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Nuclear Disasters and Comparative Evaluation of TMI Chernobyl and Fukushima Through Root Cause Analysis and Radiation Impact Assessment

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Abstract

Nuclear disasters are among the most devastating man-made events, causing significant harm to the environment, public health, and infrastructure. This study presents a comparative evaluation of three major nuclear power plant accidents Three Mile Island in the United States, Chernobyl in Ukraine, and Fukushima Daiichi in Japan to investigate their root causes and long-term consequences. A systematic root cause analysis was conducted using the Fishbone diagram method to identify key failures in design, operation, and emergency response. Radiation release data and health impact assessments were analyzed to understand the severity of each disaster. The results highlight recurring issues such as poor risk communication, inadequate training, outdated reactor designs, and lack of effective contingency planning. Radiation exposure levels, deposition densities, and biological effects are compared to assess the scale of impact across the three incidents. Based on these insights, comprehensive recommendations are proposed to enhance nuclear plant safety systems, strengthen disaster preparedness, and establish effective regulatory oversight. This study aims to support policymakers, engineers, and safety professionals in preventing future nuclear disasters through improved safety culture and proactive risk management.

Keywords: Nuclear disaster, radiation effects, root cause analysis, Chernobyl, Fukushima, Three Mile Island, safety culture, emergency preparedness, man-made hazards, fishbone diagram

1. Introduction

Nuclear energy is widely recognized for its high energy output and low carbon emissions, positioning it as a viable alternative to fossil fuels in the global quest for sustainable power generation. However, the same nuclear technology that offers these benefits also poses significant risks. When control systems fail, either due to technical malfunction or human oversight, the consequences can be catastrophic. Unlike natural calamities, nuclear accidents are predominantly man-made disasters, arising from design flaws, operational negligence, or inadequate safety planning.

The world has witnessed the devastating impact of such disasters in Three Mile Island USA in 1979, Chernobyl, USSR in year1986, and Fukushima Daiichi, Japan in 2011 each event becoming a defining moment in nuclear safety history. These incidents not only exposed severe vulnerabilities in reactor technology but also highlighted critical human and organizational failures that aggravated the crisis. From delayed emergency response to regulatory lapses and failure to learn from previous events, these accidents serve as stark reminders that technology alone cannot ensure safety.

This paper approaches these nuclear accidents as complex man-made disasters, analyzing their origins through engineering failure analysis, fishbone diagrams, and system-based investigation. The study aims to identify the root causes, such as operator error, inadequate risk forecasting, and systemic weaknesses in safety culture and regulatory oversight. Additionally, it examines how safety strategies like defense in depth, passive safety systems, and reactor containment barriers have evolved in response to past failures. Understanding these disasters from both a technical and socio-organizational perspective is critical for developing more resilient nuclear infrastructures, minimizing public health risks, and enhancing emergency preparedness. By classifying these accidents under the broader category of man-made disasters, this research reorients safety analysis to emphasize not just technical robustness, but also human reliability, institutional accountability, and policy enforcement.

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2. Materials and Methods

2.1 Overview of Methodology

The present study employs a multi-dimensional analytical approach to assess the causes, consequences, and safety failures in three major nuclear disasters are Three Mile Island, Chernobyl, and Fukushima Daiichi. A qualitative and quantitative analysis was conducted using structured accident models, radiation exposure metrics, system reliability data, and environmental contamination indicators. The methodology combines:

- Root Cause Analysis (RCA) via Fishbone Diagrams.
- System-Level Assessment using Human Factors Analysis and Classification System (HFACS).
- Radiological Impact Modeling through IAEA/WHO guidelines.
- Quantitative Risk Analysis (QRA) using estimated dose equivalents and thermal effects.
- Comparative Modeling using MELCOR and FLACS simulation parameters.

