# Rocketplane® XP – Conceptual Design Study

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**The Rocketplane XP is a suborbital spaceplane due to enter service in late 2007 that will carry paying participants and microgravity scientific payloads to an altitude greater than 330,000 ft. XP's tight development and production schedule demanded a very short and concise conceptual design phase with a high degree of confidence. Processes were developed to perform rapid turn around trades in performance, weight allocation, systems engineering, structural concepts, jet and rocket propulsion, volumetric efficiency, and thermal protection. The results from these disciplines were integrated in order to arrive at candidate configurations; and finally after iteration, at a baseline which meets all the requirements. XP's unique conceptual design process allowed quick progression into preliminary and detailed design phases and formed a foundation of knowledge and methodology that can be applied to future concepts.**

## I. Introduction

Since the mid 1990's, a resurgence of interest has been building for sub-orbital space flight. This interest was encouraged by the X-Prize® and the eventual success of SpaceShipOne™. In 2002, the Futron Corporation conducted a survey of the suborbital space tourism market[1]. The survey was restricted to people in the United States with a household income of at least US$250,000 annually, or a minimum net worth of US$1 million. The survey was robust in that it provided a balanced portrayal of both the high points and the difficulties of a realistic suborbital trip.

Figure 1 shows the percentage of respondents who are willing to pay for realistic suborbital space travel at a range of price points. This data is for a 15 minute trip on a suborbital trajectory preceded by a week of training. Note that 16% of the respondents are willing to pay in excess of the maximum price point of US$250 thousand and just over 50% are at least willing to fly into space at some price point.

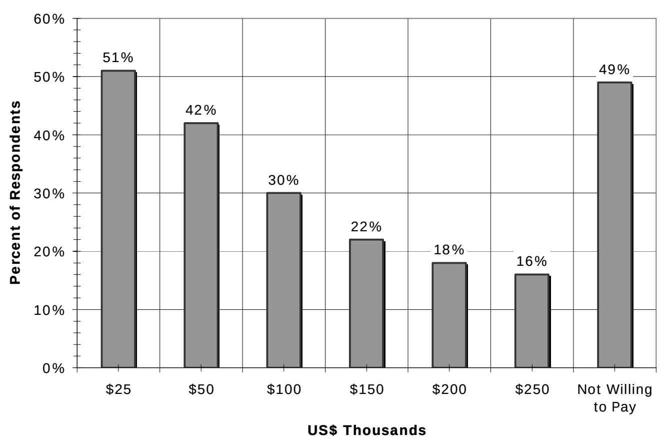


**Figure 1. Survey respondents willing to pay for suborbital travel[1].**

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Futron also developed a forecast of the growth of suborbital space tourism flights over the next 15 years, see Fig. 2. For this analysis, a base service price of US$100,000 is assumed for the 1st five years followed by a linear reduction in ticket price to US$50,000 by 2021. It is clear from this data that there is a significant market just for suborbital tourism flights. Note, this forecast does not account for other niche suborbital markets that show significant promise such as surveillance, point-to-point transport, or satellite launch.

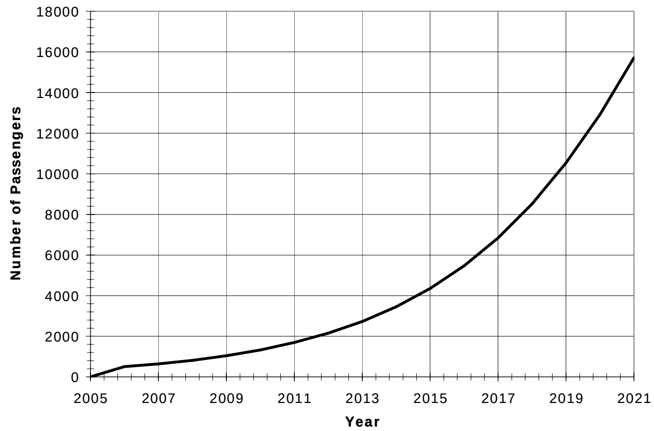


**Figure 2. Suborbital market forecast[1].**

**XP Design Requirements and Objectives:**

The mission requirements defined by Rocketplane, based on the market survey and business case analysis results, are simple and yet technically demanding:

- Safely fly to a minimum altitude of 100 km (328,100 ft or 62.1 miles)
- Carry 4 adults (1 pilot and up to 3 passengers)
    - Each passenger weighing a maximum of 250 lbs
    - The pilot weighing a maximum of 200 lbs
- Capable of a twenty-four hour turn-around time between flights
- Proprietary limits on per-flight recurring costs
    - Translates into reusability and maintainability requirements
- No unusual equipment for passengers and crew comfort and safety such as pressure or anti-g suits.
- A sensation of weightlessness for at least 3 minutes.
- Passengers shall be able to see out of the vehicle directly and clearly.
- Takeoff and land at the same spaceport

In addition to these requirements, the XP design team has placed the following design objectives:

- Two consecutive flights to mission altitude per week
- Conventional aircraft horizontal takeoff and landing architecture
- Utilize the fuselage structural concept of the LearJet 25 series aircraft
- Operate out of the Oklahoma Spaceport (Clinton-Sherman airfield near Burns Flat, OK)
- Utilize a LOX/RP-1 (kerosene) rocket engine
- Design for safe unpowered return to base

The nominal mission for the XP consists of 11 segments, each of which has design requirements associated with it. These segments are shown in Fig. 3.

