Planning and Design Method for Heavy Launch Vehicle Launch site for Manned Mars Exploration Mission

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Abstract: The manned Mars exploration mission is an important application for the future use of heavy launch vehicle. With larger scale and more system, its launch site planning design and construction are difficult. Launch vehicle overall design, launch site planning design and test launch mode are considered as a whole of feedback iteration. For the huge system engineering of manned Mars exploration, the design of the launch site is mainly affected by the mission scale, launch vehicle overall design and test launch mode. Analysis of factors such as mission scale and window cycle, more than two heavy launch vehicle launch pads are needed for the manned Mars exploration mission. Therefore, it is necessary to consider the multi-pad construction. According to the preliminary genera parameters of heavy launch vehicle and the climate characteristics of Wenchang launch site, analysis the test launch mode that suitable for China's heavy launch vehicle. And then, the horizontal planning and the vertical plannig method are suggested for heavy launch vehicle launch site. Thereby achieving technically feasible, safe reliable and cost controllable purposes. Provid ideas and methods for China's future large-scale space mission launch site planning.

1. Preface
As a significant tool for human beings to enter the space, the heavy launch vehicle shows a country’s highest level in space technology, which turns out to be an inevitable trend of the international aerospace development. With continuous efforts in space exploration, various nations have aimed at the deep space which is more distant, and the world’s strong countries in aerospace all have proposed a deep space exploration programme including mars exploration[1-2], carrying out the demonstration and development of the heavy launch vehicle in varying degree.

The fact that Mars has been a terrestrial planet[3] boasting humanity’s most deepest exploration by now makes manned Mars exploration one of the significant trend of the international aerospace future development, and there are demonstrations of the manned Mars exploration programme in varying degree from the United State, Russia, Europe and other countries and organizations[1,4,5]. The manned Mars exploration programme is on a large scale, such multiple systems with excellent task implementation capacity as corresponding spacecrafts(spaceship, payload), launch vehicle, launch site, measurement and control and their close coordination are required.

US and Russia both have performed the research and development of the heavy launch vehicle, with multiple heavy rocket launch pads built. While China started the demonstration work for the heavy rocket launch site construction late and there are few relevant research literatures. Several modes such as “three vertical”, “three horizontal, “two horizontal and two vertical” are compared in [6] taking into account the transportation of the heavy launch vehicle and the construction scale of launch site facilities,
and the “three vertical” mode can be given priority for China’s heavy launch vehicle considering technical inheritance. Based on the analysis in this paper, the test and launch mode is closely related to both the launch vehicle design and the launch site construction. During the comprehensive demonstration of system engineering, these three serve as a whole with continuous feedback and iteration.

Fig.1 Restrictive relation between the launch site construction, launch vehicle design and the test and launch mode

The scale of aerospace engineering missions determines such important parameters as the quality and the size of spacecrafts, becoming an input condition for the research and development of the launch vehicle. According to the system engineering method, the demonstration is aimed to achieve optimal balance under constraints of technical feasibility, cost economy and systematic reliability, thus the engineering model is simplified as follows.

Fig.2 Simplified engineering model

Based on the model and given the launch site construction planning, the basic input of the manned Mars exploration mission at the present stage is: (1) requirements for engineering objectives: launch times for the manned Mars exploration mission, window constraint, load weight etc. (2) heavy launch vehicle design: basic parameters and the technical state of the heavy launch vehicle, external interface, technical development trend etc. (3) requirements for the test and launch mode: technical states of the test, assembly and transport of the launch vehicle, basic conditions of test guarantee etc. At the present stage, project objectives and the initial technical state of the launch vehicle are taken as the basic input of the planning and demonstration of the launch site construction. Based on the basic conditions of the launch vehicle and launch site, the test and launch mode applicable to China’s heavy launch vehicle is analyzed. And then the horizontal and vertical construction planning of the launch site is proposed.