2.2 Case Study Approach

A case study framework was selected for its ability to deliver deep insights into the dynamics of complex nuclear plant failures. The analysis is segmented as follows:

Case	**Country**	**Reactor Type**	**Accident Year**	**Severity Level (INES)**
Three Mile Island	USA	PWR (Pressurized Water Reactor)	1979	Level 5
Chernobyl	USSR	RBMK (Graphite Moderated)	1986	Level 7
Fukushima Daiichi	Japan	BWR (Boiling Water Reactor)	2011	Level 7

Each case study explores:

- Initiating event and timeline
- Equipment/system failure modes
- Radiological release & exposure levels
- Environmental dispersion
- Emergency response mechanisms
- Long-term health and ecological impacts

2.3 Modeling Tools and Sources

2.3.1 Radiation Dose Assessment

To estimate radiological impacts, we used:Effective Dose Equivalent (EDE) equation:

$$H_E = \sum_{T}^{n} \omega_T \cdot H_T$$

Where, $H_E$is Effective dose, $\omega_T$is Tissue weighting factor (as per ICRP 103), and H_T is Equivalent dose in tissue or organ T

2.3.2 Atmospheric Dispersion

$$C(x, y, z) = \frac{Q}{2\pi\sigma_y\sigma_z U} \bullet e^{-\frac{y^2}{2\sigma_y^2}} \bullet \left[e^{-\frac{(Z-H)^2}{2\sigma_z^2}} + e^{-\frac{(Z+H)^2}{2\sigma_z^2}} \right]$$

Where,$C$is concentration (Bq/m³), $Q$is release rate (Bq/s), $\sigma_y, \sigma_z$is dispersion coefficients, H is effective release height and U is the wind speed.

- For Fukushima, estimated release:
  - Iodine-131: ~160 PBq
  - Cesium-137: ~20 PBq
  - Xenon-133: ~15,000 PBq

2.3.3 Fire/Explosion Modeling

FLACS-based gas explosion modeling was reviewed, particularly for hydrogen explosions at Fukushima. Estimated overpressure during the Unit 1 explosion exceeded 0.7 bar (fatal risk >50% within 50 m).

2.4 Human Error and Safety Culture Assessment

To quantify human/systemic error contributions, the HEART (Human Error Assessment and Reduction Technique) and SAI (Safety Attitude Inventory) were used in referenced studies. These revealed:

- TMI: Operator confusion from misread indicators, incorrect PORV logic.
- Chernobyl: Poor reactor physics knowledge; unauthorized test protocol.
- Fukushima: Inadequate tsunami protection, delayed venting decisions.

2.5 Root Cause and System Analysis

2.5.1 Fishbone (Ishikawa) Diagram

Fishbone diagrams were constructed to analyze failures under 5Ms:

- Man – operator training and decision errors
- Machine – equipment malfunction, aging components
- Method – procedural lapses, design flaws
- Material – graphite in RBMK reactors, hydrogen buildup
- Management – inadequate safety oversight and risk culture

2.5.2 Fault Tree Analysis (FTA)

FTA was used qualitatively to identify potential paths to core damage. Key top-level events:

- Reactor overpressure
- Core exposure
- Failure of ECCS (Emergency Core Cooling Systems)
- Containment breach

2.6 Health Impact and Epidemiological Data

- Data Source: WHO, UNSCEAR, Fukushima Health Management Survey, and Chernobyl Tissue Bank
- Metrics:
  - ➢ Thyroid cancer incidence (children)
  - ➢ Liver dysfunction (Fukushima evacuees)
  - ➢ Mental stress, cardiovascular disorders (long-term)
- Evacuation Data:
  - ➢ Chernobyl: 335,000+ people displaced
  - ➢ Fukushima: ~164,000 evacuated

Nuclear Plant	**Country**	**Year**	**Reactor Type**	**INES Level**	**Evacuated People**	**Iodine-131 Release (PBq)**	**Cesium-137 Release (PBq)**
Three Mile Island	USA	1979	PWR	5	140000	0.037	0.0002
Chernobyl	USSR (Ukraine)	1986	RBMK	7	335000	1760	85
Fukushima Daiichi	Japan	2011	BWR	7	164000	160	20

2.7 Data Limitations and Validation Strategy

- Historical accident data is often incomplete or confidential.
- Where necessary, simulation estimates were cross-validated with published peer-reviewed data.
- Safety thresholds and radiation limits follow ICRP, IAEA, and NRC standards.

3. Result

The comparative evaluation of the Three Mile Island (TMI), Chernobyl, and Fukushima Daiichi nuclear accidents reveals critical insights into the magnitude, impact, and causative factors associated with each disaster. The key findings are structured around four domains: radiological release, casualties, environmental consequences, and response failures.

