The Design of a Suborbital Model Rocket Capable of Payload Delivery

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In this senior design project, a suborbital rocket is designed, built and tested within a budget of $1250. The main requirement is that the rocket must reach a minimum altitude of 100 m, complete two consecutive launches, carry two separate payloads during each launch and have a total mass of less than 1.36 kg. Components of the rocket, including the propulsion system and structure must be commercially available. The rocket must withstand the force of takeoff and descent to allow for quick reconstruction for a consecutive launch. The payload bay is designed to hold and deploy two different payloads, a Candrone and Re-entry Vehicle, at the required altitudes. Each payload has no more than 350 grams of mass and fits within the payload bay (114.3 mm diameter and bay height of 203.2 mm) in the rocket body. With the performance requirements and budget constraints, the proposed rocket design adheres to all relevant safety regulations and guidelines for model rockets. The completion of this project will demonstrate the feasibility of design and building of a model rocket with a limited budget.

I. Introduction

It is common for a rocket's mission to include payload deployment whether it is a satellite or weather device. These rockets are required to reach a Low Earth Orbit and successfully deploy their payloads without damaging them. While this rocket is not designed to reach such high altitudes, the purpose of this project is similar. There have been many payload carrying rockets such as the Pegasus Launcher [1]. This was a multistage payload release system that carried a satellite to a Low Earth Orbit before splitting its outer shell to release the payload. While there are many rockets studied like this, smaller-scale payload release rockets are less popular. In this project, a small-scale model rocket was designed and built to release a payload with reusability in mind. A unique payload deployment system was introduced and studied where the payload is released out of the bottom of the rocket rather than from the top of the rocket. Before manufacturing the rocket, a series of simulations were performed where the stability, structural loading, aerodynamic efficiency and performance testing were done. After manufacturing, testing was done to create a hold down sequence which would allow all engines to ignite before launch. The requirements set forth for this project are to reach an altitude of 100 m, record environmental conditions, video record payload release and can be reassembled within an hour for a consecutive flight. The legal requirements set forth will be discussed in the following section and the conceptual design.

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II. Conceptual Design

A. Legal specifications

There are a few noteworthy legal restrictions that are placed on this project as it must conform to Class 1 model rocket standards as stated by the FAA [2]. This limits the total mass of the rocket, including the payload, to 1500 g. The mass limit also takes into consideration the mass of the engines. While multi-engine designs, such as this one, are allowed, the total impulse of all engines combined must be less than 320 Ns, as well as the total mass of propellant being limited to 125 g. The material used for the body of the rocket is required to be paper/carboard or breakable plastic. Most importantly, no active guidance system may be used. All these requirements must be adhered to for launch approval.

B. Rocket Geometry Design

Given that the main mission parameters for this rocket are oriented towards payload deployment, capturing flight data, and reaching an altitude of 100 m, the rocket geometry was determined by addressing each mission goal. As previously stated, in order to accommodate the unique payload deployment system, the fuselage of the rocket is wider than that of model rockets of comparable size. The external design of the rocket can be seen in Fig. 1. To accommodate the need for on-board computer, camera, sensors, and payload release controllers, a housing is in the nose of the rocket to hold all of the electronics necessary for the mission parameters.

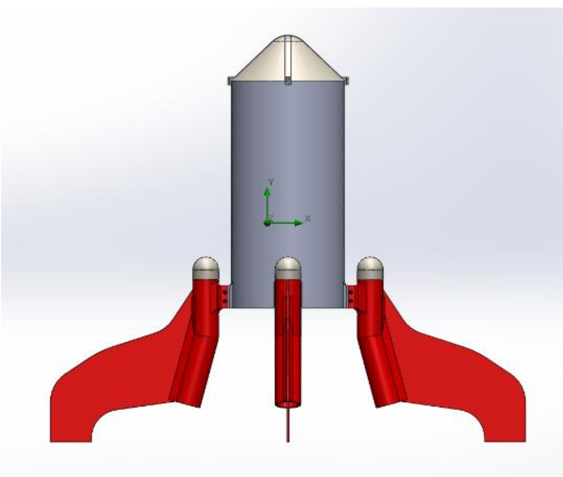

Fig. 1 External CAD model of the rocket.

