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Research on Safety Impact Assessment Method of Rocket Launching for Nuclear Power Plant

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Abstract: With the rapid development of commercial aerospace activities, the risk from new external human-induced events, such as those originating from nearby satellite rocket launch sites, requires evaluation.. This paper investigates the risk posed by a satellite rocket launch site, which is only 26km away from the nuclear power plant. In view of the lack of evaluation guidelines for rocket impact nuclear facilities at home and abroad, this study refers to the analysis framework of aircraft impact in the U.S. Department of energy standards, combined with the flight characteristics of the rocket, establishes an impact frequency probability assessment model suitable for rocket launch. Based on the four factor formula, this model defines and quantifies the key parameters such as the number of rocket launches per year, the probability of single launch failure, the conditional probability of crash deviation to the plant area and the effective impact area of the nuclear island. A variety of conservative scenarios are set up to evaluate the impact risks of mature and commercial rockets at different launch frequencies. The results show that the risk level of mature rocket series is far lower than 1× 10-7/year screening threshold under the extremely conservative scenario of security control system failure, indicating an acceptable risk. When the launch frequency of commercial rocket with high failure probability is high, the risk may exceed the screening threshold. In addition, the impact of explosion, electromagnetic interference and vibration of rocket launch can be ignored. The results of this study provide quantitative basis and decision support for nuclear power plants to deal with the risk control of adjacent space launch activities, and serves as a valuable reference for improving China's nuclear safety regulatory framework.

Key words: Nuclear power plant; Rocket launching; Probabilistic safety assessment; Risk assessment; Impact frequency; External human events.

1. Introduction

In recent years, China's aerospace industry has entered a high-speed development stage, especially the surge in the demand for commercial satellite launch, with new launch sites and pads are emerging. Some launch sites may be located close to important industrial facilities (such as nuclear power plants) and are geographically close, thus introducing a new type of external human event risk, rocket launch and fall impact, which is not fully considered in the traditional design.

In China's current nuclear safety guideline HAD101/04 "external man-made events in plant site selection of nuclear power plants" [1], a screening method based on distance and probability is proposed for aircraft impact events. A satellite rocket launch site near the nuclear power plant is about 26km away from the plant site in a straight line, which is within the range of 30km specified in the guidelines,it cannot be directly screened out. Therefore, a further quantitative probability risk assessment is needed. It is worth noting that the impact of commercial aircraft is mainly considered in the existing design basis of CPR1000 and other second-generation nuclear power plants, and rocket launches are not covered.

Internationally, the U.S. NRC and DOE have published standards, such as NUREG-0800 [2] and DOE-STD-3014-2006 [3], which provide a mature methodology for the probability risk assessment (PSA) of external event impact. However, there are no official evaluation criteria for rocket impact on nuclear facilities. The flight path, dynamic characteristics, failure mode and safety control mechanism of the rocket are significantly different from those of aircraft, and the direct application of the aircraft impact assessment method has limitations.

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Therefore, this study aims to fill this gap, taking the nuclear power plant and its adjacent satellite rocket launch site as a specific case, to explore and establish a set of probability risk assessment method applicable to the impact of rocket launch on nuclear power plant. By quantitatively analyzing the impact frequency, this study determines the risk level is defined, and the targeted risk management and control suggestions are put forward, in order to provide scientific basis for the safe operation and regulatory decision-making of nuclear power plants.

2. Evaluation Methods and Models

2.1 Evaluation Framework

The proposed site of a satellite rocket launch site is 26km away from the nuclear power plant in a straight line, and the rocket flight path projection line is 8km away from the nuclear power plant (as shown in the figure below). The trajectory of rocket launching may affect the safe operation of nuclear power plant. Based on the analysis logic of aircraft impact in DOE-STD-2006 standard and the technical characteristics of rocket launch, the frequency evaluation model of rocket impact nuclear power plant is constructed. The framework of aircraft impact risk analysis proposed in DOE-STD-3014-2006 is consistent with the principles of China's nuclear safety guideline HAD101/04 and has wide applicability. This framework usually includes aircraft crash rate, determining the probability of impact conditions according to the coordinate distance, calculating the effective impact area and so on. This study focuses on the probability analysis of the core impact conditions.

