Developing Off-site Emergency Preparedness and Response Model (OEPRM) for Severe Accident of NPP in a Densely Populated Country Using System Dynamics Approach

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1. Introduction

Spread of radioactivity from the reactor vessel of NPP and from the uranium fuel into the open area in a deadly NPP accidents can cause severe health and environmental risks, especially in a densely populated. The three most serious accidents, Three Mile Island, Chernobyl and Fukushima demonstrated that emergency response to protect plant personnel, emergency workers and the public beyond the site boundary is an essential component of the overall plant safety. Additionally, the Fukushima accident has ignited the nuclear power plant (NPP) operators, regulators, and stakeholders throughout the globe to review the adequacy of their emergency preparedness and responses which can handle general radiological emergency in a systematic and efficient manner.

NPP accidents are classified as nuclear accidents and incidents depending on the severity. Severe accident (SA) is certain low probability accident that are beyond design basis accident which may arise due to multiple failures of safety systems leading to significant core degradation and jeopardize the integrity of many or all of the barriers to the release of radioactive material.

The weakness to the off-site emergency response in the time of Fukushima accident was observed. So, it is crucial to develop an off-site emergency preparedness and responses model (OEPRM) for radiological emergency in densely populated country from the Fukushima emergency response lesson.

The main objectives of this study are to find the influencing factors of systems and sub-systems of OEPRM, to find the interdependency among the influencing factors, and to develop a conceptual qualitative OEPRM for densely populated NPP country in case of SA using system dynamics (SD). There are a number of desirable features in respective of site, infrastructure, regulations, and stakeholders of an NPP which can together make an effective off-site OEPRM.

This study uses the SD approach which is a powerful methodology and computer simulation technique for framing, understanding, and decision making of complex problems. SD is a qualitative and quantitative tool with causal loop and feedback loop diagrams, appropriate for modelling the inter-relationships such as cause-effect relations, non-linear behavior, and time-delay effects for a complex project over time. Casual loop shows interrelations among different factors of a system while feedback loops are closed chains of cause and effect links in which information is fed back to generate further action in the system [1].

In this study, Vensim computer software tool is used to develop the OEPRM for radiological emergency of SA through qualitative approach of SD. The conceptual OEPRM explains cause-effect relationships among the system, subsystem and factors as well as it can provide users a comprehensive dynamic visual view.

2. Overview of Off-site Emergency Preparedness and Response of NPP Accident

NPP is designed and operated with full consideration to safety and safety system are designed to minimize the probability of radiation release from the plant. However, the probability is not zero for happening NPP accidents and accidents have happened. The emergency planning for the protection of plant personnel, emergency workers, public, and environment beyond the site boundary provide the last level of defence in depth of the safety of NPP. Establishing arrangements and capabilities for emergency planning is one of the 20 main elements of the International Atomic Energy Agency (IAEA) milestones approach for the establishment of a national nuclear power programme. While emergency planning requirements are set by the regulatory body in line with national law, implementation is the responsibility of the owner. It is necessary to involve local and national government in the process. Emergency sheltering or public evacuation may be recommended by the owner, but the authority to order remains with local governmental authority [2].

The arrangements to respond a radiation emergency need to be consistent with those applied in response to any emergency and provide a framework for all organizations to deliver a coordinated response. The infrastructural elements such as authority, organization, coordination, plans and procedures, logistical support and facilities, training, drills and exercises and quality assurance programme are required for providing the ability for efficient response which meets the international requirements [3].

Emergency preparedness and response regulations are part of the overall regulations for establishing a nuclear power programme. Regulations are required to clearly allocate responsibilities regarding preparedness for and response to a radiation emergency. The legal basis is required in the preparedness and response to radiation emergency related to governmental infrastructure, organization, initiation and termination, and taking action related to precautionary, urgent and early protective and others. Allocation of functions and responsibilities in emergency preparedness and response are required by considering the fact that one or more functions may be performed by several bodies such as state agencies, the government, the regulatory body, a national coordinating authority, operators and response organizations [3].

