NPS-AM-24-091

ACQUISITION RESEARCH PROGRAM
SPONSORED REPORT SERIES

Analyzing Solid Rocket Motors and the Changes in the Industry that Affect the Defense Industrial Base

December 2023

LCDR William R. Gureck, USN

Thesis Advisors: Dr. Nicholas Dew, Professor
Jeffrey R. Dunlap, Lecturer

Department of Defense Management

Naval Postgraduate School

Approved for public release; distribution is unlimited.

Prepared for the Naval Postgraduate School, Monterey, CA 93943.

The research presented in this report was supported by the Acquisition Research Program of the Department of Defense Management at the Naval Postgraduate School.

To request defense acquisition research, to become a research sponsor, or to print additional copies of reports, please contact the Acquisition Research Program (ARP) via email, arp@nps.edu or at 831-656-3793.

ABSTRACT

The United States has a powerful defense industrial base. However, a growing weak spot within this base is solid rocket motor (SRM) production. Several factors contribute to this issue, including a slowdown in research and development of munition energetics and the consolidation of SRM manufacturers over the past two decades, limiting options for the Department of Defense. Additionally, new commercial space companies hold promise in providing a remedy to industry weaknesses yet face barriers in competing for defense contracts due to stringent requirements and expensive and lengthy qualification standards. Importing materials from adversarial countries further threatens the military's supply chain during wartime. To mitigate these challenges, this paper emphasizes the importance of both continuing research in advanced technology and strengthening the domestic supply chain. Encouraging domestic manufacturers and suppliers should foster resilience, reduce reliance on external trade routes during conflict, and enhance the defense industrial base's adaptability and innovation. By implementing the recommendations of this thesis, the U.S. defense industry can maintain its technological edge and the U.S. can remain a formidable competitor in an ever-evolving global security landscape.

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

First and foremost, I would like to thank God for blessing me with this amazing opportunity and for guiding me through this long process. There were many days that seemed incredibly challenging and daunting with all the information that had to be absorbed and digested, but I knew that faith would get me to the end. Without HIS grace, I don't think I would have ever finished this thesis.

This research never would have started if it weren't for the request from CAPT Jonathan Garcia and his curiosity in the commercial space industry. Piles of documents provided and hours of phone calls with CAPT Garcia allowed for this research to point in the right direction and to get the proper level of information to do both the defense and SRM base justice. Thank you, Sir, for all your help and mentorship!

Thank you to Ellen Chang for being the coordinator with all the space companies, as she had a vast network of contacts to assist with the research. Without her, there wouldn't have been any conversations with all the amazing companies listed in this thesis. She was also a great resource for input and had numerous status pings on how I was doing—they were always appreciated.

A tremendous thank you to all the companies that I was able to interact with this past year, for their time and energy getting me educated on the space industry and the complexities associated with it. I'd like to especially thank Jessica Jensen, Doug Stewart and Benjamin Reed at SpaceX for their time and coordination for providing information on how SpaceX works, but also for a wonderful tour of the facility in Hawthorne, CA. Lastly, a big thank you to Matt Steele at Aerojet Rocketdyne for endless support and 24/7 email responses for the hundreds of questions I had regarding AR and the SRM field. I don't believe I would have been nearly as knowledgeable on a lot of things if it weren't for him. His coordination and efforts allowed for a "once in a lifetime" tour of the AR facility in Canoga Park, CA, for which I can't thank him enough.

My advisors, Professor Nick Dew and Professor Jeff Dunlap, were instrumental in ensuring I was pointed in the right direction with this thesis and provided continuous guidance when I was hitting writer roadblocks. Nick was always there to push me along, and for that I'm incredibly grateful. Thank you both for your counsel and guidance.

Though this was an individual thesis, it was a shared effort with LT Marieme Gueye, who worked the systems engineering and modeling side of this research. I thank Marieme so much for her fellowship and all the help throughout the engagements with PEO IWS, space companies, digging through piles of information, and gripe chats regarding what felt like endless writing.

Last, but not least, the BIGGEST thanks goes to my rowdy kids and my extremely wonderful wife, Sarah. She was the cornerstone throughout my time at NPS and was the best at holding down the home fort when I had to hide away in my office for marathon reading and writing sessions. She was the ultimate sounding board for when I had to explain something to help formulate the writing or lull her to sleep when hashing out the complexities of rockets. Whenever I felt overwhelmed or tired, Sarah was there to push me along, or played defense for when Tom and Elle needed something. There were many challenging days these past 18-months, but my family made it all the better, and I could not have done this without them—love you all!

NPS-AM-24-091

ACQUISITION RESEARCH PROGRAM
SPONSORED REPORT SERIES

Analyzing Solid Rocket Motors and the Changes in the Industry that Affect the Defense Industrial Base

December 2023

LCDR William R. Gureck, USN

Thesis Advisors: Dr. Nicholas Dew, Professor
Jeffrey R. Dunlap, Lecturer

Department of Defense Management

Naval Postgraduate School

Approved for public release; distribution is unlimited.

Prepared for the Naval Postgraduate School, Monterey, CA 93943.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AMPAC	American Pacific
AP	ammonium perchlorate
AR	Aerojet Rocketdyne
C-C	carbon-carbon
CSIS	Center for Strategic and International Studies
DARPA	Defense Advanced Research Projects Agency
DDG	guided missile destroyer
DIB	defense industrial base
DOD	Department of Defense
FFP	firm fixed price
GAO	Government Accountability Office
GMLRS	guided multiple launch rocket systems
HTPD	hydroxyl-terminated polybutadiene
ICBM	intercontinental ballistic missile
IWS	Integrated Warfare Systems
JASSM	joint air-to-surface standoff missile
LACM	long-range land attack cruise missiles
LM	Lockheed Martin
LOX	liquid oxygen
LRASM	long-range anti-ship missiles
LRE	liquid rocket engine
M&A	mergers and acquisitions
MTA	middle-tier acquisition
NG	Northrup Grumman
PEO	Program Executive Office
PLA	People's Liberation Army
PLAAF	People's Liberation Army Air Force

PLAN	People's Liberation Army Navy
PLARF	People's Liberation Army Rocket Force
POP	period of performance
R&D	research and development
RP	rocket propellant
SAM	surface to air missile
SBIR	small business innovation research
SLS	Space Launch System
SM	standard missile
SRM	solid rocket motor
STEM	science, technology, engineering, and mathematics
TRL	technical readiness level
UAS	unmanned aircraft systems
VOD	valley of death

I. INTRODUCTION

The U.S. defense industrial base (DIB) stands as an epitome of technological advancement and global prowess. However, recent developments and events have shed light on a growing weak spot within this base, specifically concerning solid rocket motor (SRM) production and the overall declining state of the industrial condition. Several factors have been evolving for some time, including a slowdown in munition energetics research and development. Another aspect is the consolidation of SRM manufacturers over the past 20 years, resulting in a reduced number of options from which the Department of Defense (DOD) may choose. This consolidation not only narrows the field but also hampers competition, hindering the growth and innovation in SRM technology. The emergence of new commercial space companies presents a potential solution to the industry's weaknesses. These companies can contribute valuable ideas and expertise; however, they face formidable barriers in competing for defense contracts due to the lack of resources or time to qualify their product. The stringent requirements for becoming a prime or sub-vendor for defense technology contracts present significant challenges, limiting the participation of smaller space companies and thus suppressing the potential benefits they could bring to the defense industry.

The DOD uses imported materials from foreign suppliers, some that are considered adversaries to the United States, creating a critical vulnerability that poses significant risk to the military's supply chain during wartime. If these foreign sources are unable to fulfill exports or are deliberately cut off from supply routes, it could severely impact the readiness and capability of the U.S. military. Continuing research of the latest technology is only half the solution; the other half should be focused on strengthening the domestic supply chain. Encouraging the establishment of domestic manufacturers and suppliers could create a more resilient network of goods and services, reducing the reliance on external trade routes during times of conflict. By diversifying SRM production and nurturing a robust domestic base, the DIB could become more adaptable, innovative, and capable of withstanding disruptions and adversarial actions. Concrete steps and policy are required to ensure the successful implementation of a robust domestic supply chain.

A. PURPOSE

The purpose of this research is to address critical issues facing the U.S. defense industrial base, such as SRM and energetics production limitations, slowing industrial base development, and supply chain vulnerabilities. By exploring potential energetic munitions solutions and proposing strategies to strengthen the domestic supply chain, this research aims to contribute a better understanding of the defense industry's capabilities and ensure a more self-reliant and resilient defense posture during challenging times. The successful execution of this study's recommendations will fortify the ability for the U.S. to remain a technologically advanced competitor as well as sustain extended conflict, ensuring its continued prowess in an ever-evolving global security landscape.

Near-peer competitors continue to aggressively pursue technological advancements in weapons technologies, preparing for the next global conflict. As U.S. adversaries prepare for the next major war, aspects of the U.S. industrial base are in a state of stagnation, rather than focusing on the development of future weapons to combat advanced munitions and vehicles. It is imperative that the DOD consider all options for boosting the military industrial base to be able to sustain an extended conflict and not become reactionary to countering enemy weapons while also needing to surge production of necessary munitions.

B. SCOPE AND RESEARCH METHODS

The method used to conduct this research is interviewing defense and space industry companies that are primarily focused on rocket production. These interviews are conducted mainly via virtual meetings but also involve site visits to see production and test facilities. This first-hand information from interviews and site visits was combined with information gathered from open-source materials, such as journal articles, council hearings, Government Accountability Office (GAO) reports, and media package documentation from companies.

The research approach is covered in four steps. The first step is to analyze the current DIB and look at the current condition and posture of the DOD as related to SRMs. The second step is to engage and research the commercial space industry to identify challenges that companies face to produce products centered around energetics, SRMs, and even liquid rocket engines (LREs), with solutions through development and innovation. The third step is to review previous and forecasted budgets to address whether the right funding is going into increasing development, production, and inventory of U.S. energetic munitions and SRMs. The last step is to review U.S. supply chain vulnerabilities to identify where improvements can be made to boost the domestic inventory of materials and, ultimately, the inventory of munitions.

C. THE REASON FOR RESEARCHING ROCKETS

Most of the U.S. advanced weaponry relies on a form of rocket propulsion, and everything from an air launched missile, such as an AIM-9X Sidewinder, to the Trident II D5 submarine-launched ballistic missiles relies on solid rocket propellant. In the most basic of explanations, rockets are dependent on energetics to operate. The Hudson Institute report *Rocket's Red Glare: Modernizing America's Energetics Enterprise* explains that energetics "are a class of chemicals that can release huge amounts of energy in a short amount of time," which is ideal for explosives or propulsion (Schadlow et al., 2022, p. 18). To put it a different way, energetics either explode (create a shockwave) or deflagrate (burn violently and with purpose). These two forms of energetics are equally necessary to make munitions. Without either form, the munitions are most likely useless; you cannot fire a missile without a form of propulsion, and the warhead is less effective if it is not packed with explosives. As critical as these categories are, they are receiving little attention from the DOD on improving and bettering the condition of the energetics space; a clear indicator of this is that energetics were not mentioned in the most recent report covering 14 critical technologies of interest by the Office of the Under Secretary of Defense for Research and Engineering. Given the United States' current situation of limited munitions on hand and possible looming conflict with its adversaries, energetics should be on the top of every focus list related to developing weapons, as should improving inventory of these munitions (Schadlow et al., 2022).

This research does not focus on the warhead aspects of energetics but instead is focused on energetics for propulsion, in the form of SRMs. SRMs are crucial to the U.S.

arsenal, and no matter how advanced the front end of the missile is (such as with sensors or a warhead), it is useless if it cannot be launched at the intended target.

D. RESEARCH QUESTIONS

The issue that sparked this research is based around the fact that it takes too long to produce and qualify rockets, mainly missiles. The qualification optimization was not researched in this thesis, but the long lead times to produce rockets and whether the commercial industry outside of the defense space was able to produce rockets more quickly. In order to better understand the situation, the following questions were considered:

1. What problems exist with the current defense industrial base as it relates to SRM manufacturing?
2. If production time takes so long, what has caused this situation to occur and what are the bottlenecks that keep this an issue?
3. What can be learned from commercial space companies to bring in more innovation and suppliers into SRM manufacturing?
4. What can the DOD do to develop and sustain the domestic sourcing and supply chains to increase its missile inventory?

E. ASSUMPTIONS AND LIMITATIONS

The SRM industry is complex, with many aspects that cannot be covered in this paper. Experience, manpower, and time were the primary limitations to this research.

For national security reasons, some data relating to missile characteristics and operation and exact inventory levels are classified. Interaction with commercial companies resulted in the disclosure of proprietary information that is not used in this paper unless authorized by the owner of the information. Certain topics in this paper cannot be fully covered because of requests not to disclose information that would jeopardize the intellectual property of the company or violate distribution statements.

F. BENEFITS

This research is focused on providing the current situation of the U.S. defense industrial base and the challenges that already exist and are likely to arise if corrective actions are not made. The goal is to educate the reader on what the problems are and how to improve the development and inventory of U.S. rockets to better the chances of U.S. success in a war with near-peer competitors. This research should encourage those in the DOD to enact change and consider options for a best path forward, while also bringing to light the possibility for commercial companies to get involved with the DOD. The ultimate goal is to inspire a change in mindset across DOD and commercial entities to rehabilitate U.S. weapon energetics both from a production and a sourcing standpoint.

G. WHO WAS INTERVIEWED

Meetings and discussions were made with both commercial and defense rocket companies that are in various stages of development. The following companies contributed to this research: Adranos (acquired by Anduril Rocket Motor Systems), Aerojet Rocketdyne (acquired by L3 Harris Technologies), Argo Navis, Program Executive Office Integrated Warfare Systems (PEO IWS) 3.0 SM6 BLK1B office, SpaceX, Ursa Major, and X-Bow Systems. All these companies provided information for addressing the current problem in the rocket industry and the challenges associated with conducting business with the government (defense).

THIS PAGE INTENTIONALLY LEFT BLANK

II. MILITARY CONTEXT

Conflict with near-peer competitors is very likely and engagements dealing in small level conflicts have involved the United States for over 250 years. The U.S. military might is at the top on the global rankings, however, countries such as China and Russia pose a potentially significant threat as they develop and grow their militaries. With events such as the Russia–Ukraine conflict, China conducting exercises around Taiwan, North Korea testing ballistic rockets, and even the recent Israel-Palestine conflict show that reasons to use U.S. munitions, either in deployment or trade, are necessary. The purpose of this chapter is to emphasize the global situation and what U.S. adversaries are capable of, and why the United States should boost development and production of energetic munitions.

A. THE CHINA THREAT

China is showing signs that it is mirroring the military growth of the Japanese Empire at the genesis of World War II, and the evidence is increasingly apparent. China imports over 120 million metric tons of beans, grain, and meat annually from Argentina, Brazil, Canada, and the United States. President Xi Jinping recognized that if war were to occur, all of the imports would cease, which would cause widespread famine in China. To prepare for possible import cutoffs, China backtracked on its 90 billion tree-planting projects, a plan that created a 12% forest increase from 1998 to 2020. The result is that all of the forests that were planted have been wiped out to make way for crop fields and ranches (Luttwak, 2023). China's current imports are more than enough to feed the entire country, which then sparks the question for the need to wipe out so much forestation for farmland, if there is not a plan for something.

On top of the surplus of food, China is surging and increasing all aspects of their military arsenal. The DOD's (2022a) *Military and Security Developments Involving the People's Republic of China 2022* addresses the capability and size of the People's Liberation Army, including the following highlights:

- The People's Liberation Army (PLA) consists of approximately 975,000 active duty personnel, 4,400 tanks, and 9,800 artillery pieces.

- The People's Liberation Army Navy (PLAN) is the largest Navy in the world by numerical value, with approximately 340 ships and submarines, 125 of which are significant surface combatants with comparable capability to U.S. Navy ships. China's goal is to have 400 total ships by 2025, 440 ships by 2030, and 70 submarines by 2030, a significant increase from its current 44.
- The People's Liberation Army Air Force (PLAAF) and PLAN Aviation is the largest aviation force in the Indo-Pacific and is increasingly growing to match the number of U.S. forces, which has 2,800 total aircraft, 2,250 of which are combat aircraft. China intends to advance and grow its Air Force, mainly by fielding fourth and fifth generation fighters along with drastically increasing the amount of unmanned aircraft systems (UASs). The PLAAF also has the largest force of long-range surface-to-air missile (SAM) systems in the world, which are a mix of domestic and Russian air defense systems.
- The People's Liberation Army Rocket Force (PLARF) is working heavily on the advancement of its strategic deterrence capabilities while possessing approximately 135 ballistic missiles. The PLARF is continually developing new intercontinental ballistic missiles (ICBMs) with the intent to significantly improve its missile capability and production. According to 2021 intelligence, China is producing three solid-fueled ICBM silo fields in order to bring its total count to 300 new missile silos (DOD, 2022a).

Table 1 shows the approximate number of Chinese assets in the PLAN and PLAAF with available ships and aircraft near Taiwan.

Table 1. Chinese Navy and Air Force Arsenal in Total and Near Taiwan Straits. Source DOD (2022a).

	China	
	Total	***Eastern and Southern Theater Navies***
Aircraft Carriers	2	1
Cruisers	6	2
Destroyers	36	24
Frigates	45	32
Corvettes	50	N/A
Tank /Medium Landing ships Amphibious Transport Dock	57	52
Attack Submarines	56	31
Nuclear Attack Submarines	9	2
Nuclear Powered Ballistic Missile Submarines	6	6
Coastal Patrol (Missile)	84	68
Coast Guard Ships	224	N / A

	China	
	Total	***Eastern and Southern Theater***
Fighters	1,900 (2,900*)	700 (800*)
Bombers/Attack	450	250
Transport	450	20
Special Mission Aircraft	200	150

Though China is advancing its weapon technology, its focus is on increasing the production of military assets with a strategy to saturate the battlespace with forces rather than have finite amounts of high-tech systems. China's strategy of emphasizing higher numbers over advancement demonstrates a complex and layered approach to military readiness of investing in a greater number of ships, aircraft, and land-based vehicles. China is also doubling its number of orbiting satellites and producing a great number of unconventional low-tech devices like the spy balloons seen over the United States in 2023

(DOD, 2022a). The perceived reason is that China is creating a diverse and flexible military capability that is meant to overwhelm opponent forces and force the opposition to expend assets, primarily munitions, in an engagement. Speculation of China's engagement tactics may include the use of low-cost vehicles or weapons, such as UAS's and balloons, followed by a barrage of munitions from ships and aircraft. If executed correctly, the targets would have to be committed to expend all munitions in defense against the attack. By prioritizing quantity and adaptability, China is positioning itself to engage in "unrestricted warfare," a concept that leverages various dimensions of conflict, from naval and space to cyber and unconventional tactics, to achieve strategic goals. This strategy underscores China's understanding of the complex nature of modern warfare and its willingness to use both conventional and unconventional means to gain an advantage (Koffler, 2023).

