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Applying the Systems Decision Process to Design a Low-Cost, Hypersonic Rocket

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Author Note: The authors of this report present this paper as a culmination of their capstone project for their senior year at the United States Military Academy at West Point. We extend our heartfelt gratitude for the essential funding and support from Army Development Command (Army DEVCOM) Aviation and Missile Center (AvMC). This backing has empowered our team to engage in a multi-year project, which successfully led to our accomplishment of crossing the Kármán line in 2025. It is crucial to clarify that the views expressed in this paper are strictly those of the authors and do not represent the Department of Defense, the Department of the Army, the United States Military Academy at West Point, or the Army Development Command - Aviation and Missile Center.

Abstract: The United States Military Academy strives to lead technological innovation and development for the United States Army and the Department of Defense. The Space Engineering and Applied Research Tactical Hypersonic Orbital Rocket (SPEAR-THOR) capstone project focuses on designing, building, and launching a hypersonic vehicle capable of consistently reaching the Kármán Line, the internationally recognized border between earth's atmosphere and space, at an altitude of 100 kilometers and safely return to the earth's surface. This project employed the Systems Decision Process to design and launch a two-stage hypersonic rocket capable of reaching the Kármán Line. The successful, real-world performance of four rockets validated stakeholder requirements and sets the stage for further interdisciplinary research and refinements in hypersonic vehicle design. Achieving this feat with a low-cost, hypersonic rocket has profound strategic implications, enhancing the Department of Defense's warfighting capabilities by enabling the development of the next-generation of defense technologies in near-space environments.

1. Introduction

Hypersonic missiles and low-altitude satellites increasingly threaten national defense. Jeffery McCormick, the Senior Intelligence Analyst at the National Air and Space Intelligence Center, testified before the House Armed Services Committee's strategic forces subcommittee in March 2024, stating, "China now has the world's leading hypersonic arsenal." Hypersonic weapons are a cutting-edge capability that presents an existential challenge to modern warfighting—a domain the United States' adversaries are currently leading (Naval, 2025).

In the Department of Defense's (DoD) congressional budget for Fiscal Year 2024, nearly a third ($74.1 billion out of $234.93 billion) of the DoD's research, development, test, and evaluation funding is allocated to enhancing missile defense capabilities, developing high-precision lethal weapons, and advancing critical space technologies. Over the past five years, SPEAR THOR Capstone Project Teams tested various hypersonic vehicle configurations focused solely on reaching the Kármán Line while minimizing cost per vehicle. While significant progress was made, previous teams were unable to design vehicles that could reach the desired altitude and produce either consistent or verifiable results. This year, the team chose to incorporate certain aspects from previous vehicle architectures while focusing on a few, impactful architectural decisions that the team determined to make the ultimate difference in reaching the Kármán Line. The team applied the Systems Decision Process to make the necessary architectural decisions to design an improved two-stage, unmanned hypersonic rocket capable of consistently reaching the Kármán Line.

The team's research centered on the Systems Decision Process, which consists of four main phases: Problem Definition, Solution Design, Decision Making, and Solution Implementation (Driscoll, Parnell, & Henderson, 2023). From August 2024 to April 2025, SPEAR-THOR completed each phase, developing tangible products and simulations to aid in design choices and launch operation procedures. Utilizing this framework ensures proper documentation of success and failure for use throughout the lifespan of the enduring SPEAR-THOR project. The products outlining the decisions for material and design choices also created clarity by showing the benefits and drawbacks of each choice.

2. Methodology and Problem Definition

2.1 Research and Stakeholder Analysis

The results and insights from previous capstone project teams guided the problem definition phase. Although failing to reach the desired altitude, historical launches demonstrated the viability of numerous architectural components and set the stage for future designs. Because most of the team members lacked background or working knowledge of hypersonic rocketry, a three-day rocket science workshop was conducted at the beginning of the project to establish a knowledge baseline across all members of the team. The workshop included classes on topics such as rocket stability, rocket propellant, and aerodynamics. During this phase, the team also continued research efforts to determine the prioritization of design decisions that would lead to an optimal architectural configuration that maximized performance while minimizing cost. After conducting a thorough and comprehensive review of previous SPEAR-THOR project reports and a rocket science academic workshop, the team conducted a functional analysis to reduce the scope of the project to less than ten architectural decisions.