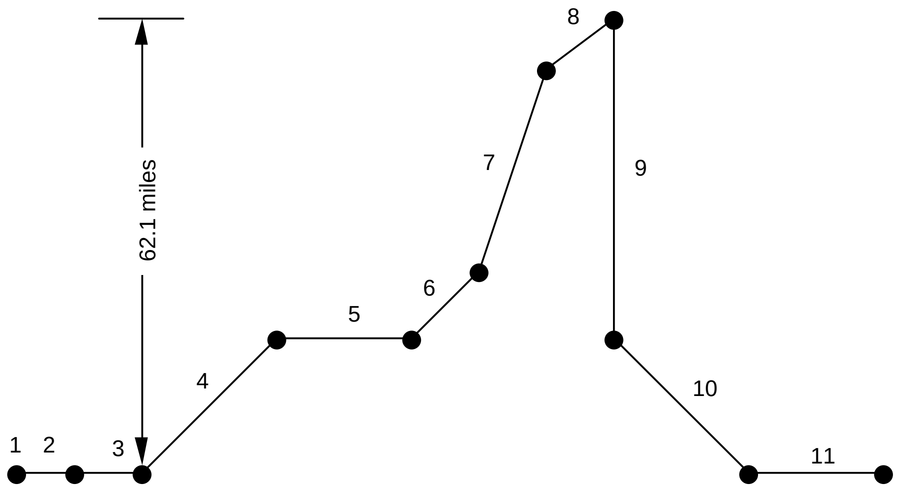


**Figure 3. XP mission segments.**

Each of these segments is defined as follows:

1. Engine Start and Warm-Up
2. Taxi
3. Takeoff
4. Climb and accelerate to subsonic cruise altitude
5. Subsonic cruise
6. Rocket propelled 3 g pull-up to ascent flight path angle
7. Rocket propelled ascent to rocket engine cutoff
8. Ballistic coast to mission altitude
9. Unpowered reentry and descent
10. Powered descent after turbojet restart
11. Landing, taxi, and shutdown

This set of mission segments results in a profile that meets the XP program requirement of a target altitude of 100 km for a horizontal takeoff/landing type aircraft. This profile assumes a duel-mode propulsion system with turbojets used for low altitude, low speed flight, and at least one rocket engine used for the high altitude, high speed portion of the mission. Note that a large portion of the XP's mission will be supersonic as is demanded by the very high mission altitude.

## II. Conceptual Design Process and Analysis

As a new company, Rocketplane faced challenges in developing processes, procedures, and documentation that are already well established at other aerospace companies. This was the case for a conceptual design process, where Rocketplane was on ground zero, with no vehicle having ever been built and no "lessons learned". This section describes the conceptual design process that was developed and how it was used on the XP program.

### A. Initial Rocketplane® XP Configuration

Rocketplane Limited, Inc. owns the intellectual property of Pioneer Rocketplane, which is not currently an operating company. Pioneer had conducted a conceptual design on a two-seat, F-111-sized aircraft powered by turbofan engines and a kerosene/oxygen-burning RD-120 rocket engine that, using an expendable upperstage, would boost a 3000-lb satellite to a circular low Earth orbit[2]. This *Pathfinder* concept (see Fig. 4) was based on utilizing aerial refueling of both the rocket propellant and oxidizer to allow for very low takeoff weights. This concept is considered too complex and costly for the simpler XP mission profile, but much of the technical research and development work done for the *Pathfinder* has been useful for the XP development program.

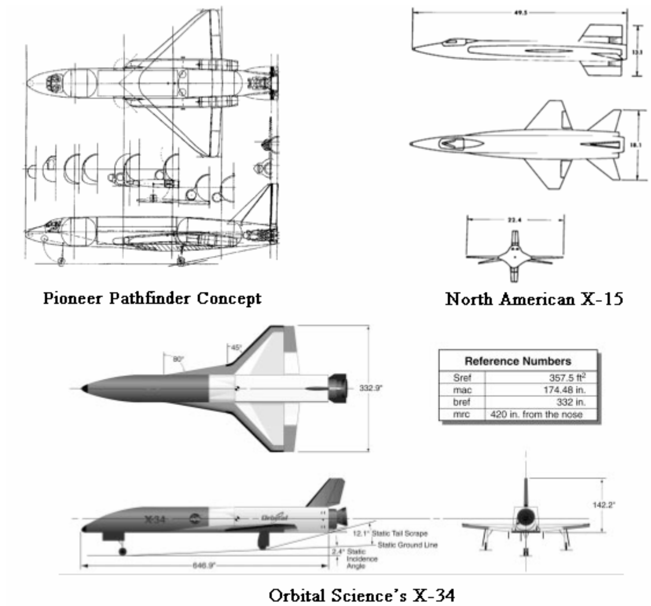


**Figure 4. Comparison of similar configurations[2-4].**

Other aircraft studied by the Rocketplane design team were Orbital Science's X-34 (Fig. 4), the Bell X-1 (original) and the Bell X-1 A, B; the North American X-15 (Fig. 4) and the Lockheed A-12 and SR-71. Rocketplane has made extensive use of the publicly available data and lessons learned on all of these successful vehicles.