B. THE RUSSIAN THREAT

Russia's military expansion history covers most of the 20th century when it experienced rapid growth post–WWII under Joseph Stalin's rule of the Soviet Union. Sparking a Cold War from 1945 to 1991, the Soviet Union was a formidable threat to the western world, and it was committed to being the largest military on the globe. The Soviet Union remained committed to the development and rapid production of military assets to prove that communism was superior to all other forms of government in the West. Even with the fall of the Soviet Union in 1991, Russia has experienced a steady growth of its military, which remains a large enough force of which to be mindful (Britannica, n.d.-a). At the beginning of this research, Russia was already engaged in conflict with Ukraine, which started in early 2022, and therefore, the exact composition of the Russian military is unknown due to losses attributed to conflict with Ukraine. However, by estimated 2023 numbers from Statista, Russia has the following assets in its military branches:

- Russian Ground Forces consist of 1,330,900 total military personnel, with 830,000 in active service. The ground element is estimated to contain 12,566 main battle tanks and 151,641 armored vehicles, along with 14,798 artillery and rocket launcher assets.
- The Russian Navy used to have a similar number of ships as the United States;

however, with the fall of the Soviet Union came maintenance and upkeep issues, which resulted in a decrease in the fleet. It is estimated that the Russian Navy has 291 ships, with 70 submarines and 86 corvettes making up the bulk of its fleet.

- The Russian Aerospace Forces are evenly spread across all platforms; the total composition of the Aerospace Force is 4,182 aircraft, with roughly 1,500 being fighters and ground attack aircraft (Statista, 2023).

Russia holds the second largest inventory of nuclear and conventional missiles, with a variety of capabilities and various ranges as depicted in Figure 1 (Center for Strategic and International Studies, 2021). Russia has an estimated 5,977 nuclear missiles, some of which—such as the R-36 SS-18 "Satan"—are capable of ranges up to 10,000 miles. Russia has contributed a vast number of resources to development of its missile arsenal with the purpose of anti-access/area denial for local conflicts but also strategic attacks against other continents (Center for Strategic and International Studies [CSIS], 2021). Significant research and development (R&D) paired with robust production capabilities have kept the Russian missile inventory strong, even with persistent usage of missiles against Ukraine.

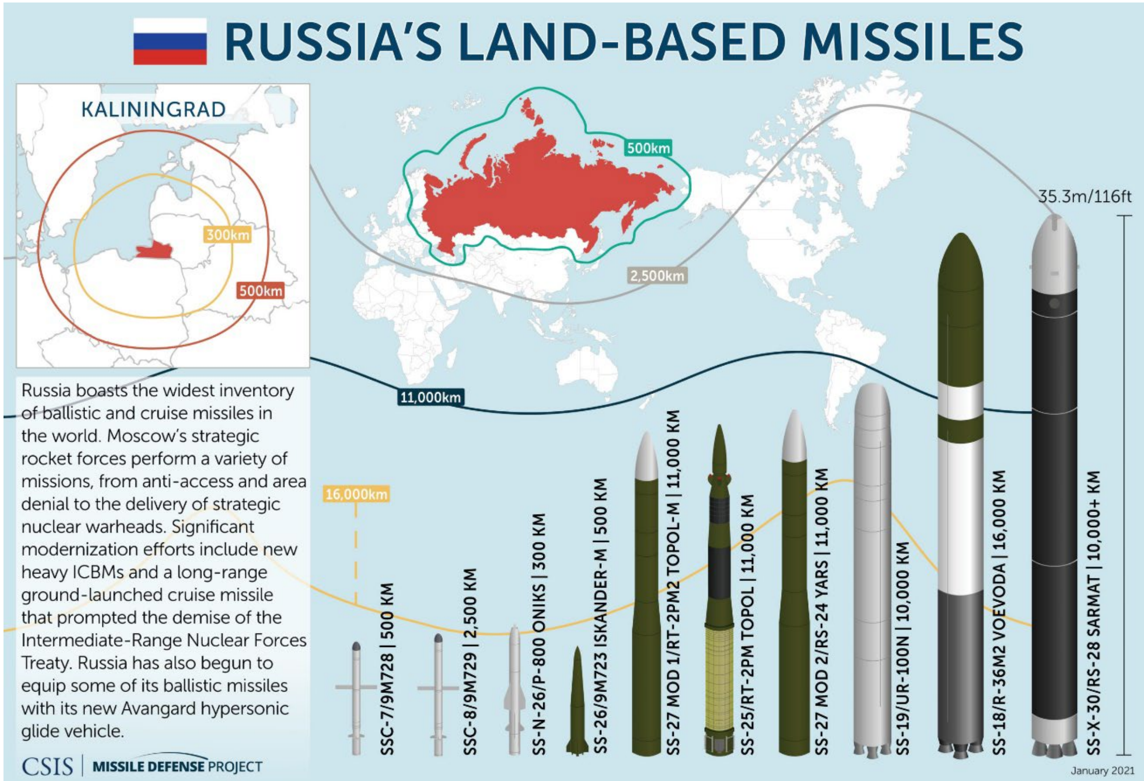

Figure 1. Russian Missiles with Capable Ranges. Source: Center for Strategic and International Studies (CSIS) (2018).

As the Russia–Ukraine conflict has gone on, the speculation is that Russia would run out of conventional missile inventory, mostly its long-range land attack cruise missiles (LACMs), which have been the weapon of choice for attacks on Ukraine. Even with sanctions and export controls, Russia has been able to continue its production of LACMs and keep pressure on Ukrainian defenses. Russia's assumed strategy was to saturate Ukrainian defenses by firing as many missiles as possible at selected targets, with most missiles failing but some being able to achieve the intended damage. With the constant barrage of missiles, analysts projected that Russia would run out of missiles, but that projection has changed as Russia has begun converting its pre-war inventory of anti-ship missiles into capable ground attack missiles and producing postwar assets to keep up with demand. It is estimated that Russia is currently able to manufacture 60 cruise missiles every month, mainly Shahed-136s, but also five Iskander ballistic missiles and two Kinzhals (Williams, 2023).

C. U.S. SUPPORT TO UKRAINE

After the start of the Russia–Ukraine conflict in 2022, the U.S. contributed both funding and weaponry to Ukraine in an effort to assist Ukraine's fighting capability against Russian forces. As shown in Table 2, Ukraine received a multitude of munitions and weapons, with a focus on SRM munitions, which equated to the transfer of 8,500 Javelin missiles, several guided multiple launch rocket systems (GMLRSs) and 1,600 Stinger missiles.

Table 2. Transfer and Inventory Replacement Timeline of Army Munitions. Source: Cancian (2023).

	Number transferred to Ukraine	Production rate (year)	Manufacturing lead time (months)	Production time (months)	Total time to rebuild (months)
155 mm ammunition (recent rate)	1,074,000	93,000	Inventory rebuild not possible because of U.S. training requirements		
155 mm ammunition (surge rate)	1,074,000	240,000	12–18	44	59 (5 years)
155 mm precision munition—Excalibur (recent rate)	5,200	1,000	22	56	84 (7 years)
155 mm precision munition—Excalibur (surge rate)	5,200	2,400	22	23	48 (4 years)
Javelin (recent rate)	8,500	1,000	24	12	149 (~8 years)
Javelin (surge rate)	8,500	2,100	24	12	56 (~5.5 years)
HIMARS (recent rate)	20	20	26	12	37 (3 years)
HIMARS (surge rate)	20	72+	26	5	30 (2.5 years)
GMLRS (recent rate)	"Thousands"	5,000	17+	?	?
GMLRS (surge rate)	"Thousands"	10,000+	17+	?	?
Stinger (recent rate)	1,600	100?	24+	192	216 (18 years)
Stinger (historical rate)	1,600	350?	24+	55	79 (6.5 years)

Color Key

- Unlikely to rebuild inventories within five years
- Inventory replacement within five years at low risk
- Rebuilding timeline unclear but substantial risk of low inventories and long replacement cycles

DOD leadership quickly realized, however, that the amount of assets given to Ukraine severely decreased the U.S. military's future inventory of munitions. Lockheed Martin and Raytheon, manufacturers of the missiles, are both looking for ways to produce the munitions quicker, but, at current production levels, it will take over 5 years to build back the amount that was transferred (Cancian, 2023).

The concern is that manufacturers of the munitions that were sent to Ukraine are sparking surge production responses both for support weapons for Ukraine and in replenishment of U.S. inventories that are dangerously low. As a result, the United States is having to push weapons manufacturers to exceed production, something for which they may have not particularly been prepared. For example, in December 2022, Lockheed Martin, the producer of the Javelin and the GMLRS, was awarded $84 million in extra funding to execute a multiyear procurement contract for additional Javelin missiles. However, even at a production rate of 1,000 Javelins per year, the company will not be able to achieve pre-conflict numbers of the missiles until 2035. Lockheed Martin did say that at its most accelerated rate, it could achieve those numbers in 6.5 years, but that is assuming no further allied transfers or conflicts requiring use of the missiles (Cancian, 2023).

The transfer of the previously mentioned munitions is just a small portion of all that has been supplied to Ukraine. According to the DOD's (2023) Fact Sheet on U.S. Security Assistance to Ukraine, the United States has committed more than $43.7 billion in assistance, to include 6,000 tube-launched, optically tracked, wire-guided (TOW) missiles; one Patriot air defense battery with supplemental missiles; 12 national advanced surface-to-air missile systems (NASAMSs) with munitions; an unreported amount of high-speed anti-radiation missiles (HARMs); over 6,000 Zuni aircraft rockets; over 10,000 Hydra-70 aircraft rockets; and much more (Department of Defense, 2023). These munitions are vital to Ukraine winning the conflict with Russia but are also crucial for the success of the United States if it were to enter into a war and be forced to sustain an extended conflict.

D. U.S. NAVY MISSILE DEFENSE SATURATION AND COST

According to U.S. Navy tacticians and strategists, Chinese maritime forces are expected to fire all their available munitions in an attack, along with Chinese ground forces deploying as many vehicles and drones as possible, to create an offensive swarm in an attempt to overwhelm engaged ships. The implication is that Chinese forces would not resort to selective tactical fires, firing one or several munitions at a time, but would instead unleash entire batteries of ordnance at intended targets. In this case, vulnerabilities in modern anti-ship missile defense are a crucial talking point. The U.S. Navy should expect that the adversary might overpower a ship by launching a barrage of missiles, and when a Navy ship or fleet depletes its entire arsenal of defensive missiles and point-defense mechanisms, it stands defenseless. Naval warfare experts refer to this tactic as saturation attacks and categorize these attacks into three main types: point, platform, and economic.

Point saturation focuses on a single engagement. Defensive mechanisms can only counter a certain number of targets at once and going beyond this capacity almost guarantees a missile strike. The highest number of targets a system can concurrently engage is secret and varies across platforms. Yet naval leaders must always factor this number into their strategies. Platform saturation evaluates a platform's sustained defense capability against repeated attacks. If a ship's defenses cannot thwart an attacker's rapid, concentrated barrage, the attacker can gradually deplete the defender's missile reserves. While considering platform saturation, point-defense tools like the close-in weapon system (CIWS) and Rolling Airframe Missile (RAM) should not be overlooked, along with electronic defenses. Until laser defense weapons become a reality, kinetic solutions are currently the best option against these attacks. However, the core concern remains the stockpile of defensive missiles.

James Turnwall's 2019 *The Navy Is Losing the Missile Arms Race* article explains that economic saturation weighs the financial implications of launching an attack against an opposition's defense and the cost associated with the defense. Factors like development expenses, supply chain costs, and defense strategies, such as deploying two interceptors for each incoming missile, tilt the balance in favor of the offensive missile due to its cost-effectiveness. Often dubbed as theater or strategic saturation, economic saturation gauges missile system efficacy across vast areas. Despite being the least explored in missile defense studies, its significance is paramount, as it concentrates technical, developmental, and employment considerations to a single overlooked metric—cost (Turnwall, 2019).

Table 3 provides a comparison of the anti-ship, air-launched, sea-skimming, supersonic Chinese YJ-12 with the U.S. Standard Missile (SM) series of naval surface-to-air missiles based on the provided details; cost estimates are based on 2018 figures and adjusted for 2% inflation by 2023 standards, and ranges are not exact. The YJ-12 cost is based on the Russian SS-N-26, which the YJ-12 is modeled after (Global Security.org, n.d.).

Table 3. Missile Range and Cost Comparison

Per Missile	Chinese YJ-12	SM-2	SM-6	SM-3
Range (nautical miles)	~215	~65	~130	~330
Cost (in millions)	$1.6	$2.1	$4.5	$20.3

From an economic standpoint, and using the data from the table, China can deploy:

- 1.4 YJ-12s for the price of one SM-2
- 2.7 YJ-12s for the price of one SM-6
- 12.3 YJ-12s for the price of one SM-3

In simpler terms, China can achieve greater theater missile saturation against the United States by spending only 8.3% to 57% of what the U.S. does on its defensive missiles. Turnwall (2019) backs this up by factoring in the engagement doctrines, which typically deploy two or three interceptors for every incoming anti-ship missile, saturating the defenses of an Arleigh Burke–class Guided Missile Destroyer (DDG) could be realized with as few as 15–23 missiles (when considering only SMs). If a DDG were to be outfitted with a full complement of 50 interceptor missiles and generously attribute point defenses with four interceptions, the number increases to 19–27 missiles (Turnwall, 2019).

The YJ-12 presents a significant, cost-effective threat to U.S. naval defenses. The missile's features, combined with its comparative affordability, offer China a strategic advantage, especially when it comes to saturating and overwhelming the defenses of a U.S. naval asset like a DDG. If engagements in the South Pacific or off the coast of Taiwan with Chinese military forces result in saturation tactics, the United States is at risk of running out of missiles not for offensive reasons, but for defense. Though the exact inventory numbers of U.S. munitions, in this case SMs, is classified, strategist experts are convinced that lengthy engagements with China would result in the depletion of both air and surface missiles in a matter of weeks, if not days (Schadlow et al., 2022).

E. U.S. MUNITIONS DEPLETION IN EXTENDED CONFLICT

The potential for major regional conflicts, such as a hypothetical U.S.–China war in the Taiwan Strait, places significant emphasis on the DOD's readiness to match the munitions demands of modern warfare. After estimating that most of the U.S. Navy's surface munitions will be spent on mostly defensive reactions, a consideration was made to research the U.S. Navy and Air Force's offensive capabilities in a maritime fight, and the long-range anti-ship missiles (LRASMs) offered illuminating insights into the battlespace situation.

In his work *Empty Bins in a Wartime Environment: The Challenge to the U.S. Defense Industrial Base*, analyst Seth Jones (2023) depicts a concerning trajectory for munitions inventories during a potential future air and surface campaign. The findings are in line with CSIS war games, indicating that munitions like the LRASM, joint air-to-surface standoff missile (JASSM), and joint air-to-surface standoff missile-extended range (JASSM-ER) could be exhausted within a week in a conflict against a major adversary. Such a scenario underscores the urgency for the U.S. Navy and Air Force to recalibrate their munitions production strategy with future potential demands in mind.

Jones (2023) further describes that in every iteration of the war games conducted by the CSIS, the United States expended an astonishing 5,000 long-range missiles over a mere 3-week period. This included 4,000 JASSMs, 450 LRASMs, 400 Harpoons, and 400 tomahawk land-attack missiles (TLAMs). This rapid consumption underscores the LRASM's utility, particularly for its capability to target Chinese naval forces from distances beyond the reach of China's formidable air defenses. He states that the war games illustrated that, particularly in the early stages of such a conflict, Chinese defenses could deter aircraft from approaching close enough to deploy short-range munitions. Long-range options like the LRASM, with strike aircraft and bombers being the primary platforms for their deployment given their ability to operate outside of Chinese missile ranges, are a capability that needs to be expanded. Jones concludes that significant challenges exists with a production timeline of nearly 2 years for LRASMs and that there is a notable lag in addressing potential shortfalls and is compounded by budgetary constraints, with the fiscal year (FY) 2023 budget proposing the procurement of only 88 LRASMs (Jones, 2023).

Furthermore, recent conflicts like the war in Ukraine offer a glimpse into the evolving nature of warfare. There is a growing reliance on UAS for a myriad of operations ranging from domain awareness and early warning to electronic warfare and information operations. Much like the Chinese spy balloons mentioned earlier in this research, the future battlefield is also likely to feature an array of military vehicles supplemented by advanced munitions, UAS, hypersonic missiles, and other complex weapons systems. These emerging technologies from U.S. adversaries will not only reshape the dynamics of warfare but also impose additional pressures on U.S. and allied production and stockpiling strategies as counter defensives and offensives are employed (Jones, 2023).

The data from the CSIS war games, coupled with an analysis of current conflict trends, highlights the necessity for strategic foresight, preparedness, and production ramp-up. Ensuring an adequate supply of essential munitions like the LRASM, along with dozens of other energetic munitions, will create a proper buffer when preparing for the evolving nature of warfare and is paramount for the U.S. military's readiness and deterrence of potential adversaries.

F. SUMMARY

Understanding the Chinese and Russian threats to the U.S. should point out the importance of requiring better and more munitions in preparation for potential conflict. The support for Ukraine can be argued as necessary, but the number of weapons and munitions sent to the country's materiel aid revealed that the U.S. has a limited inventory that now affects U.S. war endurance. An all-out war with a near-peer competitor will require the utilization of the entire military inventory along with all available munitions to keep air, land, and sea forces combat-capable. A long engagement with an adversary would be unlikely to be sustainable for the United States because a long fight would deplete its munitions quicker than the United States can replace them. This is a serious risk, and it is well understood in military circles. The DOD will have to seriously consider increasing its development of rocket technology while also building a much larger, and cheaper, inventory of energetic munitions. An increase in inventory posture will be accomplished by encouraging other producers and suppliers to enter into the industry, as well as provide further funding and decreased regulations to improve company engagement and development. These aspects will be covered later in this research.

THIS PAGE INTENTIONALLY LEFT BLANK

III. LITERATURE REVIEW

A. A BRIEF HISTORY OF ROCKETS

The principles of rockets date back to 400 B.C., when a Greek named Archytas showed the city of Tarentum his steam-propelled wooden bird, which traversed across a wire (NASA, 2021). It was the first documented time that objects could be propelled by expelling gases through a tube. In 1232, Chinese experimentations with gunpowder-filled tubes, initially attached to arrows and launched by bows, led to the realization that these tubes could self-propel through the force of escaping gas, culminating in the invention of the rocket (NASA, n.d.-a). As time went on, the Chinese continued to perfect their propulsion weapons, and eventually, other countries further developed the capability; the German fireworks maker Johann Schmidlap invented the *step rocket* in the 16th century, which was the first multistage rocket for achieving higher altitudes (NASA, 2021).

Robert H. Goddard conducted early 20th century experiments in rocketry, with a focus on solid-propellant rockets, and later transitioned to liquid propellant to achieve greater power and altitude. Despite initial challenges, he achieved the first successful flight with a liquid propellant rocket in 1926, heralding a new era in rocket flight. Nonetheless, the age of advanced rockets stemmed from solid propellant beginnings, and the value of using propellant grain was discovered as beneficial mostly to weapons (NASA, 2021). The advancements made by Goddard and other pioneers, such as Hermann Oberth, paved the way for the development of powerful rockets like the V-2. World War II demonstrated that rockets were going to play a significant role in warfare, with the German V-2 rocket becoming the world's first long-range guided ballistic missile. Post-war, German rocket scientists, including Wernher von Braun, contributed to the development of SRM weapons and liquid rocket engines, leading to the emergence of advanced government and military rockets (NASA, 2021).

On October 1, 1958, the National Aeronautics and Space Administration (NASA) was formed and sparked the rapid development of rockets. NASA became the leading organization of rocket technology development and encouraged space enthusiasts everywhere to get involved with programs centered around space flight. From the start of the Mercury program in 1958 to the end of the Apollo program in 1972, NASA focused heavily on liquid rocket engines to win the race to the moon but also paved the way for further rocket advancements in both the commercial and defense space (Wilson, 2018). After the last flight of the Saturn V rocket in 1973, there was a lull in the space program until the first launch of the space shuttle on April 12, 1981. The maiden flight of space shuttle Columbia is shown in Figure 2.