In consultation with aerospace systems experts, it is considered that the flight characteristics (such as high speed, predetermined orbit, strong controllability) of the rocket in the launching ascending phase are similar to those of the aircraft in the takeoff phase. Therefore, based on the DOE standard framework, this study decided to modify the key parameters and probability model to evaluate the impact risk of rocket launch on nuclear facilities.

2.2 Impact Frequency Model

The impact frequency is the key index to measure the risk level. The DOE standard uses a four factor formula to calculate the annual impact frequency of an aircraft on a specific facility:

$$F=N\times P\times f(x,y)\times A \tag{1}$$

In this study, f (x, y) in the formula is modified to evaluate the impact frequency of rocket

$$F_j=N_j\times P_j\times f_j(x,y)\times A_j \tag{2}$$

The parameters in the formula are defined and quantified as follows:

- F_j: The annual frequency of a rocket crash on buildings important to safety of nuclear power plant, unit: times/year. where j represents rocket type.
- N_j: Annual launch times of rocket launch site in plant site area, unit: times / year. It is necessary to consider the distribution of the firing direction. This study focuses on the analysis of the firing frequency in the firing sector that poses a potential threat to the plant site.
- P_j: The failure probability of a single rocket launch. The probability is closely related to the maturity of the rocket model. In this study, the failure probability of mature rocket series is 0.01, and that of new commercial rocket is 0.4.
- $f_j(x,y)$: The conditional probability that the rocket debris deviates from the predetermined orbit and crashes to the plant site after a single launch failure. This is the core of model modification.

1) P_j is failure probability of single rocket launch

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According to the preliminary statistics of rocket launch failure probability in the world (see Fig 1-Fig 2), the success rate of mature rocket is considered to be 99% (failure probability 0.01), and the success rate of commercial rocket is considered to be 60% (failure probability 0.4).

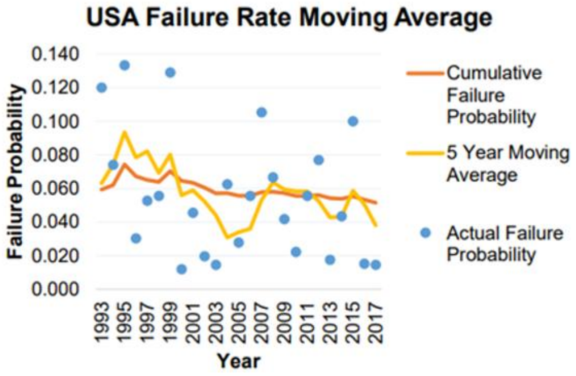

Fig. 1 USA Launch Failure Rate

Fig. 2 Russia Launch Failure Rate

2) $f_j(x,y)$ is the conditional probability that rocket debris deviates deviates from the predetermined orbit and crashes to the plant site.

Rocket launching process has strict flight safety pipeline and safety control system as illustrated in Figure 3.

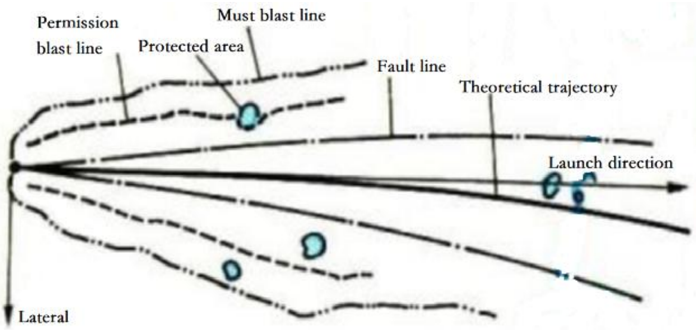

Fig. 3 Schematic Diagram of the Safety Corridor and Trajectory Markings

The calculation logic is as follows:

① Probability of deviation from flight pipeline

According to the rocket flight safety pipeline marking line, the probability of the rocket flight path being controlled in the protective pipe is very high (usually 99.7%), and the probability of deviation from the pipe is 0.3%.