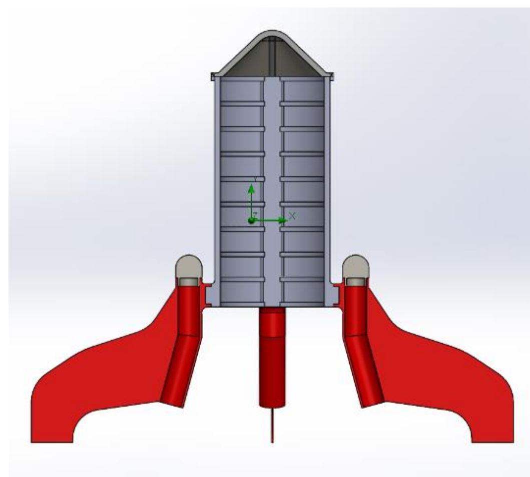

Fig. 2 Cross section view of the rocket model.

While the height aspect of the mission parameters is influenced by the geometry of the rocket in terms of weight, the main weight restriction placed on the design is set in place by the previously mentioned legal restrictions in subsection A. To address this weight restriction and make the main fuselage of the rocket as light as possible, the design utilizes horizontal and vertical supports along the wall of the fuselage to provide structural support while still allowing for the thickness of the rocket wall to be as thin as possible, which in turn reduces the weight of the fuselage.

C. Payload Interface Design and Deployment

Unlike conventional payload delivery systems used on rockets, this design does not deliver payload from the nose of the rocket. Instead, this unique payload delivery system utilizes an internal rail and payload release system to eject the payload from the bottom of the rocket. This specific design for this rocket was chosen to allow for maximum volume of the payload while also simplifying the payload ejection sequence as much as possible. Releasing the payload from the bottom of the rocket minimizes the chance for any mid-air collisions. Given that the payload is going to be housed in the main fuselage, the main fuselage was designed to have a larger diameter than model rockets of a similar scale, this again is done to maximize the volume available for payload.

The servoless motor selected will be attachable to a part of each payload [3]. This will allow for a quick and easy release when apogee is reached. The motor itself is easy to attach to the rocket and can be housed in the same area as the computer. A small, 3D attachment is designed to easily attach the motor to each payload. The motor will be actuated by the onboard computer before a pin is released and the payload is deployed.

There are two different payloads the rocket is capable of carrying a Candrone and a Re-entry Vehicle. Both will have the same size and mass limits. Due to the small mass limit given to the total rocket, each payload will need to be less than 350 grams and will have dimensional constraints of 114.3 mm diameter and a height of 203.2 mm.

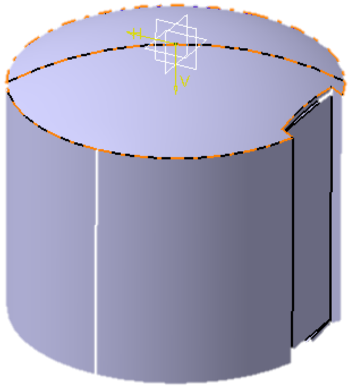

Fig. 3 Model of re-entry vehicle aeroshell.

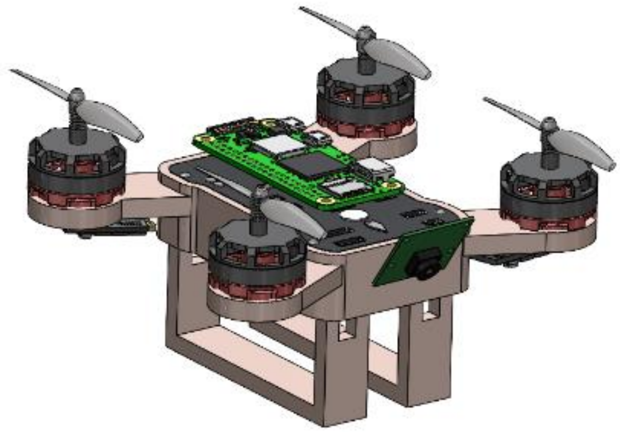

Fig. 4 Model of Candrone.