Figure 2. Space Shuttle Columbia, STS-1, Lifts Off from NASA's Kennedy Space Center. Source: Mohon (2017).

What was unique about the space shuttle was that it was the first NASA program to utilize solid rocket boosters, which were massive rockets that utilized 1,000,000 pounds of solid propellant and provided 80% of the initial takeoff thrust for the vehicle (Wilson, 2018). Due to the space shuttle's fuel requirements, and frequency of launches, thousands of manufacturers and suppliers started entering the industry to provide the level of demand required to keep the shuttles launching on time.

B. LIQUID ROCKET ENGINES VS. SOLID ROCKET MOTORS

There are two forms of propulsion methods that are mainly used in rockets, liquid rocket engines (LRE) and solid rocket motors (SRM), which achieve the same goal but operate very differently from one another. The propulsion operation fundamentals are simply shown in Figure 3.

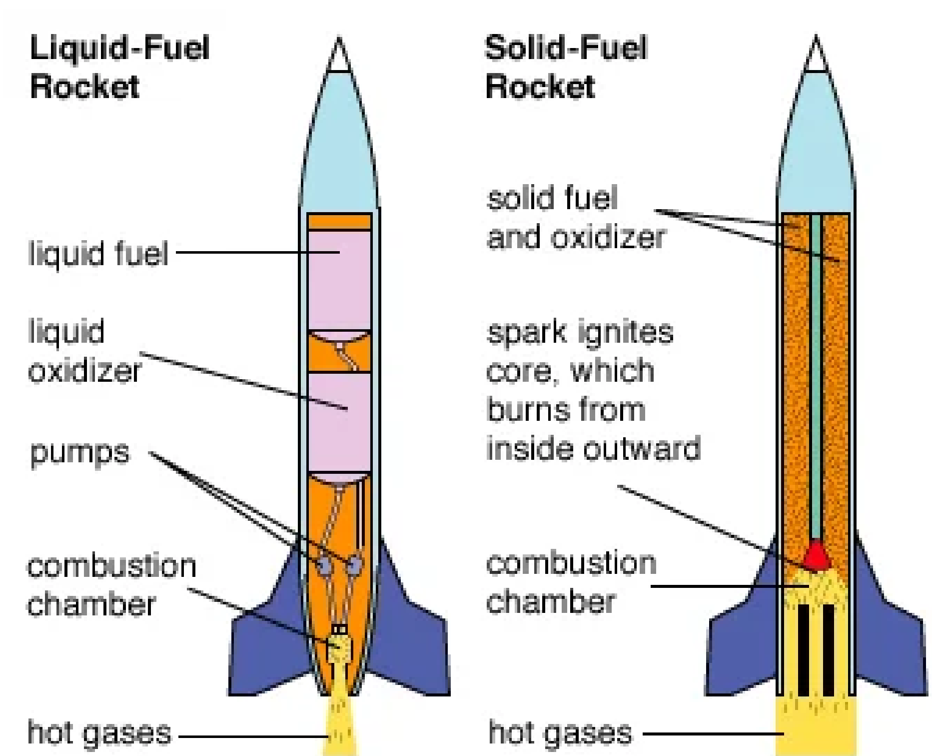

Figure 3. Cross Section of Liquid- and Solid-Propellant Rockets. Source: Britannica (n.d.-b).

LREs consist of two separate pressurized chambers that hold propellant and oxidizers. During operation, the propellant undergoes aerosolization and then combines with the oxidizer in the combustion chamber, which is ignited within that chamber to generate thrust. The two liquids are rocket propellant (RP), which is generally refined kerosene, and oxidizers, which might be either liquid oxygen (LOX) or hydrogen peroxide, depending on the application (Sutton & Biblarz, 2010). SpaceX prefers a mixture of RP-1 and LOX on its Merlin engines (SpaceX, n.d.-a). Despite its complexity, this system allows for regulation of the feeding mechanism, enabling the engine to be stopped and restarted as needed, providing complete control over the engine's performance throughout its usage. The advantage to using liquid engines is that they are intended to be reused and are used on large platforms, such as SpaceX's Falcon 9, and the now-retired Space Shuttle.

LRE systems possess inherent drawbacks due to their necessity to store the liquids outside of the rocket until they are ready to be launched, an aspect that leads to increased costs and complexity in storage and operations. Fueling the rockets to their maximum capacity is a continuous process as the LOX boils off, and in the case of the Falcon 9, fueling begins roughly 30 minutes prior to launch and can potentially be a factor for halting a launch on time (SpaceX, n.d.-a). Another issue with liquid engine platforms is that movement on the ground is dangerous and unacceptable, as the liquid shifting within the tanks can cause strain, or even damage, to the overall rocket. Due to the storing and movement of liquid, the use of LREs is not ideal for the DOD, and therefore, solid rocket motors find applicability (Sutton & Biblarz, 2010).

A solid rocket motor operates by combining fuel, oxidizers, and other additives, such as glue, into a solid composite known as *grain*. This grain is typically shaped into cylindrical or geometric forms within the body of the rocket, known as the case. When ignited, the solid propellant undergoes a process called deflagration and propagates through the propellant grain, rapidly releasing gases and heat (Sutton & Biblarz, 2010). An introduction brief from PEO IWS 3.0 at the start of this research described having the propellant and oxidizer mixed and molded within the case to remove any aspects of having to store fuel externally and is considered to have a high reliability factor, something that is extremely ideal for munitions (PEO IWS 3.0, 2023).

The office also pointed out that SRMs are also simple to store and transport since their fuel is encased within the rocket and do not require any further fueling. Simply put, SRM munitions are the most ideal, and safest, propulsion method for military use. Another benefit is that SRMs can generate a lot of rapid thrust, another ideal attribute that is preferred in military applications. SRMs can also be stacked in stages to achieve increased range and speed or provide the necessary initial thrust to begin flight. The SM is a good example of this staging, depicted in Figure 4, which requires the use of the Mk 72 booster package to have the required energy to rapidly exit a missile cell on a U.S. Navy vessel, then ignite the Mk 104 second stage motor for intercept after expending and detaching the Mk 72 booster (PEO IWS 3.0, 2023). These two stages achieve the same goal but are built differently with specific purposes; both are greatly needed for the missile to accomplish intended results. The downside to SRMs is their inability to be throttled or shut off after being ignited, and the rocket will need to burn its entire phase or self-terminate if direction or speed are not met (Schadlow et al., 2022).

Figure 4. A Mk 72 Booster in Use during a Standard Missile 6 (SM-6) Launch. Source: Hempel (2016).

C. SOLID ROCKET MOTOR COMPONENTS AND HOW THEY WORK

SRMs are preferred in defense and government space for the fact that they require very few moving parts and are ideal for reliability and long-term storability. While an LRE might have dozens of main components needed for operation, SRMs operate using four. As shown in Figure 5, the main components are propellant grain, the case, nozzle, and igniter (Purdue University, n.d.). Though these seem like simple parts, they take a considerable amount of development and manufacturing to withstand intense temperatures, high velocities, violent directional changes, and dynamic environments.

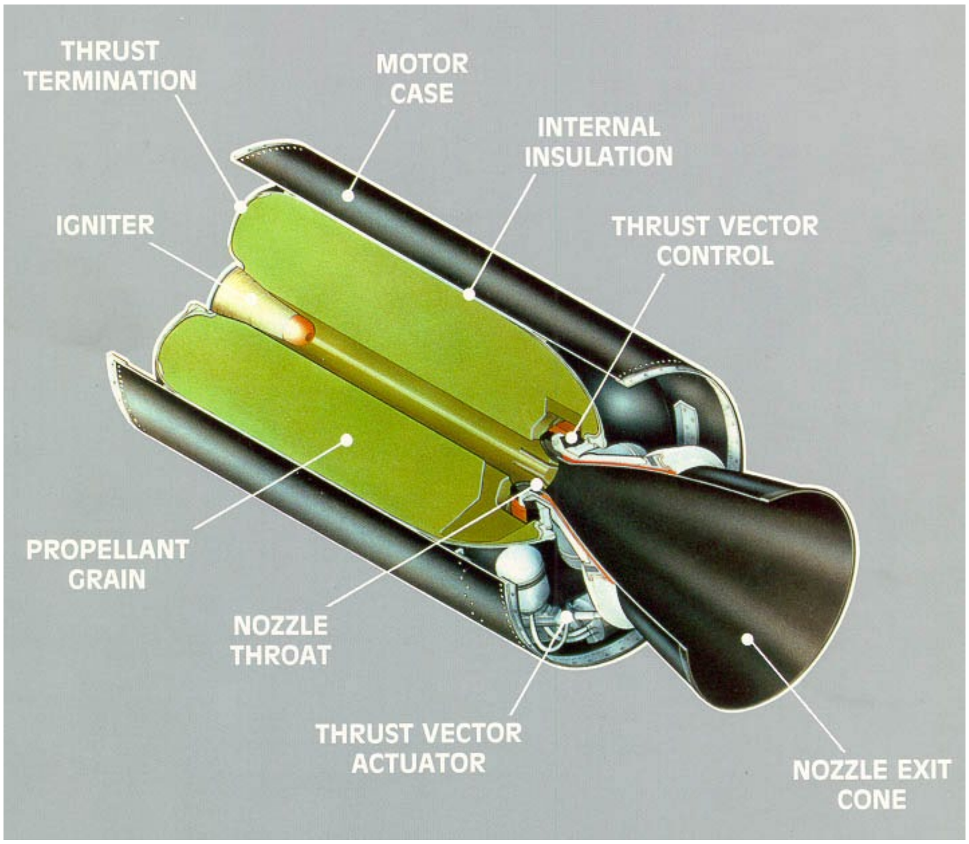

Figure 5. Solid Rocket Motor Cut-Away and Components. Source: Purdue University (n.d.).

The propellant grain is a unique part of the SRM and offers a wide range of configurations based on the desired performance and characteristics of the rocket. The propellant grain is made up of aluminized hydroxyl-terminated polybutadiene (HTPD), an fuel mixture of aluminum powder added to a rubber binder, and ammonium perchlorate (AP) that acts as the oxidizer (Sutton & Biblarz, 2010). A presentation from PEO IWS 3.0 (personal communications, January 27, 2023) at the start of this project explained that the grain is the shaped mass of processed solid propellant inside the rocket motor and the geometrical configuration of the grain governs the motor performance characteristics. They further described that propellant grains are cast, molded, or extruded bodies and their appearance and feel is similar to that of hard rubber or plastic.

The case of the rocket is the most crucial part of the whole assembly because it contains the pressure and temperature of the burning propellant. George Sutton and Oscar Biblarz in Rocket Propulsion Elements describe that the case "not only contains the propellant grain, but also serves as a highly loaded pressure vessel" and "serves also as the primary structure of the missile or launch vehicle"(Sutton & Biblarz, 2010, p. 556). In order to withstand the combustion of the grain, the case is made from high-strength metals, like aluminum, steel or titanium, then wrapped externally by wound-filament composites or plastics for extra strength (Sutton & Biblarz, 2010).

SRM nozzles are designed to focus the energy from burning propellant out the back in the form of exhaust, thus propelling the rocket forward. Nozzles require significant manufacturing efforts and are made to withstand temperatures up to 5000-degrees Fahrenheit, particularly at the throat where the case and nozzle meet (NASA, 2020). Sutton and Biblarz (2010) state that:

> Almost all solid rocket nozzles are ablatively cooled. The general construction of a solid rocket nozzle features steel or aluminum shells (housings) designed to carry structural loads, and composite ablative liners which are bonded to the housings. (p. 567)

The ablative liners are bonded to the nozzles and help control the heat dissipation and rely on heat-absorbing capacity to endure the entire duration of the burn, which requires the highest grade of materials and craftmanship (Sutton & Biblarz, 2010). The most crucial piece of the rocket is the throat, the connecting point between the case and nozzle, as it suffers the most intense level of heat and pressure.

During a discussion with Matt Steele, Director of Business Development at Aerojet Rocketdyne, he mentioned that the throat is preferably made from carbon-carbon (C-C) phenolics, a manmade material that is fabricated using woven carbon fibers in a carbon matrix that are then pressure treated to fill in the gaps between the carbon. Aerojet Rocketdyne further mentioned that the carbon-carbon phenolic fabrication process takes 6 to 9 months (cycle time) and is bound by the laws of physics; in other words, it cannot be made any faster than that time due to the nature of the production process (personal communication, February 13, 2023). He mentioned that without these throats, high-end SRMs would not be able to operate the way they have been designed, especially for military use as other materials would degrade too rapidly.

The last main component of SRMs is the igniter, which is a device that causes the combustion of the propellant grain. Steele explained in the interview that the igniter works like a small SRM, and is either located at the forward or aft section of the rocket, and fires within the propellant, thus causing an unstoppable burn of the grain through the case. Also known as squibs, the igniters are equally as complex as the actual rocket itself, and can take almost as long to make as the throats, thus posing a second cycle time constraint in the overall SRM manufacturing process (M. Steele, personal communication, February 13, 2023).

Overall, interaction with rocket companies in this research all confirmed that SRMs are much simpler than LREs but are more advanced when it comes to the unique components. Due to the complexity and specialization required for SRMs, production of an entire rocket can take anywhere from 12 to 24 months to complete, which is significant for something that can only be used once. The production time for the throats and the current manufacturing methods of the cases cause the most delay. Once the whole assembly is fabricated, propellant grain then has to be mixed and casted into the case, another aspect of the process that takes a while for pouring and curing times.

D. DEMAND FOR SRM PROPELLANT DROVE THE ROCKET INDUSTRY

The space shuttle program greatly invigorated the propellant industry due to the demand that was created by the launching of the vehicle. The program's vast requirement for solid rocket boosters led to an unprecedented demand for advanced propellants. As a result, a multitude of manufacturers emerged, focusing on R&D efforts to produce more efficient and safer propellants. This booming era not only furthered technological advances but also contributed significantly to job creation and strengthened collaboration between NASA, the DOD, and private suppliers (Young, 2007). NASA and the DOD require a healthy industrial base to maintain their necessary levels of weapon and propellant systems production, with many prime and sub-tier suppliers who also possess the drive for continuous scientific, engineering, and manufacturing expertise contributing to meet those needs. According to Evaluating Solid Rocket Motor Industrial Base Consolidation Scenarios, from 1990 to 2010 NASA demanded 1.25–2 million pounds of propellant per launch, while commercial, strategic, and missile defense propellant needs were in the tens of thousands, a drastic difference between the categories of rocket systems. A quick representation of the required amount of propellant per launch is shown in Figure 6, showing NASA's demand for propellant was 10–25 million pounds per year, almost 2 to 5 times greater than DOD's demand of 2–10 million pounds per year (Gladstone et al., 2016).

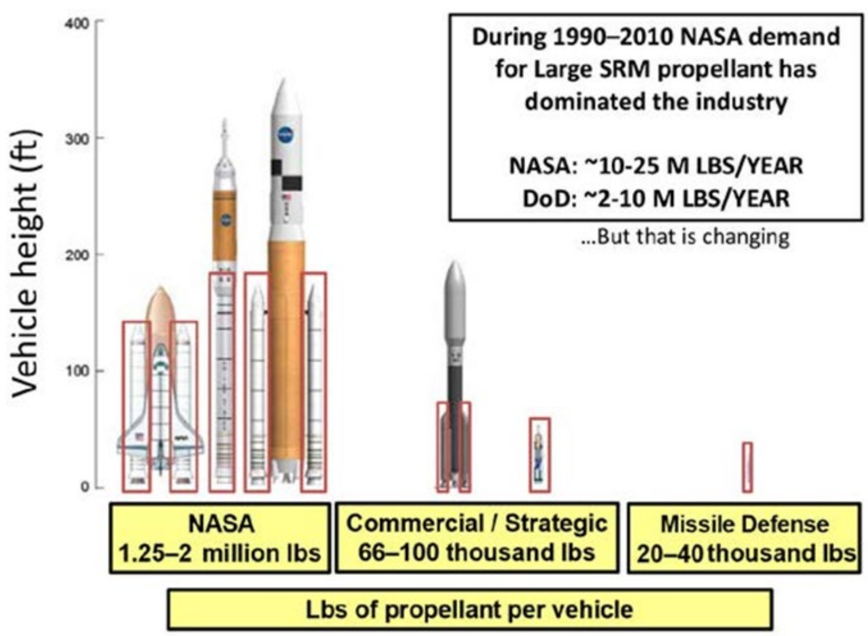

Figure 6. Required Amount of Propellant for Space Vehicles and Defense Missiles. Source: Gladstone et al. (2016).

The 1990s were the beginning of the propellant industry slowdown, even though propellant demand was at an all-time high of 35 million pounds ordered in 1990. With the space shuttle program nearing its saturation point and external challenges such as economic downturns and tragic incidents like the Columbia disaster in 2003, the reduction of shuttle missions, and consequently the demand for propellants, decreased. The industry faced additional pressure from technological advancements that favored reusable propulsion systems, such as LREs, and the rise of international space programs. As a result, many propellant suppliers underwent mergers or acquisitions, while others, especially smaller players, found it difficult to sustain operations and were eventually compelled to shut down (Gladstone et al., 2016). The government is the major customer of SRMs, and the decommissioning of the Space Shuttle in 2011, along with the slowdown of strategic rocket production, sent a shockwave through the industry.

Figure 7 shows depiction of a 2017 U.S. Government Accountability Office (GAO) report that pointed out that the space shuttle made up around 90% of the total U.S. demand for SRM propellant during the program's service, and the cancellation of the program resulted in a dramatic reduction in demand for SRM propellant within the industry (Chaplain, 2017).

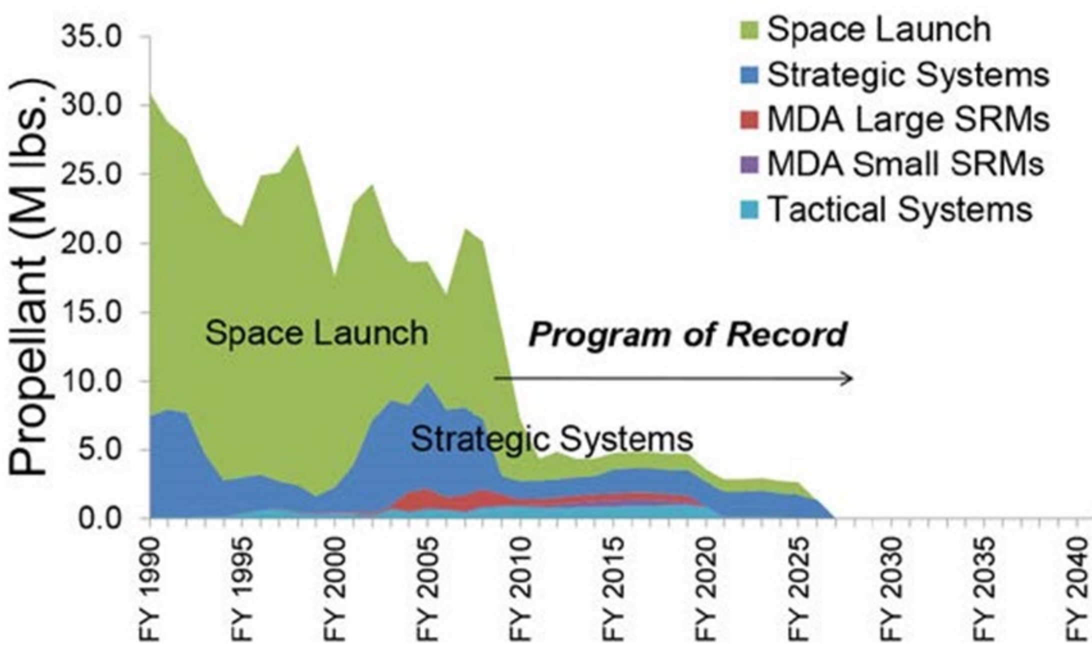

Figure 7. Historical and Future Demand of Large and Tactical SRMs. Source: Gladstone et al. (2016).

