Multiple external hazards compound level 3 PSA methods research of nuclear power plant

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Abstract. 2011 Fukushima nuclear power plant severe accident was caused by both earthquake and tsunami, which results in large amount of radioactive nuclides release. That accident has caused the radioactive contamination on the surrounding environment. Although this accident probability is extremely small, once such an accident happens that is likely to release a lot of radioactive materials into the environment, and cause radiation contamination. Therefore, studying accidents consequences is important and essential to improve nuclear power plant design and management. Level 3 PSA methods of nuclear power plant can be used to analyze radiological consequences, and quantify risk to the public health effects around nuclear power plants. Based on multiple external hazards compound level 3 PSA methods studies of nuclear power plant, and the description of the multiple external hazards compound level 3 PSA technology roadmap and important technical elements, as well as taking a coastal nuclear power plant as the reference site, we analyzed the impact of off-site consequences of nuclear power plant severe accidents caused by multiple external hazards. At last we discussed the impact of off-site consequences probabilistic risk studies and its applications under multiple external hazards compound conditions, and explained feasibility and reasonableness of emergency plans implementation.

1. Introduction
After the Fukushima nuclear accident, the severe accidents consequences evaluation has also raised more and more attention, especially the nuclear power plants suffered from multiple external hazards compound cases. Some external hazards may occur simultaneously and may affect the plant’s safety function or result in degradation of the safety function of nuclear power plant. It is an important measure to protect the safety of nuclear facilities. Because of the impact of meteorological, geological hazards under multiple external hazards conditions, the emergency plans implementation feasibility and rationality also need to be explored [1].

Based on the nuclear power plant multiple external hazards compound level 3 PSA methods studies, and the description of the multiple external hazards compound level 3 PSA technology roadmap, important technical elements that different from the internal event level 3 PSA. We took a coastal nuclear power plant as a reference site, and considered the site’s earthquake and tsunami compound hazards and high winds and heavy rain compound hazards. And combined with source term study results of multiple external hazards compound Level 2 PSA, as well as the consideration of extreme meteorological conditions we analyzed multiple external hazards compound caused nuclear power plant severe accident and its impact of plant consequences. Then we calculated some cases, discussed
plant consequences probabilistic risk studies and applications under multiple external hazards compound conditions.

2. Technical method

2.1. Evaluation method
Multiple external hazards compound level 3 PSA methods are almost same as commonly level 3 PSA, but some key technical elements need to be considered as multiple external hazards affected factors. First, source term study results come from multiple external hazards compound Level 2 PSA; Second, considering the impact of extreme weather conditions in high winds and heavy rain compound hazards, and it requires the select of a representative weather condition sequence to calculate, and also we need new sampling method to process meteorological conditions in order to verify the different weather conditions effects; Third, considering that the impact of emergency response in earthquake and tsunami compound hazards may results in evacuation failed, and so on[2]. These affected technology elements will be described in section 2 in detail. The definitions for external hazards and extreme conditions are based on the nuclear power plant design basis. For example, seismic external hazard analysis scope is from 0.2g seismic acceleration to above. The high winds external hazard is wind speed more than 20m/h.

The estimation of accident risks requires consideration of both frequencies of accident occurrence and those accidents consequences. NUREG-0396 description for severe accidents consequence risk analysis of probability theory evaluation method [3] is as follows: As the release category i, through calculating dose complementary cumulative frequency distribution (CCDF) curve, it can obtain meteorological conditions probability $p_i(x)$ exceeds the specified dose. If the occurrence frequency of release category i is $f_i$, , in the x distance, the conditional probability exceeds a specified dose in considering the entire accident spectrum is as follows:

$$p(x) = \frac{\sum_i p_i(x)f_i}{\sum_i f_i} \quad (1.1-1)$$

Multiple external hazards compound level 3 PSA consequence risk analysis results are described in section 3.1. Multiple external hazards extreme weather conditions affected analysis results are described in section 3.2.

2.2. Grid structures
In this research, we taking a coastal nuclear power plant as a reference site, and getting site characteristics of relevant data. Site around of 80km is as an analysis evaluation area, which radially divided into 12 loops.