2.2 Functional Analysis

To outline the decision criteria, the team constructed a functional hierarchy shown in Figure 1 displaying the fundamental objective of the rocket and the functions needed to achieve this goal including thrust, telemetry and data transmission, recovery, and stability. From these primary functions, the team determined strategic objectives within these areas and the value measures to calculate their operational effectiveness (Driscoll, Parnell, & Henderson, 2023). The functional hierarchy was crucial in the selection of the two launch configurations for January 2025, driving forward the entire design selection process. Figure 1, shown below, allowed the team to pinpoint the specific functions essential for maximizing the probability of achieving the system's fundamental objective. This functional hierarchy appropriately reduced project scope and informed the team on what design decisions needed to be prioritized. This is elaborated upon in the Solution Design and Decision-Making sections.

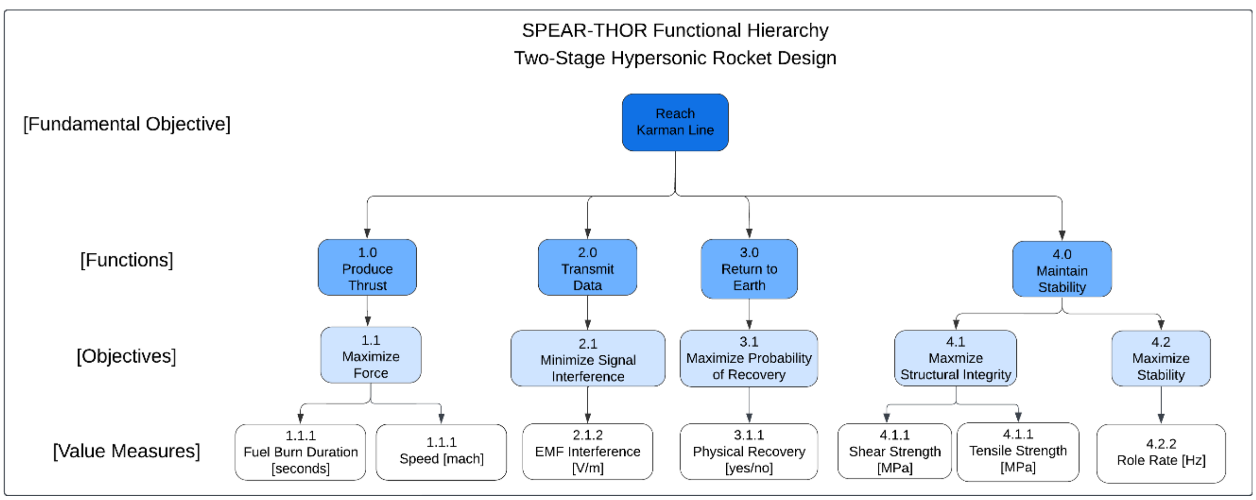

Figure 1: Functional Hierarchy

3. Solution Design

To provide objective data in support of value measure scoring, the team created pareto frontiers highlighting the dominant solutions for various functional objectives. The pareto frontiers in Figure 2 and Figure 3, plot material options for the payload bay, displaying several types of aluminum alloy and fiber glass. Maximizing structural integrity was key to the survivability of the vehicle. Therefore, the material choice must maximize shear strength while minimizing weight and cost. In previous launches, the team used fiberglass payload bays to reduce GPS interference. However, this material experienced catastrophic structural failure and is thus considered sub-optimal for future operations (Jung et al., 2024). As shown in Figure

2, the two fiber glass options reflect these findings with low shear strengths (Bilida, 1971). Of all the material options, aluminum 7075 possessed the highest shear strength, with the highest density. This alloy is commonly used in various commercial aircraft and spacecraft and is a benchmarked product in today's aviation industry (NASA, 2023). Although ranking the highest in terms of shear strength and density, this aluminum alloy is a very expensive option as shown in **Error! Reference source not found.**. This increased material cost may prove detrimental to the overall cost minimization of the project. A critical aspect of the team's problem statement consists of designing a "cost-effective solution for Army hypersonic research," making individual unit cost a key factor in final design selection. The weight of the vehicle directly impacts its performance. Therefore, the team conducted a tradespace analysis of material density vs. shear strength. Aluminum 7075 outperformed other materials, but also proved to be the densest material. Overall, different types of aluminum alloys were denser and stronger than fiberglass. This validated team assumptions and impacted final material choice. The stronger the material, the denser it is, impacting vehicle weight. The team needed to determine the level of shear strength required to ensure survivability while not sacrificing on potential vehicle altitude. Although Aluminum 7075 was clearly the strongest potential vehicle material, it was not the most weight or cost-effective option. The team considered other options along the pareto frontier for both Figure 2 and Figure 3 when scoring for material selection.