The emergency zones for a proposed site of the nuclear installation are required to be established to ensure the safety of public which are: a precautionary action zone (PAZ) in 0-5 km, for which arrangements are required to be made with the goal of taking precautionary urgent protective action; an urgent protective action planning zone (UPZ) in 5-30 km radius, to avert dose off-site; and arrangement of food restriction planning (FRP) in 300 km radius for prompt restrictions on products and agricultural protective planning in line with international standards [4].

3. Fukushima Lesson Related to Emergency Response

The Great East Japan Earthquake occurred at 14:46 Japan Standard Time on Friday, March 11, 2011, with a magnitude of 9.0, off the eastern coast of Japan causing widespread damage to the infrastructure of the region's electricity, water, roads and railway.

The units 1-5 of the Fukushima Daiichi NPP experienced extended SBO events, which exceeded 9 days in units 1 and 2, and 14 days in units 3 and 4. The NPPs were unable to cope with the extended loss of electrical power and plant heat removal, the units 1, 2 and 3 suffered damage as the fuel overheated and melted. The reactor pressure vessels that enclose the reactor cores were eventually breached in those units, and radioactive material escaped from the reactors. The radioactive material confined in the primary containment vessels was further released directly to the environment either in a controlled manner or in an uncontrolled manner. The radioactive releases resulted in radiological exposure of the workers at the site and the general public residing in the surrounding communities and caused radiological contamination of the environment in those areas. In order to reduce radiation exposures, people within a radius of 20 km of the site, as well as other specified areas, were evacuated, and restrictions were placed on the distribution and consumption of food and drinking water [5].

At the time of Fukushima accident, separate arrangements were in place to respond to nuclear emergencies and natural disasters at the national and local levels but there were no coordinated arrangements. Besides, emergency response was not addressed in relevant training and exercise programs. The arrangements to respond to nuclear emergencies envisaged in Japan that, following the detection of relevant adverse conditions at an NPP, a notification would be sent from the plant to local and national governments. The national government would then assess and determine whether the situation was to be categorized as a nuclear emergency. If the situation was categorized as a nuclear emergency, a declaration to that effect would be issued at the national level, and decisions about necessary protective actions would be taken on the basis of dose projections. Arrangements did not foresee the recommendation of public protective actions based on plant conditions without additional assessment and judgment by the off-site authorities but it was experienced in Japan [5].

The Fukushima accident revealed vulnerabilities mainly on infrastructure and regulations in the conventional emergency response approaches. The lack of communication, coordination, critical information sharing made the frequent change of evacuation order. Misconceptions were also prevalent concerning radiological emergencies and the possible health effects of radiation exposure. To avoid the emergency response difficulties occurred in Fukushima, lessons need to be implemented by the nuclear industries.

4. Conceptual OEPRM for Densely Populated NPP Country

Emergency response is the last level of defence in NPP safety. Before constructing and operating the NPP, it is essential that not only the SA risks be estimated, but also an efficient and well-resourced risk control and disaster management system is designed, and well-rehearsed in advance. Even the most experienced, technologically advanced and rich countries experienced SAs and have enormous difficulty in managing a higher international nuclear event scale, illustrated by the Fukushima experience. It is essential to consider how any country can quickly evacuate and relocate just a few hundred thousand people from the NPP site after any SA, not to expected one million.

The conceptual OEPRM of SA of NPP is shown in Fig. 1. The proposed OEPRM is formulated on the basis of effective infrastructure system and well defined regulations. Infrastructure system requires dynamics of communication, transportation and various center. Communications depends mainly on communication medium and power. Transportation requires available vehicles and medium of way while emergency center, evacuation center and hospitals are the main subsystems of center. Conversely, regulations system are classified into three categories namely: protective actions, integrated capabilities, and responsibilities of involved parties. Regulations related to precautionary, urgent and migratory protective actions plus information disseminations are the main requirements for protective actions. Emergency planning zones, criteria for emergency facilities and classifications of emergency levels are the vital parts of integrated capability related regulations. Utility, regulatory authority, central government and local government are the main responsible parties in dealing with emergency response.