② Failure probability of safety control system

Once the rocket deviates from the pipeline, the ground safety control system will issue a self destruction command. This study conservatively assumes a failure probability for the safety control system $P_{failure}$ of 1×10^{-3}.

③ Trajectory crossover probability

Even if security controls fail, the rocket wreckage will have to fly right over the plant. Assuming that the total flight time of the rocket from launch to orbit is about 80 seconds, and the time of its flight path projection covering the plant site is about 1 second, the probability of trajectory crossing is 1/80=0.0125. In conclusion, the calculation formula of the conditional probability $f_j(x, y)$ is as follows:

$$f_j(x,y)=0.003\times P_{failure}\times 0.0125 \text{ and } P_{failure}=1\times10^{-3}$$

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resulting in $f_j(x,y)=3.75\times10^{-8}$.

3) A_j is the effective impact area of safety-important buildings in nuclear power plant

According to the length, width and height (151m, 93m and 56m) of the nuclear island of 2 units in the nuclear power plant, the dimensions for a six-unit nuclear island are conservatively estimated to be 1000 m in length and 93 m in width. Jielong-3 is a medium-sized four stage solid launch vehicle. The length of the arrow is 31.8m, the diameter of the first and second stages is 2.65m, the diameter of the third stage is 2m, and the diameter of the fourth stage is 1.2m. The fairing with diameter of 2.9m and 3.35M can be selected. The parameters cot(Φ) and S are general values adopted from the DOE standard.