Companies that supplied SRM-related products had to adapt to the changing environment, either by merging or being very limited to the availability of sub-tier suppliers, some of which were single-source. Chaplain did point out that NASA hinted that the industry would see an increase in demand for solid propellant due to the Space Launch System (SLS), which requires two large SRMs, each of which require 1 million pounds per launch. However, the demand will remain relatively low for the time, since the program has had only one launch to date, on November 16, 2022, with planned future launches over the next 3 years (NASA, n.d.-c).

E. CONSOLIDATION OF SOLID ROCKET MOTOR COMPANIES

Since 1995, defense solid rocket motor manufacturers have consolidated and merged, narrowing the options the DOD has with various vendors. Figure 8 shows that within the past 20 years, the number of major U.S. SRM manufacturers went from six to two, Aerojet Rocketdyne (acquired by L3 Harris Technologies in July 2023) and Northrup Grumman (NG), along with the starting of a Norwegian company, Nammo Raufoss, an alternative manufacturer for the SRM portion of the advanced medium-range air-to-air missile. These mergers and acquisitions (M&A) in turn decreased the number of prime and sub-tier suppliers from 5,000 to 1,000, heavily limiting competitive options across the entire SRM market (Mak, 2017).

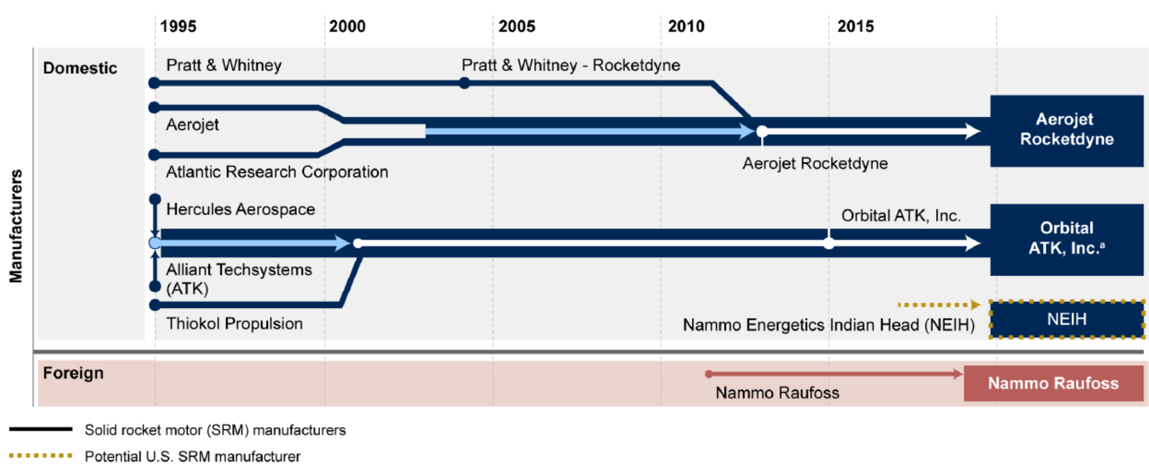

Figure 8. Industry Trends of SRM Manufacturers since 1995. Source: Mak (2017).

The consolidation of defense SRM companies is one aspect of the overall consolidation of defense companies. According to the DOD's (2022b) *State of Competition Within the Defense Industrial Base*, the 1990s experienced a drastic consolidation within the U.S. defense industry as "aerospace and defense prime contractors shrank from 51 to 5: Lockheed Martin, Raytheon, General Dynamics, Northrop Grumman, and Boeing" (p. 4). Table 4 shows the decrease in prime vendors from 1990 to 2020 and what spaces in the industry have consolidated the most.

Table 4. Decrease in Contractors for Major Weapon Categories. Source: DOD State of Competition (2022b).

Weapons category	Total U.S. contractors			Current U.S.-based prime contractors
	1990	1998	2020	
Tactical missiles	13	3	3	▶ Boeing ▶ Lockheed Martin ▶ Raytheon Technologies
Fixed-wing aircraft	8	3	3	▶ Boeing ▶ Lockheed Martin ▶ Northrup Grumman
Expendable launch vehicles	6	2	2	▶ Boeing ▶ Lockheed Martin
Satellites	8	5	4	▶ Boeing ▶ Hughes ▶ Lockheed Martin ▶ Northrup Grumman
Surface ships	8	5	2	▶ General Dynamics ▶ Huntington Ingalls
Tactical wheeled vehicles	6	4	3	▶ AM General ▶ General Motors ▶ Oshkosh
Tracked combat vehicles	3	2	1	▶ General Dynamics
Strategic missiles	3	2	2	▶ Boeing ▶ Lockheed Martin
Torpedoes	3	2	2	▶ Lockheed Martin ▶ Raytheon Technologies
Rotary wing aircraft	4	3	3	▶ Bell Textron ▶ Boeing ▶ Lockheed Martin (Sikorsky)

There are various reasons for the consolidations, but mainly the decrease in war and conflict forced companies to band together or exit the industry entirely. The reason for merging gives companies more likely opportunities to be awarded contracts or achieve development of new systems while surviving the acquisition process, but limit the options of the buyer, in this case the DOD. Major capability acquisitions are just that and require years-long design, prototyping, development, initial production, testing, full rate production, operational fielding, and sustainment, which can be extremely challenging to bidders to survive the entire pipeline (Defense Acquisition University, n.d.). The companies that merge become too large and too strong while forcing out new entrants into the market. New program opportunities are limited, and those that become available run the potential for forcing out smaller bidders who do not meet the requirements or cannot reach acquisition completion due to funding and/or not meeting contract requirements (DOD, 2022b). Maiya Clark notes in her 2022 report *Promoting Defense Industry Competition for National Security's—Not Competition's—Sake* that:

> The United States needs both a strong national defense and a strong defense industrial base. A strong industrial base includes healthy and innovative prime contractors, as well as a robust ecosystem of subcontractors and lower-tier suppliers to design and manufacture defense end items and their components at a reasonable cost to their customer, the U.S. Department of Defense (DOD). (p. 1)

In essence, the goal of the DOD is to acquire the highest quality products, such as the most technically advanced weapons systems, at the most reasonable price, which is best achieved through competition (M. Clark, 2022). However, the consolidation of companies does not create an opportunity for the DOD to maximize this aspect.

Clark (2022) further explains that the defense industry does not follow the typical free market design, as the DOD is the only customer in the defense industry that has to follow the "constitutional mandate to defend the country, [and] must operate under the constant imperative to make sure companies in the market can provide an uninterrupted supply of materiel the DOD needs" (p. 2). Thus, the DOD faces the challenge of striking the right balance between selecting the right prime vendor for the materiel and not being subjected to limited selection and sourcing risk due to there being too few vendors for the requested product.

The issue that forms with these consolidations is that the limited number of companies reduces competition and creates a sourcing risk for the DOD. A reduction in competition allows prime contractors to stick more to their prices or meet delivery requirements since they run the potential of being the only supplier of a needed requirement. In essence, the reduction in competitors affects overall key supplies and equipment available while neutralizing small businesses wishing to do business; thus affecting supply chain operations and any possible innovation and performance improvements for government contracts (DOD, 2022b).

1. Single and Sole Source Suppliers

Single-source and sole-source suppliers refer to situations where buyers procure goods or services from one supplier, but the context varies. With a single-source supplier, a buyer intentionally chooses to work with only one supplier, even when alternative suppliers are available, often due to quality, relationship, or strategic reasons. In contrast, a sole-source supplier scenario arises when there is no alternative, and the buyer has no choice but to purchase from that one supplier because no other suppliers offer the required product or service. Both situations create dependencies between the buyer and supplier, but the dynamics and motivations differ (Perry, 2023).

The decrease in demand across the SRM industry caused major M&As and pushed smaller suppliers to leave the market as it was no longer profitable to supply the DOD and government. There was a ripple effect across suppliers as more prime contractors merged and sub-tier suppliers decreased since only trusted and preferred vendors would get business. Without warning, suppliers would become unavailable and therefore disrupt the supply chain for missile production, thus causing those left to supply goods and services to control pricing and timing (Mak, 2017). The problem that exists is that fewer sub-tier suppliers are available to prime contractors and cause a situation where long lead times or price inflation can occur, thus extending procurement time and overall unit price. In the Gladstone et al. report (2016), a risk assessment, displayed in Figure 9, was emphasized based on companies who made key parts for SRMs, mainly regarding NASA, and the associated programs affected if the suppliers became unable to fulfill orders.

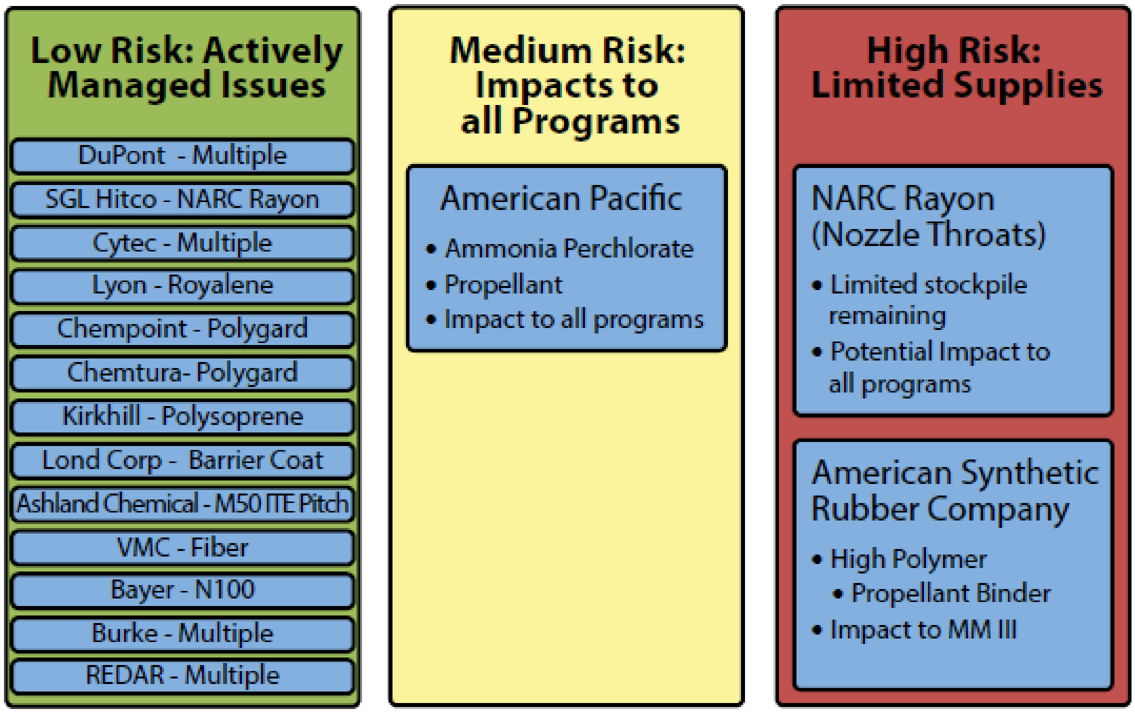

Figure 9. Supplier Program Risk. Source: Gladstone et al. (2016).

Though the figure shown is a snapshot of the overall SRM industry and a small fraction of the DIB, it still brings to light that limited suppliers exist in certain areas and have a high potential of affecting production if the suppliers were to exit the market. As mentioned in the solid rocket motor component section of this research, two of the four main components of the rocket motor are part of the medium to high-risk category. In the medium-risk category is AP, which is the oxidizer component of the grain of the SRM and is mainly produced by American Pacific (AMPAC). Before Aerojet Rocketdyne opened their new Camden, AR facility in 2022, AMPAC was the leading and only trusted producer of AP, which relied heavily on DOD and government demand to produce AP at a steady rate, at a fixed cost (DOD Office of Inspector General, 2020a). AMPAC was the single source supplier of AP, meaning it was the DOD's deliberate choice to buy AP from the company even though other suppliers were available, but would make those other suppliers difficult to approve for use in defense munitions (Gladstone et al., 2016).

In the high-risk category, the North American Rayon Corporation (NARC) rayon nozzle throat components were the preferred material for the space shuttle nozzles until the notice from the company to halt production of the rayon material in 1997 due to financial reasons (Cook et al., 2000). As a result, NASA stockpiled as much of the material as possible to ensure proper levels of SRM production were achieved, which caused the frantic buying of rayon from NARC as they were the only supplier of the ablative material. Another aspect of the company shutting down forced NASA to go through a replacement phase and rush to certify a new or substitute material from another company (Cook et al., 2000). American Synthetic Rubber Company, who produces the binder to make HTPD that acts as the glue to keep the grain together, is the only supplier of the product for all SRM propellants (Harbaugh, 2019).

The key take-aways from this section is that the availability and reliance on single and sole source suppliers pose a huge risk to SRM programs. For the past 30 years, companies who make parts for SRMs have dwindled or consolidated, thus creating limited opportunities for the DOD and government and overall causing a national security issue. Even prime contractors suffer from limited sub-tier suppliers and are either forced to produce the needed supplies, known as vertically scaling, or horizontally scale by finding suitable suppliers who meet the quality and needs to remove the capital and management burden.

2. Limited to No Competition

As mentioned previously in Maiya Clark's (2022) paper, competition is good for the market and especially for the DIB, since "competition normally results in better products, at lower prices, delivered faster" (p. 4). The M&As of defense prime contractors created an environment where little competition exists, and fewer options are available for the DOD and government. Not only do fewer contractor options increase the potential for higher cost contracts and longer delivery times, it also negatively affects the likelihood for smaller businesses to participate in order to provide better platforms and create resilience in the DIB (M. Clark, 2022).

The lack of competition has also affected the possibility for improvements in research and development since the companies who bid hold the market on what can be produced. A 2017 GAO report recognized smaller companies were unable to enter and compete, while those who already participate inside the DIB are not compelled to rapidly develop unless the compensation, such as increased funding is in place, or the requirements to the product are specifically asked by the buyer (Sullivan, 2017). Figure 10 shows the competitive rate over the past 10 years, which is dollars obligated for competitive contracts (two or more offerors) that is divided by total obligated dollars. These rates are dependent on mission, type of product, services required, and current global events (DOD, 2022b).

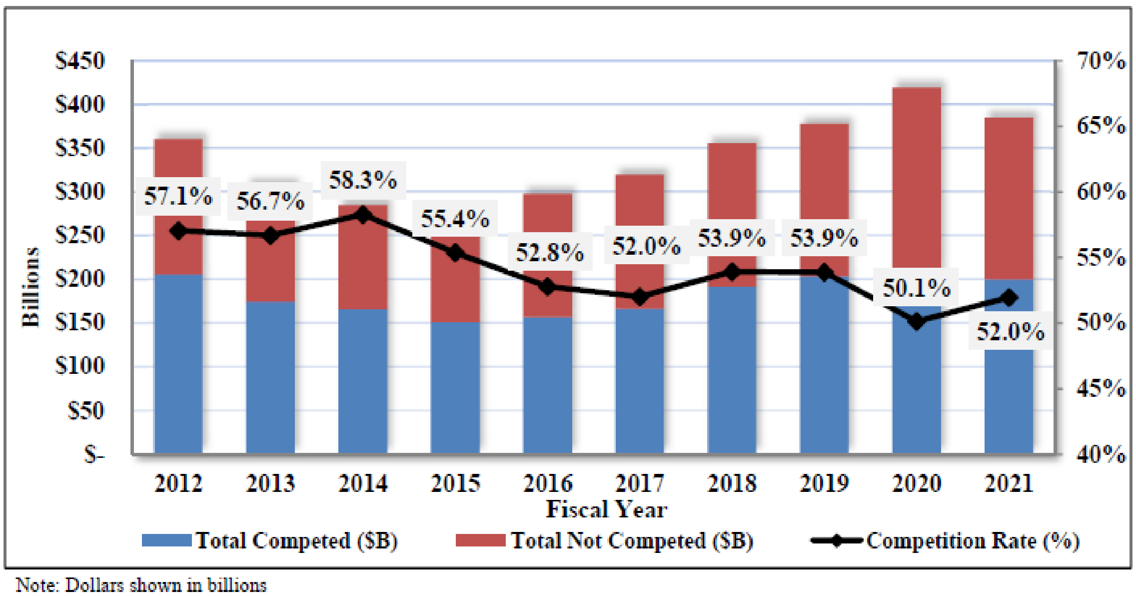

Figure 10. DOD Competitive and Non-competitive Trend. Source: DOD State of Competition (2022b).

What the graph depicts is that competition across all categories in the DOD has experienced a small decline to a steady rate of competition based on funding obligated and that there is opportunity for competitive growth. However, in the missiles and munitions (M&M) category the market has too few competitors—those in business are large and established companies, with vast experience, propriety designs, and technology (DOD, 2022b). The trend of decreasing competition could continue into future years and will further affect the ability for the DOD to effectively develop and replenish M&Ms in an affordable and rapid manner.

F. PORTER'S FIVE FORCES AND BARRIERS TO ENTRY

Barriers to entry are major aspects that prevent entrants from entering a market and are determined based on a series of aspects that either make it easy or difficult for companies to compete within the market. The barriers stem from Michael Porter's Five Forces Model, as shown in Figure 11, in which rivalry within a market is affected by buyers and sellers, along with new entrants and available products. Each of the five forces have different levels of effect on industries and the scales can be drastic depending on the involved parties and complexity of the products or services (Porter, 2008).

Figure 11. Porter's Five Forces Model. Source: Porter (2008).

In the case of defense, the threat of new entrants as well as threat of substitutes is low, while the bargaining power of suppliers is potentially high, such as the lack of competition in the SRM industry. Identifying and recognizing these forces allows organizations and companies, both involved and looking to get involved, to determine whether entrance into them market is worthwhile. Porter (2008) writes in his work, *The*

Five Competitive Forces That Shape Strategy that barriers to entry are based on the threat of entry aspect force and "depends on the height of entry barriers that are present and on the reaction entrants can expect from incumbents" (p. 81). Which means that if new entrants fear retaliation from incumbents, those already established in the market, then entry barriers are high and the threat of entry is low. The threat is what drives industry profitability and the threat of entry itself, not the actual entry of a new competitor, prevents further profitability of incumbents (Porter, 2008).

With Porter's Five Forces and the barriers to entry in mind, in relation to the defense industry, the consolidations of SRM contractors have created an environment where threat of entrants is low and the DOD is in a position where the limited entrenched suppliers are able to bargain more effectively for profitability and schedule determination. The DOD needs to consider these forces and how they are affecting new entrants into the SRM industry and allow for new technological capabilities that will encourage growth and innovation within the DIB.

G. DOD OBSTACLES FOR COMMERCIAL INDUSTRY

1. Challenges Commercial Companies Face with Defense

Working with the DOD and the government can be potentially intense for companies, especially small businesses looking to sell within the DIB. In the 2017 GAO report addressed earlier, it was stated that interviews were conducted with 12 innovative companies that did not regularly conduct business with the DOD and pointed out key challenges, shown in Table 5, as to why they were deterred from selling their products or services to improve military use. These challenges were responsible for preventing competitive growth within the DIB as the energy, funding, and time were too much for interested businesses from effectively achieving a contract. GAO identified that companies were expending tremendous resources to compete for DOD contracts, such as one of the 12 companies interviewed disclosed that it required 25 full-time employees over the course of 12 months and millions of dollars later to prepare a proposal for a DOD contract; something that normally took three part-time employees 2 months and only thousands of dollars for a commercial contract of the same product (Sullivan, 2017).