After studying the reference aircraft, an initial conceptual configuration was chosen for the XP. The starting configuration (Fig. 5) was a conventional delta-wing configuration, much like the X-34, but utilizing a LearJet 24 fuselage with turbojet engines mounted on the aft fuselage. The modifications to the original LearJet airframe included the addition of a delta wing, removal of the horizontal tail, addition of rocket propellant tanks, rocket engine, and a thermal protection system. This was the starting point for the conceptual and preliminary design phases that followed.

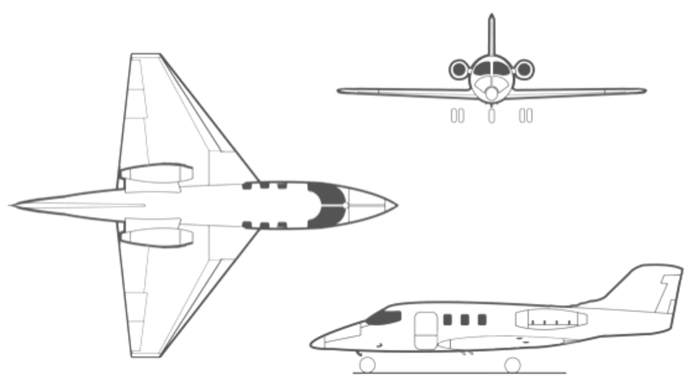

**Figure 5. Initial Rocketplane® XP configuration.**

In a 4-5 month effort, each portion of the vehicle was researched for basic properties, requirements, and possible commercial off-the-shelf (COTS) component options. Systems such as turbojet and rocket propulsion, electrical power, flight control actuation, aerodynamics, thermal protection system (TPS), reaction control system (RCS), and cryogen tanks were researched in this fashion to provide configuration options. Catalogs of the system properties were compiled to provide trends in weight, performance, cost, and reusability for use in sizing exercises. Additionally, basic research was conducted on the current and near-term future availability and maturity of potential technologies. This was particularly important in the search for electrical power, flight control actuation, and cryogenic tank technologies.

**The Matrix:**

As requirements for each discipline were developed, and the options in technology were collected, it was clear that some way to catalog and compare the potential configurations to help achieve a viable conceptual design was needed; hence, the birth of “The Matrix”. While The Matrix itself was little more than a Microsoft® Excel™ spreadsheet, the philosophy behind The Matrix provided Rocketplane’s conceptual design team the tool it needed to support an aggressive development schedule.

The underlying philosophy in the development of The Matrix was to assign weighting factors to each component and discipline which include but were not limited to: cost, potential schedule impact, Technology Readiness Level (TRL), reusability, life-expectancy, reliability, manufacturability, replacement costs, servicing costs, intra-flight inspection and routine maintenance, weight, and whether or not hazardous material handling was necessary. The Matrix became the focal point of a series of trade studies using combinations of discrete COTS components to determine the best possible configuration. Since it was desirable to use COTS components, it was easy to include such parameters as maintainability and servicing cost based on product information which is not typically available at a conceptual design level.

Traditionally, at a conceptual design level, the vehicle parameters are allowed to vary continuously in order to meet the requirements. This process results in a highly optimized design, however, this approach does not account for discrete steps found in COTS components.

The Matrix provided a means to integrate various discrete COTS components with “rubber” components into a series of feasible vehicle configurations at an earlier stage that would otherwise be possible. The series of configurations and their parameters were compiled into a proprietary score referred to as the “smileage factor”. This factor combined all of the individual component weighted decisions into an overall integrated system score. This allowed Rocketplane to make design decisions and reduce the number configurations examined using parameters such as maintainability, servicing, and reliability at a conceptual design level. At this point, experts were pulled in to make the final decisions based on their experience resulting in component and configuration selection decisions early in the design.

Sections presented below are provided as examples that go into further details on the processes followed for performing various disciplinary investigations that were included in The Matrix.

### C. Propulsion

The propulsion spreadsheet was used to create trend plots by varying several key characteristics of potential rocket propulsion systems. This workbook traded rocket chamber pressure, various means of providing the motive flow of rocket fuel, various propellant combinations, and traded the jet engine/rocket combination vs. rocket only configurations. This was done with a discrete database of existing rocket and jet engine characteristics in order to select off the shelf propulsion systems rather than sizing to a theoretical system that does not actually exist. The engine selection was discrete, but the propellant systems were continuously sized in a more traditional manner.

Contrary to conventional wisdom, for the XP mission profile, results of The Matrix showed conclusively the utility of the turbojet engines. This also revealed the benefits of higher chamber pressures when coupled with a turbopump fed system, or conversely the benefits of a lower chamber pressure when used with pressure fed systems.

### D. Aerodynamics

In the design cycle of an aerospace vehicle, it can be difficult to draw a hard line between the conceptual, preliminary and detailed design phases. The process followed for evaluating the aerodynamic characteristics of the XP candidate designs during various design stages in this section. The output of this process is fed back into The Matrix. Figure 6 shows the methodology used for XP, with steps starting at conceptual design through preliminary design and then into the detailed design phase. These are a list of aerodynamic codes and methods that were used:

i. S&C DATCOM[5,6]
ii. VLAERO+[7]
iii. PANAIR[8]
iv. MGAERO[9]
v. VECC[10] (S/HABP)

The following describes the steps shown in the methodology presented in Fig. 6:

1. Define (or modify) a configuration to be analyzed based on experience / engineering; this configuration definition should include the basic wing planform, airfoil selection, aero control concept, fuselage shape and volume, etc (see Fig. 5).

