptualization and design of the study, Investigation and literature search, Visualization, Writing-Original draft preparation. **Reha Metin Alkan:** Study curation, Validation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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