Table 5. Areas of Concern from Company Observations. Source: GAO (2017).

Challenges That Deter Companies from Developing Products for Military Use	
Complexity of DOD’s process	Intellectual property rights concerns
Unstable budget environment	Government-specific contract terms and conditions
Long contracting timelines	Inexperienced DOD contracting workforce

Another aspect that affects potential entrant companies is the inability to prove their product or service to meet the needs or requirements of the DOD. Instead of selling directly to the DOD, some companies must spend several years demonstrating their product within other companies or organizations before they can establish a viable proposal through that company or directly to the DOD (Sullivan, 2017). In relation to SRMs, these challenges are further amplified for any companies looking to provide their innovative products and services since the DOD is not willing to take the risk with unqualified designs.

Funding and timelines have a greater effect on participation from new entrants and have a high chance of either preventing a company from wanting to engage with the DOD, but also surviving the contracting process. DOD funding for new contracts or programs generally take 2 years to establish, and are oftentimes plagued with delays from continuing resolutions and sequestrations which result in companies risking going out of business or losing investors (Sullivan, 2017). Traditional acquisition timelines, such as major capability acquisitions (MCA), take upwards of 10 years to complete and therefore the FY 2016 National Defense Authorization Act (NDAA) created 2 to 5 year rapid acquisitions, or middle-tier acquisitions (MTA), to rapidly develop prototypes for DOD components and their desired capabilities (Defense Acquisition University, n.d.). MTAs were a move in the right direction; however, if the DOD component did not define the proper requirements for the desired capability or have changes in budget or priorities in the short time span, it would affect a contractor to the point of failing a program, resulting in contract termination (DOD Office of Inspector General, 2020b).

2. Regulations and Requirements

Two other reasons for keeping new entrants from participating in the market and selling to the DOD are the challenging regulations and requirements associated with the organizations. To sell or establish a contract with the DOD, or government, the seller must get registered with the System for Award Management (SAM.gov) and often times need to apply for security clearances. Registering at SAM.gov can be a potentially lengthy process and have various obstacles that slow down the timeline for gaining access in order to start bidding on contracts. For some companies, these aspects could prevent entrants from wanting to even pursue dealing with the government. As for security clearances, this is the most significant setback for a new entrant into the DIB as the process costs large amounts of money and takes a considerable amount of time, ranging from 1 to 5 years to complete (Sullivan, 2017).

H. VALLEY OF DEATH

Companies getting started in any industry, particularly in science and technology, will have to endure the valley of death (VOD) to get to the completion of development and eventually deployment in missions. VOD is a term that describes the shortfall in funding to prove that a design or technology works, with the goal of production and mission use. The VOD is a portion of the technology readiness level (TRL) scale that is measured across a 9-level scale as shown in Table 6, with 1 being an idea and 9 representing successful mission operations. Within the TRL scale, the VOD sits between levels 2 and 7, depending on the application and the user's willingness to accept risk (Belz et al., 2021).

Table 6. Technical Readiness Level Definitions. Source: Belz et al. (2021).

TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in a space environment
8	Actual system completed and ''flight qualified'' through test and demonstration
9	Actual system ''flight proven'' through successful mission operations

Risk is a significant aspect that plays into the scale, where both the buyers and sellers look at the VOD as the most challenging area to cross, with the buyer having to trust the phase of development as being acceptable for use and the seller managing the funding to develop and prove the design meets the buyer's risk tolerance (Belz et al., 2021). Depending on the complexity of the design and use of the product, the seller either must raise their own funds or get the confidence of private venture capitalists, or crowdfunding, to fund development. Receiving funding from these channels can be a good start but has the potential to raise some issues with the developer, as they are subjected to a payback or possibly surrendering some ownership in the product (Zwilling, 2013).

The VOD is a very problematic situation for new companies, and even established companies looking to develop a newer product capability or design. To assist with crossing the VOD, developers can apply to small business innovation research (SBIR) programs. SBIR programs are awarded in multiple phases, primarily aimed at transitioning research from early TRLs to more advanced and developed TRLs for incorporation into DOD or NASA projects, even potential market applications.

The Defense Advanced Research Projects Agency (DARPA) SBIR program is structured into two phases in order to improve federal R&D, with the goal of increasing competition, productivity, and economic growth (DARPA, n.d.-c). Within Phase I, a participant in the DARPA SBIR program could be awarded $225,000 for a 10-month period of performance (POP). After proving a viable design and product, the participant can then request for Phase II in which a much greater award amount, ranging from $1 to 2.75 million for further development and qualification over a 24-month POP (DARPA, n.d.-b). According to DARPA budget reports, the agency has been increasing their budget slightly over the past several years, going from $3.868 billion for FY 2022, $4.119 billion for FY 2023, and a proposed $4.388 billion for FY 2024 (DARPA, n.d.-a).

NASA also has an SBIR program, which has three phases, and the funding is not nearly as much as DARPA but has assisted many companies to get funding to prove their designs, with expectation that the product can be utilized in the space industry. NASA's SBIR program Phase I grants up to $150,000 in funding over the course of 6 months with Phase II awarding a maximum of $850,000 during a 24-month POP. Phase III of NASA's SBIR does not offer funding but a chance for infusion or commercialize the product for industry with no time or funding limits (NASA, n.d.-d). According to NASA's FY 2024 budget proposal, the space technology budget has increased from $1.1 billion in FY 2022 to $1.391 billion in FY 2024, with $300 million being allocated specifically for the SBIR program (NASA, 2023).

Both the DARPA and NASA SBIR programs assist greatly in helping companies push new innovative ideas across the VOD. However, it still only makes up a fraction of the overall R&D of DOD, and federal, spending. The DOD has had minimal influence on emerging companies looking to develop for the government and therefore the spending for R&D has not grown over the past several decades. As shown in Figure 12, DOD spending for R&D went from $69 billion in 1987 to $75 billion in 2013, while the commercial sector invested 200% more, going from $114 billion to $341 billion over the same amount of time (Sullivan, 2017). However, one thing to point out is that military branches contribute funding under their own research programs, such as the United States Air Force Research Laboratory (AFRL), which has greatly helped some companies listed in this research but their funding in generally less than DARPA.

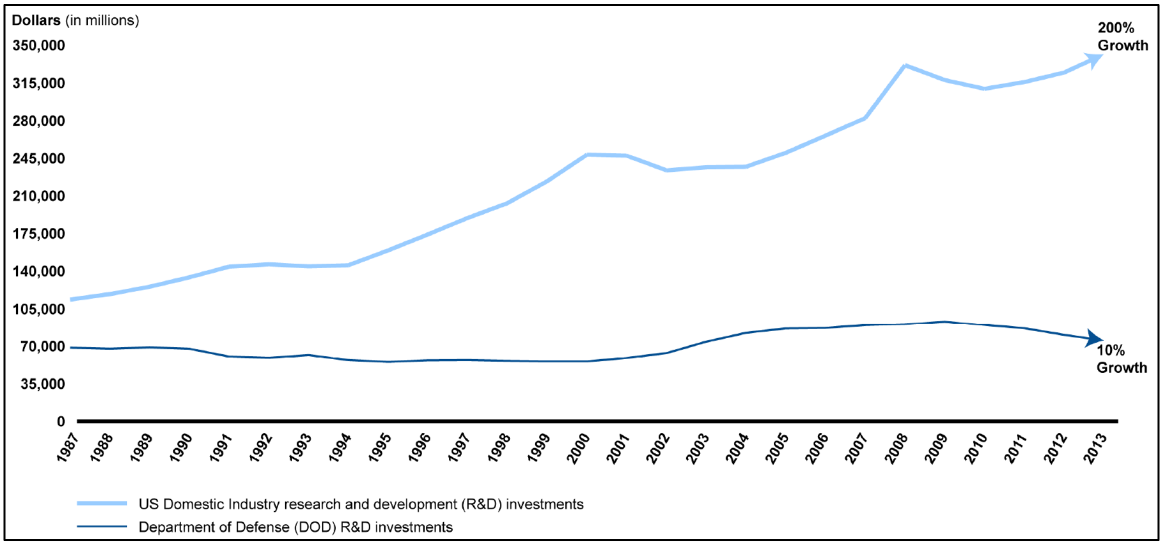

Figure 12. DOD vs. Private Sector R&D Spending. Source: Sullivan (2017).

I. VULNERABILITIES IN THE SUPPLY CHAIN

"If logistics wins or loses wars, what wins or loses logistics?" (Jordan & Mapp, 2023, para. 1). The supply chain supporting the DIB is crucial to the United States' success in developing, maintaining, and deploying military forces. When the supply chain is affected, it has rippling consequences across the entire market and U.S. economy, more so on the SRM, to include the M&M, industry. Schadlow et al.'s *Rocket's Red Glare* identifies major six challenges within the DIB supply chain as aging industrial base, intermittent production lines, broken business models, shrinking workforce, crushing regulations, and dependence on foreign sources (Schadlow et al., 2022). These challenges have contributed to the stifling of growth in the supply chain but also will become significant issues if left unchanged.

1. Aging Industrial Base

With the SRM industry consolidating with minimal entrants into the market, the U.S. DIB is in a concerning condition with many clear limitations. Currently, Northrup Grumman and Aerojet Rocketdyne (now L3Harris) are the only two major producers of SRM propulsion systems, with NG focusing more on the booster rockets for the Artemis SLS (NASA, n.d.-b). Though NG is still in engaged with making SRMs for defense, it makes up a fraction of the amount of AR's involvement in the SRM market, creating a bit of a producer bottleneck in the industry. As mentioned earlier in this research, the consolidation and decrease in the DIB has resulted in a decrease in sub-tier suppliers. In relation to energetic materials, the M&M industrial base was found to have 300 suppliers, resulting in individual points of failure and that 98% of 198 second- and third-tier suppliers rely on single or sole source vendors (Schadlow et al., 2022).

In the 2017 DOD industrial capabilities report to Congress, it was mentioned that the SRM industry suffered from limited suppliers due to the inconsistent demand signal as well as retirements of programs, such as the space shuttle, which prevented new entrants but also unmotivated facility updating or renewal (Office of the Under Secretary of Defense, 2018). Though the report is over 5 years old, the theme is consistent throughout annual reports provided by the DOD, in which all of them address that the lack of competition within the DIB has affected the supply chain but also created a condition where surge production would be too slow to respond to demand, if the signal was generated (Office of the Under Secretary of Defense, 2018).

2. Intermittent Product Lines

The major SRM manufacturers do not sell to commercial entities; therefore they are mostly reliant on the DOD for defense needs, and the government for space missions, which can become problematic for the supplier if demand is inconsistent (Mak, 2017). Intermittent production lines have been a result of fluctuations in conflicts and the need of programs along with the sporadic, and lack thereof of, funding within the DOD; all of which have made suppliers hesitant in updating their facilities (Schadlow et al., 2022). Traditionally, the DOD established year-by-year procurements for products which sometimes were skipped due to decrease in need. However, implementation of multiyear procurements (MYP) have assisted with avoiding any chance for certain years to be not renewed and interrupt the product line of the seller and have given a more defined plan for manufacturers to receive the capital they need to expand or maintain consistent production (PEO IWS 3.0, personal communications, September 12, 2023).

3. Broken Business Models

The government, and DOD in particular, is a tough customer due to lack of clarified and rapidly changing requirements. At any point in a program acquisition, the DOD has the chance for modifications to schedule, funding, and risk, or even cancel programs entirely with little notice. The *FY2020 DOD Industrial Capabilities Report* (2021) points out that:

> Conflict-driven procurements for missiles, munitions, and supporting energetic components make it difficult to maintain consistent and steady production demand. Steady demand enables industry to better plan for longer term stable production, negating the risk of the production line "going cold" (impacting readiness) and enabling greater surge capacity. (p. 86)

Drastic changes in demand hinder industries from streamlining their infrastructure and managing their workforce effectively, but also discourages new entrants from wanting to do business with the DIB (Schadlow et al., 2022).

4. Shrinking and Less Experienced Workforce

For any industry, the workforce is what dictates success or failure. The workforce in the SRM industry is seeing a decline in experienced workers, and companies, both old and new, are struggling to hire enough qualified personnel. Almost all the companies engaged in this research attested to the challenge of hiring employees who possess the right level of education and talent. The common theme of concern about the workforce was that the number of new graduates in science, technology, engineering, and mathematics (STEM) education, a major prerequisite for most science and technology companies, were not keeping up with the demand required. Part of the issue is that there is a stagnant U.S. K-12 involvement in STEM and increasing inability for families to send their children to higher education institutions due to rising tuition costs and inflation, resulting in a limited pool of available workers (Burke et al., 2022).

Another aspect of the SRM and space industry is that the more established legacy companies are suffering from an aging workforce and there are fewer replacements to compensate for those leaving the companies or retiring. According to the U.S. Department of Commerce *Rocket Propulsion Industrial Base Assessment of 2018*, it was discovered that "legacy" space primes, those that have been established in selling to the government for decades, had a much older workforce than that of newer space primes, as shown in Figure 13.

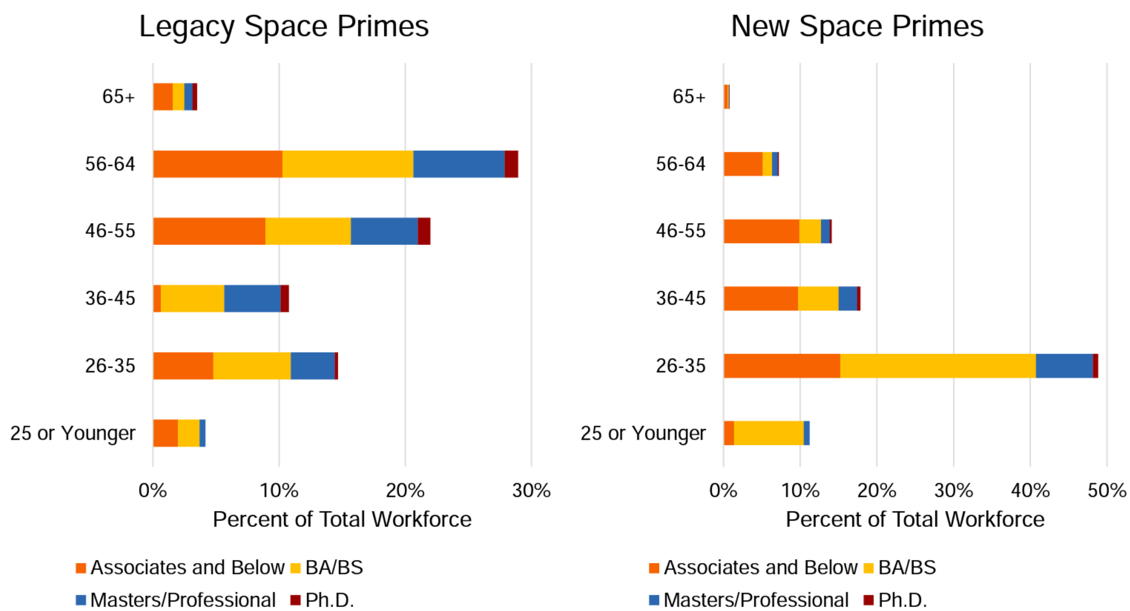

Figure 13. Employment of Propulsion Employees by Age and Education. Source: Bureau of Industry and Security (BIS) (2018).

Although the legacy space primes have a workforce with tremendous levels of knowledge and years of experience in the industry, the assumption is that they pose a risk of exiting the industry when reaching the retirement age, with a likelihood that knowledge will not be passed on. Newer space companies have the advantage of hiring young talent as they appeal to the younger generation of employees wanting to be at the cutting edge of space development. These claims were reinforced by engagement with SRM companies throughout this research, e.g., a discussion with Aerojet Rocketdyne mentioned that people are the biggest concern, including finding the right level of expertise to continue the required quality of work is a top priority (M. Steele, Director of Business Development, personal communication, February 13, 2023). Other companies agreed that personnel were crucial to the success of their business and making sure that the more experienced workforce overlapped their knowledge with the newer workforce.

According to the 2022 National Defense Industrial Association (NDIA) *Vital Signs* report, there was an average of 12.8% of STEM-trained workers in the United States in 2021, which was a small increase to previous years (NDIA, 2022). However, the report continues on by saying that companies within the DIB have concerns about a skills gap as the "pool of STEM graduates fails to keep up with the growing demand for skilled labor while the STEM workforce is aging," which has sparked calls for action by defense leaders (p. 21). In order to boost the DIB STEM workforce, the DOD should consider developing programs to boost the talent pipeline but also establishing apprenticeship programs channeled through education institutions to encourage interest in the field, which will in turn provide more talent in the industry (Schadlow et al., 2022). If left unchanged, new talent will not be able to receive the knowledge, experiences, and skills prior to the exiting of the aging workforce, thus greatly affecting the capability of the SRM industry and DIB.

5. Crushing Regulations

Starting or operating an M&M facility can be extremely costly, as well as burdensome due to the environmental and safety regulations. In some cases, the regulations could act as barriers to entry for companies looking to start or even expand in the market. An excerpt from the 2022 DOD *State of Competition within the Industrial Base* describes the challenges associated with these regulations:

> The costs to enter the M&M market are higher than other sectors due to the nature of weapon systems—particularly as safety requirements add additional layers to the design of equipment and/or facilities. For example, any company storing or using energetic materials requires larger property investments, due to quantity-distance limitations and explosion-proofing of equipment and buildings. These additional costs, while necessary and appropriate, can heavily burden any entrant into the market. (p. 19)

When it comes to companies conducting business with the DOD through contracts and acquisitions, the regulations can be just as burdensome as the safety requirements, and act as another aspect to barriers to entry. According to the 2022 NDIA Vital Signs report, DOD contracting affects the productivity of companies operating within the DIB and prevents new entrants from having any interest in joining the defense industry (NDIA, 2022). The report further mentions that the "DOD regularly issues new rules that modify the Defense Federal Acquisition Regulation Supplement (DFARS)" which these "new rules add or subtract restrictions or requirements for parties involved in the contracting process" resulting in an "overall regulatory burden that imposes costs on companies seeking to do business with the government" (p.41).

Start-up companies are most affected by the plethora of regulations and requirements related to the space industry as well as doing business with the government. The start-up companies that were engaged in this research did confirm that regulations, safety and government related, created the most significant challenges outside of product development. Test range regulations and requirements were also a key talking point as the limited missile ranges in the United States, for static and dynamic fires, impact the ability to test designs freely and rapidly. Though the rules, regulations and safety measures are necessary, they inadvertently act as barriers to entry for new entrants, thus reducing competition and innovation in the industry (Schadlow et al., 2022).

6. Dependence on Foreign Sources

A recent concern that has become a talking point across DOD and government reports is the reliance on foreign materials to produce defense munitions. COVID-19 uncovered a lot of hidden supply chain vulnerabilities affecting the U.S. economy, but mainly the DIB. The 2022 DOD *State of Competition within the DOD Industrial Base* points out that competition of the critical materials sector have been affected due to political intervention and unfair trade related to adversarial countries. These conditions force out domestic manufacturers, leaving only suppliers in adversary countries to become single-source options for specialty metal alloys, rare earth elements, and critical chemicals (Department of Defense, 2022b). The report further states that companies are not encouraged to spend the money to survey and build the infrastructure required to boost domestic production unless government incentives and partnerships with the private sector are utilized (Department of Defense, 2022b).

