The Design and Test of a Hybrid Rocket Motor

An analysis of Technology Transfer in Hybrid Rocket Design and its Foundation in the History of Aerospace Propulsion

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

The topic of this paper is the development of aerospace technology post-WWII (World War II), and the relationships that formed around it. Specifically, the design and innovation of the chemical rocket engine and its applications to various sectors of industry. These sectors will be grouped into civilian applications and military applications. Its direct application is the use in a rocket which supports the engine and its propellants (fuels and oxidizers). Their development is closely tied together enough to warrant their discussion as a single technology for the purposes of this paper. Comparably to other technologies, the groups of stakeholders formed are the researchers, designers, manufacturers, and users. More specifically, researchers have been and are mostly responsible for developments in usable propellants and usable engine mechanisms. Designers are mostly responsible for integration and application of the engine and rocket at full scale. The corporate and government bodies involved often serve in several stakeholder groups, with organizations such as NASA (National Aeronautics and Space Administration), a U.S. government civilian body, having branches in all four. Other examples include the U.S. Air force which is a researcher and user stakeholder, and General Dynamics which is a designer and manufacturer stakeholder.

The chemical rocket engine is further categorized into liquid engines which use two liquid propellants, solid motors which use two solid propellants, and hybrid motors which use one liquid propellent and one solid propellent. Monopropellant and Tri-propellent variants exist but will not be discussed. Through post WWII and Cold War efforts, liquid and solid engines have been developed to a high level of fidelity and capability; however, hybrid motor development has been relatively limited with lacking readiness for widespread use in modern day applications. The technical project addresses this need for further development with the intention to design and test a functioning motor utilizing a novel, resin 3D printed oxidizer injector. This development should improve propellant mixing and combustion efficiency. The significance being that hybrid motors currently have poorer engine efficiency than theoretical models (Glaser & Anthoine, 2023). The STS paper addresses the close relationships between the discussed stakeholders in the civilian and military sectors. This includes the history of technology transfer between the two sectors, one famous example being the adoption of civilian launch vehicles from military ICBMs (Inter-Continental Ballistic Missile) (McDougall, 1997). The geopolitical politics and funding allocations of each decade being a significant contributor to these relationships. This also includes the modern-day continuation of these relationships into the application of hybrid rocket development for civilian spaceplanes and advanced missiles. The connection to both topics being that these preexisting institutions and connections directly influence the path that hybrid rocket motor development takes and its eventual consequences.

The Design and Test of a Hybrid Rocket Motor

The hybrid rocket motor addresses downsides present in liquid and solid motors, which are used in mainstream applications. One advantage being that hybrids are notably simpler than liquid engines with only one liquid propellant feed system. Simplicity is an attractive quality as reducing the number of moving parts and failure modes improves engine reliability. Another advantage being that hybrids can throttle their thrust output, which is impossible with a solid motor (Shih-Sin, et al., 2024). This feature being necessary for fine orbital maneuvering, a technique used by civilian and military spacecraft operations. One more advantage being the significantly improved safety over liquid and solid motors. Solid motors have pre-mixed propellants, and liquid engines can rapidly mix their entire store of propellant in the case of a failure. This creates a high explosion risk, which the hybrid motor does not suffer from by separating its propellants through location and state of matter (Venugopal, et al., 2011). This improved level of safety is very attractive to manned, civilian spacecraft (Chae, et al., 2020), and carrier-borne air-to-air missiles (National Academies, 2006). In more detail, chemical rocket engines are a propulsive device that exploits chemical combustion between a fuel and an oxidizer to rapidly generate high-temperature and high-pressure gas, which is then released in one direction to produce a force. This propulsive force produces an equal and opposite reaction on the rocket.

The team has chosen to design a conventional hybrid motor, which uses one liquid oxidizer and one solid fuel. Our propellant combination being liquid nitrous oxide as the oxidizer, and ABS (Acrylonitrile Butadiene Styrene) plastic as the fuel. These were chosen as they are both easily sourced, with average expected performance. ABS was chosen over other options as it is easily 3D printable, allowing the team to explore several design options of various cross-section fuel grains. This is useful since the shape of cross-section determines the distribution of thrust over time. The motor structure will be made up of an aluminum combustion chamber with a phenolic insulator liner, graphite nozzle, resin 3D printed oxidizer injector, aluminum valves, and a high-pressure tank. The team's injector design and manufacturing will be novel to published research and will allow us to explore more complicated injector geometries. The advantage of this being the improved oxidizer distribution and combustion efficiency. The motor will be tested through a hydrostatic test, cold flow test, and hot fire test to prove the design's functionality and measure actual performance. These tests would be performed on a remote test stand with integrated sensors also designed by the team. In more detail, a hydrostatic test is conducted by pressurizing the entire motor with water, proving the motor is safe to support the pressure of combustion. A cold flow test is conducted by running all engine components except the ignitor, proving the flow of oxidizer can be safely and effectively controlled. A hot fire test is conducted by running the motor as designed, with the motor and test stand firmly stationary and all other safety precautions in place.