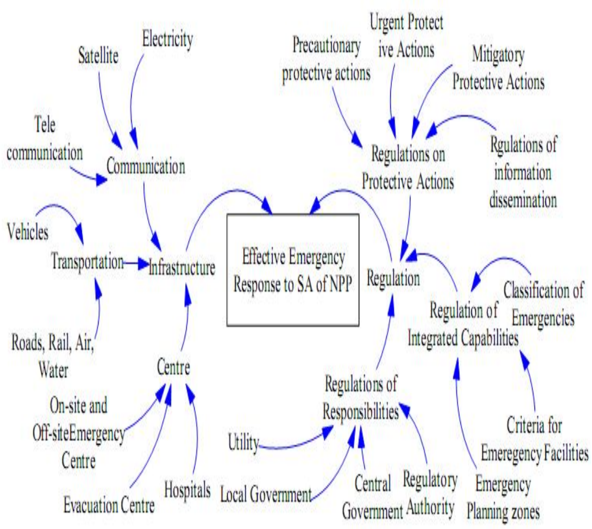

Fig. 1. Conceptual OEPRM of SA of NPP.

The Fig. 2 shows the causal loop diagram for 'Unavailability of Infrastructure' event which starts from natural calamity. As a result of infrastructure damage, communication failure, transportation unavailability and inoperability of emergency center were observed. Consequently, delay of emergency response happened and radiation hazards occurred to public and workers, which creates lack of human resources to make the infrastructure available. Here, radiation hazards ultimately provide the positive feedback through lack of human resources and boost to the infrastructure unavailability.

The Fig. 3 shows the causal loop diagram for ''Lack of Proper Regulation'' event which begins from lack of well-defined protective actions, lack of proper capable facilities, and undefined roles and responsibilities of involved parties. Subsequently, it makes delay in emergency response which assist to spread in radiation to public and workers. When radiation effects are detected to the public and workers it scares the masses and involved actors, followed by lack of coordination. This lacking of coordination ultimately provides the positive feedback loop to lack of proper regulation.

The Fig. 4 shows the causal loop diagram for ''Unavailability of Communication'' event which starts from power failure and damage of communication infrastructure caused by natural disaster. Thus, it delays in emergency response which assist to spread in radiation. When radiation effects are observed to the public and workers it causes lack of human resources to make the communication available. Here, radiation effects ultimately provide the positive response through the absence of human resources to the communication unavailability. In a similar fashion, other feedback effect can be shown for unavailability of transportation, unavailability of centres, and lack of regulations for responsibilities, integrated capabilities, and protective actions.

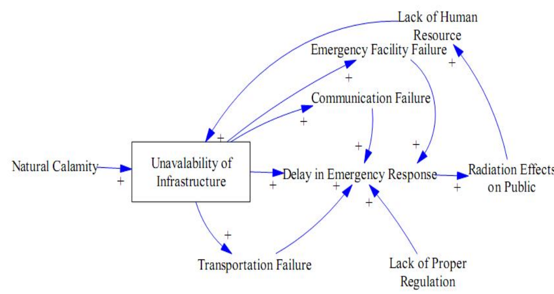

Fig. 2. Causal Loop Diagram for 'Unavailability of Infrastructure' Event.

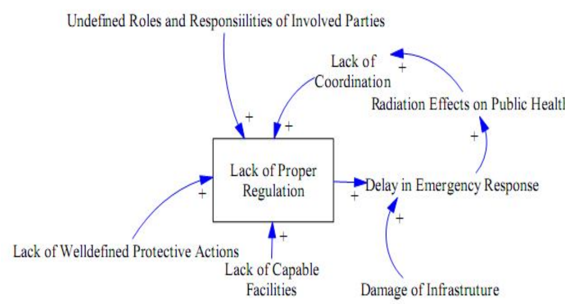

Fig. 3. Causal Loop Diagram for 'Lack of Proper Regulation' Event.