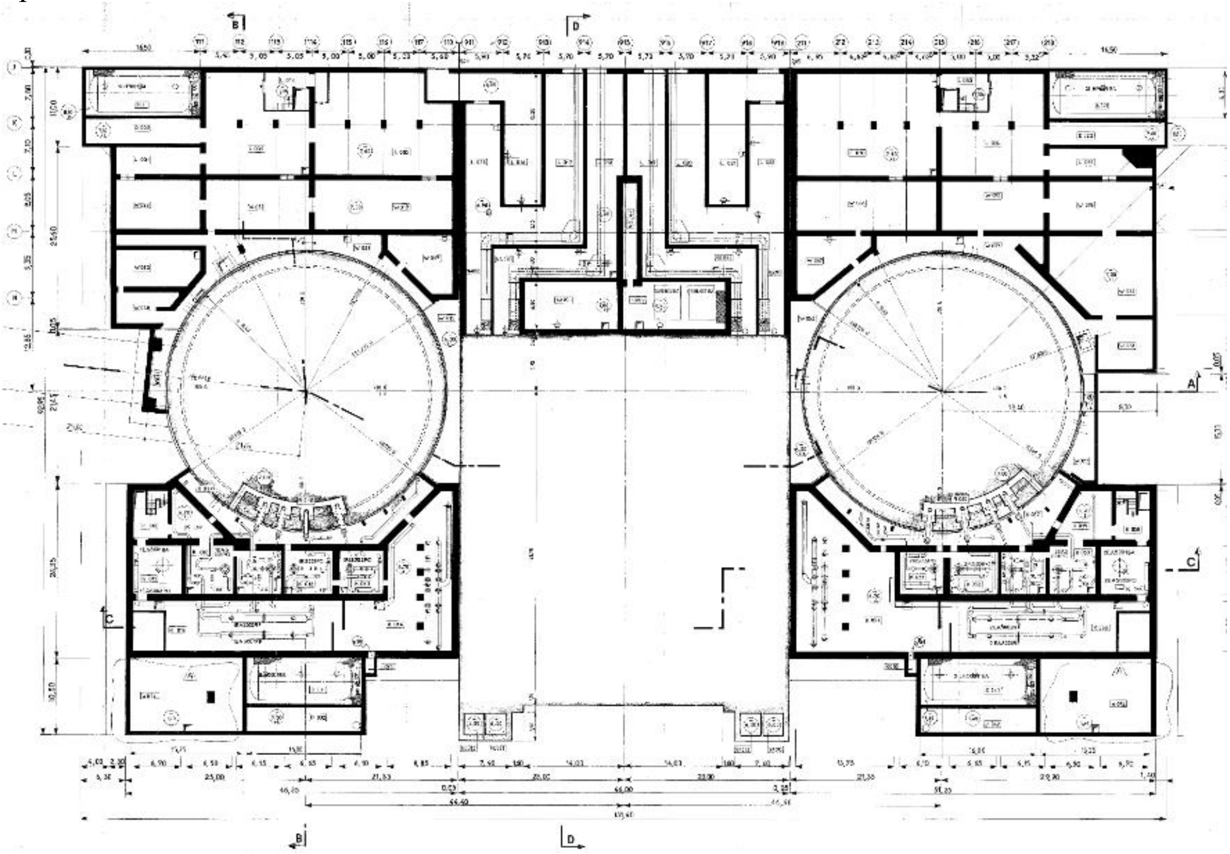

Fig.3 Nuclear island layout

Table 1 Calculation parameters of effective area of nuclear facilities

WS(m)	R(m)	H(m)	COTΦ	L(m)	W(m)	S sliding distance (m)
4	462.45	56	8.4	1000	93	75

Taking the above parameters into the calculation formula of effective area, the effective area A_j of the facility can be obtained. This area refers to an area around the facility where debris falling into the area may cause damage to the facility by direct impact or sliding. The calculation is based on the DOE standard, taking into account the length, width, height of the facility and the wingspan of the rocket. According to the size of nuclear power plant and the parameters of Jielong-3 rocket, the effective impact area A_j is calculated to be 3.54×10^{-1} km^2.

3. Case Application and Analysis of Nuclear Power Plant

3.1 Case Description and Parameter Setting

The linear distance between the nuclear power plant and a satellite launch site is 26km. The launch site is mainly used for launching at sea, and the launch platform is located in the sea area

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near Hailing Island. This study focuses on the analysis of the largest potential threat to the plant site, and the launch scenario that is aimed at the plant site (90° sector). Sketch map of rocket launching and nuclear power plant location in Fig.4.

For conservative evaluation, the following parameters are set:

1) Annual launch frequency N_j: It is assumed that the launch site has a total of 30 launches throughout the year, of which the probability of launching to the 90° sector is 25%, corresponding to 7.5 launches per year.For a conservative estimate, this study assumesn N_j=10 launches/year.

2) Security control failure scenario: the scenario of "complete failure of security control system and inertial flight of rocket debris" is considered.

3) Screening threshold: refer to the screening criteria for external events in PSA practice of nuclear power plants, and adopt 1×10^{-7}/ year is the screening threshold of impact frequency.