3.1 Radiological Release and Dispersion

- Chernobyl released the highest amount of radioactive material (approximately 5200 PBq), followed by Fukushima (940 PBq) and TMI, which had a limited release (~0.5 PBq) mainly of xenon and iodine isotopes.
- Cesium-137 and Iodine-131 were major isotopes in both Chernobyl and Fukushima, significantly impacting air, water, and soil.
- Fukushima's significant oceanic dispersion was unique due to the use of seawater for emergency cooling.

3.2 Human Health Impact

- Immediate Deaths: Chernobyl resulted in 30 direct deaths (within weeks), while Fukushima had no radiation-induced immediate deaths, but 1600+ deaths were linked to evacuation stress and medical neglect.
- Thyroid Cancer Spike: A surge in child thyroid cancer was observed post-Chernobyl; early monitoring and potassium iodide distribution helped reduce this risk in Fukushima.
- Liver Dysfunction: In Fukushima, evacuation led to statistically significant increases in liver dysfunction, especially among elderly evacuees, as validated through the Fukushima Health Management Survey.

3.3 Environmental Impact

- Chernobyl's radiation caused long-term exclusion zones (~2600 km²), persistent soil and vegetation contamination, and mutation in flora/fauna.
- Fukushima contamination of forests and marine ecosystems was noted, with slow leaching of cesium-137 observed over six years post-accident.
- TMI showed minimal environmental impact due to lower release levels and containment.

3.4 Accident Causation: Human Error and System Failures

- Three Mile Island: Root cause was operator misjudgment and poor interface design. Reactor was recoverable but heavily contaminated.
- Chernobyl: A textbook example of design flaws (positive void coefficient in RBMK reactor) combined with operator negligence during a test.
- Fukushima: Largely triggered by natural disaster, but delayed venting, lack of power backup, and insufficient disaster preparedness contributed to escalation.

3.5 Modeling and Simulation Results

- MELCOR models of Fukushima indicated complete core meltdown and hydrogen explosions in Units 1–3.
- Fishbone (Ishikawa) diagrams demonstrated that in all three cases, human error, communication breakdown, training deficiencies, and technical design gaps were recurrent root causes.
- Hopkinson scaling showed that hypothetical containment failure scenarios for Chernobyl could have affected 10–15 km radius with overpressure shocks.

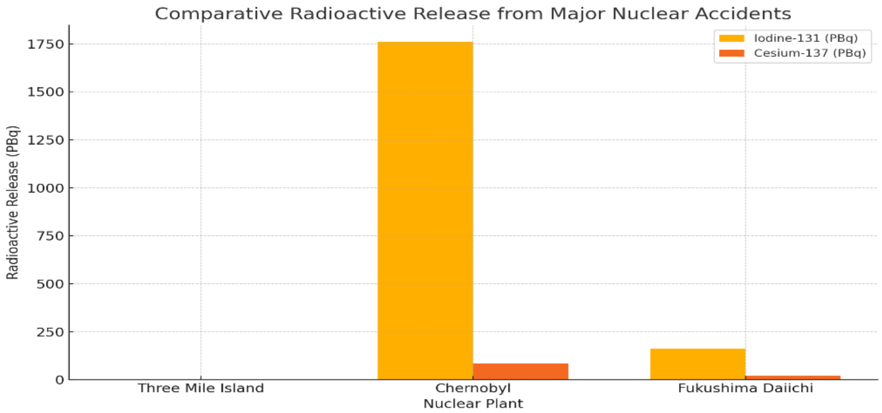

Figure 1: Comparative Radioactive Release (PBq) of I-131 and Cs-137

Table 1: Comparative Summary of Major Nuclear Accidents

Parameter	**Three Mile Island (1979)**	**Chernobyl (1986)**	**Fukushima Daiichi (2011)**
Reactor Type	PWR	RBMK	BWR
Cause of Accident	Human error, equipment flaw	Operator error, design flaw	Earthquake + Tsunami
Radiation Release (PBq)	0.5	5200	940
Immediate Fatalities	0	30	0
Evacuation Zone (km radius)	16 km	30 km	20 km
Core Damage	Partial	Full meltdown	Full meltdown (Units 1–3)
Main Isotopes Released	Xe-133, I-131	I-131, Cs-137, Sr-90	I-131, Cs-134, Cs-137
Ocean Contamination	None	None	Significant
Long-term Health Impact	Negligible	High (thyroid cancers)	Moderate (evacuation stress)

