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Performance and Combustion Analysis of Solid Rocket Propellant Using Aluminum Powder, Ammonium Perchlorate, and HTPB

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Abstract:

In this paper, the design and performance evaluation of a small-scale solid propellant rocket were discussed to be made up of a mixture of powdered aluminum (Al), ammonium perchlorate (NH_4ClO_4), and hydroxyl-terminated polybutadiene (HTPB). A 92.5 cm with a diameter of 5 cm and total mass of 0.854 kg, well-designed rocket using Creo software with optimal structural and aerodynamic performance was considered. Parametric parameters include a center of gravity located at 69.4 cm with a center of pressure of 61.8 cm, therefore developing excellent stability in the case of flight. The propellant formulation consisting of aluminum as fuel, ammonium perchlorate as an oxidizer, and HTPB as binder was selected in such a way that burning efficiently would optimize thrust output. Static tests were conducted on the launch vehicle using calibrated gauge instruments to measure the thrust force, specific impulse (I_{sp}), and burn rate. The static tests were complemented by a GPS-enabled launch test that provided real-time recording of altitude and trajectory. Preliminary results of thrust profiles show well-defined shapes, and the value of specific impulses also is quite satisfactory. Detailed analysis of the thrust-time curve, the specific impulse, and the burn rate indicates the performance of the propellant composition. Such studies and findings add to the greater understandability regarding the efficiencies of solid rockets, and it has potential applications towards the improvement of small-scale rocketry along with further advancements in propellant formulation.

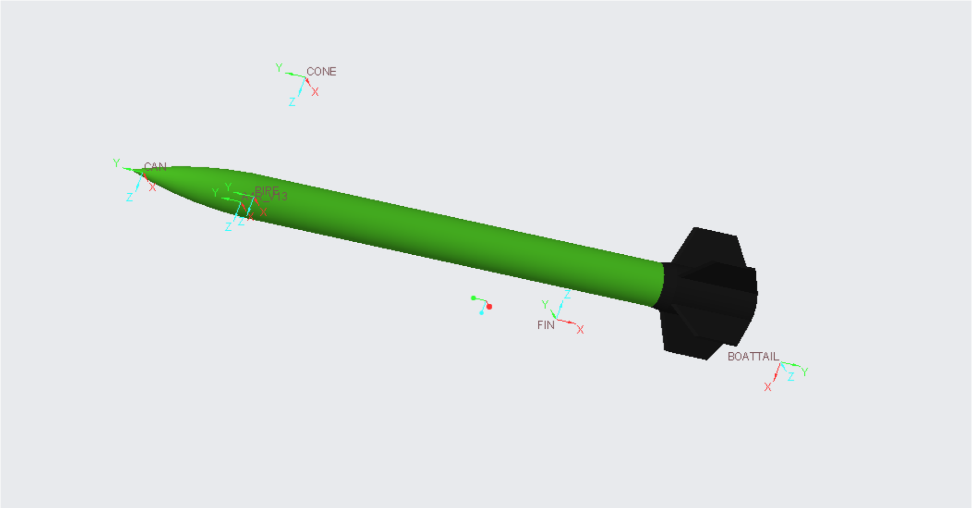

Fig.1 Solid Propellant Rocket Model Designed Using Creo

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1. Introduction

One of the areas where great emphasis is being placed upon optimizing solid propellant compositions is to reach higher levels of performance, achieve better combustion efficiencies, and enhance stability, among aerospace and defense applications characterized by simplicity, reliability, and the capability to generate high thrust in a compact configuration. This is a work concerning the development of the performance analysis of a low-scale solid propellant rocket using a fuel mix of custom powder aluminum (Al), ammonium perchlorate (NH_4ClO_4) and hydroxyl-terminated polybutadiene as a binder.

The impetus for this study comes from the need to produce more reliable and efficient solid rocket motors for space and military applications. Inasmuch as solid propellants are denser sources of energy, have higher storage stability, and have provided most of the favor due to their propensity for storability or longer shelf life, an important factor in their performance is contingent on the exact formulation of the fuel components. Aluminum has a high amount of energy available, besides releasing stable oxides during the combustion process, thus enhancing the released overall heat. The ammonium perchlorate acts as an excellent oxidizer that allows the quick release of the products of combustion, while the HTPB acts as a binder that provides structural integrity for the propellant and contributes to the energy output.