2. Determine the aerodynamic characteristics of the configuration arrived at in step 1 with a minimal amount of engineering effort. In case of XP the following three methods have been used:
    i. low fidelity aero codes (Vortex-lattice methods[7]),
    ii. theory / historical data (of vehicles with similar mission profiles), in case of XP, X-34 was a good match[11-13] and
    iii. semi-empirical methods (DATCOM[5,6], Roskam[14], etc.)
3. From the methods in step 2, a conceptual aerodynamic database is created (or modified).
4. The next step is to verify if the requirements are met. At a conceptual design level, this is best achieved using 3 DOF simulations for the rocket propelled portion of the mission using trajectory simulation tools like Optimal Trajectories by Implicit Simulation (OTIS)[15,16]. Airplane performance approximations are used where appropriate for the airplane portion of the mission profile and stability & control requirements are checked using standard first order approximations (Roskam[14]).
5. A check is performed to see if the top level requirements are met; if they are met, then proceed to step 6 otherwise go to step 1 and modify the configuration and repeat steps 2 through 5 until the requirements are met (inputs, if any, available from other disciplines are also considered at this stage and evaluated to make sure there is no conflicts).
6. At this stage preliminary design level aerodynamic analysis for some of the important flight conditions is performed. In case of XP, PANAIR, VECC and MGAERO codes were used at this evaluation. The research wind tunnel at OU was also utilized to check some key parameters.
7. A preliminary verification of the requirements from the more detailed aerodynamic data from step 6 is performed. If the requirements are met, proceed to step 8, otherwise, go to step 1 and modify the configuration and repeat steps 2 through 7 until the requirements are met (inputs, if any, available from other disciplines are also considered to make sure there is no conflict).
8. Detailed design level aerodynamic analysis is performed; two industry standard ways of doing this:
    i. higher order CFD and
    ii. wind tunnel tests

    In case of XP both these approaches have been followed with wind tunnel testing (low speed at Wichita State University's 12 ft subsonic tunnel and high speed testing at NASA-Marshall Space Flight Center's trisonic tunnel) focusing on gathering the clean configuration aerodynamics at a wide range of angles of attack, angles of sideslip and Mach numbers, as well as gathering a large volume of stability and control data. The higher order CFD was used primarily for determining the pressure distributions on the entire vehicle for providing inputs to the structural loads and aerothermal analysis teams.
9. With an updated aero database from step 8, 6 DOF trajectory simulations are developed. In the case of XP, a 6 DOF simulation was developed using MATLAB/SIMULINK. In addition to the nominal trajectory analysis a detailed dispersion analysis and stability analysis is also performed.
10. At this step verification is made to determine if the mission requirements are met. If the requirements are met, proceed to step 11, otherwise, go to step 1 and modify the configuration and repeat steps 2 through 10 until the requirements are met (inputs, if any, available from other disciplines are also considered to make sure there is no conflict).
11. At this step, a final converged aero design of the vehicle is reached, which means the vehicle Outer Mold Line (OML) is frozen and pending any internal system layout details, plans for the flight test article can be begun.

The steps 5, 7 and 10 show why the conceptual, preliminary and detail design stages cannot be discussed individually. For example, if at step 7, a change to the configuration is warranted, then the first step an aerodynamicist has to perform is to gather conceptual design level data for the change included into the design; and continue into the following phases of the design cycle. The flow chart presented in Figure 6 does not provide each and every detail of the process(s) followed, but it is aimed at providing the reader with a feel for the generic approach used.

