Postponed Launch Strategy for Interval-style Narrow Window Missions of Cryogenic Rockets

Yufei Gu [1, a, *], Cechan Liu [1, b], Shaojiang Chen [1, c], and Yuanming Fu [1, d]

[1] Xichang Satellite Launch Center, Xichang, China.

[a] yfg123123@qq.com, [b] 415616248@qq.com, [c] csj0502@163.com, [d] 834284269@qq.com

Abstract. To enhance the capability of delaying launches at the launch site and improve the utilization rate of narrow launch windows for deep space exploration missions, this paper presents a comprehensive study on delayed launch strategies for cryogenic liquid rockets. By analyzing the characteristics of deep space mission windows and identifying key risk factors and operational challenges associated with delayed launches, this paper has developed a time-phase-based decision framework that integrates test systems and fault types. This framework has been tailored to the specific features of a large-scale cryogenic rocket in China, enabling the formulation of targeted emergency response strategies for different mission phases and target windows. The proposed approach has been validated through actual operational missions and demonstrated its effectiveness in improving mission planning flexibility and reliability.

Keywords: cryogenic rocket, interval-style, narrow window, postponed launch, response strategy.

1. Introduction

Cryogenic liquid rockets, with their high specific impulse, non-toxicity, pollution-free nature, and high cost-effectiveness, have become the mainstream direction in the development of new rockets and will gradually replace conventional propellant rockets. Compared with conventional rockets, cryogenic rockets cannot verify the working performance and reliability of onboard components under low-temperature conditions during routine testing. After the cryogenic fuel enters the rocket, sudden failures such as sealing leakage and decreased insulation resistance may occur due to low-temperature deformation, condensation, etc.; large cryogenic rockets have many pre-launch test items and complex processes, and the risk of mission postponement due to various reasons is relatively high. In 2022, the SLS was postponed multiple times due to hydrogen leakage issues; in 2023, the mission of launching the X-37B using the Falcon Heavy rocket was also postponed due to a malfunction.

Compared with ordinary launch missions, narrow-window and zero-window missions such as deep space exploration and space station rendezvous and docking leave less time for pre-launch fault handling. Any unexpected situation may cause the mission to miss the current launch window and lead to postponement. Due to the volatile, flammable, and explosive nature of the propellant, the organization and command and emergency handling of postponed launches after the propellant enters the cryogenic liquid rocket are more difficult[1-2], putting forward extremely high requirements for the fault handling, special fuel and gas support strategies, and pre-launch plans at the launch site. How to improve the postponed launch response capability of cryogenic liquid rocket narrow-window launch missions and propose scientific and reasonable postponed launch strategies and emergency response plans has become a research hotspot. Sarah G. et al. conducted a study on mission abort decision-making for Mars exploration using non-adptive neural networks[3]; Ma et al. conducted simulation analysis on the impact of heat leakage in the liquid hydrogen filling system on rocket launches and formulated relevant countermeasures[4]; Zhang et al. studied the multiple liquid hydrogen leakage issues during the first flight of the SLS rocket in the United States, providing reference for the handling of liquid hydrogen leakage issues after rocket filling in China[5]; In addition, China is developing technologies such as automatic docking and zero-second detachment of fluid connectors and hold-down and release to improve the emergency handling capability for aborted launches[6-7]. Currently, scholars mainly focus on individual faults or key issues before launch, lacking a systematic postponed launch handling strategy covering the entire process after cryogenic rocket filling for decision-making by commanders at all levels at the launch site. Therefore, based on the experience of multiple actual combat missions of large and medium-sized cryogenic liquid rockets and combined with the characteristics of cryogenic rockets and deep space exploration mission windows, this paper studies the postponed launch strategy.

2. Difficulties in Postponed Launch Analysis

2.1 Window Characteristics

The launch window refers to the time range within which a launch vehicle is allowed to launch a spacecraft, also known as the allowable launch period or launch opportunity. Launch windows are divided into daily launch windows, monthly launch windows, and annual launch windows. For daily launch windows, the size of the range is also called the window width. Deep space exploration missions are constrained by celestial motion laws and orbit design, and their window widths are generally narrow, usually measured in minutes.