In a 2018 Supply Chain Resiliency of the United States report to President Trump, the DOD discovered that China is the single or sole-source supplier for various specialty chemicals that are used in M&Ms (DOD, 2018). The issue with this case is that no other source or replacement materials exists, while the "time and cost to test and qualify new materials can be prohibitive" (DOD, 2018, p. 49).

One of the chemicals identified comes from a rare mineral, antimony (shown in Figure 14), which is required in most weapons and military equipment (Harris, 2022). The use of antimony in SRMs could not be confirmed; however, the strategically critical mineral is required for bullets, explosive formulations (warheads), nuclear weapons and production, infrared sensors, communication equipment, and is even needed in the creation of tungsten steel (Blackmon, 2021). Antimony is just one example of many resources that can cripple the DIB if conflict with a supplier, such as China, were to halt trade.

Figure 14. Crystals of the Antimony Ore Stibnite. Source: Blackmon (2021).

J. SUMMARY

In a time when it seems that LREs are dominating the aerospace industry, solid rocket motors are still the necessary choice for defense. SRMs provide a capability and simplicity for warfare that LREs are unable to achieve and that is why they are still being utilized today. Until the implementation of hypersonic missiles, SRMs will be the primary M&M for fighting and are greatly needed for any future conflict.

The industry has seen many changes over the past 30 years and consolidation of primary contractors and subcontractors has caused a pinch in the DIB, which has created issues across the market. Though the current suppliers are specialized and have the facilities and manpower in place to supply defense customers, it does appear that the production does not meet the demand signal. Also, the established suppliers are large enough to keep new entrants from entering the market and that does affect the ability for the DOD to have additional options or reduce the chances of single suppliers. The number of single- and sole-source suppliers has a high potential of disrupting production of necessary SRMs for missiles and will prevent any future innovation.

The VOD and barriers to entry are tremendous issues for new entrants and even established manufacturers and suppliers looking to create better missiles. Without proper funding and competition within the industry, the number of participants in the market will remain drastically low. A secondary consequence to limited suppliers is that students and workforce are not encouraged, or educated enough, to enter the STEM industry when the demand for STEM-related workers is higher than ever. When the supply of workers is barely meeting the increasing demand, then there will be a scarcity that will slow down or halt any development within the SRM industry and DIB.

Lastly, COVID-19 showed the world that supply chains are fragile yet vital to the global economy and the U.S. reliance on foreign sources to obtain raw materials and manufactured goods has pushed domestic suppliers to exit the market. Vulnerabilities start to produce themselves when materials and components are sourced in other countries, especially in adversarial ones, and becomes even worse when no backup source exists within the United States.

IV. ROCKET COMPANIES

This chapter is meant to review and describe what current rocket companies, start-up and established, are doing in the industry. These companies produce LREs, SRMs, even both, and are making great strides to develop innovative products and techniques to boost the rocket industry. The purpose of interacting with these companies was to get a sense of the overall culture and the challenges associated with rocket production, as well as to discover what practices can be further investigated, adopted or utilized to remedy the current situation with energetic munitions related to defense. Interaction with the following companies, other than Relativity Space, were conducted via emails, online internal presentations, and site visits.

A. SPACEX

For the past 10 years, SpaceX has been at the forefront of the space industry and has revolutionized commercial space capabilities. Owned and operated by tech billionaire Elon Musk, the privately controlled company has been able to pull off a lot of achievements and developments that other smaller space companies, even public traded companies, are unable to fully replicate. Through tenacity and development, SpaceX has been able to produce the first ever reusable booster rockets, the main propulsion piece of the company's flagship, Falcon 9, shown in Figure 15. When visiting SpaceX's facility in Hawthorne, CA, a claim was made that SpaceX has been able to bring 70% of global launches out of the United States, a staggering amount compared to the zero U.S. launches in 2010.

Figure 15. Falcon 9 Makes First Successful Landing on Drone Ship, *Of Course I Still Love You*. Source: Wired (2017).

To date, SpaceX has achieved 274 launches, 232 successful booster landings, and 207 launches using previously used rockets or "reflights," most of which were for the delivery of the company's Starlink communication system (SpaceX, n.d.-a). In August 2023, SpaceX hit the record for launching 83 Falcon 9 and Falcon Heavy missions within a 12-month period, or average 6.9 launches every month. Elon Musk has proposed that by the end of 2023 the average will be 10 launches per month, and up to 12 launches per month in 2024 (S. Clark, 2023). Along with the Falcon missions, SpaceX has been putting effort and resources into the development of their latest rocket, Starship, which is meant for super heavy lift capability, as well as the choice vehicle for achieving the goal of sending humans to Mars.

SpaceX has been able to achieve all these major milestones through taking a lot of risk while developing rockets and qualifying them for testing through aggressive methods. In a way, the company was willing to accept failure during testing to better understand what needed to be improved or modified, as failure gave the greatest result of what to change. The level of risk acceptance gave SpaceX the right amount of acceleration through development and achieving qualifiable designs that would later be used for actual launches. It goes without saying, however, that when SpaceX does any launches that involve hardware or people, the company's risk tolerance is as close to zero as possible and launches are based on a launch acceptance scale.

During a discussion with the company, Jessica Jensen, SpaceX Vice President of Customer Operations and Integration, discussed Elon Musk's algorithm for use in design and manufacturing and for solving complex problems (personal communications, May 12, 2023). For reference, the algorithm was presented by Musk to Tim Dodd of *Everyday Astronaut* during a tour of Starbase that covered the five steps of the algorithm (Sesnic, 2021).

1. **Question requirements and understand the intent of requirements.** This is the first step that sets all the other steps in motion and relies on questioning the reason a requirement exists. Ensure the requirements are fundamental requirements rather than related to how to do something. This step also focuses heavily on people rather than an organization and that even the "intelligent" people need to be questioned when a requirement is established, which also allows for the tracing of that requirement if it needs to be changed or eliminated.

2. **Delete the part or process step.** This step can apply to both manufacturing and qualification and is a significant one for optimizing any process. Understanding what part or step can be removed from the process chain and "if parts are not being added back into the design at least 10% of the time, not enough parts are being deleted" (Sesnic, 2021, para. 10). In other words, removing parts or steps that have been added over time because of the "it has always been done this way" or the "it is a requirement, so it must be important" mentality are vital to optimizing a process.

3. **Optimize and Simplify a Design.** Musk stressed that this MUST be the third step and too often designers skip to this step first, which causes the optimization of a part or step that should not exist. The key to this step is to question parts or steps that seem irrelevant to the process and try to have one part do many things.

4. **Accelerate the process.** Musk emphasized that "you're moving too slowly, go faster! But don't go faster until you've worked on the other three things first" (Sesnic, 2021, para. 12). During the discussion, Jensen explained that production lines can always go faster and the best way to figure out how to accelerate is to "be the part" through the process in order to find the bottlenecks. Once a hold-up is discovered, repeat steps 1–3.

5. **Automate.** This is the final step of the process and should only occur after all the previous four steps have been intimately analyzed; this will avoid automating something that should not exist or is too complex. In a discussion with SpaceX, Jensen added that automation should not be utilized if the output has reached high output production rates where it is more worthwhile to automate for something requiring increased precision, such as welds or electronics placements. This step should not be used for volume production alone and must be the last step, not the first, which is a common starting point for companies.

The takeaway from all these steps is that the algorithm encourages a producer to think about the overall system and processes that go into making a product. Often, manufacturers rush to streamline their production chains without ever looking at the why and how, which later results in inefficiencies and slowdowns. Musk's algorithm pushed SpaceX to rapidly design and develop the Raptor engine, Falcon, and Super Heavy rocket as well as optimize the production lines.

Benjamin Reed, Customer Correspondent, who lead the tour during a visit of the SpaceX headquarters described that SpaceX's production optimization led to a "hardware rich" posture at the company which lead to increasing output which resulted in making

85% of rocket parts “in-house” and outsourcing the rest to cover simple and small piece parts (B. Reed, personal communication, September 15, 2023). The earlier discussion with Jensen reinforced Reed’s explanation as design and production optimization involved vertical scaling due to some external suppliers could not keep up with SpaceX’s pace; such as a company making valves took 12 months to produce the part which forced SpaceX to make it themselves (J. Jensen, personal communication, May 12, 2023). Production at the company is so streamlined that a Merlin engine, shown in Figure 16, can be built within 4 to 5 months from part procurement to full assembly, and 1.5 months if all parts are already on hand.

Figure 16. Line of Merlin 1D Engines at SpaceX Headquarters. Source: Hodges (2015).

Inventory on hand is also another advantage that SpaceX has in the industry, where the company has stock of almost every part for both engines and rocket bodies with a focus on having the parts ordered or fabricated to match the production demand. During the tour of the headquarters, it was claimed that SpaceX can roll out the second stage for the Falcon

9 every 5 days, which are then kept in inventory. The claim even mentioned that Raptor engines (shown in Figure 17), which are used in Starship, are completed daily at the SpaceX Texas facility due to production optimization (B. Reed, personal communication, September 15, 2023). SpaceX currently has hundreds of Raptor engines in inventory, a preemptive number for when Starship requires 33 Raptor engines on the Super Heavy first stage (SpaceX, n.d.-a).

Figure 17. Line of Raptors Being Completed at Central Texas Facility. Source: Elon Musk (2021).

The takeaway from SpaceX is that the company is heavily focused on creating the most efficient production and supply chain, which in turn allows for providing the right level of consistent and reliable space lift capability. According to Jessica Jensen, SpaceX's customer base is hundreds deep, with NASA being a significant customer, due to the proven delivery concept of the company (J. Jensen, personal communication, May 12, 2023). Due to the optimized design and production, along with incredible trust in the process, SpaceX only conducts business under firm fixed pricing (FFP) for their services, meaning they agree to the price of the service at the time of agreement rather than changing the price at delivery. Utilizing FFP is attractive to customers since it absolves the buyer of any risk associated with the cost and encourages the seller to create efficient pathways to production. Jensen acknowledged that NASA was more motivated to take the risk of doing business with SpaceX at the start due to the company's proven design performance but also the fact that services were awarded under FFP contracts. Though SpaceX has no intention to produce SRMs, it is not entirely out of the realm of possibility that the company can get involved in defense munitions and could be an attractive supplier based on optimization if the DOD and SpaceX can come to an agreement. The involvement of Starshield already seems like a "foot in the door" for both parties and could be a potential chance of bridging the gap to make SpaceX a viable alternative to energetic munitions production if the need were to arise (SpaceX, n.d.-b).

B. URSA MAJOR

Ursa Major was founded in 2015 and is based out of Berthoud, CO. The company produces mainly LREs for commercial and defense but entered the hypersonic market in 2020 as well as started researching SRMs. During a presentation by the company, they mentioned that the target customers were both commercial and government, to include DOD. Ursa Major's production methods include non-traditional methods by heavily using additive manufacturing to reduce fabrication cycles and maximize overall performance of engines. The mission of the company is to provide expeditious production and surge capability of propulsion hardware while at the same time keeping the cost low. In 2022, Ursa Major was able to deliver their first copper-based 3D printed LRE combustion chamber (shown in Figure 18) which took 1 month to manufacture rather than the original 6 months using traditional manufacturing processes (Ursa Major, 2022). Another advantage of the company's additive manufacturing capabilities is that they are able to surge production by increasing production cells quickly adapt to demand, rather than having to build additional facilities or increase workforce (Ursa Major, n.d.-a).

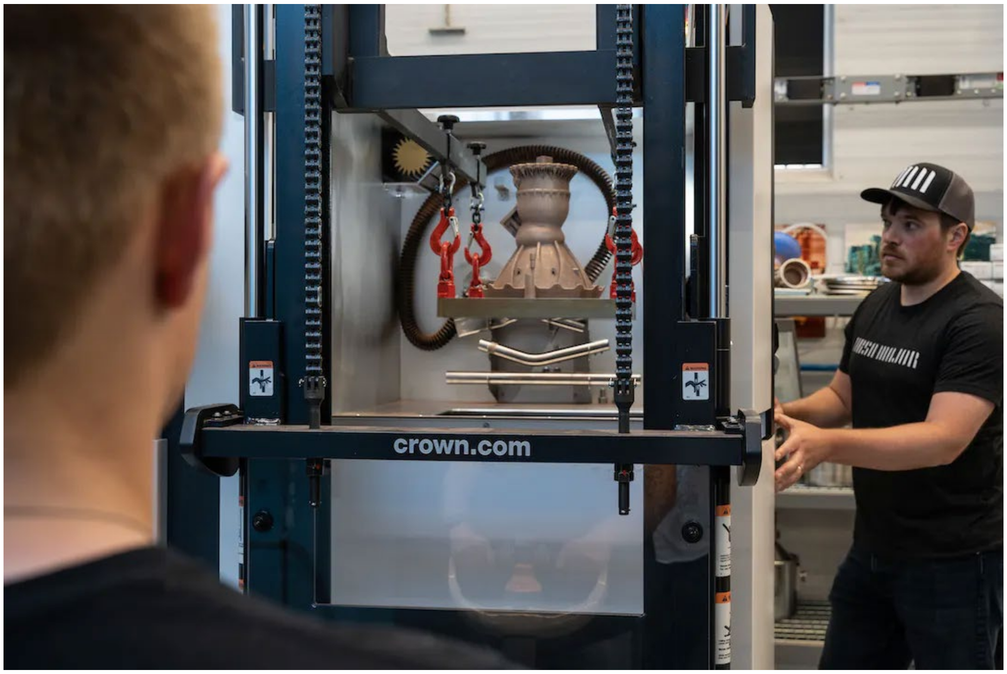

Figure 18. A Copper Rocket Engine Component in an EOS 3D Printer, Ursa Major's Advanced Manufacturing Lab in Youngstown, OH. Source: Ursa Major (2022).

During an online group discussion with the Ursa Major team regarding supply chain and production obstacles, they described that it takes at most 18 months for sourcing parts and upwards of 6 months to manufacture an engine after parts are in hand (personal communications, April 14, 2023). However, the use of 3D printing parts has really helped speed up the process and allowed for the company to vertically scale when necessary. When asked about sourcing materials and parts, the company responded that it is smarter to outsource when it makes sense to not carry the capital or burden of manufacturing the part in-house. Some suppliers are strictly specific because of the high capital to start production of a particular part. For instance, C-C throats require complex machinery and space, something other manufacturers are not willing to set up for vertical scale. Ursa Major reinforced the idea that 3D parts give tremendous ability to make parts locally. Another advantage to additive manufacturing is that it give the company the capability to reduce the need for tooling or fabrication when developing a design and allows for multiple iterations of an idea before committing to a full design (Ursa Major, personal communications, April 14, 2023). One of the major bottlenecks that Ursa Major mentioned is machining parts, and additive manufacturing helps bypass the hurdles associated with having to modify tooling or combining various manufactured parts into one assembly.

Ursa Major's most exciting development is the concept and design of the Draper engine (shown in Figure 19) which is a 4,000-pound thrust closed-cycle hydrogen-peroxide engine designed mainly for hypersonic applications. The significant milestone with Draper is that it allows for storable liquid propellant for use in an LRE that acts a lot like an SRM in terms of rapid-response launches. According to the company, Draper harnesses the performance and capability, along with the flexibility for reuse, of LREs for use in platforms that would require the use of only SRMs by not having to fill tanks of propellant prior to launch. In a 2023 press release by Ursa Major, advantages of the engine are that:

> Draper's safe handling and storability lead to applications and maturation of responsive launch operations, including, point-to-point delivery, quick mission planning, on-orbit servicing, fuel depots, global range and mobility, hypersonic systems, and survivable and responsive launches. (Para. 7).

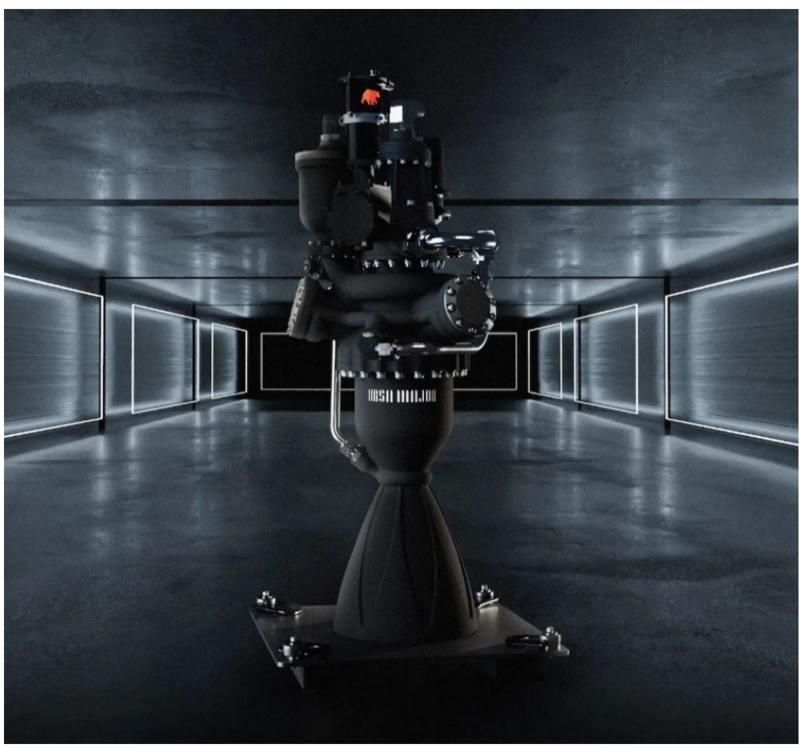

Figure 19. Ursa Major's Storage Liquid Engine, Draper. Source: Ursa Major (2023).

The takeaway from Ursa Major is that the company has been able to harness the benefits of additive manufacturing to reduce the production time of most rocket parts. By using 3D printing capabilities, Ursa Major can rapidly manufacture rocket engines in less time than traditional methods while at the same time being able to scale when meeting appropriate surge demands. Another significant takeaway is the Draper engine technology which is changing the rules of having to use SRMs on military platforms due to safety, as Draper is a safe and practical alternative to military missiles. Being able to store hydrogen peroxide at room temperature allows for on-demand launch options as opposed to keeping the propellant at cold temperatures, such as LOX. There is vital application for this technology and the DOD could find use in utilizing Draper style propulsion for replacing boosters, like those of the SM, that could be reused while the intercept end remains expendable as an SRM. With the combination of additive manufacturing and closed-cycle engines, energetic munitions could see a drastic increase in capability, performance, and replenishment.

C. ANDURIL (FORMERLY ADRANOS)

Formerly known as Adranos, the rocket company was founded in 2015 by Purdue University students; Brandon Terry and Chris Stoker, and it was acquired by Anduril in June 2023. The company is known for their creation of ALITEC, a new age fuel for SRMs. In an interview with Royce Beal, who at the time of discussion was the Senior Scientist of Adranos, he explained that ALITEC is a cutting-edge fuel alloy designed to optimize the performance of rocket propellants (interview, April 7, 2023). Beal explained that ALITEC is crafted as an aluminum-lithium alloy and aims to replace traditional aluminum powder in composite propellants while still leveraging AP as the oxidizer. The alloy composition and methodologies for its creation, storage, and utilization are proprietary, making ALITEC a critical component in securing technological and competitive advantages. He added that one of the main features of the propellant that ALITEC produces chlorine as an exhaust product during the burning of the grain which attaches to the lithium in the fuel. This reaction releases additional heat, making more energy available and a possible 40% range increase for the rocket system. While the specific thermochemical details are confidential, Beal did point out that the industry recognizes that replacing aluminum with aluminum-lithium results in notable performance improvements.