The aeroshell that will house the rover is shown in Fig. 3. It is designed to fit the rail system designed in the rocket. The shell is designed to protect the rover vehicle inside the aeroshell. The servoless motor will be attached to the top of the aeroshell. The center of mass will lie on the vertical axis of the rocket. This will allow the rocket to remain stable. The Candrone is shown in Fig. 4. The legs of the Candrone are designed to fit into the rail system for smooth deployment. A 3D printed attachment has been designed to attach to the back of the Candrone to attach to the servo-less motor.

III.Stability Testing

When considering the stability of a rocket booster design, the Center of gravity and Pressure locations must be found. Using OpenRocket software, the preliminary computer aid is adjusted to achieve a stability rating of at least one caliber [4]. A stability caliber of one is representative of a "stable" design and is correlated to the Center of Pressure (CP) and Center of Gravity (CG) locations are perfectly aligned. A rocket's stability is directly related to the difference in locations of gravity over the main body's diameter. The results of the OpenRocket analysis yielded a longer skinner, body with large surface area wings extended off the main body. In doing so, the overall length of the rocket is increased on top of added stability produced by the large wings. The combinations of these effects resulted in a stable design that fits within the legal restrictions in subsection.

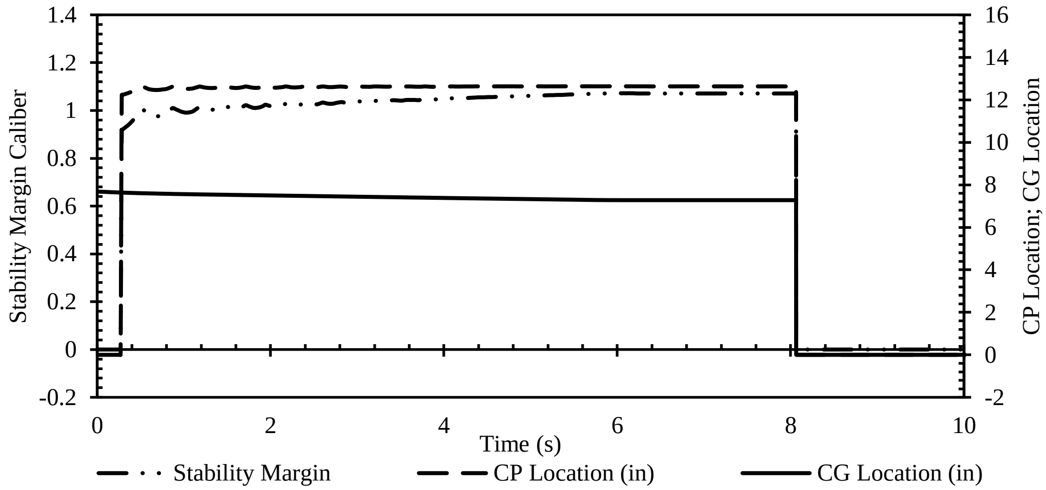

Fig. 5 Stability Test Results

The results, shown in Fig. 5, prove the stability of the rocket. The stability margin (SM) needs to be greater than or equal to one to be considered stable but should be less than two as it will become over stable. If it is over stable it will tend to gradually turn into the wind. The equation used to calculate the stability margin is shown in Eq. (1).

$$SM = \frac{CG - CP}{D} \tag{1}$$

The CP is the location on the rocket's body (with diameter D) where the aerodynamic forces can be considered to act. To be considered stable, the CP should be located under the CG. The CG is the point in a body where the entire mass can be considered to be concentrated. With this point, the force of gravity can be considered to act at this single point.

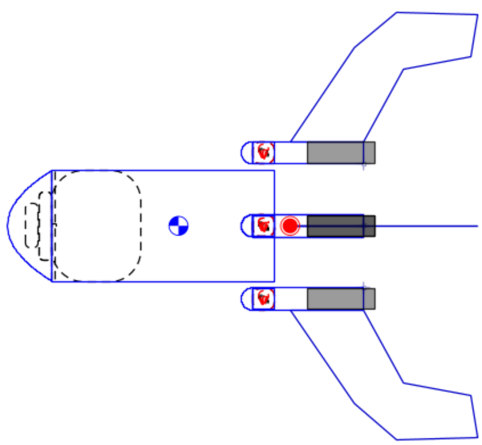

Fig. 6 The location of CG (blue) and CP (red).

