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ASSESSMENT OF THE NAVY SOLID ROCKET MOTOR PRODUCTION PROCESS

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THESIS

ASSESSMENT OF THE NAVY SOLID ROCKET MOTOR PRODUCTION PROCESS

by

Marieme Gueye

December 2023

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The United States Navy continues to challenge the presence of the People's Republic of China in the Indo-Pacific region. To strengthen the deterrence posture, the 2022 National Defense Strategy emphasizes the expansion of missile capabilities through the acquisition of missile systems. The propulsion system is the heart of the missile, thus increasing the solid rocket motor (SRM) production rate will directly correlate to the increase of the missile inventory. SRM production process encompasses two major processes: fabrication and qualification. As such, this thesis conducts a thorough analysis of the PEO IWS 3.0 fabrication process and qualification process. When analyzing the fabrication process, amongst all fabrication activities, order procurement has the most significant impact in total fabrication duration. When analyzing the qualification process, SpaceX compressed, which includes early requirement analysis, rapid prototyping, and testing in parallel, is the most time efficient process amongst all others. Future work in this topic should include the integration of fabrication and qualification into the overall production process.

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ASSESSMENT OF THE NAVY SOLID ROCKET MOTOR PRODUCTION PROCESS

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The United States Navy continues to challenge the presence of the People's Republic of China in the Indo-Pacific region. To strengthen the deterrence posture, the 2022 National Defense Strategy emphasizes the expansion of missile capabilities through the acquisition of missile systems. The propulsion system is the heart of the missile, thus increasing the solid rocket motor (SRM) production rate will directly correlate to the increase of the missile inventory. SRM production process encompasses two major processes: fabrication and qualification. As such, this thesis conducts a thorough analysis of the PEO IWS 3.0 fabrication process and qualification process. When analyzing the fabrication process, amongst all fabrication activities, order procurement has the most significant impact in total fabrication duration. When analyzing the qualification process, SpaceX compressed, which includes early requirement analysis, rapid prototyping, and testing in parallel, is the most time efficient process amongst all others. Future work in this topic should include the integration of fabrication and qualification into the overall production process.

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LIST OF ACRONYMS AND ABBREVIATIONS

AGARD	Advisory Group for Aerospace Research and Development
AIM-9	air intercept missile nine
AMRAAM	advanced medium range air-to-air missile
ANOVA	analysis of variance
AR	Aerojet Rocketdyne
CDR	critical design review
CTV	controlled test vehicle
DOD	Department of Defense
DOE	design of experiment
DTRM	dual thrust rocket motor
DTV	developmental test and verification
EDPM	ethylene propylene diene monomer
GALCIT	Guggenheim Aeronautical Laboratory at California institute of Technology
GTV	ground test vehicle
ICBM	intercontinental ballistic missile
JATO	jet assisted takeoff units
LRE	liquid rocket engine
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Sea System Command
NAWS	Naval Air Weapon Station China Lake
NDS	National Defense Strategy
NPS	Naval Postgraduate School
OPTEVFOR	operational testing and evaluation force
OTA	operational test agency
PEO IWS 3.0	program executive office integrated warfare system
PRC	People's Republic of China

SM2	standard missile 2
SM6	standard missile 6
SRM	solid rocket motor

EXECUTIVE SUMMARY

The United States Navy (USN) continues to challenge the presence of the People's Republic of China (PRC) in the Indo-Pacific region. The 2022 National Defense Strategy (NDS) highlights the deterrence against the PRC as one of the department's pacing challenges (Austin 2022). To strengthen the deterrence posture and improve defensive capabilities, NDS emphasizes the expansion of missile capabilities through the development and acquisition of missile systems. As such, increasing the current missile inventory can significantly contribute to the defense of national interest. The propulsion system is the heart of the missile; thus, increasing the propulsion production rate will directly correlate to the increase of the missile inventory.

Program executive office integrated warfare systems 3.0 (PEO IWS 3.0) oversees production and fielding of surface to air missiles onboard all naval surface vessels. Their solid rocket motor (SRM) production process, which has been used for decades, is rigorous but lengthy and currently takes approximately five years for missile production. This production timeline is unreasonably long given the current circumstances in the Indo-Pacific region. As such, the goal of this thesis is to assess the Navy's current production process through the lenses of rocket motor industry companies such as SpaceX and Northup Grumman.

Although the navy uses SRMs for propulsion method, most industry companies use liquid rocket engines (LRE). Both propulsion methods are beneficial, so the first step of the research is to gain understanding of both methods' familiarization, advantages, and disadvantages. SRMs have only a few parts; most importantly, they can be deployed within a moment's notice, and they can be stored safely onboard ships for years. All these desirable attributes make it the propulsion method of choice for the Navy. However, its industrial base is severely lacking as there are only two SRM manufacturing companies in the country: Aerojet Rocketdyne and Northup Grumman. LREs have a lot of moving parts, they take minutes to launch upon notice and they are not safe to be stored in close proximity environments due to the toxic chemical releases. Although it is not a convenient propulsion

method for the Navy, its high performance, re-usability, and throttleability makes it the propulsion of choice for most industry companies.

Upon engaging with PEO IWS 3.0 and rocket industry companies, it was determined that the production process encompasses two major processes: fabrication and qualification. As such, this thesis conducted a thorough analysis of the Navy's fabrication process, followed by an analysis of the Navy's qualification process.

The Navy SRM fabrication process, provided by PEO IWS 3.0, was simulated using ExtendSim, resulting in a total duration of 352 weeks. An initial experimental analysis was conducted assuming a 10% reduction in fabrication activity durations. This resulted in a reduced fabrication duration of 338.2 weeks and 4.82% reduction in overall fabrication time. Notably, order forgings, case manufacture, and case preparation were identified as significant factors affecting total fabrication time at this reduction rate. Subsequently, a second analysis was conducted based on actual reduction percentages provided by the Aerojet Rocketdyne team, ranging from 30–90%. Even with these substantial reductions, the total fabrication time was only reduced to 290 weeks or 18.4%. Notably, order forgings, case manufacture, and order nozzle were the most significant factors that affected total fabrication time at those various reduction rates. Overall, order forgings remained the most influential factor, consistent with both analyses and document engagement with the AR team. Therefore, it emphasizes the significance of addressing forgings procurement for fabrication timeline improvement. Once the fabrication analysis was completed, the qualification process was evaluated next.

The PEO IWS 3.0 qualification process was modeled using ExtendSim. Using the PEO IWS 3.0 process as guidance, SpaceX provided a streamlined process, referred to as "SpaceX compressed," based on their current LRE production method. This SpaceX compressed process included conducting requirement analysis, early fabrication of prototypes, and conducting testing in parallel. To bridge differences between the process, a hybrid process, SpaceX non-compressed was formed, blending attributes from both SpaceX compressed and PEO IWS 3.0 processes. Initial qualification durations were PEO IWS 3.0 at 52.3 months, SpaceX compressed at 31.5 months, and SpaceX non-compressed at 39 months. It is important to note that most major programs are subjected to schedule risks. GAO (2020) detailed that DOD programs suffer schedule risks depending on the implementation of good milestone practices. When all good practices are implemented, programs incur low schedule growth of 5–15% whereas programs that do not implement good practices experience high schedule growth of 40–50%. Both low growth and high growth analysis were conducted for all three processes. Low growth analysis resulted in PEO IWS 3.0 at 54.7–60.1 months, SpaceX compressed at 33.2-36.2 months, and SpaceX non-compressed at 41–44.8 months. High growth analysis resulted in PEO IWS 3.0 at 72.7–77.9 months, SpaceX non-compressed at 44.1–47.2 months, and SpaceX compressed at 54.5–58.5 months. A sensitivity analysis revealed that even with a 50% schedule increase, SpaceX compressed outperformed both the PEO IWS 3.0 and SpaceX non-compressed processes. This highlights the efficiency of SpaceX compressed, thus presenting PEO IWS 3.0 with the opportunity to adopt such streamlined processes as a minimum standard to expedite missile production.

Future work on this topic will include the integration of fabrication and qualification into the production process. Although this thesis was able to analyze fabrication and qualification processes respectively, due to time constraints it was unable to integrate the two processes, which will be valuable in determining the overall impact on the production process.

References

Austin, Lloyd, J. 2022. *National Defense Strategy*. Washington, DC: Department of Defense. https://www.defense.gov/National-Defense-Strategy/.

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I. INTRODUCTION

The 2022 release of the National Defense Strategy identifies the People's Republic of China's (PRC) aggressive posture in the Indo-Pacific region as a serious threat to the United States National Security (Austin 2022). As the United States Navy continues to maintain its posture in the Indo-pacific, so does the PRC, leading to heightened tensions in that region. To strengthen the Navy's deterrence posture in the Indo-Pacific region, the 2022 missile defense review highlights the importance of development and acquisition of missile systems. As such, increasing the missile inventory directly contributes to the defense of national interest.

The propulsion system is the heart of the missile but also its most resource intensive part. Thus, increasing propulsion production will lead to increased missile production. In the rocket industry, there are two main propulsion systems utilized: solid rocket motor (SRM) and liquid rocket engine (LRE). The United States Navy uses predominantly SRMs while the rest of the rocket industry utilizes LREs. These differences in propulsion choices naturally cause major differences in their respective production cycle. However different they might be, both LRE and SRM production processes encompass two major steps: fabrication and qualification. This chapter introduces the background of the research and defines the problem. Then it states the research question, explains the methodology employed, establishes the benefits of the study, and concludes by providing the organization for the remainder of the thesis.

A. BACKGROUND AND PROBLEM DEFINITION

The United States Navy currently has a fleet of 297 ships, all of which are equipped with a large variety of missiles for self-defense and defense of high value assets (O'Rourke 2023). When operating in highly contested areas such as the South China Sea, it is imperative that those surface combatants are outfitted to their maximum missile carrying capacity with the possibility of quick replenishment to sustain a kinetic engagement.

Within the Navy, Program Executive Office Integrated Warfare Systems 3.0 (PEO IWS 3.0), a subcomponent of Naval Sea systems command (NAVSEA), is responsible for designing, producing, and fielding surface ship missiles. As the program office that fielded the standard missile 2 (SM-2) and standard missile 6 (SM-6), PEO IWS 3.0 has been producing shipboard missiles for decades utilizing SRMs as their propulsion of choice.