2. Basic input of the manned Mars exploration mission launch site construction at the present stage

2.1 Launch times and window constraint of the manned Mars exploration mission

By engineering calculation, the equivalent LEO load mass of the manned Mars exploration mission
scale is large; a 4-6 people Mars expedition mission for 2-3 years can be achieved when the equivalent load mass reaches thousands of tons evaluating by oxyhydrogen power drive\[7\] or reaches 650 tons evaluating by heat kernel power drive\[8\]. At present, there is no specific engineerable planning of manned landing to Mars and many programmes are still during theoretical demonstration, among which the V5.0 version of the landing scheme presented by NASA based on Ares 5 launch vehicle, the manned Mars exploration schemes based on China’s heavy launch vehicle proposed by He wei, Zhu xinbo and other people are specific in recent years. Their launch mission scale is as follows.

| Scheme                     | The amount of heavy launch vehicle mission | The amount of large-scale launch vehicle mission | The amount of heavy launch vehicle mission in the first stage | The amount of heavy launch vehicle mission in the second stage |
|----------------------------|-------------------------------------------|------------------------------------------------|-------------------------------------------------------------|---------------------------------------------------------------|
| NASA Ares 5 scheme         | 7                                         | 1                                              | 4                                                          | 3                                                            |
| He wei’s scheme            | 7                                         | 1                                              | 4                                                          | 3                                                            |
| Zhu xinbo’s scheme         | 10                                        | 2                                              | 4                                                          | 6                                                            |

All the three schemes adopt engineering design with a stage of two missions, which are to complete the launch mission within two cycles when there is the nearest relative location of the earth and Mars; there are 26 months between two stages, with about 14 days’ window cycle in each stage. All schemes require a mission to launch 3-6 heavy launch vehicles in succession within about 14 days. Given such factors as the occupation time of launch vehicles from the same launch pad, the recovery cycle after launch, at least two or more launch pads are taken turns to use to meet the requirements for the manned Mars exploration mission.

2.2 Relatively clear technical state of the heavy launch vehicle

It is proposed in [9] that “heavy launch vehicle refers to the ones and their derivable configurations with over 2000 tons of takeoff weight and LEO lifting capacity of 100 dwt load.” The launch vehicle types that have been or are under development include N-1\[10\], Energiya\[10-11\], Saturn V\[10-11\], Ares V\[11\], SLS\[11-12\] and BFR etc. of Russia and USA. China’s heavy launch vehicles still remain in the stage of demonstration, many parameters are not determined yet. According to the comparison and analysis of heavy launch vehicles, combined with the analysis and conclusion in [1], the basic technical states of China’s heavy launch vehicles can be preliminarily estimated, which are the input of the launch site construction: (1) the diameter of the rocket body reaches 10m level; (2) the length of the rocket body reaches 100m level; (3) the takeoff mass reaches over 4000 tons, with over 400 dwt rocket body and over 100 dwt single module; (4) the rocket body structure is a fully hydraulic one with 4 boosters bound.

3. The test and launch mode of the heavy launch vehicle

The test and launch mode of the heavy launch vehicle is limited by the basic technical state of the vehicle and the basic construction conditions of the launch site.

3.1 Analysis of the test and launch mode based on the basic technical state of the launch vehicle

The main technical test and launch states of the launch vehicle in the launch site include 5 key states such as transportation, test, assembly, transfer and launch. Due to the fact that most launch vehicles are transferred to the launch site in horizontal state and blasted off in vertical state at present, 3 key technical states including test, assembly and transfer are mainly analyzed in the paper in view of the operational difficulty of the test and launch, security and reliability, environment protection and adaptation, the scale of facilities and equipments, and complexity.