![Figure1. Grid Structure Schematic](image-url)
In the consequence analysis code (MACCS2), the surrounding area of reference site of 80 km was meshed [4]. The surrounding area of reactor is divided into polar coordinate grids, the reactor at the center is located in the coordinate of \( r=0, \ \theta =0 \), and every 22.5° azimuth will be a circumferential region which has been divided into 16 sectors. Figure 1 is a grid structure schematic. N represents the north orientation.

3. Multiple external hazards LEVEL 3 PSA Technology Elements impact analysis

3.1. Multiple external hazards compound accident source term

The starting points of multiple external hazards compound consequence analysis is relevant multiple hazards compound level 2 PSA produced radioactive source term and frequency. The radioactive source term is the key parameter to determine the accidents off-site consequences, and the final form of level 2 PSA analysis, as well as the inputs of off-site consequences probability evaluation, which include the radioactive fission product’s releasing volume, releasing time, duration time, releasing height and so on. The radioactive source term includes many different radionuclides, and they are different in physical and chemical natures, as well as in migration behaviors in the environment and risk impacts on society. This severe accident source term adopts multiple external hazards compound Level 2 PSA results.

3.2. Multiple external hazards meteorological processing method and Atmospheric dispersion

Multiple external hazards include extreme weather conditions such as high winds and heavy rain, and we need new sampling method to process meteorological conditions in order to verify the extreme weather conditions effects. Multiple external hazards extreme weather conditions need to make many meteorological groups to examine the impact of high winds and heavy rain. Therefore, we considered to separately extract a number of weather sequences such as heavy rain and high winds as sample box. In addition, constant weather conditions of heavy rain and high winds also were analyzed. External hazards weather conditions processing approach shows in Figure 2.

![Figure 2. Multiple External Hazards Extreme Weather Conditions Processing method](image)

Took the reference site meteorological data of many years as sampling data, and used category sampling method to sample meteorological sequence. The sampling bin was based on the multiple external hazards extreme weather. When applying Gaussian plume model to calculate multiple external hazards consequence, the atmospheric diffusion parameters also need to be amended. Because the reference site geographical conditions is hilly terrain, and ground roughness is large, so take the use of atmosphere diffusion parameters of larger ground roughness (\( z_0=1m \)). Diffusion coefficient is related with atmospheric turbulence structure, ground clearance, ground roughness, leak duration time, sampling interval, wind speed and distance leaving the leak source. For other site-related parameters,
such as mixing layer height, shielding factor and etc., selecting conservative values through sensitivity analysis [5].

Model assumes pollutant concentration distribution is a Gaussian distribution in space. According to the traditional Gauss formula, when the plume are not limit to the ground and the inversion layer, Gaussian plume model can be expressed as follow:

\[
\chi(x, y, z) = \frac{Q}{2 \pi \sigma_y \sigma_z} \exp \left[ -\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right] \exp \left[ -\frac{1}{2} \left( \frac{z-h}{\sigma_z} \right)^2 \right]
\]

Where: \( \chi(x, y, z) \) is time integral air concentrations at the downwind position \((x, y, z)\), Bq \cdot s/m\(^3\); \( Q \) is source intensity, Bq; \( u \) is the average wind speed, m/s; \( \sigma_y \) and \( \sigma_z \) is horizontal and vertical standard deviation of plume respectively, m; \((x=0, y=0, z=h)\) is the source term position; \( h \) is the release height, m.

3.3. Dose response and health effects

Radioactive substances are released into the atmosphere after a severe accident, and because the atmospheric diffusion, deposition, the body accumulated radiation dose from the plume irradiation and ground deposit irradiation. Dose-response model is converting radioactive substances concentration to the human body cumulative radiation dose. Figure 3 is a dose assessment and health effects evaluation schematic. Considered exposure pathways include: plume immersion radiation, ground deposition irradiation, inhalation irradiation, re-suspended inhalation irradiation, skin deposition irradiation. Early accident radiation exposure considered only the first three. Plume immersion irradiation pathway expected dose could be calculated by the following formula [6]. Plume immersion outside irradiation:

\[
DC_k = \left( \sum \frac{AC_i^C \cdot DFC_{\infty k}}{C} \right) C \cdot F \cdot SFC
\]