The two primary methods of propulsion are SRMs and LREs. Although both have advantages and disadvantages, SRMs are PEO IWS 3.0's propulsion of choice for a plethora of reasons. For quick visual comparison, Figure 1 illustrates both SRMs and LREs.

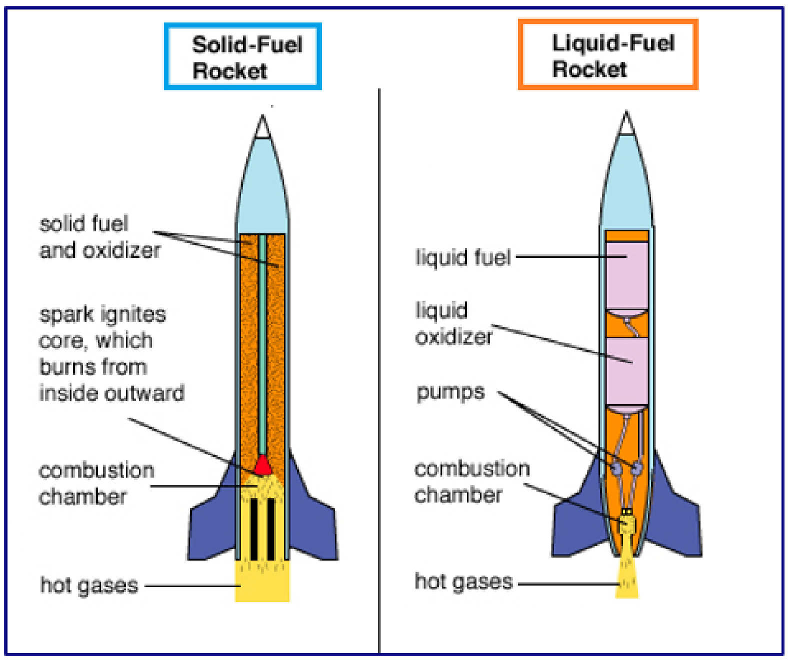

Figure 1. SRM vs. LRE. Source: PEO IWS (2023).

As noted in Figure 1, SRMs are a simpler design that come with less moving part making them easier to store. The solid grain, mixture of fuel and oxidizer, is stored in the case making it a compact and convenient design for shipboard storage. LREs on the other hand have more components such as separate tanks for fuel and oxidizers thus requiring more storage space which is inconvenient for naval vessels. Not to mention that liquid chemicals can emit toxic gases which can be extremely harmful to the Sailors whose living quarters are usually adjacent to missile storage areas. Last and most importantly, SRMs have the unique ability to propel missiles within seconds of acquiring an enemy target.

While forward deployed, ships need the ability to respond instantaneously to imminent threats as that could be the difference between life and death which is the capability that SRMs provide. In contrast, LREs require minutes of preparation prior to being ready for launch, which can be detrimental to the ship and crew safety. Overall, the reasons discussed highlight the advantages SRM which make it the propulsion of choice for the Navy.

As a crucial part of the missile, SRMs are also considered the most challenging subsystem. Thus, increasing the SRMs' production rate leads to an increase in missile production, which in turn aids in the rapid replenishment of the depleting missile inventory. PEO IWS 3.0 has been using the same SRM production process for decades. Although it has been working, these older practices are not efficient in an environment where rapid missile replenishment is crucial. As such, PEO IWS 3.0 has reached out to the Naval Postgraduate School (NPS) to investigate production processes used throughout the rocket industry.

Due to time and budget constraints, this research will only consider existing technology. No technology being developed after 2023 will be considered throughout this research. This thesis will not consider hybrid propulsion and will only focus on the two primary propulsion methods utilized by the rocket industry: SRMs and LREs. This thesis will focus on process improvement of the current SRM production process using the current propulsion technologies and Model Based Systems Engineering tools.

B. RESEARCH QUESTIONS

This thesis seeks to answer the following questions:

- How can PEO IWS 3.0 improve its current rocket motor production process by reducing the duration of the fabrication time?
- How can PEO IWS 3.0 improve its current rocket motor production process by reducing the duration of the qualification process?

C. METHODOLOGY

The overarching goal of this thesis is to improve the current rocket motor production process by adjusting the two key processes: fabrication and qualification. The thesis will first conduct a thorough analysis of the fabrication process which will be followed by a thorough analysis of the qualification process. The three software tools that will be used are ExtendSim, Minitab, and JMP. ExtendSim is a discrete event simulation tool that is utilized to perform process simulation to gain a better understanding of the system's performance. In this case, it will be used to model the fabrication process and the qualification process respectively. ExtendSim will be used in conjunction with Minitab and JMP, statistical software tools, for data analysis.

As a system engineering student, it is important to conduct research guided by the systems engineering process. This research's principal focus is to improve the fabrication and qualification process which corresponds to making adjustments to the bottom and right-hand side of the system engineering vee process shown in Figure 2.

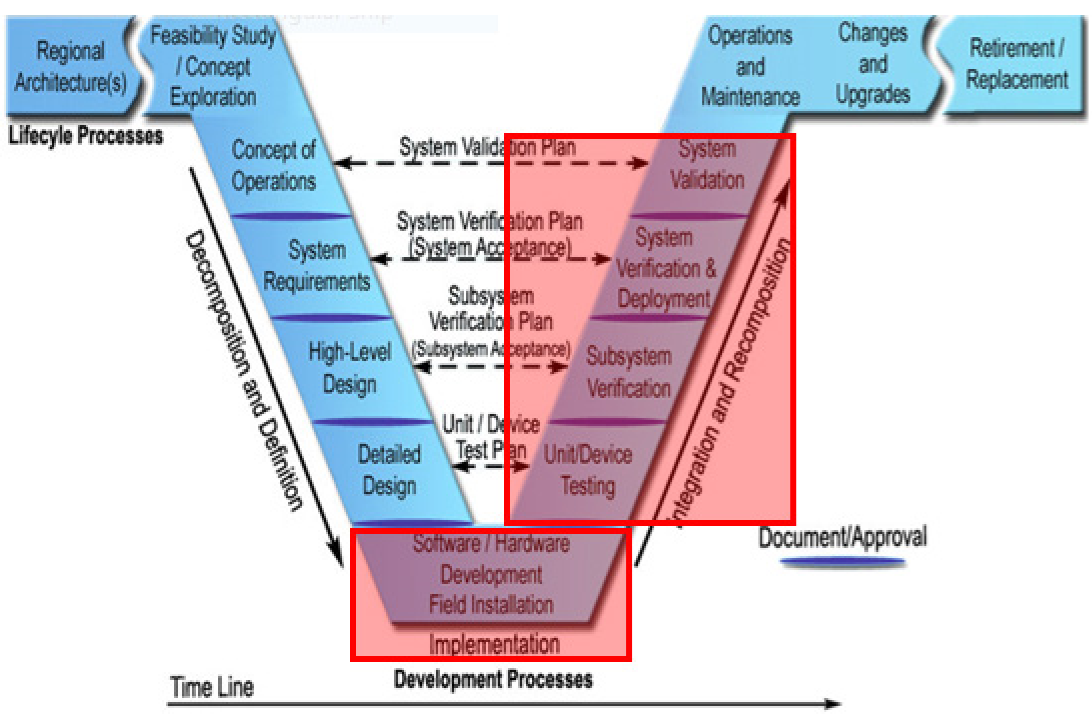

Figure 2. System engineering vee. Adapted from National ITS Architecture Team (2007).

D. BENEFIT OF STUDY

Overall, this thesis aims to assess PEO IWS 3.0's production process by separately analyzing their fabrication and qualification processes. Analyzing each process separately will lead to the identification of the most influential factors that can be adjusted to facilitate the rapid replenishment of the depleting missile inventory. Missile inventory replenishment directly affects the warfighter's ability to defend this nation, its allies, and their interests. It also contributes to the expediated readiness of the nation's strategic and tactical assets.

In recent years the propulsion industry has mainly focused on new technology development to increase missile production. However, those improvements can take years to reach full scale production. No current research focuses solely on improving the current production process utilizing existing technology. This research will be the first of its kind to generate an improved SRM production process upon conducting a thorough and detailed analysis of the current process. This thesis aims to analyze the current SRM production method, review practices used throughout the commercial rocket propulsion industry, and construct an improved SRM production process.

E. THESIS ORGANIZATION

The remainder of the thesis is be structured as follows:

- Chapter II – SRM/LRE familiarization and documented engagements

This chapter encompasses a two-part literature review and documented engagements with rocket propulsion companies. The first literature review covers the historical relevance and background of SRMs followed by a discussion on inefficiencies encountered within that industry. The second literature review covers the historical background of LREs, and the advantages noted within that industry. The literature reviews are followed by documented presentations received by this thesis from other rocket propulsion companies.

- Chapter III – Fabrication process analysis

This chapter provides the ExtendSim model of the current PEO IWS 3.0 SRM manufacturing process followed by an in-depth analysis of the model. The statistical analysis conducted using design of experiments highlights the factors that are important for fabrication timeline reduction.

- Chapter IV – Qualification process analysis

This chapter provides analyses on the current PEO IWS 3.0 qualification process and two other derived processes, SpaceX compressed and SpaceX non-compressed. ExtendSim is used to model all three processes and thorough analyses will be conducted using various statistical software such as Minitab and JMP.

- Chapter V – Conclusion

This chapter summarizes the research efforts and addresses the proposed research questions. It also offers concluding remarks and highlights future research opportunities.

II. SRM/LRE FAMILIARIZATION AND DOCUMENTED ENGAGEMENTS

Propulsion systems are a crucial component of any rocket system. The Advisory Group for Aerospace Research and Development (AGARD) (1988) states, "the purpose of SRM and LRE is to provide propulsive force for a missile or other aerospace vehicle" (9–1). To gain insight into existing literature, this literature review is broken up into two major sections. Each section will focus on SRM and LRE, respectively, their historical background, major components they are comprised of, and current industry trends associated with each propulsion system. The reviews will highlight causes of the current industry conditions and the subsequent impact of those conditions on the overall present rocket industry. This will be followed by written documentation of the rocket companies the research team interacted with to gain insight into other existent production process.