(1) Selection of the test state
The test operation and the guarantee of operational feasibility in horizontal state become more
difficult as the rocket diameter increases. Compared with the test operations of China’s Long March 3A Series Launch Vehicle and Long March 5 Launch Vehicle, US Falcon 9 and the former Soviet Union’s Energiya, it can be found that large-scale gantry ladder and lift truck need to be equipped in horizontal test and special-shaped technological equipments and working platforms are also needed when the rocket diameter gradually increases from 3m to 6.8m. Due to the large horizontal span of the rocket body in horizontal state, multiple special-shaped working platforms are likely to be arranged at the same horizontal high to ensure operational feasibility of different parts of the rocket body. The diameter of China’s heavy vehicle reaches 10m level; the horizontal test operation guarantee is more difficult. Considering the horizontal test of the fully hydraulic 4-direction strap-on booster structure requires the arrangement of multiple platforms, operation accessibility guarantee of the core and the top and bottom of the booster is hard to achieve, operational difficulty of entering the cabin in horizontal state is large, and the arrangement of the work platform in the cabin in horizontal state is difficult, therefore the operation of replacing large equipments, pipelines and valves under emergency conditions is very complicated.

Fig.3 Sketch of the horizontal operating platform of a heavy launch vehicle with 10m diameter

Vertical state test requires the construction of a high and large vertical assembly and test plant which is equipped with responding work platforms; operations between the platforms are ensured through a working ladder, which is arranged when there are operations in the cabin. The test around the rocket body in vertical state is ensured by the platform, the inner wall of the rocket body can arrange standing points, with accessibility easy to be guaranteed. Specific examples refer to China’s Long March 5 launch vehicle and US Saturn 5 launch vehicle.

Analyzing the above factors, China’s heavy launch vehicle is supposed to adopt the vertical test state.

(2) Assembly state

Horizontal assembly is appropriate for the series active launch vehicle or “line-shaped” parallel strap-on launch vehicle, which avoids the construction of large-span plant and reduces the requirement for clearance. Falcon Heavy launch vehicle and Energiya are both in horizontal assembly. But the former uses the general core as the binding structure and three modules are arranged in parallel in the same way, with little assembly difficulty and small-scale workshop; the latter is equipped boosters and space shuttles around the rocket body, which has a assembly plant of 60m height and 120m length. The assembly process of the rocket body is completed through special lifting equipments and special-shaped technological equipments, with difficulty in horizontal assembly, with complicated mechanism and large scale and investment in the construction of the plant which are as much as that of the vertical assembly plant equivalent rockets. The scale of the core of China’s heavy launch vehicle and its boost modules are larger than that of Energiya. If the horizontal assembly mode is adopted, then the requirements for the size and carrying capacity of the special lifting equipments and special-shaped technological equipments in the assembly plant are more demanding, with much more difficulty and investment in design.
Vertical assembly requires the construction of a large-span vertical assembly plant, such as US vertical assembly area of Saturn 5 with buildings of 160m height. The stress load of the rocket body in vertical assembly is basically the same as that in the refueling launch stage and the flight process, which is easy to maintain the consistency of the stress state.

In conclusion, based on the guarantee difficulty, investment scale and technical inheritance, the vertical assembly stage is supposed to be adopted for the 4-direction strap-on heavy launch vehicle.

(3) Transfer state

The launch vehicle transfer is classified into two methods as overall transfer and segmented transfer. If the “one horizontal and two vertical” test and launch model is adopted, then the vehicle is in segmented transfer before assembly. Horizontal transfer vehicles are generally adopted in segmented transfer, the guarantee of segmented transfer is not difficult. If the “three vertical” or “three horizontal” test and launch mode is adopted, then overall transfer is needed for the launch vehicle, which includes two transfer methods of horizontal and vertical transfer.

Analyzing from technical inheritance and the complexity of transfer mechanism, China’s launch vehicles on active duty such as Long March 6, Long March 11 and Fast Boat 1 etc., which adopt the horizontal overall transfer method, are all small-sized liquid or solid launch vehicles, with relatively small diameter, length and weight of the rocket, less than 100 tons of the whole rocket. Foreign launch vehicles in horizontal transfer include Russian Soyuz, Proton, Energiya and US Falcon 9 series launch vehicle etc., among which Energiya boasts its large scale, and Energiya-Buran weighs 190 tons approximately, its horizontal transfer equipments weighting 2756 tons, the design of its supporting arms complicated. According to the fact that the dead weight of China’s heavy launch vehicle exceeds 400 tons, it is estimated that such technology of horizontal transfer on the same mass scale is without precedent in the world. In addition, there is few technical experience in horizontal transfer in China, leading to difficulty in overcoming this issue.