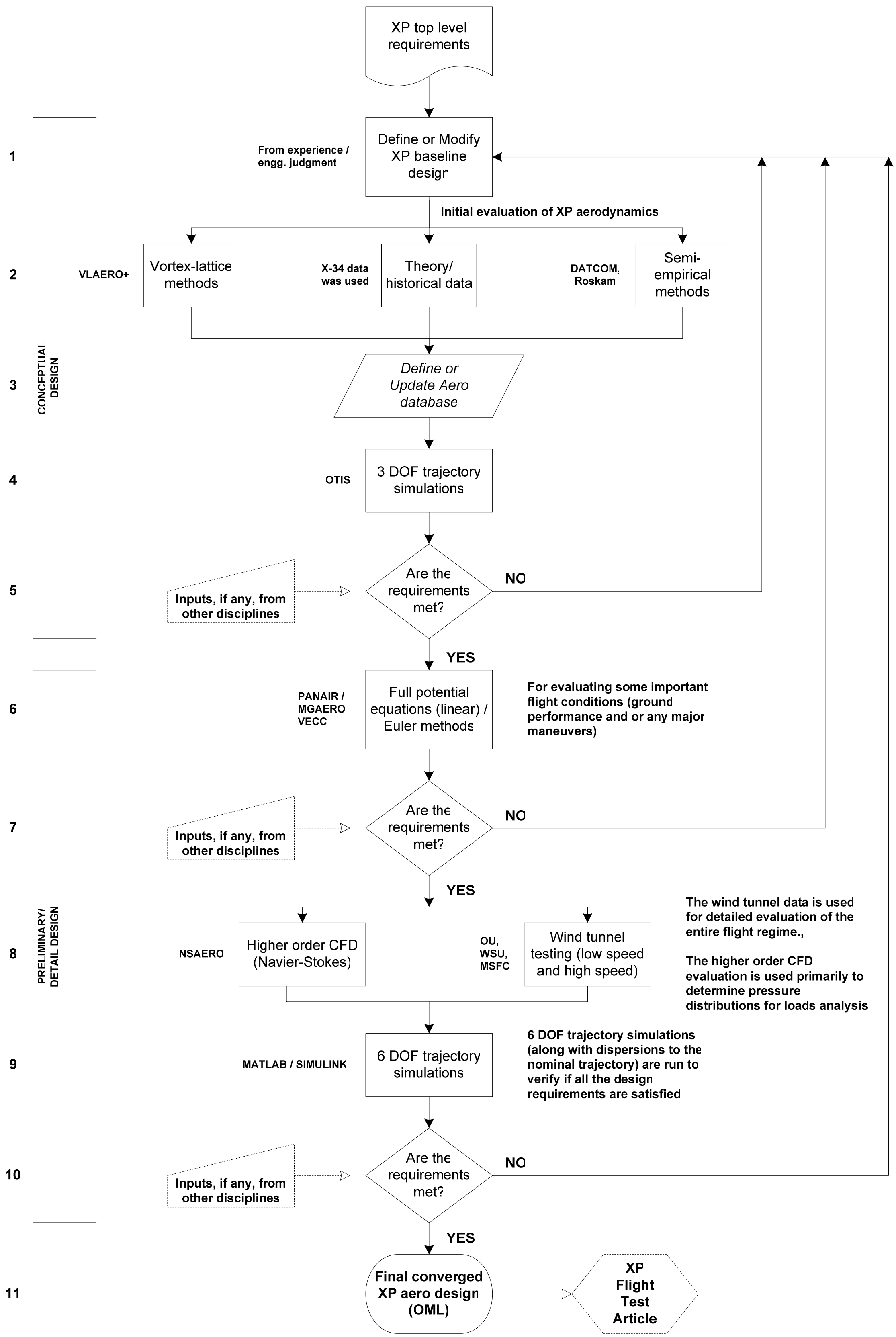


**Figure 6. Rocketplane® XP aerodynamic design process (pre-flight test).**

**E. Structures**

Structural design of the XP vehicle has evolved based upon various inputs. An iterative process was followed giving consideration to various factors such as loads, safety requirements, weight, performance, environmental factors, fabrication costs, material costs, delivery schedule, fatigue, and fracture properties. Primary sizing and evaluation requirements were mainly driven by the vehicle loading, requiring the development of basic aircraft loads as well as sub-orbital induced loads due to the unique operational requirements of the XP vehicle. The primary structure is based upon load paths developed to carry loads throughout the vehicle. A survey of similar performance vehicles (X-15, SR-71, F-106, etc.) allowed for initial design choices to be assessed and evaluated. Production capabilities were also considered at this time to determine feasible fabrication methods, however, alternate methods were considered with later trade studies and analysis.

To establish design goals as well as trade design goal options for increased performance or weight reduction a mutual agreement on structural parameters was established. Trajectory data and associated variables (max q, load factors, temperature, control surface inputs, pressure, integrated load, drag, etc.) were evaluated.