A. SOLID ROCKET MOTOR

SRM propulsion has been used since the 1950s. Its capability ranges from short and medium range tactical missiles to long range strategic missiles, all of which provide national defensive capabilities. That said, building and maintaining a healthy missile inventory is vital to national security. However, there have been numerous challenges associated with the SRM manufacturing process that hinder said inventory. This thesis provides a historical background of SRM, discusses the main subsystems and considers three major contributors 1) narrow pool of SRM manufacturers 2) long lead times for crucial components 3) destructive testing methods.

1. Historical Background

In the United States, SRMs development dates to the 1940s. They first came into use due to their relative simplicity and relatively smaller number of moving parts. According to Price (1998) the modern era of rocket propulsion began in the 1939–1941 time frame due to the country's need for ordnance devices as World War II began. He further explains that as technology evolved, SRM became more missile / ordnance oriented while LRE became more utilized for space travel.

According to DeLuca (2017), in 1936 GALCIT (Guggenheim Aeronautical Laboratory at California Institute of Technology) led a project that was meant to implement solid rocket motor propulsion for the development of the jet assisted takeoff units (JATO) for the U.S. Army and Air Force marking SRM inception. As noted throughout history, the need for military advancement drove the country's technological growth spur. DeLuca (2017) further states that the program was directed by Dr. Theodore Von Karman, along with his three associates, who eventually created the Aerojet engineering corporation in 1942. He elaborates, explaining that in 1948, the same team discovered the use of ammonium perchlorate as a composite propellant, which is a significant contribution to the SRM industry that is still used today, nearly 70 years after the fact (DeLuca 2017). Price (1998) highlights GALCIT as one of the most vital development agencies of this era due to their technological breakthroughs.

As the industry grew, so did the application of SRMs and its technological progression. Price (1998) expresses that the 1950s marked the expansion of SRM into variety of applications from short and medium range tactical missiles such as AMRAAM (Advanced Medium Range Air-to-Air Missile), SM6 (Standard Missile 6), AIM-9 (Air intercept Missile) sidewinder, to long range strategic missiles such as SM3 (Standard Missile 3), ICBM (Intercontinental Ballistic Missile). As stated, the technological flexibility of solid propulsion allows for its diverse application in short, medium and long-range missiles.

2. SRM Components

A generic solid rocket motor, as shown in Figure 3, highlights the four main components: igniter, propellant grain, motor casing, and nozzle. Each subsystem is discussed separately along with its function.

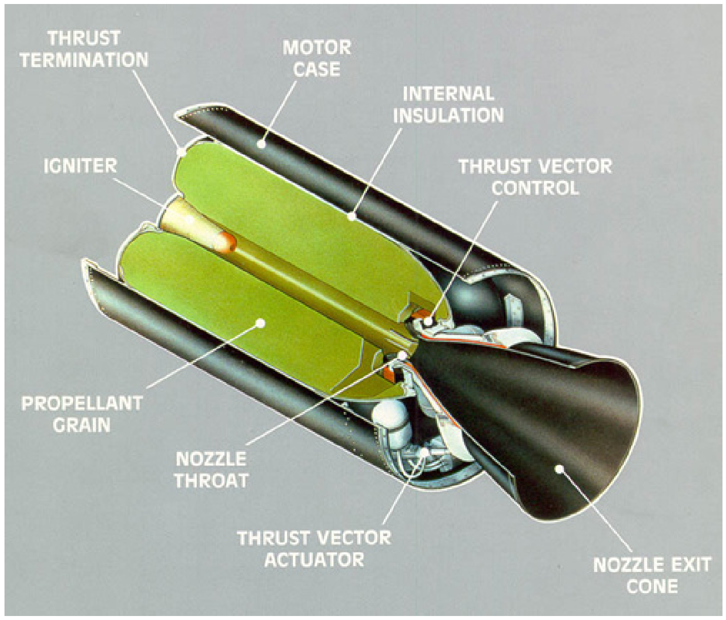

Figure 3. Solid rocket motor features. Source: PEO IWS (2023).

The first major component is the igniter. As its name indicates, it ignites the propellant grain thus initiating the combustion reaction. Barret (1971) defines the purpose of the igniter, "to induce the required combustion reaction in a controlled and predictable manner and at a stipulated rate" (2). Kumar, Nayana and Shree (2016) elaborate on Barrett's definition, stating that the ignitor initiates the combustion systems by providing an electric signal with high specific energy. Barrett (1971) details that the ignition system encompasses an initiation system and an energy release system, both are contained into a hardware that is embedded into the propellant grain. He expands further stating that the initiation system converts the electrical, mechanical or chemical stimulus into an energy output thus activating the motor ignition process. Once ignited, Barrett (1971) specifies that the energy release system supplies the heat flux necessary to ignite the propellant grain in the motor and raise it to a self-sustaining combustion level. Once combustion starts, the igniter's role is completed allowing the propellant grain to keep burning.

The next major component is the propellant grain. The propellant grain is a solid, paste-like mixture, consisting of two main elements: a fuel and an oxidizer. According to the AGARD 1998 report, the mixture of these two ingredients, along with other polymers/ binders, is poured into the motor case using various geometries. AGARD (1998) explains that the burning of the surface area is dictated by the grain geometry which dictates the mass flow rate, thus defining the thrust profile of the motor. Prasad et al. (2022) make the same observation stating that grain geometry determines the gas amount, burn time and rate based on the size and shape of the grain. Both sources emphasize the importance of the propellant grain and conclude that grain geometry dictates overall motor performance.

The next major component is the motor case. The AGARD 1988 report explains that the role of the motor case is to protect and store the grain until usage and serve as the combustion chamber for high pressure and high temperature burning while in use. The AGARD 1998 report provides a wholesome definition stating that the motor case "is a containment for propellant grain, a pressure vessel during motor burn, and a structure member to carry missile loads" (1–5). The motor case contains internal insulation protection which provides thermal protection to the case. According to AGARD (1988), insulation provides flow erosion resistance in the areas where the grain burns to the wall before the entire grain is consumed. The most common insulator used are ethylene propylene diene monomers (EPDM) (Kumar, Nayana, and Shree 2016). They explain that because the motor itself does not contribute to the energy produced, it should be as light weight as possible. AGARD (1998) also concurs with that statement explaining that being light weight results in a higher motor mass fraction, and higher performance. According to Kumar, Nayana, and Shree (2016) the most common material used for motor casing are metals and composite materials. They share some examples of metals and composites used for motor casing such as resistance steels and high strength aluminum alloys and glass, Kevlar, and carbon respectively. They expand on the topic stating that motor case is also referred to as "the combustion chamber due its ability to withstand 3–30Mpa of internal pressure and 2000–3500K of heat produced" (Kumar, Nayana, and Shree 2016, 3). Overall, the motor case, combustion chamber, is where the chemical reaction takes place prior to being converted into kinetic energy.

The last major component is the nozzle. AGARD (1998) explains that upon burning propellant grain in the combustion chamber, it is then expelled through the converging-diverging nozzle providing thrust. It also explains that the primary function of the SRM nozzle is to channel and control the expansion of hot gases from the chamber thus producing the thrust profile required. Kumar, Anaya and Shree (2016) elaborate stating geometry of the nozzle is important as it determines the amount of total chemical energy that is converted into kinetic energy for propulsion. They explain that controlling the conversion rate of the chemical energy from the propellent grain to kinetic energy allows for the optimal thrust profile needed for a specific design (Kumar, Nayana, and Shree 2016, 2). Thus, it can be concluded that the nozzle plays an important role as it guides the thrust profile of the motor.

Each component plays an important role and collectively contributes to the functionality and performance of the motor. Now that SRM familiarization has been established, the next step is to discuss challenges noted throughout the SRM industry.

3. SRM Industry Challenges

The SRM industry has been subjected to numerous challenges in the past two decades. The following section will be addressing industry challenges such as narrow pool of suppliers, long fabrication lead time, and destructive testing methods.

a. Narrow pool of manufacturers

The Department of Defense (DOD) and National Aeronautics and Space Administration (NASA) depend on commercial companies to produce SRM propulsion systems. Conversely, the SRM industry's main customer base is the DOD and NASA. A 2017 GAO report states that SRMs are used by more than 40 DOD missile programs. Likewise, the 2011 NASA council report highlights NASA as the largest consumer of SRM propellant over the last 20 years with production demand of 30 million pound of propellant per year. Thus, one can reasonably conclude that it is the government's demands that significantly drive the survival of the SRM industry.

In 2010s, NASA retired the space shuttle program and was given directive to cancel the constellation program. A 2011 NASA council report explains that both cancellations had drastic impacts on the SRM industry as it drove the SRM demand to less than 4 million pounds of propellant a year. Years after NASA's report , the Office of Under Secretary of Defense for Acquisition, Technology and Logistics voiced the same impacts in a 2016 report stating that NASA's retirement of the space shuttle and the cancellation of the constellation program have resulted in significant under-utilization of existing facilities resulting in their consolidation (255). Figure 4 shows a graphic representation of the Solid rocket motor demand and the drastic decrease noted in the 2010s as a result of those cancellations.

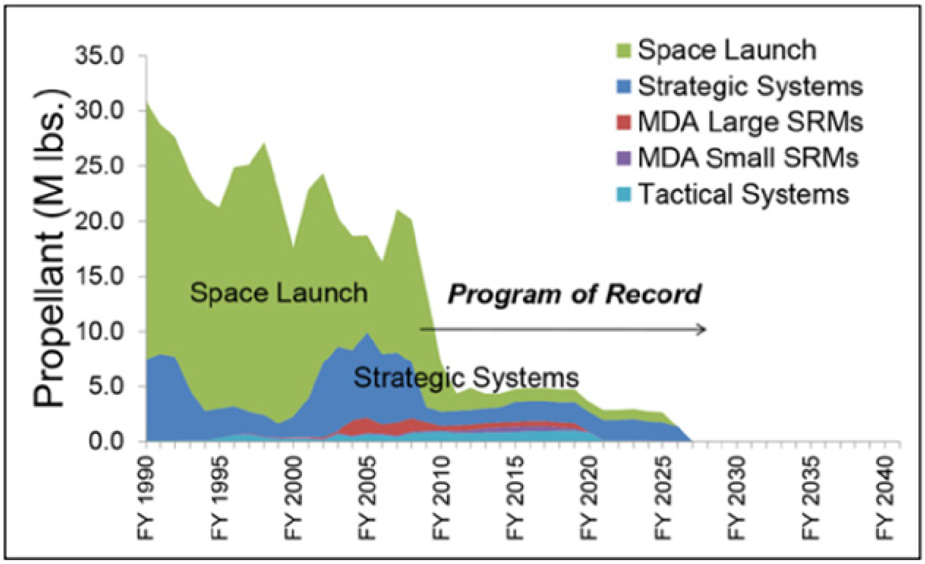

Figure 4. SRM demand decrease. Source: Gladstone, Gould, and Patel (2016).