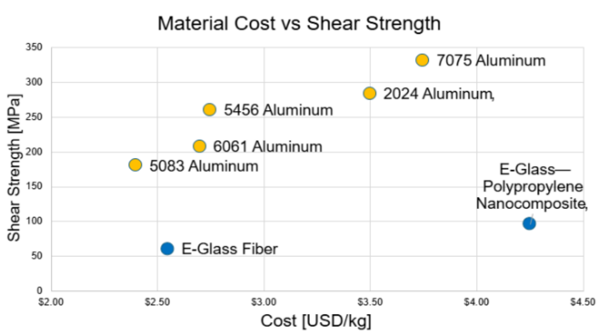

Figure 2: Material Cost vs Factor of Safety Tradespace

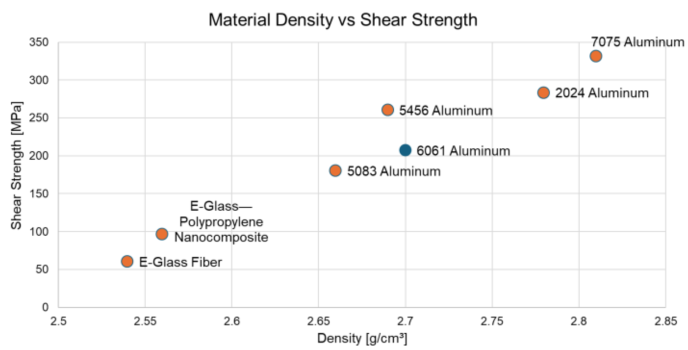

Figure 3: Material Density vs Shear Strength Tradespace

Additional tradeoffs to consider for the rocket's design were total vehicle cost and altitude at apogee. As shown below in Figure 4**,** rocket designs from Academic Years (AY) 2021 through 2024 were considered. In this scenario, WREN and CORA outperformed all other alternatives, with the greatest altitudes of over 140 km and the lowest per unit costs of under $40,000 (Zander, 2024). These configurations optimize both cost efficiency and performance in terms of altitude at apogee. The decision to use an aluminum alloy instead of fiberglass helped significantly lower the cost of the vehicle while also improving survivability of the aircraft. The aluminum did not experience catastrophic failure in flight and allowed the team to successfully recover the vehicle's nose cone which housed the flight computer. The data from the flight computer validated the telemetry data obtained through GPS and significantly increased the reliability and confidence of the vehicle's performance to include altitude and airspeed.

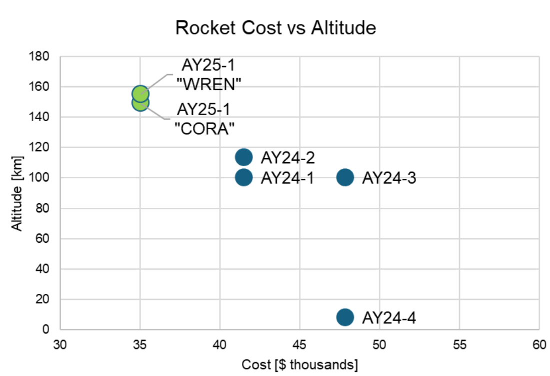

Figure 4: Rocket Cost vs Altitude Tradespace

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4. Decision Making

By plotting pareto frontiers, the team outlined the dominant solutions and visualized the tradeoffs for design decisions related to booster diameter, payload bay material shear strength, and cost. These factors are derived from our initial functional hierarchy and are data driven measures for the objective functions. By using this data, the team created an objective and accurate weighted scoring matrix for displaying these design alternatives (Driscoll, Parnell, & Henderson, 2023). The weighted scoring matrix provides the goal for each of these alternatives and ranks them in terms of their performance (raw score) and relative importance (relative weight) for rocket effectiveness. These scores are weighted and then summed to produce total scores for each design alternative. These are shown graphically in Figure 5 through the use of a stacked bar chart. WREN and CORA scored higher than the 2024 vehicles because of the overall cost, material strength, and expected apogee. The expected apogee scores derived from team simulations using RASAero Aerodynamic Analysis and Flight Simulation Software.