This composition of propellant is analyzed for the combustion characteristics along with the overall performance under controlled conditions. A solid rocket motor was designed using the industry's leading parametric 3D CAD software to ensure that the design had precise structural and aerodynamic configurations. The height of the rocket is 92.5 cm, and its diameter is 5 cm, within a total mass of 0.854 kg. The CG was at 69.4 cm and CP 61.8 cm, so the flight profile stabilized. In the experimental phase, static tests were conducted to determine key performance parameters such as thrust, burn rate, and specific impulse (I_{sp}). Gauge instruments are employed to measure the thrust profile throughout the combustion process. Relative rocket performance in altitude and trajectory during flight is measured through a GPS-based system. These experiments are crucial to carry out the study on applicability of the fuel mixture in real applications, as well as the propellant behavior under various regimes.

This research contributes to the ongoing advancements in solid rocket propulsion by offering insight to optimize formulations of propellants. Based on the results obtained from this study, future designs of small-scale rockets could be made especially for applications of payload delivery into space, the military defense mechanisms, and space exploration. Furthermore, documentation of the design process and test results makes the paper provide a framework for further research and development in the field of solid propellant technology.

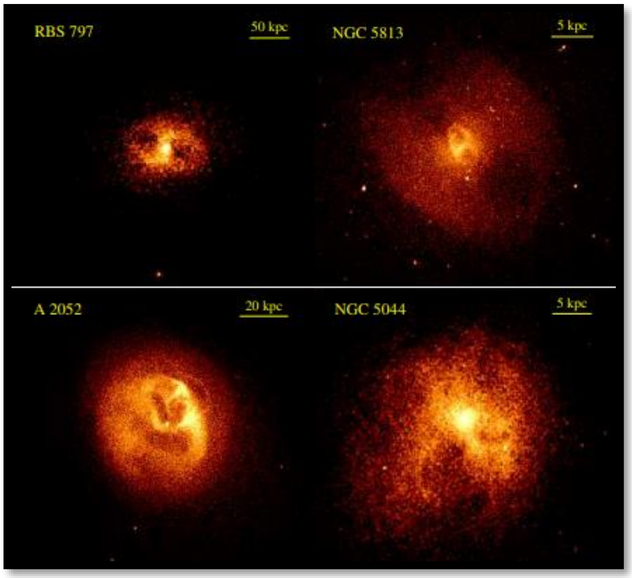
2.Literature Review

For a very long time, a lot of research and development have been involved in solid rocket propulsion. It has been developing the crucial role in applications related to military and space exploration. The performance of the solid rocket system is mainly provided by the fuel, the oxidizer, and the binder forming the propellant. These components may directly affect thrust, specific impulse, burn rate, and combustion stability. Advancement in technology continues to improve these aspects toward greater performance and higher efficiency in general, hence forming a strong case in the field. This paper forms a literature review on advancements made in solid rocket propellant technology-which includes key ingredients of powdered aluminum (Al), ammonium perchlorate (NH_4ClO_4), and hydroxyl-terminated polybutadiene (HTPB)-in discussing modern methodologies applied in rocket design and their performance. Aluminum powder is well known to be the main fuel component of solid rocket propellants because it offers a good high energy density that makes it possible to perform the oxidative exothermic during burning. Sutton and Biblarz, 2016: "It is evident that the products formed during combustion have good thermal stability and are able to generate high quantities of heat.". Early works laid out the fact that aluminum is the best fuel as it was in abundance, had rich energy content and burning characteristics. Recent efforts have focused on the utilization of nano-scale aluminum particles. It has been found that reactivity and burn rates are larger for the micron sized ones. As per Ren et al. (2020), nano-aluminum increases the propellant combustion efficiency with increased stability but at a higher thrust.