These cancellations significantly reduced the demand in the SRM industry. GAO (2017) concurs, stating that loss of suppliers is a result of the decreased SRM demand. The reduced demand eventually caused the manufacturers to consolidate. That opinion is supported by Figure 5 which pictorially depicts the consolidation of the companies along the years. This consolidation results in only two manufacturers remaining in the SRM industry, Aerojet Rocketdyne and Northup Grumman as shown in Figure 5.

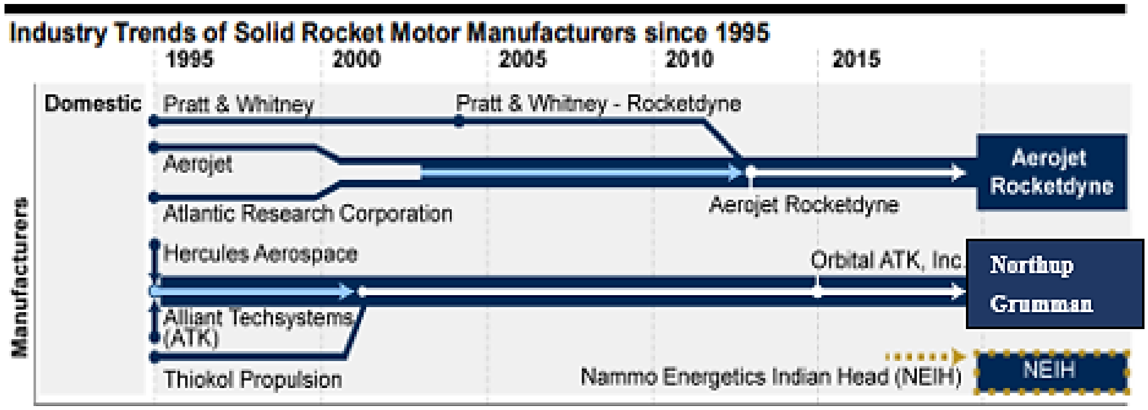

Figure 5. SRM Manufacturer consolidation. Adapted from GAO (2017).

Having only two manufacturers in any industry is problematic let alone a unique industry such as SRM. These limited options force the DOD into single or sole sourcing. The Defense Industrial Base and Supply Chain Resiliency report defines single sourcing as a case when "only one supplier is qualified to provide a required capability" and defines sole sourcing as the case when "only one supplier can provide the required capability" (Office of the Under Secretary of Defense for Acquisition and Sustainment and Office of the Deputy Assistant Secretary of Defense for Industrial Policy 2018, 48). This thesis would argue the SRM industry is subjected to both single and sole sourcing which is problematic. Having a single or sole supplier, therefore not much competition, provides no incentives for the supplier to improve cost, service, or quality of the product. The Council of Economic Advisers (2016) report agrees with this assessment and states that "competition may lead to greater product variety, higher product quality, and greater innovation." The Defense Industrial Base and Supply Chain Resiliency report agreed with the council economic advisors and took it a step further by identifying single and sole sourcing as the top ten risk archetypes threating America's manufacturing and defense industrial base. It explains further stating that reduced competition, as currently seen, can lead to higher prices and lower quality (Office of the Under Secretary of Defense for Acquisition and Sustainment and Office of the Deputy Assistant Secretary of Defense for Industrial Policy 2018). This opinion in shared in academia by Larson and Kulchitsky (1998) whom described sole sourcing as giving supplier little to no incentive to corporate for improved performance thus resulting in lower quality, higher total cost and less supplier cooperation.

Due to the NASA cancellations, the SRM industry consolidated to two primary suppliers: Northup Grumman and Aerojet Rocketdyne which is problematic for the defense industrial base. Now that there is an established understanding of the SRM industrial base, the next step is to discuss issues associated with part procurement.

b. Long fabrication time for crucial components

Unfortunately, many crucial components have long led time resulting in delays SRM fabrication. The components most subjected to long lead times are propellants and nozzles.

(1) Propellant concerns

In rocketry, the propellant is the most integral part as its combustion provides the propulsion required. In SRM, the propellant fabrication process is overly complex, tedious, and time consuming. The first part of the process focuses on creating the propellant mixture. The propellant, a mixture of oxidizer, fuel and other additives, must be combined at the right temperature, pressure, and dosage to achieve the consistency required. Noel (1973) concurs with that statement stating that "the mere difference in mixing times, chemical dosage amount, casting duration, and cure time can cause variations in the overall propellant properties" (14). The second part of the process focuses on evaluating grain geometry and design. The propellant mixture is poured into the motor case and solidifies into a grain, which is molded to adopt a certain geometry. The AGARD 1998 report emphasizes the importance of this process, stating, "this is crucial as the grain geometry/ design entirely determines the mass flow rate of the burning surface and thrust profile, therefore, dictating the performance of the rocket motor. Figure 6 shows a few different propellant geometries and their associated thrust profile.

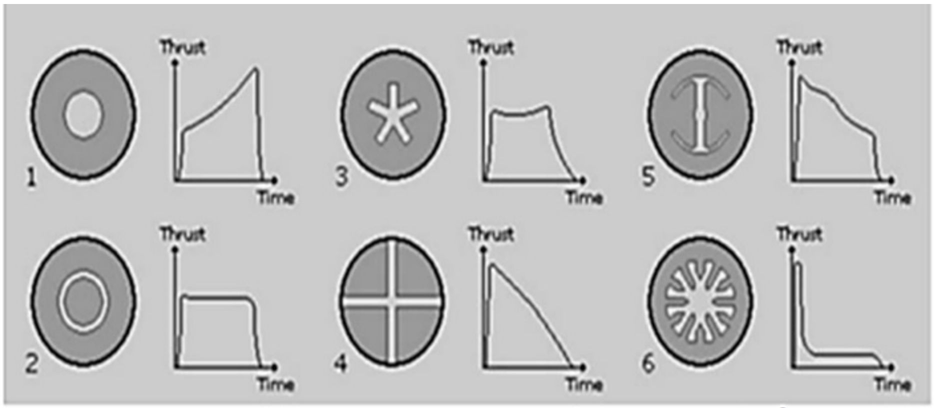

Figure 6. Grain geometry and thrust profiles. Source: AGARD (1998).

An improper fabrication process can result in rocket motor failure. AGARD (1998) report states that propellant failure is determined as any structural malfunctioning that causes the grain to deviate from designed performance. Both Noel (1973) and (AGARD) 1998 reports highlight examples of basic failure modes such as surface cracks, debonding of interfaces, excessive deformation, and auto ignition. It is important to note that the smallest mistake or inconsistency during the mixing and grain design process can cause failure, which results in total loss of the rocket motor. Once the motor is destroyed, the process starts all over again exhausting more time and more resources. This further extends the timeline of an already lengthy fabrication process. Now that the propellant concerns have been addressed, the focus is shifted to nozzle concerns.

(2) Nozzle concerns

As discussed in the SRM component section, the nozzle is a critical part of the solid rocket motor as it determines the resultant thrust profile. Controlling the expansion of the hot gases at the nozzle helps manage the thrust profile of the vehicle thus controlling the range of the motor (Ellis and Keller 1975)

According to Ellis and Keller (1975), the nozzle is designed to withstand temperatures between 5100°F to 6000°F. They explain that due to the extreme temperatures and conditions, the nozzle has to be made of materials that can withstand those temperatures while also maintaining the efficiency of the motor. Upon years of research, the best nozzle materials are carbon-carbon composites as they exhibit less erosion, are extremely heat resistant, more light weight and provide 1% or more in nozzle efficiency (Ellis and Keller 1975).

These highly desirable products usually experience long procurement delays. According to Maahs (1989), in 1989 carbon-carbon composite took three to nine months to make (1). In 2023, this timeline is further exacerbated due to the supply chain delays imparted by the COVID-19 pandemic. Thus, it is reasonable to state that carbon-carbon composites procurement will also be affected further expanding an already lengthy procurement time. As such, this crucial component's delays, causes the manufacturing of the solid rocket motor to also be delayed.

Nozzles are made of special materials such as carbon-carbon composites as they need to withstand great temperature and pressure. However, there are great delays associated with the procurement process thus affecting the overall production time. Now that the nozzle concerns have been discussed, the next item of discussion is the destructive testing methods.

c. Destructive testing methods

Due to the potential catastrophic results associated with its malfunction, SRM is subjected to extensive testing to ensure its proper functionality and performance. According to Genov et al. (2020) all destructive testing are "considered the gold-standard measurements for the performance of the system" (471). They also state that it plays a significant role in ensuring safety and performance of the motor. Ellis and Kellers (1975) elaborate further stating that although there are multiple destructive testing methods, such as chemical analysis, aging, mechanical testing, the live firing test remains the most significant test performed to evaluate the performance of the rocket motor.

Firing tests occur at various stages of motor development, much like an iterative process, addressing different problem areas thus providing pertinent motor data and characteristics. The AGARD 1998 report divides firing testing into three categories. They begin with prototype firing testing which is conducted upon design completion and is designed to check for thermal shocks, cycling, and involuntary ignition conditions. Next, the report mentions sub-scale firing test which is performed to test SRM response to complex loading with focus placed on structural and ballistic concerns. Lastly, the AGARD 1998 report states that full-scale testing is conducted last to ensure full compliance with all operational requirements given by the customer. The report highlights the importance of conducting live firing tests at every phase.

Although essential, each firing test conducted comes at great expense as once the motor is testing, it is destroyed. Expectedly, the 1998 AGARD report concurs and emphasizes this observation by referring to the rocket motor as a one shot device/one shot proposition that can only be used once. Unfortunately, this is concerning due to SRM's high cost and long fabrication timeline mentioned in previous sections. This essentially means that after testing each SRM, another one has to be built as a replacement and also to incorporate all the lessons learned for design improvement. To conclude, for each test completed, many man hours and materials are lost, and more financial means are exhausted.