The vertical overall transfer method is adopted in US Saturn V and the space shuttle, which is on a large transfer scale. The vertical transfer scale of China's Long March 5 on active duty exceeds 2000t, the development of vertical transfer platform for the heavy launch vehicle has good technical inheritance. Hence, the overall vertical transfer method is supposed to be adopted for China’s heavy launch vehicle in view of technical inheritance and feasibility.

3.2 Analysis of the test and launch mode based on the basic construction conditions of the launch site

The diameter of the rocket body of China's heavy launch vehicle reached 10 m level; due to the inconvenience for air and land transport, Wenchang launch site along the coast is appropriate for launch. Under the circumstances of “high temperature, high humidity and high salt spray" [15], there exists the risk of typhoons at Wenchang launch site most of the time every year [16]. The forecast period lasts 5 to 7 days, disastrous weather such as rainstorm and thunderstorm comes frequently [17-18], and the shallow wind is strong in certain time at the coastal launch site. According to the characteristics of the launch site above, the key points of the test and launch mode design are analyzed as follows.

(1) Occupation time analysis of the launch site

Among multiple test and launch modes, the launch vehicle in “three horizontal” or “three
vertical” mode has relatively short occupation time of its launch pad, and meanwhile has capacity to transfer the overall rocket to the assembly and test plane in emergency. While the modes such as “three solid”, “one horizontal and two vertical” have long occupation time of the launch pad, hence the anti-typhoon capacity should be taken into consideration in the construction of guarantee conditions and mobile anti-typhoon large facilities must be built around the launch pad. Considering the scale of the heavy launch vehicle, a mobile test plant over 100 meters with capacity to resist typhoon is difficult to design and requires large investment.

Distance from the launch vehicle assembly and test plant to the launch pad

Due to the “three high” environmental characteristics of Wenchang launch site and the strong shallow wind in certain time, there are strict requirements for the environment guarantee of the launch vehicle transfer. Meanwhile, transfer time is also required to be reduced as much as possible, therefore distance from the launch vehicle assembly and test plant to the launch pad should be as close as possible. It takes 5-6 hours for the whole process of vertical transfer for 6km of US Saturn [14]. The situation of China's heavy launch vehicle transfer is similar to that of Saturn 5, which on one hand requires a possible reduced distance from the assembly and test plant to the launch pad and on the other hand technologically requires wind prevention, load reduction and environment control.

3.3 Summary of the test and launch mode of the heavy launch vehicle

Based on the analysis above, combined with the factors such as construction investment, technical feasibility and inheritance and environmental adaptation of the launch site, the heavy launch vehicle at Wenchang launch site is supposed to adopt a “three vertical” mode where distance between the assembly and test plant and the launch site is as close as possible.

4. The planning idea of the launch site construction based on scale control

In order to make good use of land resources, the construction scale of the launch site is reduced on the premise of technical feasibility, security and reliability, as a way to reduce and control the cost. Based on the defined basic overall parameters of the rocket and the test and launch mode, the planning of the horizontal construction of the launch site is performed based on the calculation of explosive equivalent; taking into account the scale control and the improvement of subsystem capacity, the layout planning of vertical space is carried out; according to the requirements of more than two launch pads for manned Mars exploration task, constraint conditions of the distance between launch pads are added, hence the construction planning of the launch sites for heavy launch vehicle which are qualified for China’s manned Mars exploration task is formed.