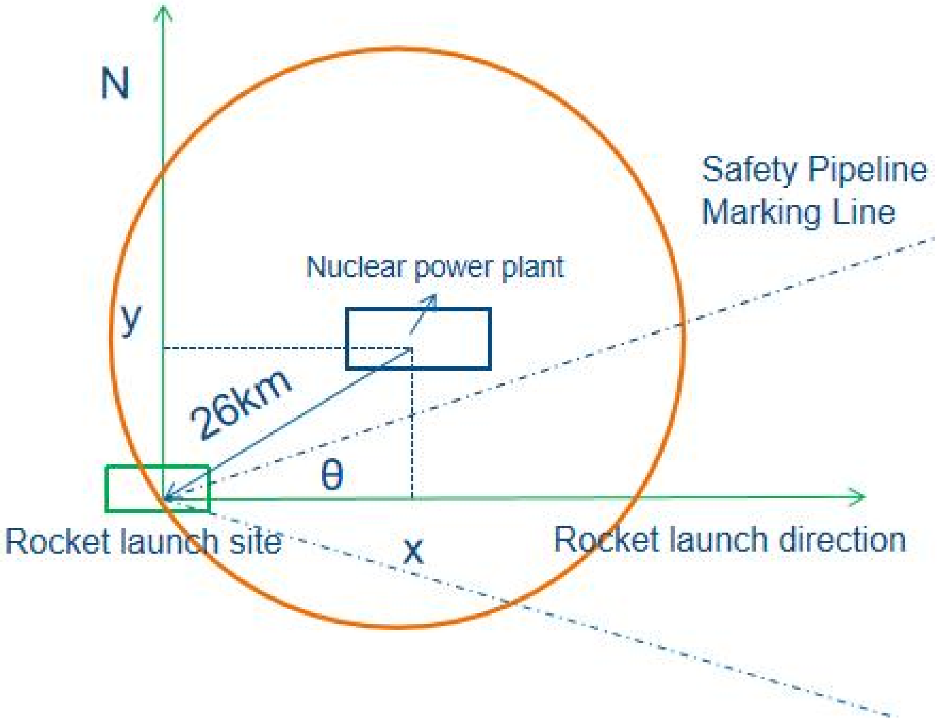

Fig.4 Sketch map of rocket launching and nuclear power plant location

3.2 Calculation and Analysis of Impact Frequency

Based on the above models and parameters, the impact frequency under different rocket types and launch frequencies is calculated, and the results are shown in Table 2.

Table 2. Calculated Impact Frequencies under Different Scenarios

Accident scenario	Rocket type	Times of 90 o annual firing Nj (times / year)	Single launch failure probability Pj	Conditional probability Fj (x, y)	Effective area Aj (km ²)	Crash frequency Fj (/year)
Scenario 1	Mature rocket	10	0.01	3.75×10-8	3.54×10-1	1.33×10-9
Scenario 2	Mature rocket	100	0.01	3.75×10-8	3.54×10-1	1.33×10-8
Scenario 3	Commercial rocket	10	0.40	3.75×10-8	3.54×10-1	5.31×10-8
Scenario 4	Commercial rocket	19	0.40	3.75×10-8	3.54×10-1	1.01×10-7

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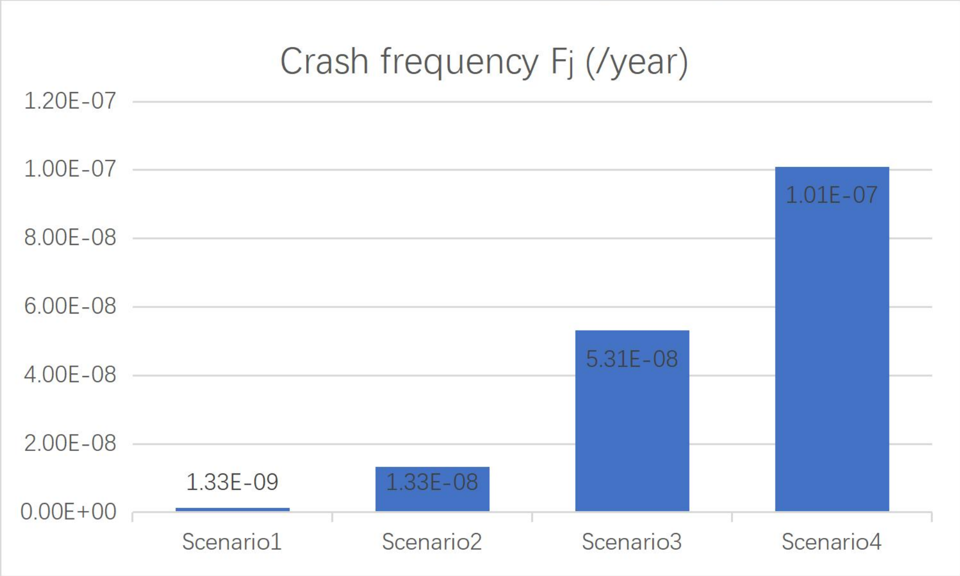