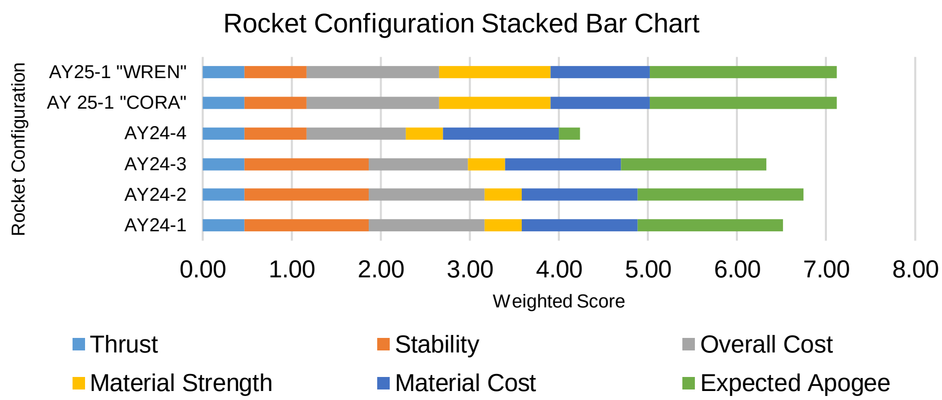

Figure 5: Weighted Score Stacked Bar Chart

The weighted scoring matrix produced the scores necessary to make the final design selection. As shown above, the design configurations from the launches in January 2025 possessed the highest weighted scores. Using these designs as a baseline for the three launches in April 2025, the team made the following design decisions.

For the 2025 spring campaign, the team elected to design the payload bay from aluminum 6061 as opposed to other aluminum and carbon fiber designs. Aluminum 6061 was one on the pareto frontier in terms of material cost, and the team determined that this material met a sufficient safety factor for implementation in the payload while significantly reducing the overall cost of the unit. While aluminum 7075 proves to be the superior option in terms of shear strength and factor of safety, the team valued the cost efficiency of 6061 to a greater degree. In addition, all aluminum payload bays have maintained a one-hundred percent recovery rate of the nose cone over the past three years, increasing its reliability.

The team had two options regarding rocket stabilization: spin stabilization and drag stabilization. By modifying the fin cant angle, the team is able to manipulate the rate of spin throughout launch. This technique allows the rockets to counteract any significant effects from thrust misalignment and allows for improved pressure dispersion and thermal loading across the airframe (Le et al., 2021). While the CORA and WREN designs achieved the highest apogees using spin stabilization, the team is ultimately interested in utilizing a drag stabilized design for the possible future implementation of active flight controls along with camera integration. For these reasons, the team elected to pursue two spin-stabilized rockets and one drag-stabilized rocket for the launches in April 2025.

To enhance thrust performance, the team opted for a large booster diameter. In previous years, teams utilized a 98-millimeter design; however, recent configurations operating with 127 millimeters delivered apogees tens of kilometers higher. This motor was first implemented in AY2023 and provides a greater thrust profile while not posing a significant risk to stability. Yielding the greatest success in previous launches, this design was continued in all three launches in April.

Overall, optimal performance while minimizing cost are key aspects of future rocket development. Figure 6 illustrates the final architectural configuration of the hypersonic rockets, launched in January and in April 2025.

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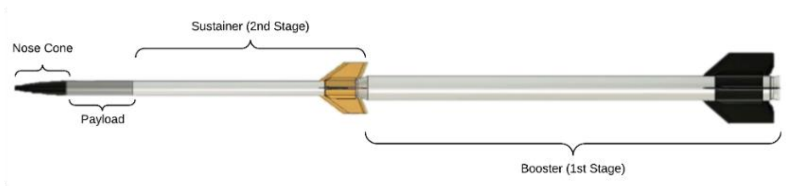