It is one of the most widely used oxidizers in composite solid propellants due to its high oxygen content and rapid decomposition under thermal stress. Such properties allow a balanced combustion reaction with fuels like aluminum. The necessary oxygen for such an efficient combustion of the fuel is provided by ammonium perchlorate decomposition. Ponomarev et al. (2018) investigated the effect of particle size of ammonium perchlorate on the burn rate characteristics of the propellant; it was found that with smaller particle size, the combustion rate increased, whereas with larger ones, it ensured the burn time, thereby allowing tailoring of the oxidizer to the desired performance needs. This effect due to the particle size plays a very important role in tailoring the burn rate in such a way that the rocket motor performs optimally in the desired operating condition. HTPB has emerged as one of the largely accepted binders in formulations of solid propellants. It possesses flexibility, low-temperature mechanical properties, and is considered a good secondary fuel and binder. The dual role imparted by HTPB to contribute to both energy output and structural integrity is useful for modern composite propellants. Li et al. (2019) discovered the thermochemical properties of HTPB in propellant mixtures and claimed that they enhance the structural cohesion of the propellant and give a small nonzero amount of energy during combustion. It is this particular characteristic of HTPB that it can play a role both as a binder as well as a fuel, and it has enhanced specific impulse and burn efficiency with stable combustion at any operational condition.

The amorphous, metal-rich, combustive refractory composition of aluminum, ammonium perchlorate, and HTPB in composite propellants ensures a well-balanced formulation that could offer high energy release, good mechanical stability, and reliable combustion. According to Chung et al. (2017), adjustments of these ratios have been found to directly affect the burn rate of propellant and thrust output. A higher concentration of aluminum will raise the thrust, but it may cause partial combustion, and this has to be mixed up with the right proportion of ammonium perchlorate or HTPB. On the other hand, a higher concentration of the oxidizer will increase efficiency in combustion, but this may cause pressure pulses in the combustion chamber. Balancing the two is necessary in maximizing performance while keeping safety and stability intact. Modern developments in computer-aided design and computer simulation have significantly improved the design process of solid rocket motors. In general, a parametric CAD tool like Creo is mostly used in the precise design of geometries regarding the assessment of aerodynamic stability and structural integrity analysis under stress. Kim and Lee proved in 2022 that CAD tools must be used to optimize rocket design as a motor has to become efficient yet stable under flight conditions. Simulation software also enables scientists to predict fluid dynamics and the stress of materials before ensuring grain formation in a propellant and ensure proper combustion.

Performance testing for solid rockets is carried out by performing static as well as dynamic tests. Static testing tests thrust, burn rate, and specific impulse by using gauge instruments that capture information in real time, as has been done in this research. Launch tests that will comprise GPS-enabled systems and altitude, trajectory, and flight dynamics measurements will assure them of being tested under realistic,



real-time conditions by Barrow and Dyer, 2020. Such testing is critical for verification of predictions done during the design phase on theoretical grounds and confirmation of propellant performance with actual in-flight conditions. In recent times, alternative fuels and additives for improvements in solid rocket propellants have evoked a lot of interest. There has been keen interest among researchers in the use of boron and magnesium as additives to gain energy density, but they have drawbacks-the former is costly, while the latter is inefficient in their combustion characteristics. Research by Zhang et al. (2023) concluded that future breakthroughs in rocket propulsion may come from nano-structured materials or hybrid propellant formulations, which are perceived to offer superior performance with fewer concerns for combustion instability problems and high cost of manufacturing.

Environmental problems related to chlorine-containing by-products of traditional ammonium perchlorate-based propellants have also motivated designers to look for greener alternatives for rocket propellants. For instance, Ammonium dinitramide (ADN), which is effective but does not give harmful products of combustion, has gained prominence as an environmentally friendly oxidizer. More research in this direction is thus needed to develop advanced technologies for solid rocket propellants not only meeting performance requirements but also environmental regulations. The literature presents substantial progress in solid rocket propellant technology, particularly in the optimization of combinations of fuel, oxidizer, and binder. The aluminum-ammonium perchlorate-HTPB combination has proven an effective formulation for small rockets that scale well, trading performance for safety. With further and up-to-date developments, it is hoped that improvements in solid rocket propulsion systems would ensue, considering developments in nanomaterials, additives, and environmentally friendly propellants. From this well-formulated approach, it develops the combustion characteristics of a composite propellant and has done further improvement on performance.