4.1 Horizontal planning and design

The horizontal planning of the launch site is based on the security design specifications of the launch site required by the project. Taking into account the extreme case of the launch vehicle explosion, the impact on the launch site includes explosive blast, heat radiation of the fireball, noise, fragment shattering etc.; by engineering calculation, explosive blast overpressure value is a main factor for the distance calculation.

(1) Security distance between the launch pad and the launch vehicle assembly and test plant

Security distance between the launch pad and the launch vehicle assembly and test plant can be classified into two types as follows under different engineering safety design specifications.

One is the remote setting mode adopted by US Cape Canaveral 39 launch site where the Saturn 5 mission is carried out and by French Ariane III launch site and China’s Wenchang launch site. When the launch rocket is implementing refueling launch, the assembly and test plant can perform test in parallel, which is conducive and significant to the large-scale aerospace engineering. In fact, in order to ensure the smooth execution of the mission of landing to the moon, when 3-4 rockets are tested and launched in parallel at Cape Canaveral 39 launch site and 1 rocket is performing refueling launch at launch pad, the test work for 2-3 rockets is carried out in the assembly test plant simultaneously[14].

The other type is the close setting mode adopted by US Cape Canaveral 41 launch site, Japan’s
Yoshinobu launch site, and Cape Canaveral 39A launch site where Falcon heavy launch vehicle performs its test and launch mission. It is conducive to the increase of test and launch efficiency; however, when the rocket is exploded, the assembly and test plant and its facilities and equipments are likely to be destroyed. Therefore, it takes high risk of products damage when consecutive launch missions are implemented.

On the premise of assured safety design, distance between the rocket assembly and test plant and the launch pad should be as close as possible, so as to enhance test and launch efficiency and reduce the cost\(^{[19]}\). By estimate, the explosive equivalent of the heavy launch vehicle with 4000t of takeoff mass is temporarily calculated 1200t(TNT). \(^{[20]}\) proposes when the liquid rocket is exploded on the ground, it can be estimated as 1.8-2 times of air explosion equivalent according to different reflection of the ground shock wave, therefore the safety requirement for ground explosion is higher. Take 1.8 times of air explosion equivalent and adopt Sadaovsk formula:

\[
\Delta p = 0.1 \frac{\sqrt[3]{W}}{R} + 0.391 \left( \frac{\sqrt[3]{W}}{R} \right)^2 + 1.236 \left( \frac{\sqrt[3]{W}}{R} \right)^3
\]

With satisfied condition as follows

\[
\frac{h}{\sqrt{W}} < 0.35, \quad 1 \leq \frac{R}{\sqrt{W}} \leq 10 \sim 15, \quad W > 100kg
\]

Where, \(\Delta p\) is overpressure of the shock wave peak value, MPa; \(W\) is explosive equivalent, kg; \(R\) is the radius from the shock wave peak to explosion center, m; \(h\) is the height of the explosive point. It can be figured out that, when the explosive equivalent \(W\) equals to 1200t, the overpressure of the shock wave value 1km away is estimated 0.016Mpa, and the overpressure of the shock wave value 3km away is estimated 0.004Mpa. If the facilities can sustain overpressure of 0.004 Mpa, then the construction needs to be carried out 3km away from the launch pad, if the bearable overpressure expands to 0.016MPa, then the distance from the launch pad can be reduced to 1km.

(2) Safety distance between the launch pad and the propellant reservoir area

The sympathetic detonation effect of the launch vehicle full of propellants at the launch pad and that of the liquid propellant reservoir area are mutual, i.e., the mutual impact of the rocket explosion and the explosion in reservoir area should be taken into consideration. In engineering, such settings as protecting wall, flameproof dam can be adopted to enhance the prevention of sympathetic detonation. Due to the limitation in island scale, the hydrogen reservoir area of Japan’s Yoshinobu launch site was located not far from the rocket transfer orbit and the flameproof dam is equipped for security. Its design idea can be used for reference.