SRM is a great propulsion method that has been used for centuries due to its reliability and technological adaptability. However, its industrial base has significant issues that add to the challenges of its procurement. Now that SRM has been thoroughly discussed, the next section will focus on liquid rocket engines.

B. LIQUID ROCKET ENGINE

As seen in recent years, the liquid rocket engine industry has been a tremendous asset in transporting payloads to space as evidenced by SpaceX. Due to their high specific impulse and overall performance, LREs have a myriad of applications ranging from manned flights, payload delivery, cargo transport, to deep space explorations, and others. LREs have been actively used since the 1960s, however its industry has experienced exponential growth in the last 10 years. This literature review will first provide the historical background, then identify the major components that make up the LREs and lastly discuss the major advantages that contributed to the rapid increase in more rocket engine companies.

1. Historical Background

Liquid rocket engine technology has been utilized for several decades. According to Sutton (2003), liquid engine propulsion is the technology that propelled the United States into the “space age” (78). He supports that statement by explaining that the 1960s mark the era when most, if not all, space vehicles and satellites started using liquid engines solely as means of propulsion. Price (1998) concurs with this statement stating that space travel visionaries focused on the usage and development of LRE making it an indispensable asset in that industry. It can be concluded that the 1960s really mark the beginning of the LRE technology era.

LRE history cannot be told without mentioning the most important American rocket pioneer. The first person in the world to accomplish full LRE design, construction and testing is American physics professor Robert Hutchinson Goddard (Sutton 2003). Sutton states that Professor Goddard is the landmark of LRE development as he was the first person to conduct a successful static hot fire test in 1923 followed by a successful first flight in 1926. Professor Goddard’s research efforts continued throughout the years as he was the first to design and fly a rocket with “movable tail” in 1937 which eventually turned into the earliest form of thrust vector control (Sutton 2003). Sutton highlights that although Goddard conducted some early SRM research, he abandoned that field to focus on LRE due to its higher performance. In the rocket industry, Goddard is known as the father of modern rocketry.

Much like a lot of technologies, LRE propulsion was initially developed for military applications. Sutton (2003) states that “in 1950s–1970s, LRE were selected as a means of propulsion for the initial ballistic missiles helping to urgently replenish the missile inventory needed by the U.S. Government” (11). The rocket’s mission dictates the amount of thrust required from the rocket engine thus thrust values vary significantly from one engine to the next. Sutton (2003) highlights that Goddard’s first rocket produced 40–100 Ibs of thrust, limiting its applications to small sounding rockets. Looking at present day, rocket engines are reaching thrust levels as high as 1,800,000Ibs and fulfilling both military and civilian missions as demonstrated by SpaceX.

2. LRE Components

A typical liquid rocket engine is comprised of five main parts: the fuel, the oxidizer, the pumps, the combustion chamber and the nozzle as shown on Figure 7. Each subsystem is discussed in detail in the following sections to highlight its purpose and functionality.

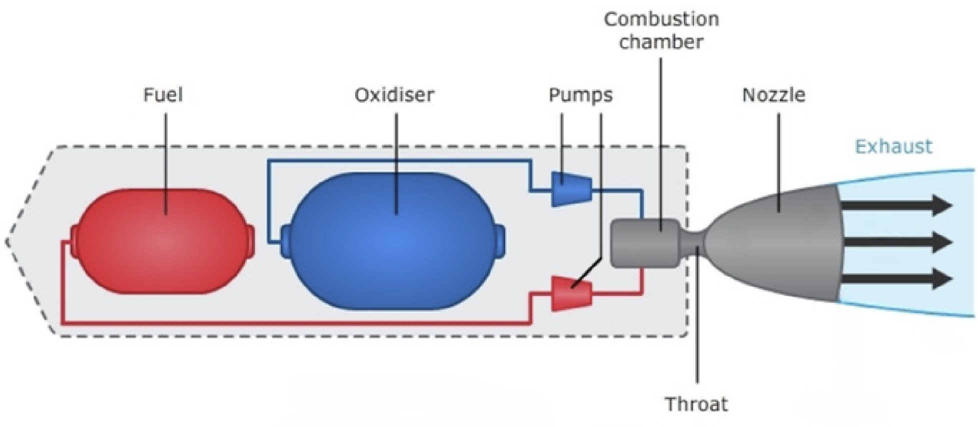

Figure 7. Liquid rocket engine components. Source: NASA (2021).

The first component discussed are the fuel and oxidizer. Huang and Huzel (1967) state that the LRE industry uses liquid propellant to describe the combination of fuel and oxidizer Figure 7 shows the fuel and oxidizer held in separate tanks until they reach the combustion chamber via the pumps which is an example of a bipropellant liquid system due to the fuel and oxidizer being held separately. Huzel and Huang explain further that although bi-propellant systems are most commonly used due to their higher performance, monopropellant systems are also an option, but mainly for smaller systems. They define monopropellants as single propellant in a pre-existing mixture of fuel and oxidizer or a single compound that can be decomposed. They proceed to explain that monopropellant's major disadvantage is lower performance and it can be very unstable thus making bipropellant systems more desirable option (Huzel and Huang 1967). Bipropellants are broken up into two main categories hypergolic or non-hypergolic compounds. Hypergolic compounds ignite spontaneously upon mixing whereas non-hypergolic compounds use ignition systems to ignite the fuel and oxidizer mixture once it reaches the combustion chamber (Huzel and Huang 1967). Some examples of fuel commonly used are kerosene, alcohol, hydrazine and its derivatives, and liquid hydrogen. Commonly used oxidizers are nitric acid, nitrogen tetroxide, liquid oxygen, and liquid fluorine (Huzel and Huang 1967). The propellant is an integral part of the LRE as it provides kinetic energy required thus dictating rocket performance.

The next subsystem discussed is the pump which falls under the larger umbrella of propellant feed systems. As the name indicates, propellant feed systems deliver propellant from the tanks to the combustion chamber and are usually categorized as either pressure-fed or pump-fed (Cannon 2010). Cannon (2010) explains that pressure-fed systems depend on the propellant tank pressures to supply propellant to the combustion chamber making it an undesirable choice as it operates mainly in low pressures. On the other hand, pump-fed systems utilize turbopumps to transfer propellant from the tanks to the combustion chamber making them well suited for high-pressure, high-performance systems (Martensson et al. 2007). Bissel and Sobin (1974) concur with that statement and explain further that the turbopumps are designed to receive propellants at low pressure, keeping the tanks light weight, and delivering the propellant at high pressure thus keeping the combustion chamber pressure elevated. Martensson et al. (2007) conclude that the turbopump system determines the chamber pressure which in turn dictates the resulting thrust produced. Bissel and Sobin (1974) highlight the complexity of turbopumps and explain that they are system of systems that include turbines, gears, inducers and pumps. They elaborate that turbopumps are designed for the lowest minimum weight allowing the engine to deliver a higher payload thus maximizing engine performance. Lasty, they note that specific turbopump performance is always determined based on the engine it is fitted to (Bissel and Sobin 1974). Ultimately, the design of the engine determines the design of the pump.

The third subsystem discussed is the combustion chamber. As the name indicated, the combustion chamber converts the incoming propellant into high pressure and high temperature gas through combustion (Huzel and Huang 1967). Gill and Nurick (1976) provide further detail stating that the combustion chamber includes injectors which control the flow of the propellant into the chamber. They highlight its importance by explaining that injector mixture ratio and mass flow rate determine the combustion rate of the propellant thus directly affecting the stability, duration, and overall performance of the engine .The combustion chamber in a bipropellant system's optimum mixture ratio is richer in fuel and lower in oxidizer thus providing maximum flame temperature (Huzel and Huang 1967). Mishra (2017) concurs with this point, explaining that propellant mixture ratio is crucial as the temperature and pressure in the chamber determine its exit velocity thus engine performance. Overall, the combustion chamber in LRE serves the same purpose as in SRM with the addition of the injectors that help control the amount of thrust produced by adjusting the fuel to oxidizer ratio.

The last component discussed is the nozzle. Much like in the SRM, the nozzle's main function is to efficiently convert the combustion gases into kinetic energy which is high gas exhaust velocity (Mishra 2017). LRE nozzles are also converging-diverging types such that they can accelerate the velocity of the gases to reach supersonic speeds, according to Huzel and Huang (1967). They explain that the convergence part of the nozzle increases the speed of the fluid flow until it reaches sonic velocities at the throat, the flow in this region is referred to as choked. They continue to explain that the divergence section then increases the fluid flow to supersonic velocities thus propelling the rocket forward (Huzel and Huang 1967). Overall, the nozzle converts high pressure and high temperature gas expelled from the combustion chamber to high thrust jet required for engine propulsion.

Now that the rocket engine's main features have been discussed, the following section will discuss the advantages noted throughout the LRE industry.

3. LRE Advantages

There are many advantages to using LRE for space application. The following section addresses are higher performance, reusability and throttleability.

a. Higher performance

LREs have many great advantages which contribute to the industry's growth in liquid engine start-up companies. The major advantages are higher specific impulse, reusability, and throttleability.

A major advantage of LRE is that it produces higher specific impulse than SRMs Although there are several parameters used to describe rocket performance, specific impulse is the most important and common one used (Mishra 2017). Mishra defines specific impulse as the “thrust per unit weight flow rate consumption of propellant.” Although Huang and Huzel (1967) agree with this statement, they explain specific impulse as the force generated by the vehicle thrust and the propellant weight consumption in a given time commonly expressed on seconds. Mishra (2017) concurs with that statement but also warns against using seconds as a mere measurement of elapsed time. He explains that it “represents the time during which the thrust delivered by the rocket engine is equal to the propellant weight which also indicates how much impulse can be generated per unit weight of propellant”(Mishra 2017, 16). For comparison purposes, Table 1 shows the specific impulse of LREs and SRMs.

Table 1. Rocket engine values. Adapted from Mishra (2006).

Rocket engine	Isp (s)
Rocket Motors	200 – 310
Liquid engine	300 – 460

As discussed Table 1 shows that LRE have higher specific impulse than SRM. The advantage of having a higher specific impulse is better engine performance as the engine produces more thrust for the same amount of propellant. Mishra (2017) concurs with that point and adds that a higher specific impulse means that the engine is operating at extended range which translates to superior performance (17). The higher performance benefit that LREs provide make it an extremely desirable option for the rocket industry and the go-to option for the up-and-coming rocket companies. The next biggest advantage of the LREs is their reusability.

b. Reusability and Throttleability

A unique and extremely desirable aspect of LREs is their ability to be reused numerous times and be adjusted during flight contrary to SRMs.