Fig.5 results of frequency of rocket impact on nuclear power plant under different scenarios

As shown in Table 2 that under the extremely conservative assumption of "failure of safety control system":

- For mature rocket series, even if the annual launch frequency is as high as 100, the impact frequency is 1.33×10^{-8}/year which is also far less than 1.0×10^{-7}/year.The screening threshold of indicates that the risk level is acceptable.
- For commercial rockets with high probability of failure, the impact frequency reaches 1.01×10^{-7}/year when the number of annual launches in the 90° sector is 19. This suggests that if the rocket with high failure risk is used in high frequency in the future, its cumulative risk cannot be ignored.

The models and parameters used in this study (such as failure probability of safety control and trajectory crossing probability) are conservative, and the calculated results are the upper limit of risk. The actual risk, especially for mature launch vehicles, will be much lower than this estimate. In addition, this study focuses on the situation of security control failure. For the more likely scenario of "normal start of security control system", the rocket will disintegrate in the air and form debris dispersion. At this time, the risk mainly changes to debris impact, and its impact range and destructive force are significantly smaller than the overall impact. Therefore, ensure that the launch site has a high reliability safety control system is a key aspect of risk management and control, and to accurately design the debris falling area and keep it away from the nuclear power plant.

3.3 Analysis of Other Influencing Factors

In addition to direct impact, other effects related to rocket launch need to be considered:

1) Explosion impact: according to HAD101/04, the screening distance of explosion event is 5-10km. In this case, the launch site is 26km away from the plant site, which is far beyond the screening distance. The impact of the blast wave on the safety of the plant site can be ignored.

2) Electromagnetic interference: the frequency of communication and control system in the process of rocket launching is usually set independently, and the protection system of nuclear power plant has strong anti electromagnetic interference ability. Through proper frequency planning and electromagnetic compatibility (EMC) design, adverse effects on the I & C system of nuclear power plant can be avoided.

3) Vibration impact: As the launch site is an offshore platform with no direct physical connection to the mainland. The ground vibration generated by rocket launch cannot be effectively transmitted to the plant site 26 km away, and the vibration impact can be ignored.

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4. Conclusion

This study employed a probabilistic safety assessment (PSA) method to systematically investigate the risk impact of satellite rocket launch on nuclear power plant. By modifying the aircraft impact model in DOE-STD-3014-2006 standard, a set of methods suitable for the assessment of the probability risk of rocket launch impact on nuclear power plant is established, which can provide reference for similar assessment. Under the extremely conservative assumption, the impact risk of the launch of mature rocket series on the nuclear power plant is far lower than the screening threshold, and the risk is acceptable. The risk of high failure rate commercial rocket in high frequency launch may approach or exceed the threshold value, which needs to be focused on. For risk management and control, it is recommended that the launch site should give priority to the rocket model with mature technology and high reliability for launches in the vicinity of the nuclear power plant. For the rocket with high failure risk, the annual launch frequency in the firing sector that poses a threat to the nuclear power plant should be strictly controlled. Ensure the high reliability of the safety control system, and strictly design the debris dispersion area after the rocket self destruction to keep it away from the nuclear power plant and other sensitive facilities. For non-standard tasks such as rocket power system test, special risk assessment shall be carried out and the most strict safety measures shall be taken. To sum up, the results of this study provide a quantitative decision-making basis for nuclear power plants to respond to adjacent space activities, which is of positive significance to ensure nuclear safety and promote the coordinated development of space industry. The future research can further deepen the flight path simulation, debris impact effect analysis, and consider the risk changes brought by new formats such as rocket recovery technology.

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