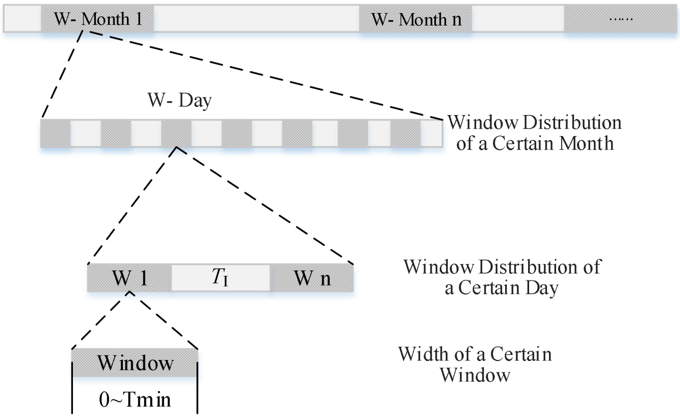

Fig. 1 Schematic Diagram of Launch Window

Deep space exploration missions often have only a few days available in a specific month of a certain year[8]. There are N launch windows every day, and each window width is TI. When TI is less than 30 minutes, it is usually called a narrow window. There is a certain time interval TI between the daily windows. When TI is zero, that is, T1-1 and T1-2 are consecutive, it can be called a continuous multi-trajectory window; when TI is not zero, it is called an interval multi-trajectory window. If the mission fails to be successfully launched within the specific window of the current month, it often has to be postponed for one to several months or even several years before the next launch can be organized. Therefore, the launch window is particularly precious.

Taking the Mars exploration mission as an example, a window period occurs every 26 months, and each country generally has about two weeks of available windows, with multiple consecutive minute-level windows every day, which can be called a continuous narrow-window mission. For a certain lunar exploration mission, affected by the coupling of orbit and related tasks, there are only X days available in a specific month of the year, and there are Y windows every day, with a certain time interval between the Y windows. There are a total of X*Y discontinuous available windows throughout the year, which can be called a multi-trajectory interval narrow-window mission. This type of mission has strong launch window constraints, large changes in orbital parameters, and puts forward high requirements for trajectory design, launch vehicle capacity adaptability, launch site organization and command, postponed launch emergency plans, and special fuel and gas support.

2.2 Difficulties Analysis

Large-scale cryogenic liquid launch vehicles are restricted by the coverage of low-temperature condition testing and verification. After the cryogenic propellant enters the rocket, the probability of failure increases due to factors such as material stress, decreased sealing, and decreased insulation of electrical equipment. In addition, the pre-launch process of cryogenic rockets is complex, with many test items and essential parameters, and the probability of sudden abnormalities before launch is relatively large, making it difficult to achieve on-time launch and posing a high risk of postponed launch. Statistics show that from 2004 to 2023, the Delta-IV rocket was launched 15 times, postponed 5 times. the Falcon 9 rocket was launched 281 times, postponed 55 times. the Atlas V rocket was launched 80 times, postponed 20 times. Japan's H-II series rockets were launched 40 times, postponed 7 times. Table 1 presents the primary launch delay statistics. It can be seen that for large-scale cryogenic liquid rockets, postponed launch is an unavoidable difficulty for all countries.

Table 1. Statistics on the Delayed Launches of Mainstream International Launch Vehicles

Launch Vehicle	Postponement Situation	Postponement Rate
Delta IV	Launched 15 times from 2004 to 2023, failed and postponed 6 times	33.3%
Ariane 5	Launched 117 times from 1996 to 2023, failed and postponed 20 times	12.8%
Falcon 9	Launched 281 times from 2010 to 2023, postponed 55 times	19.5%
Atlas V	Launched 80 times from 2010 to 2023, postponed 20 times	25%
H-II Series	Launched 40 times from 2010 to 2023, postponed 7 times	17.5%
Falcon Heavy	Launched 8 times from 2018 to 2023, postponed 5 times	62.5%
Space Shuttle	5 space shuttles, launched a total of 139 times, postponed 22 times	15.8%
Atlantis	Retired from 1985 to 2011, launched 37 times, postponed 6 times	16.2%

For cryogenic rockets, on the day of filling and launching, as the mission process progresses, its reversibility and postponed launch capability gradually decrease.

1) Before the propellant enters the rocket, the overall reversibility of the system is the highest. The program can be paused at any time to restore the state, and after the fault is eliminated, the filling and launching program can be restarted, and the postponed launch capability is not affected.

2) After the conventional propellants enters the rocket, due to the limitation of propellants temperature and quality, for a long-time postponement, part or all of the kerosene needs to be drained back, and after secondary temperature adjustment, it is refilled again.