Where: \( k \) is plume segment through grid caused organs \( k \) irradiation dose, Sv; \( CiC \) is the plume centerline \( i \) nuclide time integrated air concentrations, Bq \cdot s/m\(^3\); \( DFC_{\infty i} \) is \( i \) radionuclide for \( k \) organ semi-infinite plume dose conversion factor, Sv \cdot m\(^3\) / (Bq \cdot s); \( C \) is limited plume correction factor; \( F \) is exposure time share when the plume passes, \( F = te/t_0 \), \( te \) is people exposure time (s), \( t_0 \) is the duration time of the plume through a segment (s); \( SFC \) is Plume irradiation shielding factor.

**Figure 3.** Dose evaluations and health effects schematic

3.4. Multiple external hazards Emergency response

There is difference between multiple external hazards compound level 3 PSA and commonly level 3 PSA about emergency response. In the external hazards compound circumstances, such as earthquake and tsunami compound disaster, its ground transportation will be greatly affected. Early evacuation is more difficult. Most residential are brick houses around the nuclear power plants, shielding performance is better, but these residential brick houses may be affected by earthquake and tsunami, and shielding performance will decrease. Therefore, refer to international general emergency response principles and emergency response measures, it has take into account of the nuclear power plant relatively realistic emergency response measures and evacuation plan in multiple external hazards.

Average speed of the car, under normal weather conditions is 30Km/h, under bad weather conditions is 15Km/h, generally night weather is 25Km/h, bad weather at night is 12.5Km/h. In contrast, NUREG-1150 assumes 4.3Km/h (delayed 1 hour), the technical guide which is a development site guideline adopted 16Km/h in United States, while the average evacuation speed is 7.5Km/h obtained in RSS(Reactor safety research)[7]. The average speed of the car is a relevant parameter, because we need to complete evacuation before reactor releasing. The consequence of a
severe accident will be more severe if the time of evacuation is longer. Based on the above, and considering multiple external hazards conditions such as earthquake and tsunami compound disaster. Consider that earthquake may cause highway unavailable, and not consider early evacuation but the shielding effects.

4. Calculation results analysis

4.1. The site boundary dose risk
Dose assessment provides the conditional probability distribution, these consequences probability distribution is based on the assumption that the source term caused by accidents has occurred, that the consequences probability distribution is caused by different weather conditions change result in dose change. Table 1 is each release category average dose risk of whole body dose at the site boundary in seven days.

| Release categories | Release categories description                                  | Body Average dose (Sv) | Risk (Sv / reactor years) | Percentage in total risk |
|--------------------|----------------------------------------------------------------|------------------------|---------------------------|--------------------------|
| CFV                | Emission was filtered, the core melt is not covered by water   | 1.80E-01               | 1.60E-10                  | 0.61%                    |
| CFL                | Containment late failure, spraying is not operating, the core melt is not covered by water | 7.07E+00               | 1.86E-09                  | 7.13%                    |
| CMT                | Containment foundation melt wear failure                       | 2.15E+00               | 2.12E-12                  | 0.01%                    |
| CFE                | Containment early failure, containment spray is not running    | 9.34E+01               | 1.79E-08                  | 68.78%                   |
| CIS                | Containment isolation failure                                  | 1.42E+02               | 8.51E-11                  | 0.33%                    |
| CBP                | Containment bypass, no cleaning fission products clean, radioactive leak directly into the environment | 2.32E+02               | 6.03E-09                  | 23.14%                   |
| Total risk         |                                                                 | 2.61E-08               | 100.00%                   |                          |

We can draw the results from Table 1 that when no emergency response, CFE (early failure) and CBP (containment bypass, no cleaning fission products) these two-release categories possess higher dose risk, but lower release frequency. Therefore, when compound external hazard caused radioactive release is inevitable, we should try to lead release categories with serious consequences into less effected categories by necessary mitigating means as much as possible, such as CFV (filter drain) release category which can result in lower dose risk.