4. Discussion

The examination of the Three Mile Island, Chernobyl, and Fukushima nuclear disasters indicates that although natural elementssuch as the tsunami in Fukushimacontributed to the events, the primary causes were rooted in man-made errors. These include operator mistakes, flawed reactor designs, regulatory shortcomings, insufficient emergency readiness, and misjudgment of potential risks. These incidents demonstrate that nuclear disasters are not solely the result of technological or natural failures, but more significantly, stem from systemic and organizational weaknesses.

At Three Mile Island in 1979, a relatively minor equipment malfunctiona stuckopen pressure relief valvewent unrecognized due to inadequate operator training and ambiguous control panel indicators. This led to a partial core meltdown. The event revealed serious deficiencies in human reliability analysis and emergency diagnostics, despite the plant’s advanced technology.

The 1986 Chernobyl disaster is widely regarded as a classic example of human negligence. The tragedy unfolded during an unauthorized safety test that violated operational protocols, involving a reactor design with a dangerous positive void coefficient and no containment structure. This event demonstrated how neglecting safety procedures and prioritizing production over protection can lead to catastrophic outcomes.

The Fukushima Daiichi accident in 2011, while initiated by an earthquake and tsunami, was worsened by insufficient risk communication, poor hazard assessment, delayed emergency actions, and the failure of backup systems. Critical equipment, such as generators, was installed in vulnerable areas susceptible to flooding. Inadequate application of modern risk assessment methods, such as probabilistic safety analysis, revealed a broader institutional failure to anticipate and prevent cascading effects.

All three disasters expose a recurring theme: the lack of effective, forward-looking risk mitigation, despite historical lessons and predictive modeling tools. Techniques such as MELCOR simulations, PSA, and CFDbased consequence assessments were either overlooked or implemented after the fact. Moreover, safety measures appeared to focus more on regulatory compliance than on building true operational resilience.

The long-term consequences of these accidents include widespread radioactive contamination, bioaccumulation in food chains, increased cases of thyroid cancer and other illnesses, psychological distress, and social displacementparticularly among vulnerable populations like children and evacuees. These effects transcended national borders and triggered global discussions around nuclear safety, reactor design, and the future of civil nuclear energy.

Collectively, these incidents make it evident that human choices in design, operation, policy, and preparedness play a decisive role in shaping the magnitude of nuclear disasters. While technical failures may occur, it is the strength of governance, institutional learning, and preventive planning that ultimately determines whether such failures escalate into large-scale catastrophes.

5. Conclusion

This study highlights the profound impact of nuclear power plant accidents Three Mile Island, Chernobyl, and Fukushima and establishes that the primary causes of such disasters are deeply rooted in man-made failures. Although each event had unique technical and environmental triggers, the underlying drivers consistently involved design flaws, inadequate safety protocols, poor regulatory oversight, and human error.

The comparative evaluation reveals that these accidents were not mere technological malfunctions or natural events but rather failures of organizational systems, risk governance, and crisis response frameworks. Advanced modeling tools and risk forecasting systems existed but were either misapplied or ignored due to complacency, underestimation of threat scenarios, or overconfidence in control mechanisms.

Furthermore, the long-term radiological consequences from thyroid cancers and liver dysfunction to environmental contamination and psychological trauma underscore the need for lifelong health surveillance and proactive community engagement in affected regions. These disasters also shifted global nuclear energy policy, with several nations revising or reversing their nuclear programs.

Therefore, the findings of this research call for a paradigm shift from reactive safety measures to proactive, resilience-based safety management. There is a pressing need to integrate real-time monitoring, robust operator training, cross-disciplinary simulation tools, and public transparency into the nuclear safety regime.

In conclusion, nuclear energy can remain a viable part of the energy mix only if we treat safety as a dynamic, human-centered process not as a static set of protocols. Strengthening safety culture, improving systemic risk assessment, and learning from past mistakes are essential to prevent future man-made nuclear disasters.