3) After the cryogenic propellant enters the rocket, due to the restriction of low-temperature test verification coverage, the reliability and insulation performance of the onboard components under low-temperature conditions cannot adapt to a long-time postponement. To achieve a postponed launch, the propellant needs to be drained back, and the engine needs to be warmed up and retested before it meets the requirements for being refueled and launched again.

4) Especially after the pre-cooling of the cryogenic engine and the detachment of the filling and draining connector, due to the limitation of the temperature rise of the key components of the engine, the maximum allowable postponement time is in the order of minutes, which is generally less than the window interval, and it is often impossible to postpone to other windows on the same day without implementing the reverse process.

For narrow-window launch missions, the "fighting opportunity" is fleeting. If a fault occurs before launch and is not handled in time, it will lead to mission postponement. Compared with ordinary windows, interval-style narrow-window launch missions have more coupling factors for postponed launch, higher risks, and greater difficulties in organization and implementation, and it is urgent to conduct research on the overall postponed launch strategy.

3. Postponed Launch Problem Analysis

It can be seen that for interval-tyle window missions, there are multiple discontinuous windows every day. After a fault occurs before launch, it is necessary to combine the fault handling difficulty and the window interval to decide whether to postpone to other windows on the same day or to postpone to the next day or later windows. At the same time, combined with the handling difficulties, the pre-launch process can be divided into stages such as before propellants L1 enters the rocket, before the L2 begins to enter the rocket, after the L2 enters the rocket and before the L3 begins to enter the rocket, after the L3 enters the rocket and before the connector detaches, according to the degree of the rocket's adaptation to the low-temperature filling process.

During the filling and launching stage, any fault in any system can be divided into three situations: affecting the mission process and the external system, affecting the mission process but not affecting the external system, and not affecting the mission process. Therefore, the problem of postponed launch during the filling and launching stage due to various reasons can be summarized as a multi-constraint and multi-objective problem of time stage, test system, and fault type. Before you begin to format your paper, first write and save the content as a separate text file. Complete all content and organizational editing before formatting. Please note sections A-D below for more information on proofreading, spelling and grammar.

$$\begin{cases} m(W) = \frac{1}{1-k}\sum_{X_i \cap T_j \cap C_l = W} m_1(X_i)\cdot m_2(T_j)\cdot m_3(C_l) \\ \quad k = \sum_{X_i \cap T_j \cap C_l = \varphi} m_1(X_i)\cdot m_2(T_j)\cdot m_3(C_l) \end{cases} \tag{1}$$

Among them, W represents the window, and m(W) represents the possibility of choosing a certain window for postponement under various possible situations of X, T, and C. The target of the interval style narrow-window mission is denoted as W, the window on the first day is denoted as W1, the window on the second day is denoted as W2, and there are M windows every day, with an interval of △t between each window.

X represents each system participating in the filling stage. In the cryogenic rocket filling and launching process, there are mainly multiple systems such as filling, control, measurement, and power participating in the test, which are respectively denoted as systems X1~Xn.

T represents the time period: before the propellant L2 begins to enter the rocket, after the L2 enters the rocket and before the L3 begins to enter the rocket, after the L3 enters the rocket and before the connector detaches, and after the connector detaches, which are respectively denoted as T1~Tj.

C represents the fault type: when C is 1, the entire system needs to suspend the filling and launching program, and the fault system performs troubleshooting while the other systems maintain their states; when C is 2, only the fault system needs to suspend the program for troubleshooting, and the other systems continue to operate normally; when C is 3, the fault system performs fault handling within a specific time, and the entire mission process continues as normal. k is the conflict coefficient, which is used to eliminate impossible fault situations that conflict with each other.

Taking a certain type of cryogenic rocket as an example, assume that 4 stages and 7 systems participate. After entering the fueling and launch sequence, based on the constraints of the launch window and rocket-related limitations, if an anomaly occurs before liftoff, there are three targeted delay windows available for adjustment: delaying to a subsequent window on the same day, delaying to the next day's window, or delaying to a window after the next day.

1） T1, before L2 enters the rocket. Before L2 enters the rocket, the flexibility of fault handling and postponed launch is the highest. According to the specific fault situation and the required handling time, it can be decided to postpone to subsequent windows on the same day, the window on the next day, or windows after the next day. If it is necessary to postpone to the next day, the L1 above the filling valve needs to be drained back, and the low-temperature filling system maintains its state.