3. Methodology

The rocket design and manufacturing process

The model is the takeoff point of the rocket design that was developed based on the calculations made from the thrust required and general dimensions. In designing Creo, software was used to produce an efficient three-dimensional parametric model with precision in structural elements as well as adequate aerodynamic stability. Below are the dimensions used in the design:

Nose Cone: 30 cm length, base diameter of 5 cm. This is used so there are no aerodynamic drags when it flies through the air and retains the stream wise-flow profile to maintain the rocket as aerodynamic as it can be.

Key Body: The rocket was designed to have its cylindrical body 60 cm long with a base diameter of 5 cm. It thus would guarantee a cylindrical shape which could stand structural stability hence installation of the motor.

Fins: Four fins have been included in the design. They were added symmetrically and evenly all along the bottom of the rocket. That would result in stability without much wobbling during flight. The height of the fins was 3 cm with a sweep angle of 38.9 degrees. Such a design of fins would result in stability, particularly during the ascending rocket.

The full rocket model was printed out by the 3D printing technology and was manufactured basically from Acrylonitrile Butadiene Styrene, ABS. It was used mainly due to its strength, resistance to high temperatures as well as low weight-the basic properties in any material which is going to face extreme temperatures and forces during static and launch tests. The total weight of rocket motor with structural parts was 0.854 kg.

Rocket Motors Design and construction

The design and construction of the rocket motor was a necessary structural part of the entire rocket structure. The outer body of the motor consisted of a material in the form of polyvinyl chloride since this is chemically inert and possesses strong structural properties that resist chemical degradation. This way, PVC allows the motor to have some internal pressures developed by combustion but is lightweight at the same time. We also used carbon fiber as a lining of heat resistance. Strategically positioned, it will ensure that all of the developed heat can be diverted away from the motor body to prevent melting or failure of structural members. The designed dimensions of the rocket motor were a motor length of 25 cm and a diameter of 4 cm. This ensured that the combustion chamber was maximized to ensure maximum propellant burning efficiency in that fuel.

Fuel Composition

A three component composite solid propellant was used- powdered aluminum (Al), ammonium perchlorate (NH_4ClO_4), and hydroxyl-terminated polybutadiene (HTPB). The three constituents of the fuel mix were empirically derived, based on research aimed at maximizing performance without stability sacrifice. Thus, the composition of fuel is:

Powdered Aluminum (Al): 20%.

Ammonium Perchlorate (NH_4ClO_4): 70%

Hydroxyl-terminated polybutadiene (HTPB): 10%

This formulation was adopted to counterbalance the high energy provided by aluminum and ammonium perchlorate. For using HTPB as a binder and secondary fuel, there is the possibility of cohesive combustion along with structural strength during the ignition and burn process.

To burn very efficiently, the motor nozzle was made to have an inner diameter of 0.5 cm. This was to ensure the expansion of gases and hence the generation of thrust. The nozzle was made long enough at 22 cm to allow residence time for proper igniting of all produced during combustion.

Testing protocol

Testing of the rocket motor was broadly categorized into two areas: efficiency testing of the motor and rocket launch testing.

Efficiency Motor Testing: During this static test, the computerized gauge instrument system monitored the thrust in real time. Peak thrust occurred at 31.6 N, which was attained 1.0 s after ignition. Calculation of specific impulse for the motor yields 15.004565 s. Performance thus is favorable for the selected fuel formulation and motor design. This proved to be critical information for ensuring that all theoretical expectations in the design phase were checked; thus, all performance tests passed on the motor. Rocket Launch Test On launch day, we utilized a tri-launcher system fixed at 90 degrees. We launched this system vertically straight up, and we made sure we were in controlled conditions to get proper performance metrics. For the measurement of the rocket's altitude during flight, we adopted a GPS system. During flight, this would give us real-time feedback on the elevation of the rocket. The device allowed capturing the most critical parameters of a flight, for example maximum height reached, stability in flight. It helped us understand the performance of the entire rocket system from launch up until ascending flight.