Behring et al. (2017) define a reusable engine as "a unit, subsystem, or vehicle that is to be used for multiple missions" (13). Childress-Thompson, Thomas, and Farrington (2016) highlight the same point affirming that all rocket engines are reusable as they can be restarted multiple times throughout the testing process and during space mission. They elaborate stating that the same launch vehicle can be tested at least 10 times. The advantage of retesting the same launch vehicle is that the resultant lessons learned from testing can be applied to the same model for more improved technical readiness without rebuilding from ground zero. Thus, using the same LRE multiple times allows for time, cost, and resource savings. In successful reuse, LRE acquisition cost is higher than the refurbishment cost thus reusing the same hardware saves time and money as new items are not acquired (Childress-Thompson, Thomas, and Farrington 2016). Reusability has recently become a trend as most companies like SpaceX are striving toward producing a 100% reusable rocket engine which would result in enormous savings.

Throttle liquid engines are defined as "having variable thrust upon command thus producing a varying thrust profile achieved by regulating propellant flow through control valves" (Casiano, Hulka, and Yang 2009, 5). Adjustability during flight is a feature that can only be noted in LREs as it is nonexistent in SRMs. Brown, Cannon and Halchak (2018) highlight that this capability allows for orbital maneuvering capability and controlled landing which are crucial elements of space explorations. Reusability and throttleability are the two key features that expand the application of LREs making them the perfect choice for space applications as it allows for safe and controlled transportation of human and cargo.

SRMs, LREs, and their respective industries have been thoroughly discussed hence providing familiarization and foundational knowledge on the topic. This familiarization will prove to be important as the research team interacts with companies in the rocket motor industry which is documented in the following section.

C. DOCUMENTED ENGAGEMENTS

The rocket industry has undergone a remarkable evolution marked by outstanding advancement in technologies. As such, to attain a comprehensive grasp of the industry, the research team engaged with several companies who provided great insight into their production methods and processes. The organizations that interacted with the research team are Aerojet Rocketdyne, Northup Grumman, URSA major, Anduril formerly known as Adranos and SpaceX. Each company's interaction is discussed in great detail in the following sections.

1. Aerojet Rocketdyne (L3 Harris Technologies)

As the current contractor for PEO IWS 3.0 and the primary contractor of SRMs Aerojet Rocketdyne was the first company to discuss their production process with the team. The discussion in this section will be drawn from Aerojet Rocketdyne' presentation (Mike Steel, personal communication, February 27, 2023).

Aerojet Rocketdyne stated that they encounter two major issues: procurement and qualification. They stated that for SRMs, many crucial components such as the propellant and carbon-carbon composites have lengthy procurement times. This remark is consistent with the carbon-carbon discussion held in nozzle concern section. Unfortunately, there is not much that can be done about it as they are unable to maintain a large inventory. They mentioned that they only to order" as they can only place orders upon gaining funds from DOD contracts. They emphasized that because the government is their primary customer, when consolidations occurred in 2010s, they suffered great consequences. With no customer, they were forced to close multiple facilities and lay off many qualified workers. Once they started gaining more government contracts, they had to re-establish their infrastructure by re-hiring / retraining workers and requalifying the production lines whose qualification expires if gone idle for six months or longer. Essentially every time the government decides not to invest in SRMs, they lose the infrastructure and have to rebuild from scratch once SRM procurement contracts are re-established.

The main takeaway from the discussion with Aerojet Rocketdyne is that they need continuous DOD contracts. When DOD funding pauses, so does their entire infrastructure.

As such having smaller contracts that are continuous throughout the years is much for beneficial than large contracts that are only viable for a couple years followed by a few years of no contracts.

2. Northup Grumman

As one of the primary defense contractors and the only other company that manufactures SRMs, Northum Grumman engaged with the team to discuss their current industry experiences. The discussion in this section will be drawn from Northum Grumman's presentation (Robert Gleeson, personal communication, April 6, 2023).

Much like Aerojet Rocketdyne, they stated that they also experience long lead time with certain materials. However, due to the magnitude of their corporation, they are able to hold large inventories of critical components and even manufacture their own to avoid schedule delays. An example they provided is that for a long-time ammonium perchlorate, the key ingredient in SRM propellant grain took a very long time to procure as it was only produced by one company called American pacific (AMPAC). Because there were no other competitors, AMPAC would raise their prices and deliver the product late. Instead of remaining at the mercy of AMPAC, Northup Grumman decided to make ammonium perchlorate in-house thus greatly saving resources.

Overall, the main takeaway from Northup Gruman is that when possible, having all the resources in house can save a lot of time and money.

3. Anduril (Adranos)

Andurial, formerly known as Adranos, is one of the few new solid rocket motor companies that started in 2020. The discussion in this section will be drawn from Anduril's presentation (Royce Beal, personal communication, April 7, 2023).

When engaging with Anduril, they highlighted that their technological advances make them stand out in the current industry. They claimed that their current technology surpasses the performance of the traditional ammonium perchlorate used in the rocket motor. They claim that they are the only company that currently uses this revolutionized fuel that will improve motor performance. As they are a relatively new company, they have not yet undergone a complete qualification process.

The main takeaway from Anduril is that their goal is to change the SRM industry by perfecting their fuel technology which will provide unprecedented motor performance.

4. URSA Major

As a new LRE company, URSA Major was founded in 2015 and engaged with the team to discuss their current industry experiences. The discussion in this section will be drawn from URSA Major's presentation (Brad Appel, personal communication, April 14, 2023).

URSA Major explained that although they are currently engaged in the LRE industry, which is their main area of expertise, they will eventually lean into the SRM industry as they want to become a one stop shop for all rocket propulsion. They have not yet completed qualifications, but they expressed many concerns with gaining government contracts which will allow them to evolve more as a company. They expressed major concerns with the valley of death as they have noted many startup companies that were unable to navigate through it. They stated that they have a lot to offer to the DOD and would like to see the government take more chances on smaller companies such as theirs instead of only focusing on major contractors such as Aerojet Rocketdyne.

The main takeaway from interacting with URSA Major is that they are a new company that is eager to make their mark in the rocket motor industry. If given the chance, they could help improve LRE and SRM performance by incorporating innovative technologies.

5. SpaceX

As one of the biggest rocket companies in the world, SpaceX was one of the main organizations that the team was looking forward to engaging with. Although they are a liquid engine company and have no interest in SRMs, they shared a presentation with five important tips that make a difference in any production process (Jessica Jensen, personal communication, May 15, 2023)

Requirement analysis: They conduct a deep dive into the system requirements to verify their accuracy. They trace every requirement to an individual to gain a better understanding of the accuracy of the requirement. They stated that long-standing requirements warrant the most scrutiny, especially considering the transformative changes in technology over the past two decades.

Process/Part deletion: They strive to delete unnecessary steps rather than try and optimize them. They spend a lot of time in the beginning of the project to eliminate redundant process steps before progressing further, which becomes helpful during production. This allows for high production rates which provides flexibility to accommodate failures in designs and tests, knowing that another unit is rapidly forthcoming and adaptable to modifications.

Optimize/simplify: This step accentuates the importance of first starting with refining requirements, then proceeding to eliminate unnecessary steps, prior to moving to optimization. To achieve optimization, a key strategy is to consolidate functions within a single component, to avoid inefficiencies and achieve a more desirable outcome.

Accelerate: They emphasize that production lines can always go faster. They ensure production line efficiency by taking a hands-on approach of physically locating their components. This helps identify bottle necks if there are any while also creating a sense of urgency. The example they provided was that if one of their parts was backlogged in India, the engineer in charge would go to India and stay with their counterpart to figure out the source of the bottle neck. They remain there until the part is ready at which point they will return to SpaceX with the part in hand. This is excellent practice.

Automate: This is the last step and should only be completed once 1, 2, 3, 4 are sequentially completed to avoid the automation of unnecessary or overly complex elements.

In addition to the five main points, they were proud to admit that they are "hardware rich." They hold a large inventory of all the items needed for engine construction and all assemblies are conducted in house, guaranteeing the reliability of the subsystems. Being hardware rich also allows them to test as soon as they have a design built, in their own words “test what you fly.” Overall, SpaceX provided a great presentation and helpful insights into their production process.

Upon engaging with the five companies listed above, the underlying theme was fabrication, qualification and their impact on the production process. Every company expressed issues with part procurement or taking steps towards avoiding part procurement issues. This highlights the importance of the fabrication process as without it, there is no motor. They all mentioned continuously taking steps toward expediating their qualification process to meet schedule demands. With this new knowledge in mind, the focus of Chapters III and VI will be to conduct a detailed analyzing the current fabrication and qualification processes used by PEO IWS 3.0 with the goal of generating improved processes.

III. FABRICATION PROCESS ANALYSIS

The fabrication process is an integral part of the SRM production as it is the phase where physical motor assembly takes place. As expected, a fully assembled motor is needed prior to proceeding into verification, validation, and qualification. As such, long fabrication time results in an extended overall production time. Because a reduced motor assembly time is preferred, an analysis of the current fabrication duration is conducted with the goal of identifying the activities that impact the timeline the most.

A. SRM FABRICATION PROCESS MODELING

PEO IWS 3.0 provided this thesis with the snake chart of the SRM fabrication process that is used by their contractor Aerojet Rocketdyne. Figure 8 highlights the 18 main activities that are accomplished for a complete motor assembly. The time durations are removed from each activity block as it is proprietary information. However, a fictional timeline representing each activity duration is provided for the purposes of this thesis research. The activities in Figure 8 are color coded to correspond to the general categories identified in Figure 9. AFD events are shaded green, Nozzle and Throat events are shaded red, case and propellant grain events are shaded blue, and pack and ship events are shaded black.