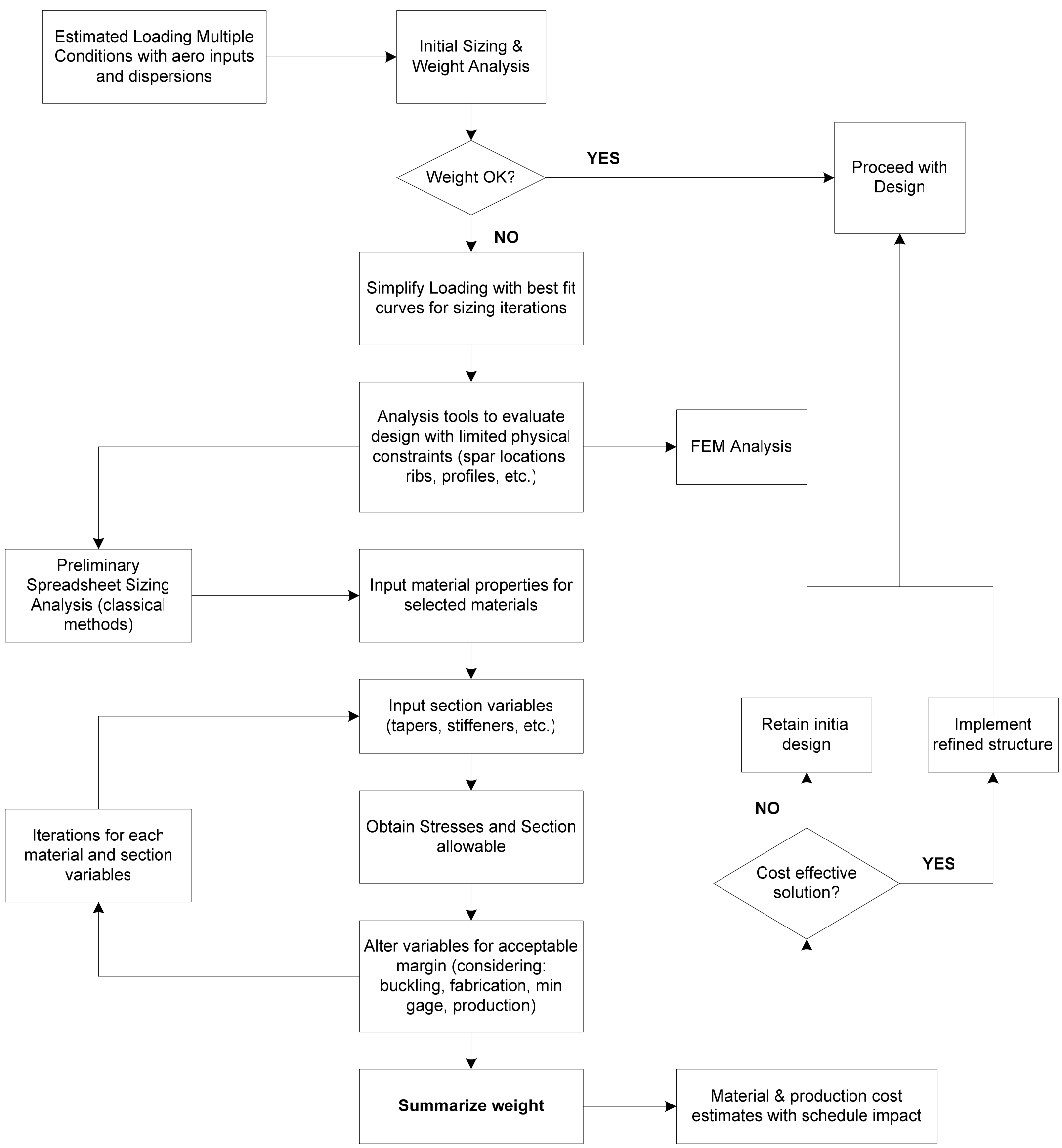


**Figure 7. Rocketplane® XP structural analysis fabrication and sizing methodology.**

Using the first pass load evaluation, preliminary structural sizing was accomplished with in-house tools, coarse grid FEM models, and classic analysis methods. The preliminary sizing received further scrutiny using options in thickness, method of fabrication, spacing and quantity of structural elements, material, and degree of complexity. The primary goal, as illustrated in Fig. 7, being an optimal weight solution that meets fabrication and cost objectives. Often times the optimal weight solution is not feasible for a prototype vehicle or within affordable manufacturing techniques in that case the results of the cost benefit analysis are retained for future use. Otherwise weight estimates are determined and provided as input into trajectory models for further refinements.

After the initial design layout is achieved, vibration responses, dynamic loading, flutter, and fatigue behaviors are estimated with finite element methods to determine if the design meets desired goals. Successful predictions allow the design to receive further evaluation and production input.

### F. Thermal Protection System

The methodology followed for the conceptual design of the XP thermal protection system involved four major steps as described in Fig. 8. First, the XP thermal environments (aerothermal and plume induced) were defined using the XP trajectory and rocket performance data. Aerothermal environments were calculated utilizing the Lanmin code (a Langley enhanced Miniver code)[17], and the Orbital Entry Aeroheating Evaluator[18], along with other supporting aerothermal techniques. Plume induced environments were defined using CEC/Trans 72, SPF2 and the MSFC Gaseous Radiation codes as well as various empirical data. Secondly, thermal analysis was performed using the thermal environments to define areas on the vehicle requiring thermal protection. The next major step in the process was to select a preliminary TPS material followed by a second round of thermal analysis with the TPS material to ensure that the structural temperature limit was not exceeded.