(3) safety distance between launch pads

To meet the engineering requirements for manned Mars exploration mission, at least more than two launch pads for heavy launch vehicle are needed to take turn to implement the task. Therefore, multiple launch pads’ spacing should be considered in the payout of the launch site. In view of not erecting rockets simultaneously, the impact of the rocket with one launch pad when it is performing refueling
launch on the structure of another launch pad should be evaluated. Calculating in the case of the overpressure shock wave which cause light damage and the slight impact of the few-layer brick structure and steel frame structure, the overpressure should be less than 0.015Mpa.

If “one horizontal and two vertical” and other test and launch mode which have long occupation time of the launch pad are adopted, then during the implementation of such large-scale engineering as manned Mars exploration, the case of two rockets erecting simultaneously is likely to happen, hence there is supposed to be sufficient allowance between two launch pads and the impact of the rocket at one launch pad when it is performing refueling launch on the erected rocket at another launch pad should be evaluated.

4.2 Vertical planning

The vertical layout of the launch site has a great impact on engineering construction investment, in particular that on the orbital “three vertical” test and launch mode. The impact of road grade on the altitude of the launch area and the impact of jet flame diversion in depth on the comprehensive payout of the launch site are the key points of vertical planning.

The impact of road grade on the altitude of the launch area

Products, special fuel and special gas are transferred in the launch site, different transport process all have specification requirements for road grade. In particular the vertical transfer of the launch vehicle, the transfer orbit has demanding requirements for road grade. The horizontal height rise of the transfer orbit is limited, in this mode the 0-0 plane of the launch vehicle assembly and test plant in the launch site is basically as equal-height as the 0-0 plane of the launch site flat. In view of the requirements of other road grade, the general height difference of the launch site should be controlled within a small range.

The impact of jet flame diversion in depth on the comprehensive payout of the launch site

The height of the launch site flat 0-0 plane, the depth of the diversion trench and the supporting height of the launch platform should meet the requirements for flame exhaust and diversion. The jet flame diversion in depth of the heavy launch vehicle is large. Considering the coastal Wenchang launch site which leads to more difficulty in deep excavation of the diversion trench, effective measures should be taken to increase the effective flame exhaust depth. A mobile launch platform for vertical transfer can provide larger height difference in vertical height compared with other platforms; lifting the construction altitude of the launch site 0-0 plane, which is to construct one or half floor of the launch site flat on the ground, will be conducive to the increase of diversion in depth and reduce the excavation depth of diversion trench and the construction difficulty; meanwhile, such facilities as short-distance high-pressure gas and power supply can be arranged in the launch site flat 0-0 plane, so as to reduce the construction scale of the launch area.

5. Conclusions

The scale of the manned Mars exploration mission and the specific main technical states of China’s heavy launch vehicle at the present stage are taken as basic input, selection of the test and launch mode of the heavy launch vehicle is discussed in detail, and a scheme for the launch site based on scale control
is proposed in the paper. The conclusions are as follows:

(1) For the manned Mars exploration mission, two or more than two launch pads are necessary.

(2) Take into account the requirements for the mission parallel test and rotating launch at two or more than two launch pads: the “one horizontal and two vertical” and other test and launch mode which have long occupation time of the launch pad need to consider the requirements for erecting rockets simultaneously, the parallel test for the technical area and the anti-typhoon capability construction of the launch area, with low technical feasibility and high investment; the test and launch mode which has short occupation time of the launch pad is supposed to be adopted, such as the “three vertical” test and launch mode.

(3) On the premise of meeting construction safety standards, distance between the launch vehicle assembly and test plant and the launch pad should be reduced as short as possible, which is conducive to the transfer environment protection, the improvement of test and launch efficiency and the reduction in the overall construction cost.

(4) By adopting the vertical planning method of lifting the launch site flat and the guarantee way of equipping the first floor underground with facilities, and shortening the distance between the low-temperature reservoir area and the launch pad by adding isolated blast establishment, the purpose of reducing the launch area construction scale can be achieved for each type of test and launch modes.

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