2）T2, after L2 enters the rocket and before L3 enters the rocket. After L2 enters the rocket and before L3 enters the rocket, due to the inability of the onboard products to guarantee working performance under long-time low-temperature conditions, it is impossible to postpone to windows after the next day without reheating and retesting. Without draining back to L2 for warming up, it can only be decided to postpone to subsequent windows on the same day or the window on the next day according to the specific fault handling time; when the L2 is drained back for reheating, it can adapt to windows after the next day. If the L3 pre-cooling work has started, the L3 pre-cooling filling needs to be suspended, and the L3 is kept in a parked state with the storage tank reheating. If it is necessary to postpone to the window on the next day, the L1 above the filling valve needs to be drained back.

3）T3, after L3 enters the rocket and before the connector detaches. If L3 has entered the rocket, without draining back the propellant, it can only be decided to postpone to subsequent windows on the same day or the window on the next day according to the fault handling time. At this time, if the large-flow L3 filling is not completed, continue filling until the final level and then transfer to the parked state, and the L2 remains in the state without refilling. If it is necessary to postpone to the window on the next day, the L1 above the filling valve needs to be drained back.

4）T4, after the connector detaches. After the L2 filling and draining connector detaches, due to the limitation of the temperature rise of the key components of the cryogenic engine, the maximum allowable postponement time is in the order of minutes, which is less than the general window interval, and it will not have the ability to postpone to the window on the same day; due to the limitation of the temperature and quality of the cryogenic propellant, it generally does not have the ability to postpone to windows on the next day and the third day and subsequent short-term windows, and the launch will be aborted and the propellant will be drained back.

4. Postponed Launch Handling Strategies

Based on the postponed launch principles in different time periods, a decision tree is drawn, and the handling strategies are formulated as Fig. 2.

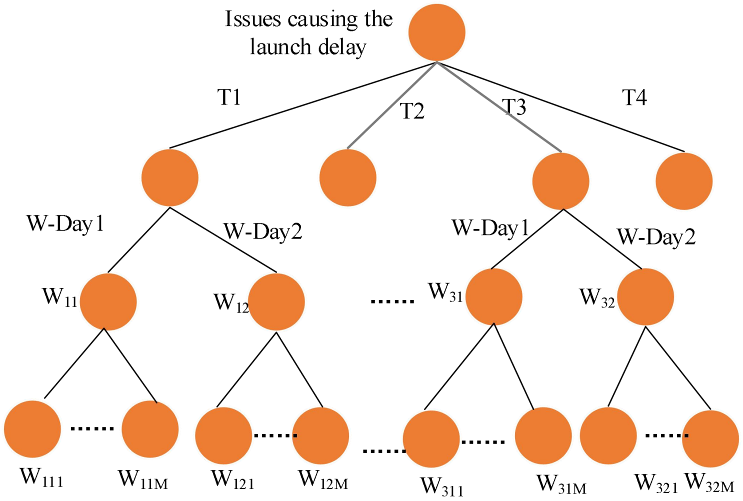

Fig. 2 Decision Tree for Postponing Launch

4.1 Before L2 Enters the Rocket (T1)

Before the L2 enters the rocket, according to the maximum envelope system, the L1 filling has been completed, and the LN2 filling and the L2 ground pipeline pre-cooling are continuously carried out. According to the fault situation, it can be decided to postpone to subsequent windows on the same day, the window on the next day, or subsequent launch windows to reorganize the filling and launching. The handling strategies for different postponed launch situations are as follows.

1）Postponing to subsequent windows on the same day (W11m). Based on the assessment, if the fault can be resolved within a short period of time, or if the fault handling has no impact on the external system and the faulty system can catch up with the process progress later, then the decision is to aim at the m-th window on the same day for launching. During the fault handling period, complete the state conversion work such as reloading the flight software for the new target window, and keep the other systems in their original states. After the fault is resolved, aim at the front edge of the new target window and continue the launching process.

2）Postponing to the window on the next day or later windows (W12m). If the analysis shows that the fault handling cannot catch up with the window on the same day, then the decision is to postpone the launch to the window on the next day or later windows. After the postponement, the L1 filling should be stopped, the L2 ground pipeline pre-cooling should be stopped, and the safety handling of the rocket and spacecraft combination should be completed. Drain back the L1 above the filling valve, conduct parking state monitoring, adjust the L1 temperature as needed, and prepare for the filling and launching work before re-entering the launch day process on the next day.

4.2 Before L3 Enters the Rocket (T2)

After the L2 enters the rocket and before the L3 enters the rocket, according to the maximum envelope task, the large-flow L2 filling has been completed, the nitrogen purging of the cabin section has started, the upper slewing platform has been opened, and the liquid hydrogen ground pipeline and hydrogen tank pre-cooling have started.