The location of the CP and CG are shown in Fig. 6. The CP is the solid red dot on the center engine. The blue and white dot at the center of the rocket is the center of gravity. The CP and CG need to be in line for the rocket to be considered stable. If CP is above the CG, the rocket will pivot about its central axis due to the weight at the bottom. If the rocket is over stable, the CG will be so far above the CP it will cause the rocket to veer into the wind.

IV. Structural Testing

A computational structural analysis was conducted to test the structural stability of the rocket in ANSYS [5]. With the thrust set at 16.6 N for each engine, the study revealed stress and deformation patterns. The results of the stress analysis throughout the powered phase of the launch is depicted in Fig. 7. Notably, the attachments for the nacelles experience the highest stress, while other parts of the body experience comparatively lower stress level. The material properties of the chosen polycarbonate indicate the structure will not fail under these stress conditions.

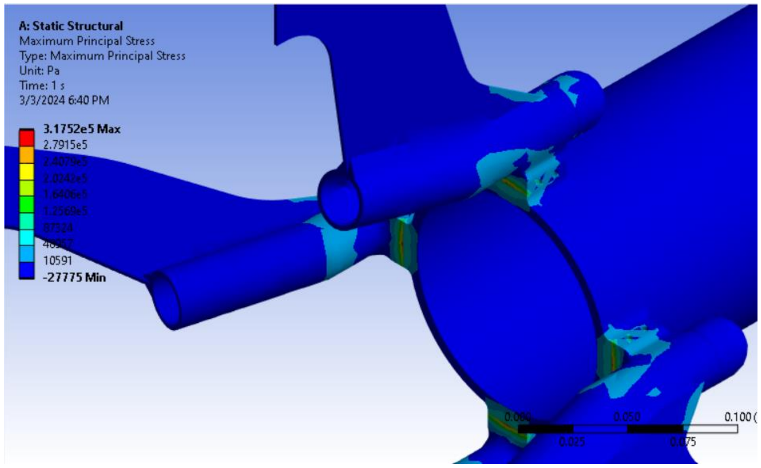

Fig. 7 Stress contours (maximum principal) during launch.

The strain is particularly concentrated at these attachments as well. These attachments will be experiencing tensile strain as they are pulled apart. The maximum strain found was $1.15\text{x}10^{-4}$ using Eq. (2). ANSYS was used to study this model and after seeing what small amount of strain the rocket experienced, it was determined that no adjustments were needed to enforce the attachments used.

$$\varepsilon = \frac{\Delta L}{L} \tag{2}$$

The deformation pattern in Fig. 8 shows the total deformation the rocket will experience during launch. While the scale factors make it seem like there is a large amount of deformation, the maximum deformation experienced is only 0.00317 mm. There is nearly no deformation on the body of the rocket. It is expected for the nacelles to experience the most deformation as this is where the engines are housed. There is no need to enforce the nacelles any further as the material is strong enough to handle this minimal deformation.

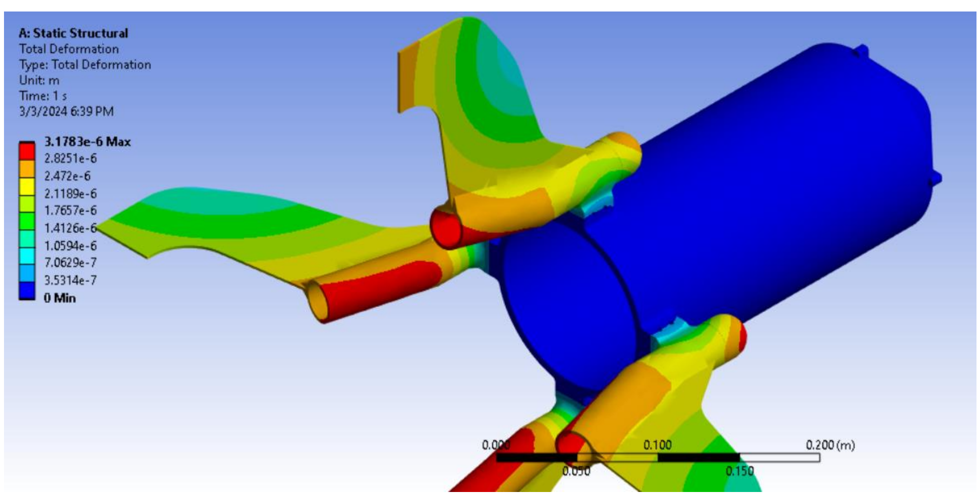

Fig. 8 Deformation contours during launch.