Figure 6: CORA and WREN Vehicle Architecture

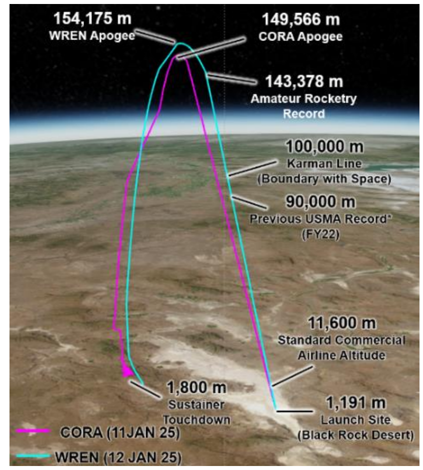

Figure 7: CORA and WREN Vehicle Flight Path

5. Solution Implementation

5.1 Planning – Risk Analysis and Mitigation

With various factors to consider, such as safety of the team, accomplishment of the mission, and schedule integrity, risk analysis became increasingly thorough. Utilizing a deliberate risk assessment worksheet (DRAW), the team ensured that all key risks were identified and mitigated prior to launch (U.S. Department of the Army, 2014). Multiple risk assessment iterations were developed, regarding operation plans, equipment inspections, and subsequent testing. Detailed launch approval briefs were prepared to ensure multiple entities review plans, training procedures, equipment designs, and simulated launches to catch oversights before any issues could delay significant milestones. The team modeled its risk assessment process on U.S. Army Aviation's current model. This risk assessment process includes an initial mission approval authority (IMAA), deliberate risk assessment worksheet (DRAW), mission briefing officer (MBO), and final mission approval authority (FMAA). The multiple layers throughout the process ensures thorough analysis by multiple individuals familiar with the mission or within the team's chain-of-command. Individuals included in this process are able to identify additional risk and provide recommendations to mitigate risk.

With the vast number of details and points of friction, the DRAW played a crucial role in ensuring proper documentation of the failure points and mitigation tactics. Utilizing the DRAW, the safety engineer generated standard operating procedures and strategies as a culmination of the previous SDP phases, which included conducting training briefings and rehearsals with the team to ensure roles and duties are clear and easily distinguishable. This phase also included the implementation of mitigation techniques to ensure operations run smoothly, including orders for extra parts and tools that may become lost or broken in transport, conducting check-ins with mission critical outside entities, such as EMS teams and the FAA, along with creating redundant operational checklists. The team prioritized safety and standardized launch operations that were not previously standardized. This standardization significantly improved process efficiency related to launch preparation, launch execution, and vehicle recovery. The deliberate and intentional treatment of safety resulted in five hypersonic launches with no accidents or near-miss issues. Conducting a thorough risk analysis was vital to mitigating project, operational, and technical risks associated with solution implementation phase.

5.2 Executing - Launch Results

The two rockets launched in January 2025 reached altitudes of over 145 kilometers approximately three minutes after ignition and reached top speeds exceeding Mach 6. These configurations verified the capability of a low cost, two-stage hypersonic rocket reaching the Kármán Line. Telemetry data played a crucial role in the success of the launch. By eliminating vehicle components that caused electromagnetic interference, the team collected reliable GPS data with enough accuracy to confidently claim a maximum apogee of 149km. After conducting uncertainty analysis, the maximum true altitude of apogee was 149.566 ± 17.40 and maximum air speed was Mach $6.22 \pm .55$ with 97% confidence. Figure 7 shows an outline of the flight path taken by the January 2025 rockets, CORA and WREN based on both telemetry and flight computer data.

Building on these successful launches, the team launched two additional spin stabilized rockets to validate reliability in the design. The first two launches in April, designated EDEN and LILY respectively, exceeded the Kármán Line reaching estimated altitudes of 136 and 149 km respectively. The successful performances of CORA, WREN, EDEN, and LILY validated that the vehicle architecture achieved the system's fundamental objective: reach the Kármán Line. Further analysis and simulation data will provide a confidence interval that will confirm these estimated apogees. The last rocket of the Spring Campaign, WREN II, demonstrated the viability of drag stabilization. This configuration was the first drag-stabilized rocket to exceed the Kármán Line in program history reaching an estimated apogee of 126 km. Utilizing drag stabilization introduces the possibility of future work focusing on the implementation of active flight controls and payload deployment, further enhancing hypersonic research for the U.S. military.

6. Conclusion and Future Research

In conclusion, the SPEAR-THOR capstone project successfully demonstrated the application of the Systems Decision Process in designing and launching a cost-effective, hypersonic rocket capable of reaching the Kármán Line. The project not only validated the viability of low-cost hypersonic vehicles but also highlighted the importance of rigorous risk management and systematic decision-making in achieving high-performance outcomes. This project demonstrated the feasibility of producing reliable hypersonic rockets at a significantly lower cost than previously believed, opening up new possibilities for continued, affordable technological development.

While recent milestones reflect progress, future projects must address several key challenges with determination. The integration of new fault identification features is critical and should follow a stringent testing protocol to avoid complications during launches, while improvements in GPS and telemetry data must be complemented by efforts to enhance their accuracy and reliability. There also remain significant challenges in the physical recovery of the rockets which necessitate future experimentation with parachute deployment and retrieval techniques. Future efforts focusing on the integration of advanced features such as payload deployment, to include satellites, and active flight controls in the support of strategic defense initiatives provides a diverse set of use cases for future research. Future capstone teams must proactively confront these challenges to build on the foundation established by their predecessors and further advance hypersonic research opportunities for the U.S. military.

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