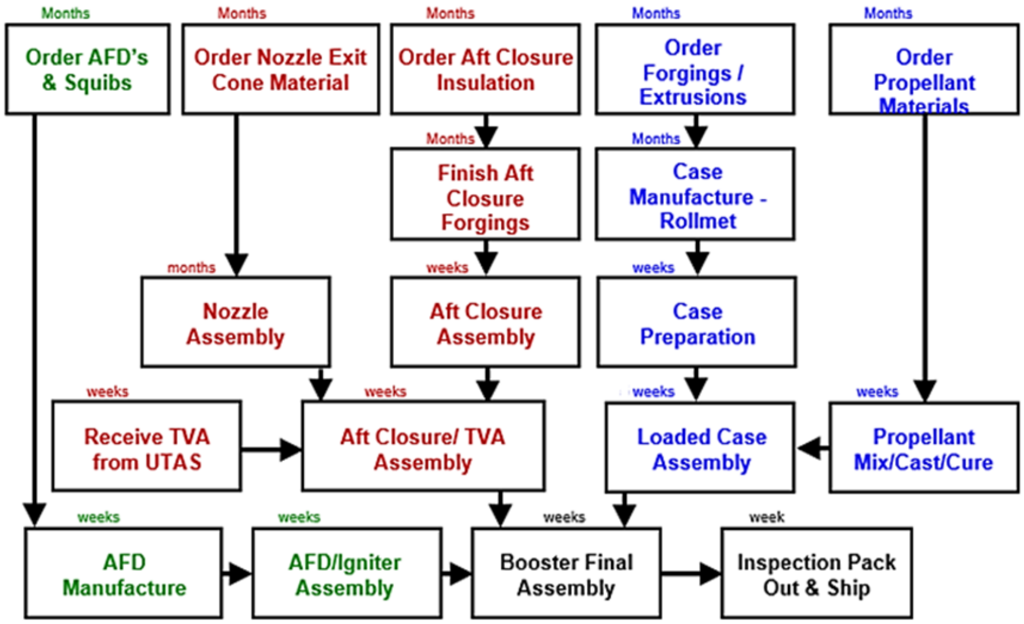

Figure 8. Snake chart of SRM fabrication process. Adapted from PEO IWS 3.0 (2023).

To further explore the snake chart in Figure 8, the discrete-event simulation software ExtendSim is used to reproduce the process and aid in conducting more in-depth analysis. Figure 9 illustrates the resultant ExtendSim model created to represent the fabrication process. The four major sections annotated as AFD nozzle and throat, case and propellant grain, pack and ship correspond to the four color-coded sections on the snake chart in Figure 8.

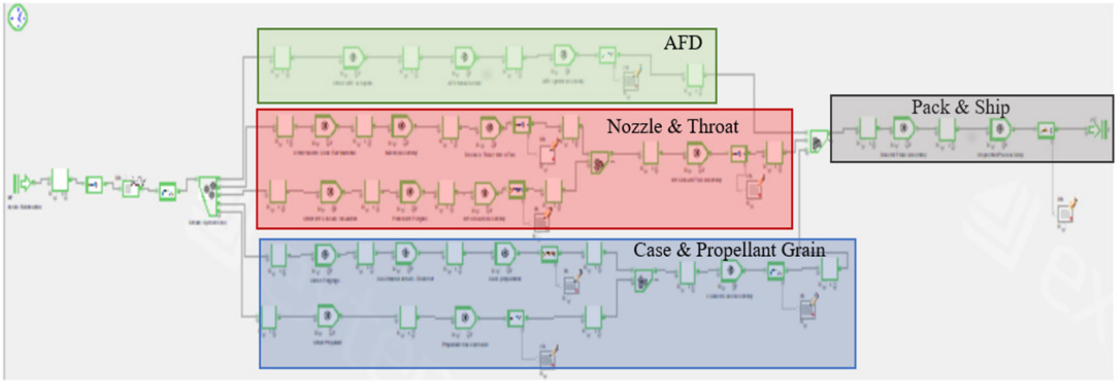

Figure 9. ExtendSim model of SRM fabrication process

1. ExtendSim Model Description

The ExtendSim model starts with a create block indicating the beginning of the fabrication process. Each activity on the diagram is represented by an activity block on the model. The create block connects to a read block, which extracts different activity durations from the input database and makes it available for use by the various activity blocks throughout the model. It is then followed by the equation block used to set the current time as the start time and assign the mean as the given values and standard deviation as 10% of the mean.

With the initial set up complete, the batch-out block is utilized to simultaneously create the five initial activity blocks corresponding to the first five blocks on the activity diagram: one within the AFD process, order AFD; two within the nozzle and throat process, order nozzle and order aft closure; and two within the case and propellant grain, order forgings and order propellant. Starting with the top green section in Figure 9 AFD follows the sequence of three activities noted in the green color-coded section of the activities diagram in Figure 8. The next two lines shown in the red box correspond to the nozzle and throat section shown in red on the activity diagram. The red lines start as individual lines with their respective activity blocks aligned successively, showing their path. However as seen on Figure 8 they merge at aft closure TVA, which is represented by a batch-in block on the model. The batch-in feature allows two individual processes to merge into one. The last two lines shown in the blue box encompass the propellant grain and case process. These two lines also start as individual processes and merge at the load assembly activity block, which is represented by the batch-in block. All three major sections, AFD, nozzle and throat, case and propellant grain merge into the booster assembly activity block, shown in gray, utilizing the batch-in feature. Upon merging all three processes, they go through the pack out and shipping process marking the end of the fabrication process.

With the snake chart converted into an ExtendSim model, a design of experiment (DOE) with several factors is conducted to analyze the fabrication process. The 18 activities are the factors/variables that contribute to the response variable total fabrication time. Upon creating the ExtendSim model, each activity is assigned a duration using the values in Table 2. It is assumed that these durations are the longest time each activity is allowed to take.

Table 2. Original activity duration

Activity	Duration (weeks)
1. Order AFD’s and Squibs	88
2. AFD Manufacture	44
3. AFD/Igniter Assembly	5
4. Booster Final Assembly	3
5. Inspection Pack Out and Ship	1
6. Order Nozzle Exit Cone Material	96
7. Nozzle Assembly	80
8. Receive TVA from UTAs	10
9. Order Aft Closure Insulation	76
10. Finish Aft closure Forgings	76
11. Aft Closure Assembly	31
12. Aft Closure/TVA Assembly	5
13. Order Forgings/Extrusions	112
14. Case Manufacture-Rollmet	84
15. Case Preparation	38
16. Loaded Case Assembly	5
17. Order Propellant Materials	64
18. Propellant Mix/Cast/Cure	6

The 18 activities represented on Table 2 are the input variables to the ExtendSim model and are also referred to as the factors. The 18 factors result in one output or response variable, which is total fabrication time. Executing the model with the given activities, the average total fabrication time calculated is 355.2 weeks.

Figure 10 fabrication duration histogram, displays a graphical representation of the dataset. It indicates that original fabrication conforms to a normal distribution with a mean of 355.2 weeks.

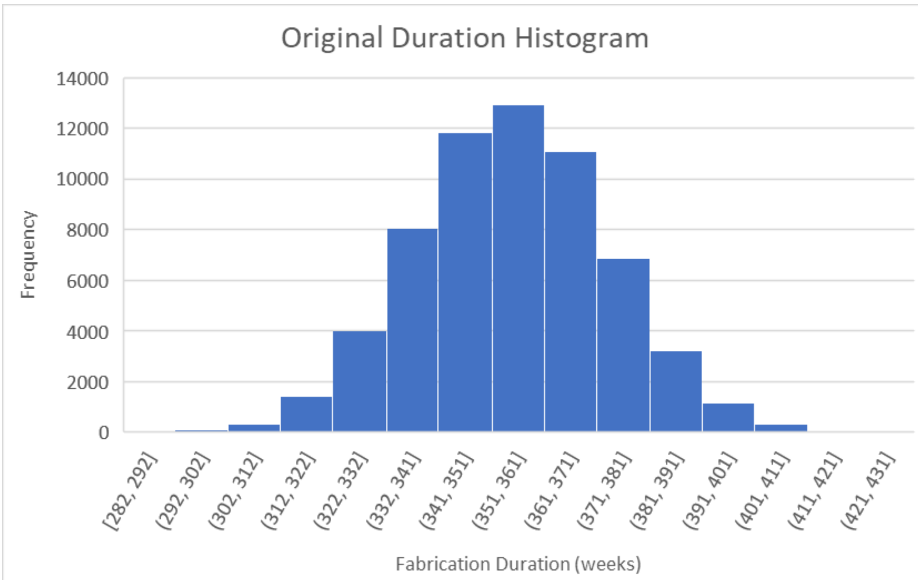

Figure 10. Original fabrication duration histogram

Upon verifying proper functionality of the model using the given values, the next step is to add more granularity to the model. Utilizing the single point values given makes for a deterministic model which is undesirable. To remedy that, the model is modified to be stochastic by assuming that all activities follow a normal distribution with the given duration as the mean and the standard deviation as 10% of the mean.

Upon model completion, the next focus is to determine which factors have the most impact on the response variable by creating a design of experiment. To narrow down the design space, the assumption is made that any activity that has a duration of 10 weeks or less will not be considered in the DOE as their impact will not be significant. That assumption reduces the number of relevant factors from 18 to 11. Focusing on the 11 factors, Figure 11 shows the process that is followed to design, test, and analyze the response-variable fabrication timeline.

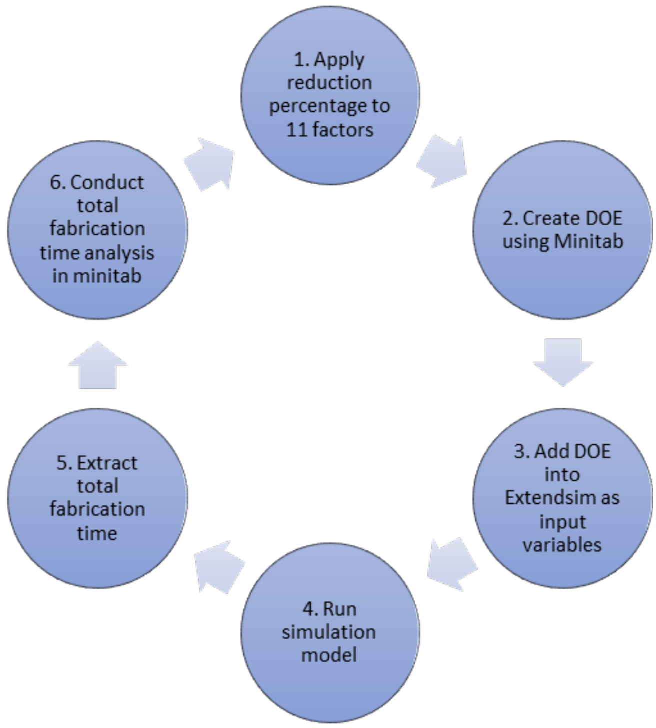

Figure 11. SRM fabrication analysis process

2. Experimental Analysis (10% Reduction)

To perform the design of experiment, a specific percentage reduction is applied to all activity durations to generate low values while maintaining the given values in Table 2 as high values. Due to a lack of provided information, a conversative 10% reduction is applied to account for the current post COVID-19 era in which procurement delays are dwindling and the in-person workforce is being restored. As such, Table 3 shows the 10% reduced duration. This experimental strategy focuses on reduced durations which allows for an assessment of the areas where improved performance, modeled as a lower activity duration, offers the largest potential impact in terms of reducing the overall fabrication timeline.