V. Aerodynamic Testing

To further validate the design and achieve a better understanding of the aerodynamic forces acting on rocket, SolidWorks flow simulation was used to analyze and visualize the aerodynamic forces acting upon the rocket [6]. Based on the maximum velocity found in the OpenRocket simulation of 44 m/s, the aerodynamic forces are calculated at the point where the calculated maximum velocity is achieved. The pressure gradient of the rocket at maximum calculated velocity is shown in Fig. 9. It can be seen that the attachment points, where the nose attaches to the main body, cause a relatively low-pressure zone. However, since the pressure differential between the high- pressure and low-pressure region of the rocket are only 2 percent, it is unlikely that this will have a large impact on flight performance.

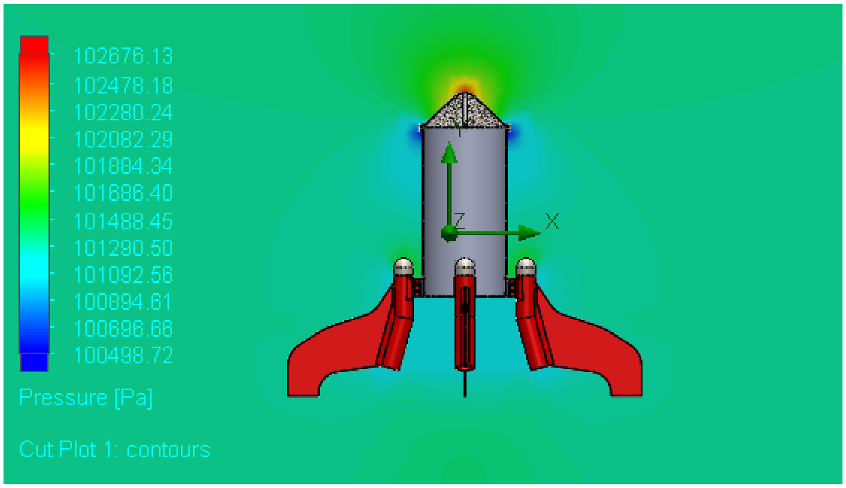

Fig. 9 Pressure forces acting on the rocket design at nacelle wing cross-section.

The velocity profile results of the SolidWorks flow simulation are shown in Fig. 10. The velocity profile follows typical velocity profiles of rockets with similar design, with velocity decreasing at the nose, the sides of the fuselage, as well as trailing edge of the rocket. Velocity losses seen alongside the fuselage of the rocket can be attributed to the friction losses between the rocket wall and air. The decreased velocity at the trailing edge of the rocket is due to the flow separation of air at the end of the rocket.

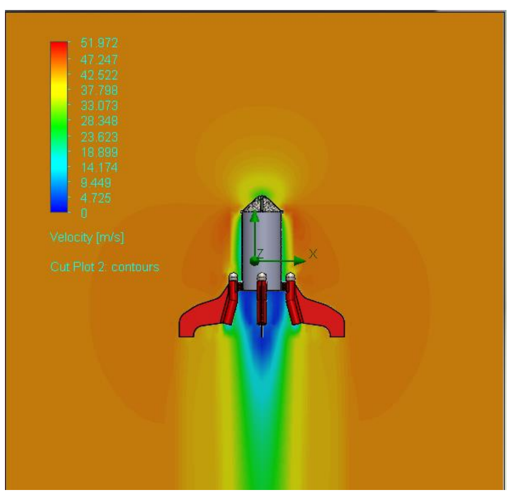

Fig. 10 Velocity contour on the rocket design at nacelle wing cross-section.

VI. Performance Testing

After creating a stable, and aerodynamic vehicle, a performance simulation was conducted using OpenRocket. A hold-down sequence will be integrated into the launch process to ensure the ignition of all four engines before takeoff. As this cannot be simulated in OpenRocket and a functional requirement of reaching an apogee of 100 m exists, an overestimation of the apogee is necessary.