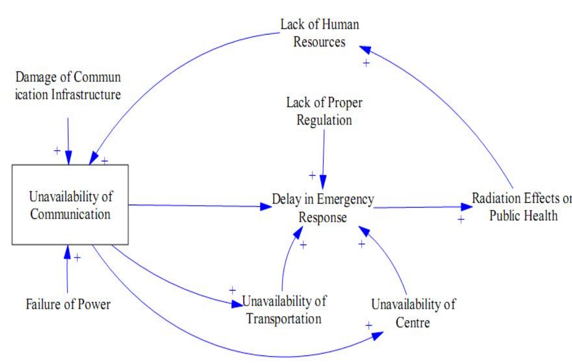

Fig. 4. Causal Loop Diagram for 'Unavailability of Communication' Event.

As the emergency response and preparedness are directed principally towards the protection of the general population and emergency workers from avoidable exposures to radiation. The most important three options such as sheltering, distribution of KI tablets and evacuation must be ready especially in the densely populated NPP country.

Sheltering is one of the first steps to be taken to protect the population in the event of environmental release of radioactive substances in case of SA. The effectiveness of this initial measure depends on the type of the residences in the locality. Information should be available as to whether the houses and public buildings are made of concrete, brick, and mud structures. It is also necessary of those houses whether they have doors and windows with shutters and whether their roofs are of concrete slabs or tiles or are of the thatched type. The designation of such areas as emergency shelter will need prior arrangements with rehearsal in advance.

The arrangements for taking of specific stable chemical compounds such as Potassium Iodide (KI) which have a reducing or blocking effect on uptake of certain radionuclides chiefly I-131 in the thyroid gland, is essential.

Evacuation is very complex and depends on many parameters. The timing of release of radiation is unpredictable, hence actions to protect the workers, public, environment and living animals required to start immediately after the measurement of exceeding predetermined criteria related to core or spent fuel pool. According to different literature related to SA progression, it may take from 24 hours to 168 hours according to the design of NPP. It means that public need to evacuate around PAZ and UPZ are within this period. Some countries has population around 30 km radius from 100,000 to 1000,000. Due to the advanced nuclear technologies, it is rational to think that evacuation time will be allowed around 72 hours in case of SA. The evacuation rate in people per hour is 13889, 6944, 1389 for 100,000, 500,000, and 100,000 people respectively.

The following top level proposal are provided to handle the radiological emergency efficiently in a densely populated country such as well-defined regulations; clear precautionary, urgent and food restriction planning zone; integrated communication and coordination among the parties; proper arrangements for sheltering, distribution of KI tablets and evacuation; and adequate infrastructure with well trained personnel for emergency response.

5. Conclusion

In this study, an OEPRM is developed for densely populated NPP country to mitigate radiological effects in case of SA using SD approach. Besides, this study focuses the weakness of emergency response in Fukushima accident and proposed solution approach.

The development of OEPRM in case of SA of NPP is very complex because of the involvement of various organization and it requires highly specialized agencies and technical experts. Moreover, if the country is agriculture based, it will make completely sophisticated. In this case, emergency preparedness can be planned focusing more on sheltering than on evacuation. Graded approach can be implemented regarding evacuation and sheltering order on the basis of either plant condition or measured radiation dose.

IAEA guidelines related to PAZ, UPZ, and FRP should be followed as well as country specific socio-economic condition must be considered for developing the OEPRM. If necessary, EPZ can be extended to 50 km radius considering the radiation spreading.

There is a need to ensure that emergency preparedness and response with well-trained personnel as well as sufficient resources to handle extended time. Diverse arrangements of evacuation center, hospitals are required considering that shifting may be required on the basis radiation dose. Basic nuclear education especially the consciousness among the mass people are essential to the country's education system.

The foremost contribution of this work is the identification of two main systems of effective OEPRM which are, system of infrastructure and system of regulations with their sub-system. Another important contribution is the use of SD approach throughout this study. The insights of this model can be observed by visualizing the dependencies among the systems, sub-systems and components. Finally, the proposed OEPRM will be well suited in a densely populated country to handle nuclear emergency in case of SA of NPP. Moreover, this emergency model can also be applied to chemical plant accident.

The proposed OEPRM model has not been implemented yet in any specific NPP accident which is a limitation of this study. In further studies, quantification of evacuation and sheltering will be conducted on the basis of proposed OEPRM.

Acknowledgements

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