4. Results and Discussion

Static Motor Test Thrust Calculation Specific Impulse

The static motor test gave important information relating to thrust generation and specific impulse of the rocket motor. In the thrust calculation test, we used a computerized measuring instrument with a gauge that took real data during the ignition phase as well as the burning phases with a high efficiency. The results showed that it had the maximum thrust at 31.6 N within only 1.0 s after its ignition. With such good thrust output, this shows that it will be able to initiate the launch sequence well, gaining the right momentum over gravitational forces for take-off. The thrust of the ascent during the first second is used as a prop to sustain the linear trajectory. This performance metric will then validate the design parameters of the rocket motor and, at the same time, point out how effective the fuel composition delivers the required energy output. The measured specific impulse of the motor was 15.004565 seconds. Metric is inevitable because it represents the efficiency of the rocket motor in converting propellant mass into thrust. A higher specific impulse means it has a better propulsion system; this will not only help to achieve greater altitudes but also improve the rocket.

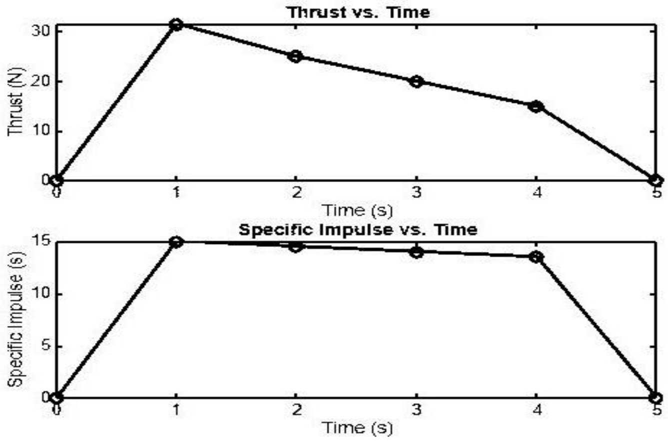


Figure 2: Graphical Representation of Thrust and Specific Impulse During Rocket Static Testing

Altitude Testing

For our altitude test, we created a GPS system that gave us real-time measurements of the altitude of the launch of our rocket. With such a sophisticated system, we could follow the trace of the rocket as it leaved the ground and trace its height at every point through its flight. The rocket was shot straight up to an angle of 90 degrees for maximum vertical height. Indeed, today the rocket tested really went up to a height of 216 meters, and that will prove our design and propulsion system are working. With a total flight of 28 seconds, the rocket landed to the ground that essentially mimics all the characteristics of projectile motion. That was really a long-lasting critical flight time since that actually gives an overall impression of how a rocket will perform and how the propulsion system is effective. The data coming from such ascents and descents will be important in further optimization of the rocket design for further tests.

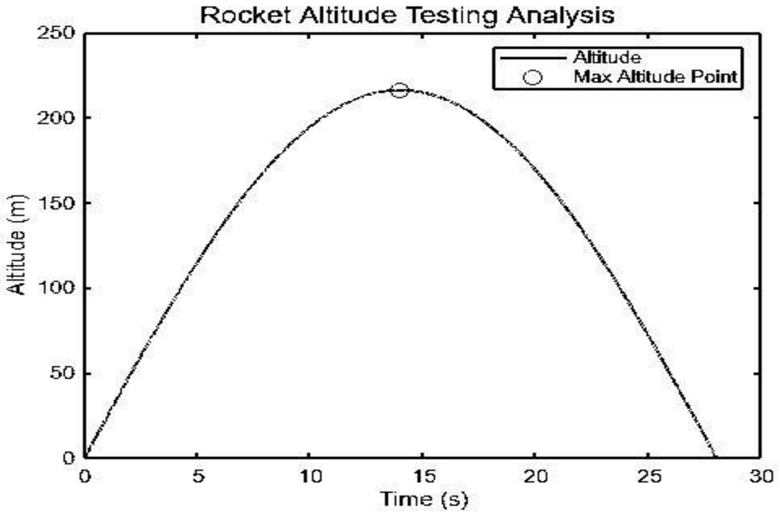


Fig 3: Altitude Profile of the Rocket Model During Flight Testing

Mach Number Analysis

Under the testing of our solid propellant rocket, it attained a maximum speed approximately equal to a Mach number of 0.24. Mach number is that dimensionless quantity representing the ratio of an object's speed to the speed of sound in the surrounding medium. In our case, the Mach number is 0.24. Therefore, it states that the rocket had travelled about 24% of the speed at which sound travels at sea level or about 343 meters per second. This relatively low subsonic speed is of utmost importance because it was demonstrated that the rocket is within a safe range for its ascension to be flown stably, and its flight dynamics were effectively controlled. The latter, in relation to this Mach number, as well demonstrates that the composition of the rocket's propulsion is able to give good performance while its fuel provides thrust without attaining critical speed limits.