1）Postponing to subsequent windows on the same day (W21m). Based on the assessment, if the system can complete the fault handling within the m-th window on the same day, then the decision is to aim at this window for launching. During the fault handling period, complete the state conversion work such as reloading the flight software for the new target window, and keep the other systems in their original states. According to the needs of fault investigation, implement reverse processes such as slewing platform closing, lifting platform adjustment as needed. After the fault is resolved, aim at the front edge of the new target window and continue the launching process.

2）Postponing to the window on the next day (W22m). According to the fault situation, if it is analyzed and judged that the launch cannot be completed within the window on the same day, then the decision is to postpone the launch to the window on the next day and reorganize the launch. First, suspend the launching process, and all systems return to a safe state. Suspend the L3 filling and transfer to the parking state. Then, the entire system transfers to the parking state: adjust the slewing platform, lifting platform and other equipment to the guaranteed state, cut off the power supply of the onboard electrical system, keep the propulsion system maintaining engine purging, change the L2 filling system to the manual state, maintain the temperature and pressure, drain back the L1 and prepare for refilling. After the fault is resolved, make a decision to carry out the preparation work for re-entering the filling and launching process. Aim at the m-th window on the next day and re-enter the filling and launching process.

4.3 After L3 Enters the Rocket and Before the Connector Detaches (T3)

After the L3 enters the rocket and before the connector detaches, compared with the stage before the L3 begins to enter the rocket, the main progress in this stage is as follows: the large-flow L3 filling has been completed, all slewing platforms have been opened, the spacecraft has been powered on, the cryogenic engine A has started vacuum pumping, the engine B has started pre-cooling, and the filling valve has been closed.

1）Postponing to the second window on the same day (W31m). In case of a sudden fault in this stage, after analysis and judgment, if the system can complete the fault handling within the m-th window on the same day, then the decision is to aim at the new window for launching. During the fault handling period, switch to manual ignition, stop the engine pre-cooling and maintain purging, complete the state conversion work such as loading the flight program for the new window, and keep the other systems in their original states. After the fault is resolved, aim at the front edge of the new window and continue the launching process, and restore to the state of pre-launch refueling.

2）Postponing to the window on the next day (W32m). According to the fault situation, if it is analyzed and judged that the launch cannot be completed within the window on the same day, then the decision is to postpone the launch to the window on the next day and reorganize the launch. First, suspend the process, and all systems return to a safe state. Switch to manual ignition and stop the cryogenic engine B pre-cooling. After completing the large-flow L3 filling, transfer to the parking state. The work of the other systems is the same as that in the T2 stage. After the fault is resolved, make a decision to carry out the preparation work for re-entering the filling and launching process. Aim at the m-th window on the next day and re-enter the filling and launching process according to the time nodes of walking the compression program before the large-flow L3 filling and walking the actual process after filling.

4.4 After the Connector Detaches (T4)

After the cryogenic propellant filling and draining connector detaches, due to the limitation of the temperature rise of the key components of the engine, it generally does not have the ability to postpone to the second window. Due to the limitation of the temperature and quality of the cryogenic propellant, it does not have the ability to postpone to the windows on the second and third days. Therefore, the mission must be scrubbed and the propellant purged.

4.5 Simulation and Verification

To quantitatively verify the effectiveness of the proposed strategy, this paper conducted verification through historical mission simulation and actual mission statistics. The strategy was simulated in several representative cryogenic rocket launch missions, and the improvement effects were significant, as presented in Table 2.

Table 2. Effectiveness Comparison before and after Strategy Implementation (Average)

Metric	Pre-Strategy	Post-Strategy	Improvement
Average postponement time	25.4h	10.3h	55.5%
Propellant loss per scrub	18.7%	7.5%	65.2%
Cross-window success rate	53.1%	83.2%	56.7%
System recovery efficiency	72.2%	88.6%	22.7%

5. Summary

By analyzing the characteristics of the windows of deep space exploration interval-style narrow-window missions and the difficulties in organizing and implementing postponed launches after cryogenic rocket filling, a delayed launch decision-making framework has been established. According to the characteristics of cryogenic rockets, four stages are distinguished: before the propellant L2 begins to enters the rocket, before the L3 enters the rocket, after the L3 enters the rocket and before the connector detaches, and after the connector detaches. Corresponding postponed launch handling strategies are formulated for different postponed launch windows, establishes a robust framework to support successful execution and successful completion of actual combat missions.

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