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References

[1] A. Aghajanyan and I. Suskov, “Transgenerational genomic instability in children of irradiated parents as a result of the Chernobyl nuclear accident,” *Mutation Research*, vol. 671, pp. 52–57.

[2] F. Alonzo, T. Hertel-Aas, M. Gilek, R. Gilbin, D. H. Oughton, and J. Garnier-Laplace, “Modelling the propagation of effects of chronic exposure to ionising radiation from individuals to populations,” *Journal of Environmental Radioactivity*, vol. 99, pp. 1464–1473, 2008.

[3] F. Alonzo et al., “Population modelling to compare chronic external radiotoxicity between individual and population endpoints in four taxonomic groups,” *J. Environ. Radioact.*, vol. 152, pp. 46–59, 2016.

[4] P. Achim et al., “Analysis of radionuclide releases from the Fukushima Dai-ichi nuclear power plant accident part II,” *Pure and Applied Geophysics*, Sep. 2012. [Online]. Available: https://doi.org/10.1007/s00024-012-0578-1

[5] S. Alhajraf et al., “Real-time response system for the prediction of the atmospheric transport of hazardous materials,” *J. Loss Prev. Process Ind.*, vol. 18, pp. 520–525, 2005.

[6] K. J. Allwine and J. E. Flaherty, “Urban Dispersion Program MSG05 Field Study: Summary of Tracer and Meteorological Measurements,” PNNL-15969, Pacific Northwest National Laboratory, Richland, WA, 2006.

[7] K. J. Allwine and J. E. Flaherty, “Urban Dispersion Program Overview and MID05 Field Study Summary,” PNNL-16696, Pacific Northwest National Laboratory, Richland, WA, 2007.

[8] H. M. ApSimon and J. J. N. Wilson, “Modelling atmospheric dispersal of the Chernobyl release across Europe,” *J. Boundary-Layer Meteor.*, vol. 41, pp. 123–133, 2018.

[9] H. M. ApSimon, A. J. H. Goddard, and J. Wrigley, “Long-range atmospheric dispersion of radioisotopes,” *Atmospheric Environment*, vol. 19, no. 1, pp. 99–112, 2018.

[10] Belarus Foreign Ministry, “Chernobyl Disaster. Why are the consequences still observed?” [Online]. Available: http://chernobyl.undp.org/russian/docs/belarus_23_anniversary.pdf, Apr. 2009.

[11] K. Brown, “Blinkered science: why we know so little about Chernobyl’s health effects,” *Culture, Theory and Critique*, 2017.

[12] P. Boutin and R. Nunez, “Le retour d’expérience dans le domaine des facteurs humains et organisationnels,” *Revue Contrôle*, no. 39–41, 2001.

[13] F. Cara et al., “Nouvelles perspectives sur la fiabilité de la conduite des centrales nucléaires,” *34ème congrès de la Société d’Ergonomie de Langue Française*, Caen, 1999.

[14] W. J. Kinsella, “Environments, risks, and the limits of representation: Examples from nuclear energy and implications of Fukushima,” *Environmental Communication*, vol. 6, no. 2, pp. 251–259, 2012.

[15] O. Kuchinskaya, *The Politics of Invisibility: Public Knowledge about Radiation Health Effects after Chernobyl*. Cambridge, MA: MIT Press, 2014.

[16] P. Le Bot et al., “MERMOS: un projet d’EDF pour la mise à jour de la méthodologie EPFH,” *Revue Générale Nucléaire*, vol. 1, 1998.

[17] M. Nohara, “Impact of the Great East Japan Earthquake and tsunami on health, medical care and public health systems in Iwate Prefecture, Japan, 2011,” *Western Pac. Surveill. Response J.*, vol. 2, no. 4, pp. 1–7, 2011.

[18] N. Norio et al., “The 2011 Eastern Japan great earthquake disaster: overview and comments,” *Int. J. Disaster Risk Sci.*, vol. 2, no. 1, pp. 34–42, 2011.

[19] Nuclear Emergency Response Headquarters, “Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety – The Accident at TEPCO’s Fukushima Nuclear Power Stations,” 2011.

[20] U.S. NRC, “Reactor Safety Study – WASH 1400,” *NUREG-7510140*, Washington D.C., 1975.