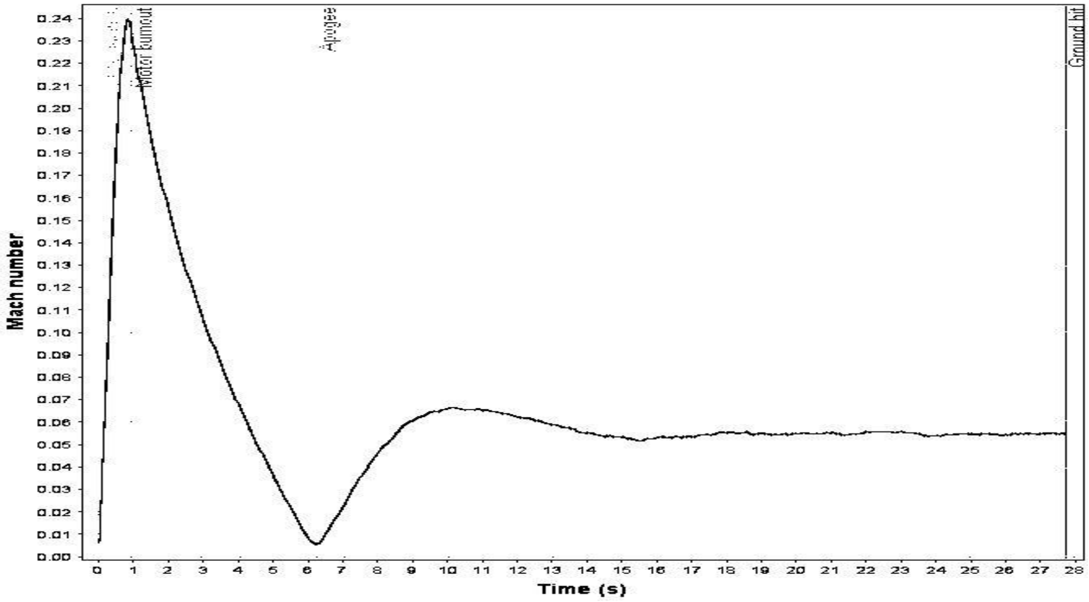


Fig.4 Mach Number Analysis of Rocket Testing

5. Conclusion

The development and testing of our solid propellant rocket provided insightful results regarding both the performance of the rocket and the efficiency of the propulsion system. Through detailed experimentation and precise measurement techniques, we achieved several key milestones that validate the design and execution of the rocket model. The **static motor testing** revealed that the rocket motor produced a maximum thrust of **31.6 N** within the first second of ignition. This immediate thrust generation was essential in ensuring that the rocket could overcome gravitational forces and initiate a stable launch. Additionally, the **specific impulse** of the motor was calculated to be **15.004565 seconds**, showcasing the efficiency of the fuel mixture and propulsion design in optimizing energy release during the burn phase. During the **altitude testing**, the rocket was launched at a 90-degree angle using a tri-launcher system, reaching a maximum altitude of **216 meters** before descending. The entire flight, from launch to touchdown, took **28 seconds**, confirming the stability of the flight path and the rocket's ability to maintain a controlled ascent and descent. The GPS system was instrumental in tracking the real-time altitude, providing accurate measurements throughout the test. Furthermore, the rocket reached a **Mach number of 0.24**, demonstrating that it traveled at **24% of the speed of sound** at sea level. This subsonic flight speed ensured the rocket-maintained stability throughout its trajectory, avoiding any excessive stresses that could have affected the integrity of the structure. These results not only validate the design parameters but also underline the successful execution of the rocket's propulsion and structural systems. The combination of thrust, altitude, and Mach number achieved during testing affirms the viability of the rocket for future developments and similar applications in aerospace experimentation. The research demonstrates a practical approach to solid propellant rocket design, providing a foundation for further exploration and refinement.

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7.Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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