One consideration in adopting ALITEC is its lower density compared to traditional aluminum powder. Depending on the application, this could be either an advantage or a disadvantage; however, it's an essential factor that needs to be accounted for in design and engineering (R. Beal, personal communications, April 7, 2023). Beal did say that concerns have been raised about ALITEC's long-term stability, especially for munitions applications which is something that might affect decisions with customers such as the DOD. ALITEC presents a transformative opportunity for rocket propulsion systems by offering enhanced heat release and energy efficiency, and it serves as an attractive alternative to traditional fuel options. It's a technology that holds great promise for both increasing performance and maintaining competitive advantages in the rapidly evolving aerospace industry.

When engaging with the company, it was apparent that they are taking the risks to develop a new propellant that is pushing the capabilities of current SRMs. As addressed by the company, ALITEC does have some downsides that affect its full application in defense missiles, but with advances in technology and qualification, there is a high probability for it to be used to get longer range and faster energetic munitions. To support their production and implementation of their product, Adranos (at the time of commencement) started production of a facility in Jackson, MS in 2022 to increase production of ALITEC and the facility is considered the largest propellant mixer in the United States (Beal, interview, April 7, 2023).

The takeaway from Adranos, now Anduril, is that the company is looking to further improve the performance of SRMs while breaking conventional practices of using AP and aluminum in propellant. With the use of lithium in the fuel and making it more mainstream, the company could promote the desire for other companies to enter the market to source and manufacture refined lithium within the United States. Beal did mention nozzle throats create the greatest production bottleneck in SRMs and that Adranos was working on experimenting with graphite throats for their motors, but did confirm that C-C throats are still the preferred and the most durable material. The acquisition by Anduril allows for the company to utilize additional expertise and additional funding to further enhance the production of ALITEC. As presented earlier, the scaling of Adranos through Anduril will give a significant edge to the company and will be able to better contribute to SRM propellant and rocket development.

D. X-BOW SYSTEMS

Pronounced "crossbow," the company aims to change traditional methods in rocket production by leveraging additive manufacturing to print solid rocket motor propellant into cases. During a online group call with X-Bow, there was major emphasis on the company's ability to provide on-demand propellant formulation mixing for various mission parameters while utilizing additive manufacturing to build in days rather than months for even years based on traditional methods (X-Bow Systems, personal communications, April 21, 2023). X-Bow's mission is to provide modular SRM production services, through additive manufacturing, to both commercial and government entities as an alternative to the much larger SRM manufacturers, Northrop Grumman and Aerojet Rocketdyne (Maranda, 2023). They saw a need for SRMs to be manufactured via additive manufacturing to decrease production time, lower overhead, reduce maintenance, and allow for endless flexibility in rocket designs and performance.

During the call, X-Bow claimed that their target customer is the DOD and the Department of Energy, and that they were also a DARPA success story through completing Phase I, Phases II, and IIA which helped them cross the VOD and therefore able to sell to the DOD (personal communications, April 21, 2023). They also included that X-Bow was able to utilize private funding as well as other SBIR programs, which in turn allowed for the company to design, create, and launch the Bolt rocket in July 2022, shown in Figure 20. This was proof of concept that 3D printed rockets and propellant could be an achievable endeavor. The testing of Bolt and continuous success at proving capabilities earned the company $60 million in funding from government SBIR funding and private investments (Maranda, 2023).

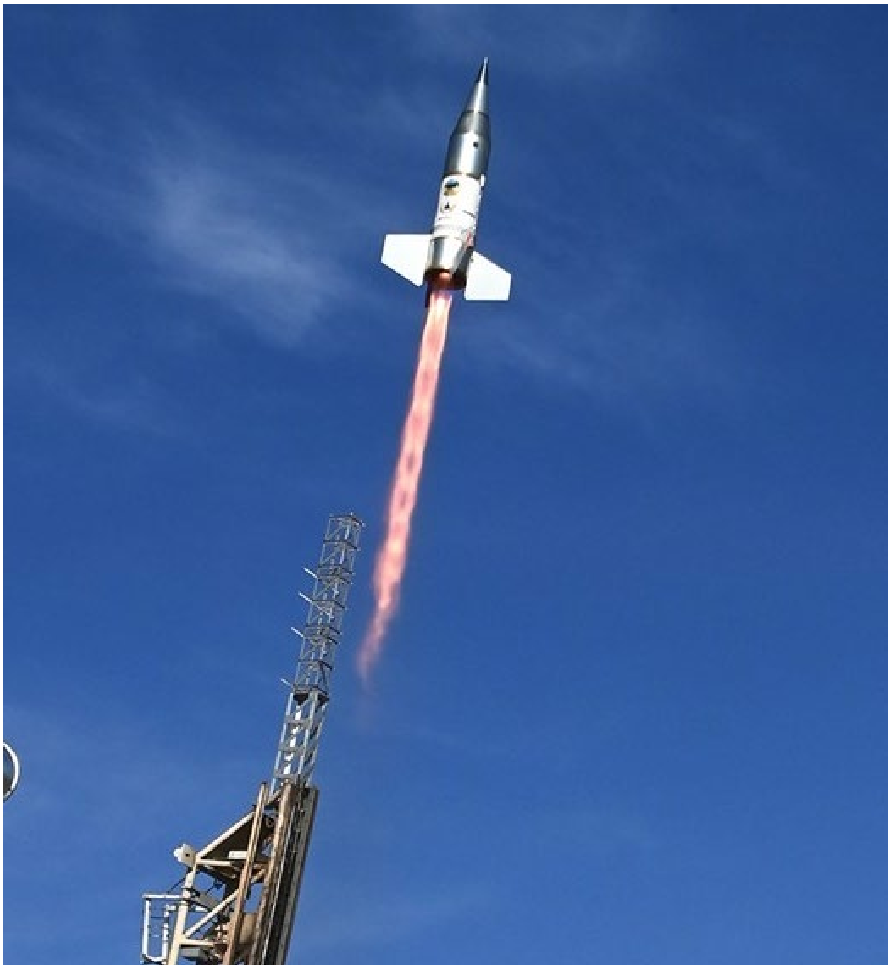

Figure 20. X-Bow’s Bolt Rocket Launch 23 July 2022 at White Sands Missile Range, NM. Source: X-Bow Systems (2023).

The takeaways from X-Bow are that the start-up company was able to leverage the innovative manufacturing ideas and tap into the SBIR funding while also going about private funds. The company’s ability to utilize additive manufacturing shows that printing SRMs is possible and drastically reduces the workforce and production timeline constraints. X-Bow did point out that they still run into the issue of long lead times for C-C throats and must plan 6 to 8 months out for orders with a separate company. However, most of the rocket assemblies are produced in-house using commercial-off-the-shelf components to build their printing machines, which reduces the overall capital required for major, traditional production equipment. One of the minor issues that was brought up regarding printing propellant into the case is that there are small amounts for air form in the extruding process, which decrease overall rocket performance by 2 to 4% but the savings in not needing massive casting machines or facilities is worth that decrease in performance. X-Bow shows that there are innovative ways to reduce the amount of work and equipment required to manufacture rockets while also producing them quicker and cheaper for the sake of some performance compromises. The company did say in a parting remark that as technology gets better, that capability and performance will get much better and therefore will no longer be a constraint during the 3D printing process. X-Bow's overall plan is to make larger and more capable rockets (shown in Figure 21) as their printing capability expands and gets more advanced that will be competitive alternatives in the SRM market (personal communications, April 21, 2023).

Figure 21. X-Bow Systems Rocket Line-Up; the Bolt Shown on Far Left. Source: X-Bow Systems (n.d.).

At the time of this writing, X-Bow was selected, in October 2023, to fulfill a DOD contract of $64 million to supply SRM boosters for hypersonic missiles under the U.S. Navy's Conventional Prompt Strike and Army's Long Range Hypersonic Weapon System programs (X-Bow Systems, 2023). This contract award is a significant step in extending the SRM industrial base in the right direction by giving production trust to companies other than the major two SRM manufacturers.

E. RELATIVITY SPACE

Though personal interaction with Relativity Space was not achieved during this research, the company is part of this chapter because of its success in designing and launching the world's first 3D printed rocket to reach space. The Terran 1, shown in Figure 22, is the latest creation consisting of a two-stage rocket, measuring 270 feet tall and 18 feet in diameter and is 85% 3D printed by mass using readily available aluminum alloy (Relativity Space, n.d.-c).

Figure 22. First Launch of Terran 1, *Good Luck, Have Fun.* Source: Relativity Space (n.d.).

The LREs, named Aeon R and Aeon Vac, are also 3D printed with the ability to create up to 258,000 pounds of thrust at sea level and 279,000 pounds in vacuum (Relativity Space, 2023a). Realized benefits to 3D printing both the rocket and the engines is that it reduces the complexity of the components and improves manufacturability, due to avoiding the need to fabricate and weld together multiple parts by printing whole assemblies. According to a 2023 Relativity press release, 3D printing allows for decreasing the part count and printing engine elements into unified parts, or "nodes of simplicity," resulting in "lowered costs, lowered engine complexity, greater robustness, rapid iteration, and the speed and scale of production required to serve customers" (Relativity Space, 2023, para. 6).

Relativity Space started the company with the idea of offering affordable heavy lift capabilities, up to 23,500 kg, to companies needing to put equipment into low Earth orbit, or 5,500 kg into geosynchronous transfer orbit (Relativity Space, 2023a). The company's target customer is commercial companies requiring lift to deploy products that will be able to ride on Terran R rockets, but they are working to enter into the government space through agreements with the United States Space Force (Relativity Space, 2021). Relativity was able to show the world that a 3D printed rocket was reliable and sustainable and therefore, the company was able to sign multi-year, multi-launch service agreements totaling $1.8 billion in backlog launches across nine customers, including Intelsat and Impulse Space (Relativity Space, 2023b). With the added funding from the agreements, Relativity Space is able to generate the capital required to continue developing their production capability by leveraging advanced additive manufacturing, artificial intelligence, and autonomous robotics to greatly outdo the current manufacturing capabilities of traditional aerospace methods (Relativity Space, 2023b).

The takeaway from Relativity Space is that they are a company willing to take the risk in producing rockets in an unconventional way and utilizing additive manufacturing to streamline the production process. Covered earlier in this research, the workforce and materials are hard to come by for rocket companies and Relativity is bypassing those aspects through the 3D process. Using the largest 3D printer, Stargate, which is shown in Figure 23, the company is able to print up to 120 ft long and 24 ft wide objects much faster than typical industry standards with a claim that their current generation of Stargate is 12 time faster than the industry-leading performance (Relativity Space, 2022).

Figure 23. Stargate Fourth Generation Metal 3D Printer. Source: Relativity Space (n.d.-a).

Though Relativity Space is focused on delivering low-cost lift solutions for the commercial market, there is high application for the defensive space if the 3D technology can be applied to SRMs. There will have to be considerations to the durability of the prints based on the requirements of defense SRMs, but Relativity Space shows that the capability exists and is qualifiable. If adopted by defense prime contractors, or Relativity contracted as a subcontractor, the ability minimizes the necessity for labor and expeditiously produces rockets when needed. The additive manufacturing presented by Relativity Space proves that scaling to additional production lines would be massively beneficial to companies and even the DOD for boosting rocket production. Instead of having to spend time and money building new facilities with proper tooling, entities can utilize 3D printing machines with unlimited scale for production of rockets and piece parts. This scaling would be invaluable in the event of a contingency situation pertaining to conflict and would even allow for proper surging production in response to increased demand of M&Ms.

F. AEROJET ROCKETDYNE (AN L3 HARRIS COMPANY)

Aerojet Rocketdyne (AR) has a rich history in the aerospace industry dating back to 1945, when the company first started getting involved with rocketry and has been at the forefront of rocket tech since then. AR was the leading producer of the engines in the Apollo program and made every RS-25 space shuttle engine throughout the 30 years of the program (L3Harris, 2023b). AR is considered the leader and one of the two major manufacturers of SRM products. The other is Northrup Grumman and is responsible for the propulsion components of key DOD tactical missiles, to include the SM, GMLRS, Javelin, and Stinger platforms (L3Harris, 2023a). AR is the primary subcontractor for weapon systems and space programs, fulling orders for LREs and SRMs.

AR came under scrutiny by the DOD over the past couple of years regarding the slow production of military munitions, but interaction with the company revealed some of the challenges. In a discussion with Matt Steele, he explained that SRM parts for energetic munitions take anywhere from a year to source, followed by 6 to 9 months to make a rocket after receiving all the material (personal communication, February 13, 2023). He further stated that throat nozzles are the longest lead time items, taking 7 to 10 months. After assembly of the rocket, the grain must be mixed, casted, and cured which can take days to weeks to fully cure based on performance requirements. The issue that was addressed by Steele regarding these lead times is that the funding for military munitions does not allow for inventory of these materials and once a contract for additional rockets is placed, then ordering and assembling can be accomplished. The company operates on a make-to-order basis as opposed to holding inventory of materials for rapid production of rocket motors.

The only customers to Aerojet Rocketdyne are prime contractors selling rockets to the DOD and producing LREs for NASA space programs. Therefore, AR is burdened by the parameters of government contracts under prime contractors and military production requirements and quality assurance examinations. All these aspects have made production within AR cumbersome and arduous for maintaining a steady output of motors and has not allowed for options for surge capability. However, to counter some of these challenges, AR was able to work out MYP for major weapon systems to include the SM and Javelin, making for a steadier procurement plan while providing the capital to expand and keep costs low for the DOD (M. Steele, personal communications, September 16, 2023). MYP contracts allowed for AR to acquire enough funding to build a new $13.5 million facility in Camden, AR in 2022 that enhanced SRM manufacturing, increased production capacity, reduced overall cost of products, and provides the space for larger rocket production (Aerojet Rocketdyne, 2022).

AR has also leveraged the capability of additive manufacturing for fabricating mainly their LREs for use in NASA's Artemis space program. During a site visit at AR's Los Angeles, CA, facility, it was apparent that 3D printing engine parts is a new vital capability. Use of the printing machines reduced the traditional manufacturing time from 3 years to 11 months and drastically decreased the number of welds on an engine from 140 to 3 which, in principle, should increase quality as well as reduce manufacturing time. By using 3D printing powders made of titanium, aluminum, and Inconel, AR can print various ranges of components that meet different levels of applications and performance characteristics. The advantage to this capability is that it supplements any potential lag in suppliers, except for the powder, for component parts and limits the need for having a large inventory if funding and opportunity does not allow for it.

The takeaway from AR is that they are the oldest and most experienced company in the LRE and SRM market but because of a strictly government customer base, crushing limitations act as barriers to progress. Aerojet Rocketdyne, having been acquired by L3 Harris, has incredible capability and an experienced workforce that needs to be further utilized by the buyers. Concerns addressed by Steele were that the company would be unable to produce rockets in time if future conflict were to expend inventory of missiles and funding does not accommodate surge capacity (personal communications, September 16, 2023). He mentioned that additive manufacturing and automation would be able to improve production timelines, but the capital investment needs to be secured and the material requirements are not qualified or perfect enough for military SRM platforms at the current time. Furthermore, increased funding and reduced requirements would assist in further expansion of additive manufacturing capabilities and even possible inventory of piece parts which, in principle, could cut production time by almost half. AR remains the most important asset at this time for energetics in the DIB and is currently the only option for improving inventories and missile development until other companies' capabilities can be expanded.

V. CONCLUSION

A. TAKEAWAY

The SRM industry is certainly complex but is also well-established; neither factor should deter the DOD from seeking new ways to develop and improve the industry. Solid rocket motors are a very specialized technology and require some of the most unique materials and manufacturing practices. However, there needs to be a mindset shift that allows for better and cheaper rocket motor production for the sake of boosting the military M&M inventory and the ability to rapidly develop design and surge production if required.

A key finding of this study is the consolidation of companies and decrease in overall competition across the DIB has limited the DOD in availability and options that also pose a risk to cost and schedule of rocket production. Consolidation of prime and subcontractors has caused a decrease in suppliers who support the SRM industry and reduce the effectiveness of the DIB.

B. RECOMMENDATIONS

Funding and profit are what drive success and rocket companies need those two monetary inputs to continue growth and development. Start-up companies especially require funding to increase capital, which in turn helps build designs and facilities for production. The DOD should consider additional mechanisms for DARPA and the military branches to receive greater funding to better support companies looking to enter into the market and/or established companies interested with innovative ideas for ways to increase production of SRMs. The VOD is a significant barrier to entry for many companies and it would be in the best interest of the United States to increase funding for programs that encourage more involvement in R&D. Due to the lack of competition across the DIB, the DOD should find ways to bring in more manufacturers and suppliers that are willing to conduct business with the defense industry and help push for improved M&Ms and reduce the amount of single- and sole-source contracts.

Congress should increase funding to the DOD for the requirement of increasing the U.S. military stockpile of munitions. The United States has not conducted a kinetic war with a near-peer competitor since WWII; however, China and Russia pose a significant potential threat and could be competitive adversaries. As shown in this research, war with capable adversaries will require the use of almost the entire U.S. arsenal of M&M and the timeline to surge production of missiles will result in running out of the inventory before being able to replenish. That is why the DOD should work with Congress to substantially boost the energetic munitions stockpile and send a demand signal to new suppliers to enter into the production of SRMs.

A lack of innovation and unwillingness to accept risk in new weapon designs has held back the military in utilizing better capabilities in the battlespace. The DOD should prioritize companies that offer a chance to rapidly improve capacity, lethality, and range of munitions. U.S. adversaries and near-peer competitors might not have nearly as advanced weaponry and M&Ms as the United States but capabilities, such as range, are superior. U.S. missiles are extremely well built and are the most advanced in the entire world but are essentially useless if the deployer is unable to get within range. That is why the DOD must encourage and contract for improved and more capable weapon systems, rather than emphasizing safety or accepting designs that are decades old and meet bare minimum specifications as the lowest price.

The DOD should find ways to accept more risk for smaller developmental projects that would allow for new entrants in the rocket and munition space to participate. There should also be plans to continuously enhance and improve munitions without the delays caused by safety and military specification standards. Though those two requirements are necessary, they stifle progressing energetic munitions and cause delays in design and qualifications. The DOD needs to innovate in its testing and qualification processes in order to achieve faster developments in missile capability and performance.

There should be some consideration for government entities, especially the DOD, to help facilitate companies and suppliers by analyzing which regulations can be adjusted or modified to make sense by today's standards. When visiting the Aerojet Rocketdyne facility, the tour team brought up the fact that some regulations that they must abide by date back to the 1960s and are still in use today. They have not been updated and they are not nearly as relevant today due to better practices and materials. These regulations are related to environmental and safety concerns and create a significant barrier to entry for start-up companies as well as for the established companies looking to innovate expeditiously. In order to streamline future production of rockets, the DOD should investigate what regulations can be lifted or modified to enhance the productivity of the SRM industry.

Congress, with the help of the DOD, should incentivize domestic sourcing and production of key minerals and components. International trade and partnerships are crucial to the global economy and support the U.S. economic policies. However, the danger is that too much emphasis has been placed on international trade and domestic sourcing has decreased at an alarming rate. There should be strong consideration to bringing mining and manufacturing opportunities back the United States that utilize state of the art equipment and facilities. Financial and investment plans should be established to assist companies with the capital required to restart mining and manufacturing operations within the United States. Reinforcing the U.S. supply chain should be top priority as it will boost production capacity and offer opportunities to generate a more robust U.S. stockpile of resources, which will be crucial in the event that imports of necessary materials cease due to conflict.