4.2. Weather conditions affected analysis
In order to research the impacts of the extreme weather condition influenced consequences, we calculate the results about time integrated air concentration and ground concentration in different wind speeds and rainfalls for new Category meteorological sampling. We can obtain the result that under high winds and heavy rain condition, radioactive concentration is high in within two kilometers of the site. We also researched the radionuclide result that under the constant weather conditions, in use of different wind speeds and rainfalls. The same rainfall is 93mm/h, different wind speeds is 10m/s and 30m/s respectively, the air concentration is high in low wind speed. If the wind speed is same, rainfall is different, the air concentration is high in the small rainfall, but the ground concentration is small. These calculations results that using of new Category meteorological sampling method and constant weather conditions are shown in Figure 4 and Figure 5.
We can see from Fig. 4. They are time integrated air concentration and ground concentration varies with the distance under the multiple external hazards conditions. The blue line is high winds and heavy rain compound external hazard. The red line is the tsunami and earthquake compound external hazard. The high winds and heavy rain radioactive air concentration and ground concentration are all higher than that of the tsunami and earthquake in the distance within two kilometers. So the extreme weather conditions mainly affect two kilometers distance. Fig. 5 shows the results under the constant weather condition.

We can see from the Fig. 5 of time integrated air concentration varies with the distance. The same wind speed is 10m/s, different rainfall is 93mm/h and 30mm/h respectively, the smaller rainfall caused more severe consequence and the I-131 time integrated air concentration is higher. The same rainfall is 93mm/h, different wind speed is respectively 10m/s and 30m/s, the lower wind speed I-131 time integrated air concentration is higher. We can also see the results on the ground concentration from the Fig. 5. The same wind speed is 10m/s, different rainfall is 93mm/h and 30mm/h respectively, the bigger rainfall caused more severe consequence, and the I-131 ground concentration is higher. The same rainfall is 93mm/h, different wind speed is respectively 10m/s and 30m/s, the lower wind speed caused more severe consequence, and the I-131 ground concentration is higher. That is because the higher wind speed, the lower I-131 time integrated air concentration.

4.3. Emergency response consequences risk analysis
There are differences between multiple external hazards emergency and normal emergency. We can see from Table 2 of multiple external hazards emergency response affection considered. In normal condition considered emergency, the site boundary body dose risk reduces two magnitudes, but in multiple external hazards condition considered emergency, body dose risk only reduces one magnitude. The frequency of multiple external hazards is low, but the consequence risk is higher than the normal conditions (internal event) considered emergency.
Table 2. External hazards compound consequences risk considered emergency

| Emergency response                                           | Dose type                                                                 | Site boundary body dose risk (Sv / reactor years) | Site boundary body dose risk (Sv / reactor years) |
|---------------------------------------------------------------|---------------------------------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| Normal Evacuation (delayed 1 hour, speed 15Km/h, evacuation range 5Km) hidden (10Km) | No emergency                                                              | 2.61E-08                                         | 5.30E-10                                         |
| Multiple External hazards Evacuation (delayed 1 hour, speed 1.5Km/h, evacuation range 5Km) hidden (10Km) | Emergency                                                                 | 4.50E-09                                         |                                                   |

5. Conclusions
We made a reference plant consequence analysis model, studied nuclear power plant severe accident consequences probabilistic evaluation methods under multiple external hazards conditions. And then we get some multiple external hazards consequence risk analysis results and risk insights as follows:

Earthquake and tsunami compound dose risk results show that some release categories have high release frequency, but its plant dose risk is low. Therefore, when multiple external hazards compound radioactive release happens inevitably, we should try to lead the release categories with serious consequences to release categories with less effect by necessary mitigating means as much as possible. This can make dose risk reduction.

High winds and heavy rain compound consequences indicate that radionuclide release has a higher risk in within two kilometers of the site. Multiple external hazards considered emergency consequence risk is higher than the normal considered emergency consequence risk. So we should not be thinking that multiple external hazards occurrence frequency is very low, and then ignore these risks, which is incorrect, but should be overall considering the plant consequences risk.

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