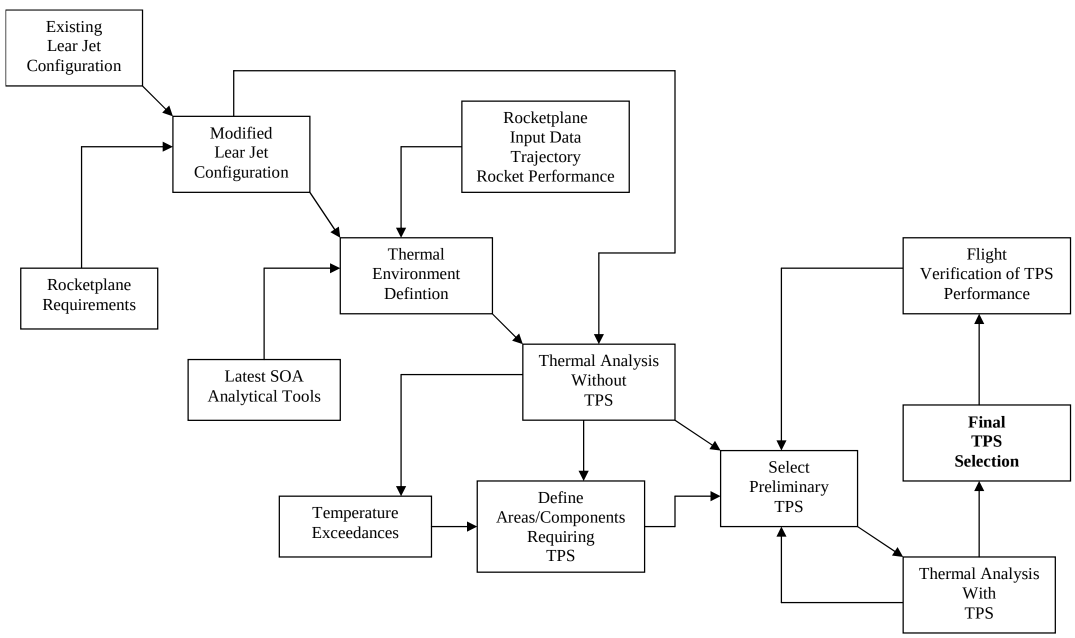


**Figure 8. Thermal protection system design methodology.**

Selection of the optimum TPS for the Rocketplane® XP vehicle was a complex and challenging task that required consideration of not only weight, but also operability, maintenance, durability, initial cost, life-cycle cost, and integration with the vehicle structure. A variety of reusable TPS concepts were analyzed using a 1-D thermal analysis model to address the requirements of the XP vehicle. The idealized TPS and structure combination considered in this study is shown in Fig. 9. This simplified arrangement was selected so that the performance of the various thermal protection systems could be directly compared. The TPS is directly attached to an underlying aluminum structure. A transient heat flux profile as obtained from the aerothermal analysis was applied to the outer surface of the TPS, and the inner surface of the structure was assumed to be adiabatic, or perfectly insulated. Transient temperature profiles at the surface as well as the interface between the TPS and structure were calculated.

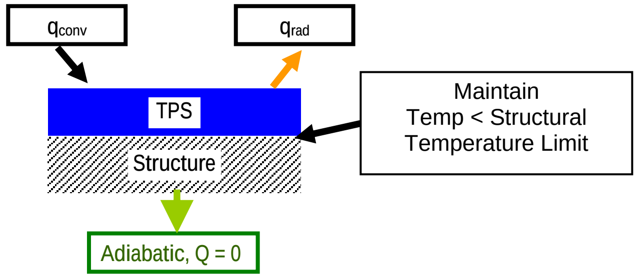


**Figure 9. Simplified thermal model.**

The TPS material used on the XP is a low density, low thermal conductivity, low thermal expansion and high emissivity nanoparticle ceramic coating capable of maintaining its characteristics from -250 to 3000 degF. The majority of the airframe will be protected with this coating while the high heating regions such as the nose cap and leading edges will be made of titanium with no additional thermal protection.

### G. Weights

Specific component weights were utilized in a discrete manner where they were available. Where component weights were not available, a series of weight worksheets were developed utilizing the empirical methods presented by Raymer[19] and Roskam[14]. These statistical methods were used to create USAF, Commercial Jet Transport, Military Cargo, and USN based estimates of the XP vehicle weights.

Each system or design element of XP was weighted towards one, or a combination of these statistical methods. By rationalizing and weighting the methods we were able to synthesize a spaceplane hybrid calculation as shown in Figure 10. For example, the rocket system can be treated as internal payload for the aircraft-like portions of the flight, giving XP an empty mass fraction and structural configuration much more inline with cargo aircraft than a fighter aircraft. However, the landing gear weight is probably more in line with a fighter model than a jet transport model.

The component weight outputs from the spaceplane hybrid weight calculator were used to size the overall vehicle weight. That weight was then used for wing sizing, propellant requirements, etc.

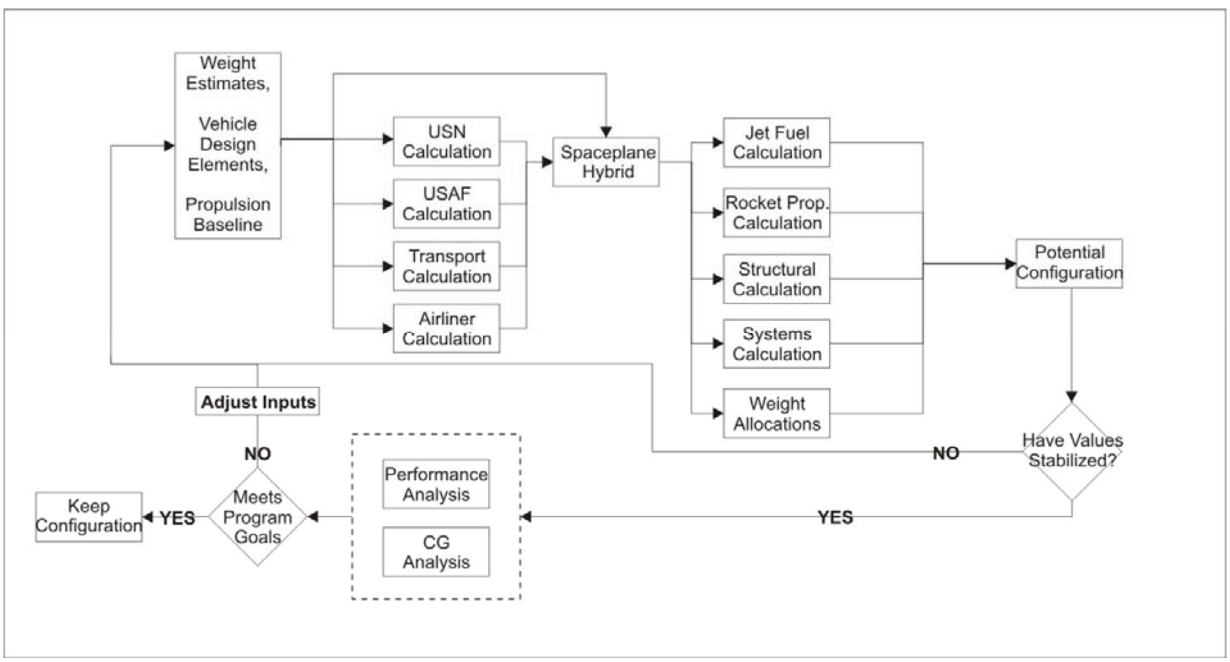


**Figure 10. Weights analysis methodology.**

The overall weight expectations following The Matrix relate well to those derived from the industry standard empirical relationships. As our subcontractors have worked into detailed design on the XP, we have found that with small adjustments to account for technological advances, our spaceplane hybrid empirical weight calculations match very well with subcontractor detailed weight reports, in some cases differing by a few percent.