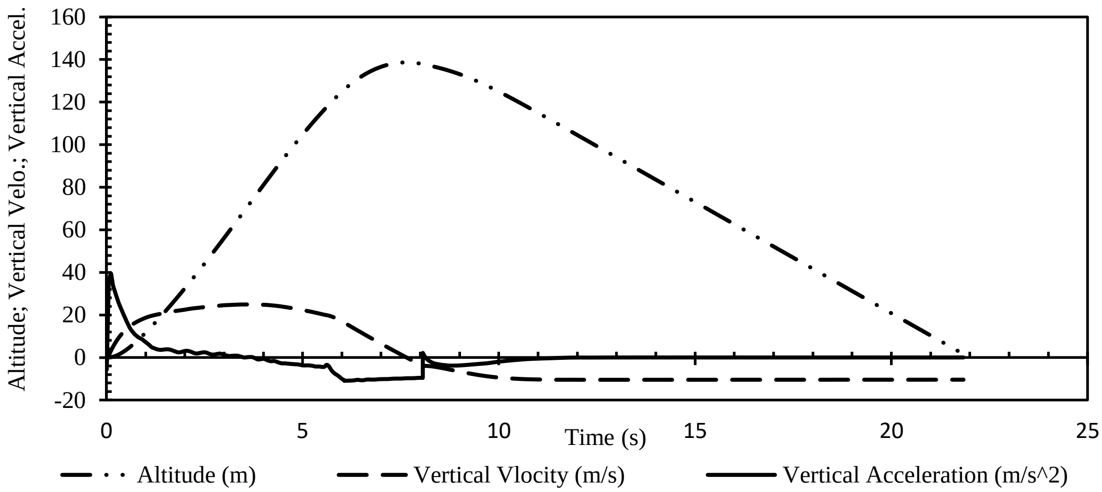

Fig. 11 Launch simulation results.

As shown in Fig. 11, apogee is expected to be around 130m which gives an allowance to incorporate a hold down sequence during launch. With a maximum acceleration of 39.4 m/s^2 occurring during the earliest period of launch, the hold down sequence is designed to be as short as possible while also allowing for safety. Optimal performance of the engines is achieved as a relatively level maximum velocity between 20 and 25 m/s is reached for three seconds. This contributes to the stability of the rocket, a necessity when using multiple engines. The apogee occurs 7.5 seconds into the launch before the parachutes deploy and the steady descent follows.

VII. On-board Computer

The on-board computer chosen is the Arduino Nano 33 BLE Sense [7]. This on-board computer will be responsible for controlling all on-board operations during the launch, aside from engine ignition. For the mission, the tasks are to record altitude, acceleration, and record a video of the payload release. Performing these tasks will be done via the barometric sensor, the nine-axis inertial sensor and the camera installed to the board. Data collected during the launch will need to be downloaded to an external drive and cleared from the computer between each flight as it is not capable of transferring data by Bluetooth or other methods during the flight.

It is also important to mention that the computer will also be tasked with controlling the actuation of the payload release system by the servo-less payload release modules. A 4.8 V, 2800 mAH battery will provide the power required for both the computer functions and the payload release. Although the combined current draw is far less than the battery's capability, a larger battery was chosen to allow for multiple launches on one battery.

VIII. Conclusion

This unique design attempts to defy conventional rocket designs with its unique payload deployment method. It has also been designed to achieve the goals set forth for the flight mission. The design follows the legal regulations set in place by the FAA while also remaining within the budget constraint set forward to the design group. In collaboration with payload teams, a payload release interface was developed to deploy the payloads while in flight. The on-board computer system operates all sensors and camera while also being responsible for payload deployment.

To validate certain performance and physical characteristics of the design of the rocket, various simulations were conducted. A performance simulation found the design of the rocket to be stable over the entirety of the flight, while reaching the altitude goal set forth. Using the data produced from the OpenRocket simulation, a SolidWorks flow simulation was used to analyze the aerodynamic performance of the rocket at its calculated maximum velocity. From this simulation, velocity and pressure contours were produced which are typical of rockets with a higher pressure and reduced velocity towards the nose of the rocket. The simulations produced no glaring errors in design which would hinder the flight performance of the aircraft. A structural stability simulation was performed to determine the stress and deformation the rocket nacelles and body would experience while the chemical rocket thrust production was at its maximum. The simulations showed that the deformation of the rocket was extremely minimal and will not be a concern.

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