An Analysis of Hybrid Rocket Design and its Foundational History

Comparable to many sectors of research, modern-day research in hybrid rocket motors is often funded by stakeholders with a history in the industry of several decades, and all the influence associated with it. The technology is a natural continuation of the efforts for innovation in rocket development that were started decades prior with arrangements made between corporate, government, and academic entities. My research will explore how these relationships developed and their formation around civilian and military applications. This is significant as a line of progression can be tracked for civilian and military demands to developments today. The disparity in applications and their mirror in the stakeholders involved will be highlighted with various recent proposals. The paper by MacKenzie (1993) will be used as reference to properly frame this analysis from a Hughsian perspective with distinction between each of the technological systems present. In more detail, the discussed stakeholders will be categorized as system builders split into civilian and military sectors.

The analysis will begin at the birth of serious rocket development in the post-WWII period. It will be discussed how the U.S. government incorporated German rocket scientists into American research, providing an early boost in capability (McDougall, 1997). This primarily occurring under Operation Paperclip, through which scientists affiliated with the Nazi party were pardoned of any crimes and relocated. The progression into the Cold War period, and the formation of the nuclear arms race and space race provide the new overarching cause of motivation for the U.S. federal government. With most funding going to military ventures, rockets were first developed into ICBMs and then repurposed for civilian launch services by institutions such as NASA (McDougall, 1997), one of the most famous being the original Atlas ICBM and the subsequent Atlas family of launch vehicles. This immediately formed a close relationship between the civilian and military sectors. Another relationship formed and solidified around this time with direct influence on rocket development is the Military-Industrial-Academic Complex (McDougall, 1997). This particular technological system starts out as an open system dependent on the political environment of the era and transitions to a closed system with the motivation of continual self-improvement. The topic will be further analyzed by utilizing the paper by Cole (1998) to provide historical context missed in the United Kingdom. This collection of context provides relevant examples of technology transfer and organizational setup still used today. Then, a review of the U.S. Airforce written by National Academies in 2006 will be used to directly quote modern-day motivations for the funding and influence of certain hybrid motor projects over others. The modern-day system builders and the resulting culture in academia will be explored through the analysis by Satta, G. and others (2015).

As discussed, some civilian designers are integrating the technology for space tourism spaceplanes such as SpaceShipOne and Two built by Virgin Galactic, and military designers are integrating the technology for carrier borne missile systems (National Academies, 2006). This disparity creates questions for the stakeholders such as what are the unintended effects of a hybrid motor designed for industry, how easily can a commercial hybrid motor be converted for military use, and should engineers compromise their design to prevent misuse? It can even be argued that efforts preventing the proliferation of this technology should mirror the efforts taken to prevent nuclear proliferation. Insight regarding these concerns over technology transfer between the two sectors is found in the actual state of modern-day space system developments.

This critical concern is raised by Waldrop in her 2004 paper and Lee in his 2023 paper. Then, evidence of the varied and yet unrealized applications will be reported such as the proposal for repurposing fighter jets as platforms to launch civilian space rockets as investigated by Olejnik, et al. (2023). Another paper proposes its application in VTVL (Vertical Takeoff Vertical Landing) aircraft, written by Chae, et al. (2020), which further blends the divide between sectors. This is because improved VTVL aircraft themselves are attractive to both sectors with the U.S. armed forces looking to replace its ageing fleet of V-22 aircraft, and the commercial air taxi market looking for a viable vehicle to enter service. My research will consider these complicated historical arrangements and analyze their impacts on the discussed modern-day developments.

Conclusion

In conclusion, the technical project will produce a physical test article, test data, and an analysis of that data. This will be done with a focus on investigating our novel oxidizer injector, directly providing new hybrid rocket motor research. The analysis through an STS framework provides insight of the technology transfer present in hybrid rocket design and contributions from system builders over the course of this system's development. In addressing this historical context, my research intends to be a resource for stakeholders in both sectors to make informed decisions. The expected result of the future research paper is that the state of hybrid motor technological developments will continue to be extremely intertwined between civilian and military applications; although, with increased interest.

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