## III. Resulting Baseline Concept

The design of the Rocketplane® XP configuration followed the processes and methodologies presented in the sections above. After iteration from the conceptual sketch shown in Fig. 5, the baseline design of the XP has matured, as shown in Fig. 11.

The current baseline of the Rocketplane® XP vehicle has an overall length of about 42 ft. The fuselage changed from a LearJet 24 to a LearJet 25 and was stretched to add additional rocket propellant and the vehicle height is about 12.5 ft. The approximate takeoff gross weight is 19500 lb. The wing span is 25.4 ft and the wing has a leading edge sweepback of 46 deg with a 70 deg leading edge strake and the outboard section of the wing has a dihedral of 4.5 deg. The leading edge strake, much like that found on the X-34 and Space Shuttle Orbiter, was added primarily to improve reentry stability characteristics. The wing consists of trailing edge, near full span, split elevons. These inboard and outboard elevons can be used to provide both pitch (symmetric deflection) and roll control (anti-symmetric deflection). The directional stability/control is provided by the all-moving butterfly or "V-tail". The V-tail was sized for takeoff rotation (not a concern for the most of the reference aircraft) and reentry directional stability & control. Other details of the configuration changed as trade-offs have been made regarding stall characteristics, stability and control characteristics, performance characteristics, manufacturability and cost.

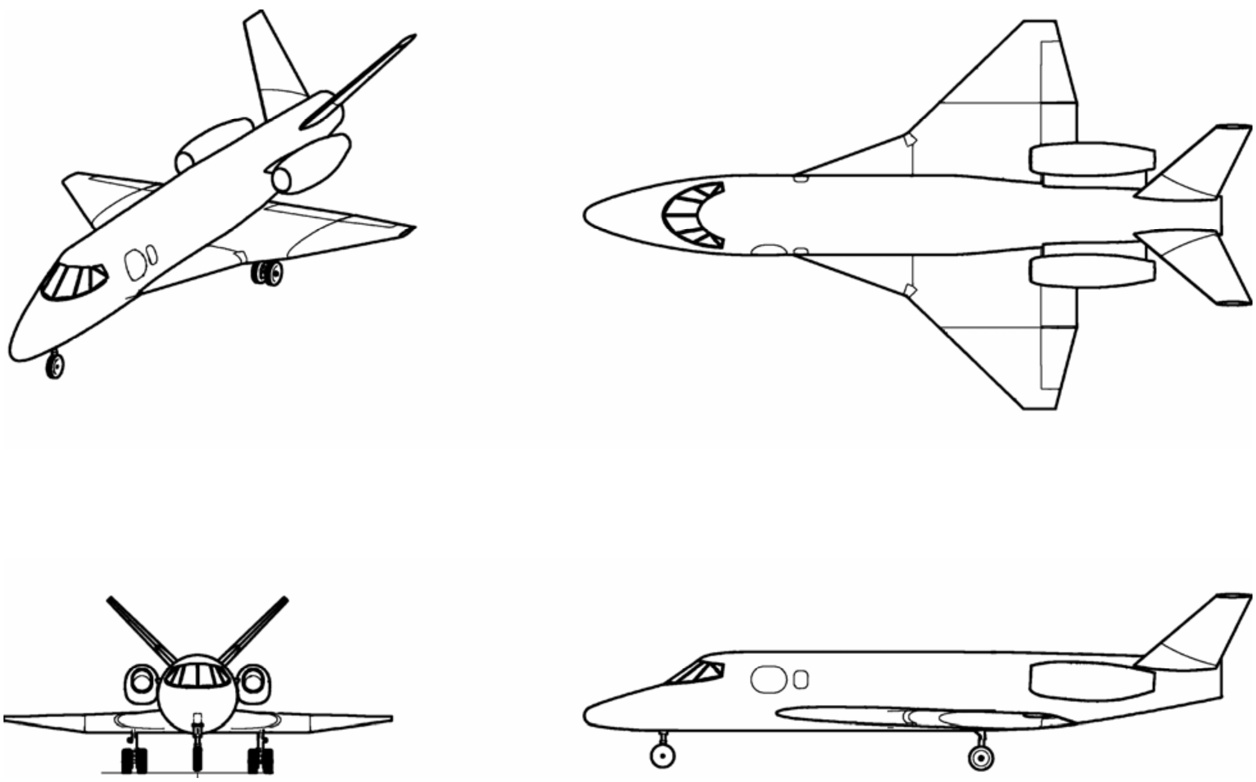

**Figure 11. Current Rocketplane® XP configuration.**

## IV. Conclusions

Rocketplane has developed a conceptual design process that integrates traditional disciplinary sizing techniques, with databases of discrete COTS system components, and parameters not traditionally used or considered during conceptual design. This process has been successfully used to rapidly develop a feasible configuration for the Rocketplane® XP.

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