C. FUTURE RESEARCH OPPORTUNITIES

This research provides an analysis of the U.S. SRM munitions posture and how the length of production time along with levels of inventory could affect fighting endurance if a major conflict were to break out between a near-peer adversary. The defense industrial base, to include SRM companies, has consolidated to the point where little competition exists and fewer options are given to the DOD for selecting contractors for newer weapon developments. As mentioned earlier, M&A have been the result of decreased demand for solid rocket motors due to program cancellations, specifically the space shuttle, that could be reinvigorated with the ramp-up defense and government needs for innovation. A desire for innovation and further weapon development drives demand, both in the defense and government space, which should encourage investment in SRM manufacturing and decrease unit costs of SRMs.

To determine if the United States is prepared for extended conflict, war gaming and supply chain simulations should be conducted to find the bottlenecks in producing the M&Ms needed to maintain fighting endurance. Further research should be conducted to look at overall U.S. mining entities and manufacturers supplying the goods needed to produce components and piece parts for munitions. Identifying domestic sources of supply and finding the weak points in international trade could assist with maintaining production of goods within the United States if embargos, or blockades, were to exist during conflict. With that, there should be further research into the supply chain pertaining to the DIB by analyzing where single and sole source suppliers exist.

Budget and funding affects everything from assisting small businesses in crossing the valley of death to increasing production for greater inventory. Therefore, further research needs to be conducted to analyze the change in funding over the past several decades and what might make the most impact for future fiscal year budgets. Looking at the impact of increasing the munitions and missile budget will better support the possibility of effectively increasing inventory levels and bringing in more contractors and suppliers into the rocket industry.

Strong encouragement to continue engaging with the companies listed earlier in this research for further insight into their developments in the industry and how they are improving their products for use by the government. Other companies that are suggested to be interviewed and researched are as follows:

Castelion

Hermeus

Northrop Grumman

Relativity Space

Rocket Lab

This list is limited as the companies mentioned in this research are a small fraction of all the great entities that already exist in the rocket industry or potentially have the capabilities required to enter the industry. Efforts should be made to further research this industry and find ways to improve the development and procurement process. The U.S. DIB is the largest in the world, but there are always chances to improve the whole base by decreasing production time, reducing cost of products, increasing inventory, boosting domestic sourcing, and allowing for aspiring companies to push innovation. Owing to the risks of a future major war, it is imperative that these aspects of the DIB be remedied sooner rather than later.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Aerojet Rocketdyne. (2022, August 9). *New Aerojet Rocketdyne facility consolidates solid rocket motor manufacturing to increase efficiency and capacity*. https://www.l3harris.com/newsroom/press-release/2023/05/new-aerojet-rocketdyne-facility-consolidates-solid-rocket-motor

Belz, A., Terrile, R. J., Zapatero, F., Kawas, M., & Giga, A. (2021). Mapping the "Valley of Death": Managing selection and technology advancement in NASA's small business innovation research program. *IEEE Transactions on Engineering Management*, *68*(5), 1476–1485. https://doi.org/10.1109/TEM.2019.2904441

Blackmon, D. (2021, May 6). *Antimony: The most important mineral you never heard of*. Forbes. https://www.forbes.com/sites/davidblackmon/2021/05/06/antimony-the-most-important-mineral-you-never-heard-of/

Britannica. (n.d.-a). *Cold War: Summary, causes, history, years, timeline, & facts*. Retrieved November 17, 2023, from https://www.britannica.com/event/Cold-War

Britannica. (n.d.-b). *Rocket (Jet-Propulsion Device and Vehicle) | Britannica*. Propellant rockets. Retrieved September 12, 2023, from https://www.britannica.com/technology/rocket-jet-propulsion-device-and-vehicle/images-videos

Bureau of Industry and Security. (2018). *U.S. rocket propulsion industrial base assessment*. U.S. Department of Commerce. https://www.bis.doc.gov/index.php/documents/technology-evaluation/2389-u-s-rocket-propulsion-industry-2018/file

Burke, A., Okrent, A., & Hale, K. (2022). *The state of U.S. science and engineering 2022 | NSF – National Science Foundation*. National Center for Science and Engineering Statistics. https://ncses.nsf.gov/pubs/nsb20221/

Cancian, M. F. (2023). *Rebuilding U.S. inventories: Six critical systems*. https://www.csis.org/analysis/rebuilding-us-inventories-six-critical-systems

Center for Strategic and International Studies. (2021, August 10). *Missiles of Russia*. Missile Threat. https://missilethreat.csis.org/country/russia/

Chaplain, C. (2017). *Surplus missile motors: Sale price drives potential effects on DOD and commercial launch providers* (GAO-17-609). Government Accountability Office. https://www.gao.gov/products/gao-17-609

Clark, M. (2022, October 19). *Promoting defense industry competition for national security's—not competition's—sake*. The Heritage Foundation. https://www.heritage.org/defense/report/promoting-defense-industry-competition-national-securitys-not-competitions-sake

Clark, S. (2023, September 7). *SpaceX broke its record for number of launches in a year*. Ars Technica. https://arstechnica.com/space/2023/09/spacex-broke-its-record-for-number-of-launches-in-a-year/

Cook, R. V., Fairbourn, M. W., & Wendel, G. M. (2000). *NARC rayon replacement program for the space shuttle reusable solid rocket motor nozzle: Screening summary.* (N20000072420). Cordant Technologies, Brigham City, UT. Thiokol Propulsion.; National Aeronautics and Space Administration, Washington, DC. https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/N20000072420.xhtml

DARPA. (n.d.-a). *DARPA budget*. Retrieved October 5, 2023, from https://www.darpa.mil/about-us/budget

DARPA. (n.d.-b). *DARPA DOD 22.4 SBIR annual BAA proposal submission instructions Release 3*. Retrieved October 3, 2023, from https://media.defense.gov/2022/Apr/26/2002984085/-1/-1/1/DARPA_SBIR_224_R3.PDF

DARPA. (n.d.-c). *How to participate in DARPA's SBIR and STTR programs*. Retrieved October 3, 2023, from https://www.darpa.mil/work-with-us/for-small-businesses/participate-sbir-sttr-program

Defense Acquisition University. (n.d.). *Adaptive acquisition framework pathways | Adaptive acquisition framework*. Retrieved October 2, 2023, from https://aaf.dau.edu/aaf/aaf-pathways/

Department of Defense. (2023). *Fact sheet on U.S. security assistance to Ukraine*. https://media.defense.gov/2023/Jul/25/2003267256/-1/-1/0/UKRAINE-FACT-SHEET.PDF

Department of Defense. (2022a). *Military and security developments involving the People's Republic of China 2022*. https://media.defense.gov/2022/Nov/29/2003122279/-1/-1/1/2022-MILITARY-AND-SECURITY-DEVELOPMENTS-INVOLVING-THE-PEOPLES-REPUBLIC-OF-CHINA.PDF

Department of Defense. (2022b). *State of competition within the defense industrial base*. Department of Defense. https://media.defense.gov/2022/Feb/15/2002939087/-1/-1/1/STATE-OF-COMPETITION-WITHIN-THE-DEFENSE-INDUSTRIAL-BASE.PDF

DOD. (2018). *Assessing and strengthening the manufacturing and defense industrial base and supply chain resiliency of the United States*. https://media.defense.gov/2018/Oct/05/2002048904/-1/-1/1/ASSESSING-AND-STRENGTHENING-THE-MANUFACTURING-AND%20DEFENSE-INDUSTRIAL-BASE-AND-SUPPLY-CHAIN-RESILIENCY.PDF

DOD. (2021). *Fiscal year 2020 industrial capabilities report to Congress*. https://media.defense.gov/2021/Jan/14/2002565311/-1/-1/0/FY20-INDUSTRIAL-CAPABILITIES-REPORT.PDF

DOD Office of Inspector General. (2020a). *Audit of purchases of ammonium perchlorate through subcontracts with a single Department of Defense-approved domestic supplier*. https://www.dodig.mil/reports.html/Article/2271272/audit-of-purchases-of-ammonium-perchlorate-through-subcontracts-with-a-single-d/

DOD Office of Inspector General. (2020b). *Top DOD management challenges – fiscal year 2021*. https://www.dodig.mil/Reports/Top-DOD-Management-Challenges/Article/2419079/top-dod-management-challenges-fiscal-year-2021/https%3A%2F%2Fwww.dodig.mil%2Freports.html%2FArticle%2F2419079%2Ftop-dod-management-challenges-fiscal-year-2021%2F

Elon Musk [@elonmusk]. (2021, July 9). *Fellowship of the Raptors https://t.co/Xz3rOsfA2h* [Tweet]. Twitter. https://twitter.com/elonmusk/status/1413736546373718016/photo/1

Gladstone, B., Gould, B., & Patel, P. (2016). *Evaluating solid rocket motor industrial base consolidation scenarios*. Institute for defense analyses. https://www.ida.org/-/media/feature/publications/r/rn/rn2016-evalsolidrocketmotor/rn2016-evalsolidrocketmotor.ashx

Global Security.org. (n.d.). *P-800 Yakhont 3M-55 P-800 Bolid SS-N-26*. Retrieved August 23, 2023, from https://www.globalsecurity.org/military/world/russia/ss-n-26.htm

Harbaugh, J. (2019, September 19). *Kentucky companies give NASA Artemis missions boost to the moon* [Text]. NASA. http://www.nasa.gov/exploration/systems/sls/M19-027.html

Harris, B. (2022, June 9). *The U.S. is heavily reliant on China and Russia for its ammo supply chain. Congress wants to fix that.* Defense News. https://www.defensenews.com/congress/budget/2022/06/08/the-us-is-heavily-reliant-on-china-and-russia-for-its-ammo-supply-chain-congress-wants-to-fix-that/

Hodges, A. (2015, May 3). *SpaceX's Merlin 1D: Built to enable human space exploration*. SpaceFlight Insider. https://www.spaceflightinsider.com/organizations/space-exploration-technologies/spacexs-merlin-1d-built-to-enable-human-space-exploration/

Jones, S. G. (2023). *Empty bins in a wartime environment: The challenge to the U.S. defense industrial base*. https://www.csis.org/analysis/empty-bins-wartime-environment-challenge-us-defense-industrial-base

Jordan, N., & Mapp, J. (2023, June 14). *In the Dark: How the Pentagon's limited supplier visibility risks U.S. national security*. War on the Rocks. https://warontherocks.com/2023/06/in-the-dark-how-the-pentagons-limited-supplier-visibility-risks-u-s-national-security/

Koffler, R. (2023, March 18). *Why China appears ready to go to war with the U.S. over Taiwan*. https://nypost.com/2023/03/18/china-could-go-to-war-with-the-us-over-taiwan/

L3Harris. (2023a). *Solid rocket motors data sheet*. https://www.l3harris.com/resources/solid-rocket-motors-data-sheet

L3Harris. (2023b, July 25). *Aerojet Rocketdyne history: More than a century in the making*. Forward. https://www.l3harris.com/aerojet-rocketdyne-history

Luttwak, E. (2023, July 18). *The clue China is preparing for war*. UnHerd. https://unherd.com/2023/07/the-clue-china-is-preparing-for-war/

Mak, M. (2017). *Solid rocket motors, DOD and industry are addressing challenges to minimize supply concerns*. Government Accountability Office.

Maranda, J. (2023, May 3). *X-Bow lands $60M in funding to support its rocket, aerospace technology*. New Mexico Inno. https://www.bizjournals.com/albuquerque/inno/stories/news/2023/05/03/x-bow-lands-jolt-of-funding-to-mature-tech.html

Mohon, L. (2017, April 12). *First space shuttle mission, STS-1, launches—April 12, 1981* [Text]. NASA. http://www.nasa.gov/centers/marshall/history/this-week-in-nasa-history-first-space-shuttle-mission-sts-1-launches-april-12-1981.html

NASA. (n.d.-a). *A pictorial history of rockets*. Retrieved September 11, 2023, from https://www.nasa.gov/sites/default/files/atoms/files/rockets-guide-20-history.pdf

NASA. (n.d.-b). *Artemis*. Northrop Grumman. Retrieved October 6, 2023, from https://northrop-grumman-lcqrd0rau-agencyq-ngc.vercel.app

NASA. (n.d.-c). *NASA launch schedule* [Text]. NASA. Retrieved September 18, 2023, from https://www.nasa.gov/launchschedule

NASA. (n.d.-d). *NASA SBIR/STTR basics | NASA SBIR & STTR program homepage*. NASA SBIR/STTR Basics. Retrieved September 1, 2023, from https://sbir.nasa.gov/content/nasa-sbirsttr-basics

NASA. (2020, August 6). *NASA motor test helps evaluate new SLS materials – Artemis*. https://blogs.nasa.gov/artemis/2020/08/06/nasa-motor-test-helps-evaluate-new-sls-materials/

NASA. (2021, May 13). *Brief history of rockets*. National Aeronautics and Space Administration. https://www.grc.nasa.gov/www/k-12/TRC/Rockets/history_of_rockets.html

NASA. (2023, March 22). *NASA fiscal year 2024 budget request*. https://www.nasa.gov/nasa-fiscal-year-2024-budget-request/

NDIA. (2022). *Vital Signs 2022*. https://www.ndia.org/-/media/sites/ndia/policy/vital-signs/2022/vital-signs_2022_final.pdf?download=1

Office of the Under Secretary of Defense. (2018). *Annual industrial capabilities report for FY 2017*. https://www.businessdefense.gov/docs/resources/2017_AIC_RTC_05-17-2018-Public_Release.pdf

Perry, N. (2023, September 18). *Sole sourcing & single sourcing: What is the difference?* https://procurementmag.com/articles/sole-sourcing-single-sourcing-what-is-the-difference

Porter, M. E. (2008). *The five competitive forces that shape strategy*. Harvard Business Review, 86(1), 78–93.

Purdue University. (n.d.). *Solid rocket propulsion*. School of Aeronautics and Astronautics – Purdue University. Retrieved September 19, 2023, from https://engineering.purdue.edu/AAE/research/propulsion/Info/rockets/solids

Relativity Space. (n.d.-a). *Factory of the future*. Relativity Space. Retrieved October 18, 2023, from https://www.relativityspace.com/factory

Relativity Space. (n.d.-b). *Good Luck, Have Fun launch*. Relativity Space. Retrieved October 17, 2023, from https://www.relativityspace.com/first-launch-gallery

Relativity Space. (n.d.-c). *The first 3D printet rocket*. Relativity Space. Retrieved October 17, 2023, from https://www.relativityspace.com/glhf

Relativity Space. (2021, August 9). *Relativity Space awarded U.S. Space Force orbital services program (OSP)-4 contract on ramp*. Relativity Space. https://www.relativityspace.com/press-release/2021/8/7/relativitynbspspacenbspawardednbspus-space-force-orbital-services-program-osp-4-contractnbsponnbsprampnbsp

Relativity Space. (2022, October 24). *Relativity Space maps path to Terran R production at scale with unveil of Stargate 4th generation metal 3D printers*. https://www.relativityspace.com/press-release/2022/10/24/relativity-space-maps-path-to-terran-r-production-at-scale-with-unveil-of-stargate-4th-generation-metal-3d-printers

Relativity Space. (2023a, April 12). *Relativity Space shares updated go-to-market approach for Terran R, taking aim at medium to heavy payload category with next-generation rocket*. Relativity Space. https://www.relativityspace.com/press-release/2023/4/12/terran-r

Relativity Space. (2023b, October 11). *Relativity Space and Intelsat sign multi-launch agreement for Terran R*. Relativity Space. https://www.relativityspace.com/press-release/2023/10/9/relativity-space-and-intelsat-sign-multi-launch-agreement-for-terran-r

Schadlow, N., Helwig, B., Clark, B., & Walton, T. A. (2022). *Rocket's red glare: Modernizing America's energetics enterprise*. Hudson Institute. https://s3.amazonaws.com/media.hudson.org/Rocket+Red+Glare.pdf

Seemangal, R. (2017, June 23). *Watch SpaceX fire off its second flight-proven Falcon 9*. Wired. https://www.wired.com/story/watch-spacex-fire-off-its-second-flight-proven-falcon-9/

Sesnic, T. (2021, August 11). *Starbase tour and interview with Elon Musk*. Everyday Astronaut. https://everydayastronaut.com/starbase-tour-and-interview-with-elon-musk/

SpaceX. (n.d.-a). *SpaceX*. SpaceX. Retrieved August 25, 2023, from https://www.spacex.com/

SpaceX. (n.d.-b). *SpaceX – Starshield*. Retrieved October 26, 2023, from https://www.spacex.com/starshield/

Statista. (2023). *NATO Russia military comparison 2023*. Statista. https://www.statista.com/statistics/1293174/nato-russia-military-comparison/

Sullivan, M. (2017). *Military acquisitions: DOD is taking steps to address challenges faced by certain companies* (GAO-17-644). Government Accountability Office. https://www.gao.gov/products/gao-17-644

Sutton, G. P., & Biblarz, O. (2010). *Rocket propulsion elements*. Hoboken, N.J. : Wiley.

Turnwall, J. (2019, November 1). *The Navy is losing the missile arms race*. U.S. Naval Institute. https://www.usni.org/magazines/proceedings/2019/november/navy-losing-missile-arms-race

Ursa Major. (n.d.-a). *Defense | Ursa Major technologies*. Retrieved October 20, 2023, from https://www.ursamajor.com/defense

Ursa Major. (n.d.-b). *Propulsion | Ursa Major technologies*. Retrieved October 20, 2023, from https://www.ursamajor.com/propulsion

Ursa Major. (2022, July 12). U*rsa Major's advanced manufacturing lab in Youngstown, Ohio cuts time to produce rocket engine components from 6 months to 1 month.* https://www.ursamajor.com/media/press-release/rocket-propulsion-companys-3d-printing-lab-delivers-first-rocket-engine

Ursa Major. (2023, May 23). *Contract funds development of storable "Draper" engine for hypersonic defense and 200,000-pound thrust "Arroway" engine as an RD-series replacement.* https://www.ursamajor.com/media/press-release/air-force-research-laboratory-selects-leading-ursa-major-for-hypersonics-and-launch-capabilities

Williams, I. (2023). *Russia isn't going to run out of missiles*. https://www.csis.org/analysis/russia-isnt-going-run-out-missiles

Wilson, J. (2006, March 5). *NASA – Solid rocket boosters* [Feature Articles]. Brian Dunbar. https://www.nasa.gov/returntoflight/system/system_SRB.html

Wilson, J. (2018, April 2). *NASA history overview* [Text]. NASA. http://www.nasa.gov/content/nasa-history-overview

X-Bow Systems. (n.d.). *We Make – X-Bow Systems*. Retrieved October 19, 2023, from https://www.xbowsystems.com/we-make/

X-Bow Systems. (2023, October 10). *X-Bow Systems Inc announces DOD contract for hypersonic solid rocket motor development*. https://www.prnewswire.com/news-releases/x-bow-systems-inc-announces-dod-contract-for-hypersonic-solid-rocket-motor-development-301951856.html

Young, C. (2007). *NASA supplier base: Challenges exist in transitioning from the space shuttle program to the next generation of human space flight systems* (GAO-07-940). Government Accountability Office. https://www.gao.gov/products/gao-07-940

Zwilling, M. (2013, February 18). *10 ways for startups to survive the valley of death*. Forbes. https://www.forbes.com/sites/martinzwilling/2013/02/18/10-ways-for-startups-to-survive-the-valley-of-death/

Acquisition Research Program
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net