Table 3. Reduced fabrication duration (10% reduction)

Activity	Duration (Weeks)	% Reduction
1. Order AFD	79.2	10%
2. AFD Manufacture	39.6	
3. AFD/Igniter Assembly	5*	
4. Booster Final Assembly	3*	
5. Inspection Pack Out and Ship	1*(no change)	
6. Order Nozzle Exit Cone Material	86.4	
7. Nozzle Assembly	72.0	
8. Receive TVA from UTAs	10*(no change)	
9. Order Aft Closure Insulation	68.4	
10. Finish Aft closure Forgings	68.4	
11. Aft Closure Assembly	27.9	
12. Aft Closure/TVA Assembly	5*(no change)	
13. Order Forgings/Extrusions	100.8	
14. Case Manufacture-Rollmet	75.6	
15. Case Preparation	34.2	
16. Loaded Case Assembly	5*(no change)	
17. Order Propellant Materials	57.6	
18. Propellant Mix/Cast/Cure	6*(no change)	

Upon obtaining the reduced values, Minitab is used to generate a 2-level factorial design with 11 factors, each of which is replicated 30 times, resulting in a total of 61440 runs. Upon generating the factorial design, the duration values are used as input variables into the ExtendSim model, which is then executed. Upon execution completion, the model generates an average total fabrication time of 338.2 weeks which is a 4.82% reduction from the original duration as summarized in Table 4. Total fabrication time values are entered into Minitab where the first step of the statistical analysis is data visualization.

Table 4. SRM fabrication duration comparison (10% reduction)

Activity	Duration (weeks)	Achieved reduction
Original time	355.2	4.8% reduction
Adjusted time (10% reduction)	338.2	

a. Data Visualization

The first step of data visualization is generating a histogram which facilitates the illustration of data variability. Looking at Figure 12, the data indicate a normal distribution with a mean of 338.2 weeks. Knowing the data distribution is crucial as it determines the statistical methods that can be used to make inferences on the data.

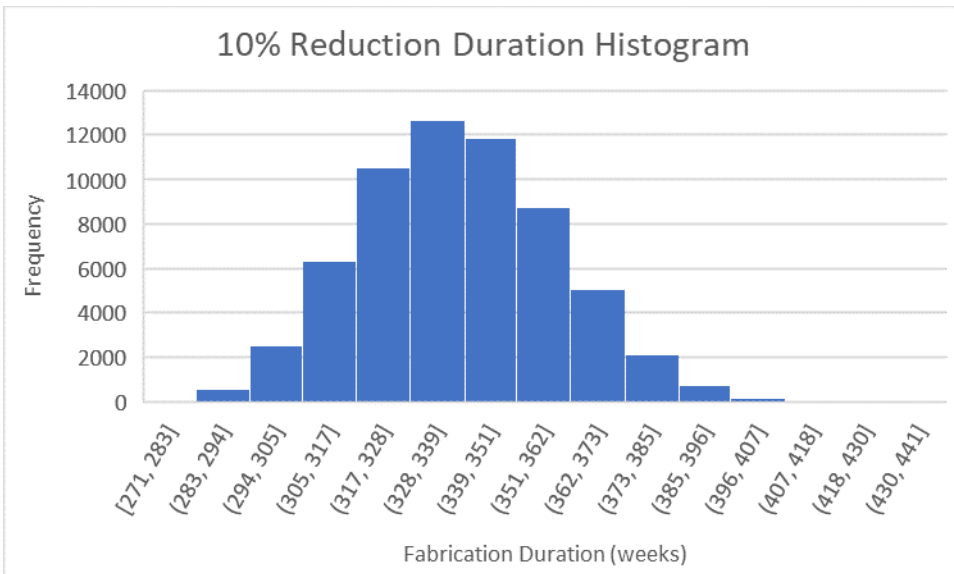

Figure 12. 10% fabrication reduction histogram

The pareto chart provides a visual representation of all the factors arranged in order of impact on total fabrication time. The results are displayed such that the higher the standardized effect, the more impactful the factor as shown in Figure 13.

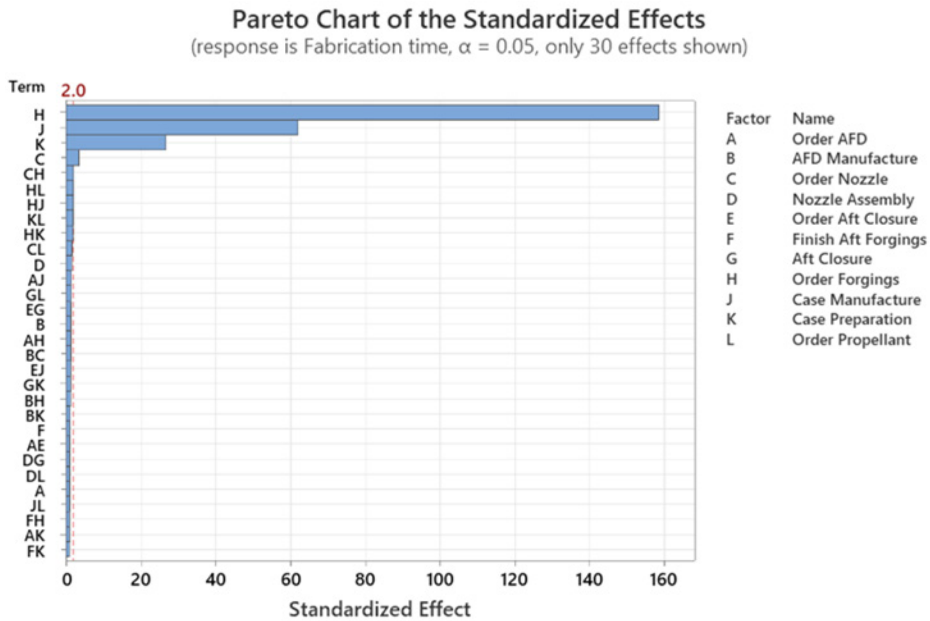

Figure 13. Pareto chart (10% reduction)

As such, looking at, Figure 11 the most influential factors are order forgings (H), case manufacture (J), and case preparation (K), respectively. Although visual representations are convenient as they provide an initial glance at the data, more in-depth analysis needs to be conducted to determine the impact of the factors on total fabrication time starting with an analysis of variance (ANOVA).

b. ANOVA (10% Reduction)

To evaluate the effects of the various factors, hypothesis testing is performed using ANOVA, at a 95% confidence level. The hypothesis testing is stated as follows:

Ho: Mean total fabrication time is not affected by any of the factors.

Ha: Mean total fabrication time is affected by at least one of the factors.

Upon conducting the hypothesis testing, all significant factors or their combinations are those with a p-value ≤ 0.05. The ANOVA table in Figure 14 displays the effects of the main factors and two-way interactions. The statistically significant factors and two-way combinations are highlighted in the red boxes.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Order AFD	1	311	311	1.07	0.301
AFD Manufacture	1	529	529	1.81	0.178
Order Nozzle	1	3648	3648	12.52	0.000
Nozzle Assembly	1	690	690	2.37	0.124
Order Aft Closure	1	12	12	0.04	0.838
Finish Aft Forgings	1	370	370	1.27	0.260
Aft Closure	1	45	45	0.15	0.696
Order Forgings	1	7331919	7331919	25158.64	0.000
Case Manufacture	1	1123877	1123877	3856.45	0.000
Case Preparation	1	208801	208801	716.48	0.000
Order Propellant	1	69	69	0.24	0.628
Order AFD*AFD Manufacture	1	32	32	0.11	0.741
Order AFD*Order Nozzle	1	114	114	0.39	0.531
Order AFD*Nozzle Assembly	1	115	115	0.40	0.529
Order AFD*Order Aft Closure	1	337	337	1.16	0.282
Order AFD*Finish Aft Forgings	1	8	8	0.03	0.866
Order AFD*Aft Closure	1	192	192	0.66	0.416
Order AFD*Order Forgings	1	528	528	1.81	0.179
Order AFD*Case Manufacture	1	668	668	2.29	0.130
Order AFD*Case Preparation	1	268	268	0.92	0.338
Order AFD*Order Propellant	1	9	9	0.03	0.857
AFD Manufacture*Order Nozzle	1	519	519	1.78	0.182
AFD Manufacture*Nozzle Assembly	1	32	32	0.11	0.742
AFD Manufacture*Order Aft Closure	1	242	242	0.83	0.362
AFD Manufacture*Finish Aft Forgings	1	0	0	0.00	0.972
AFD Manufacture*Aft Closure	1	189	189	0.65	0.421
AFD Manufacture*Order Forgings	1	436	436	1.50	0.221
AFD Manufacture*Case Manufacture	1	194	194	0.66	0.415
AFD Manufacture*Case Preparation	1	430	430	1.48	0.224
AFD Manufacture*Order Propellant	1	215	215	0.74	0.390
Order Nozzle*Nozzle Assembly	1	8	8	0.03	0.866
Order Nozzle*Order Aft Closure	1	26	26	0.09	0.766
Order Nozzle*Finish Aft Forgings	1	11	11	0.04	0.846
Order Nozzle*Aft Closure	1	7	7	0.02	0.877
Order Nozzle*Order Forgings	1	1298	1298	4.45	0.035
Order Nozzle*Case Manufacture	1	18	18	0.06	0.804
Order Nozzle*Case Preparation	1	117	117	0.40	0.526
Order Nozzle*Order Propellant	1	839	839	2.88	0.090
Nozzle Assembly*Order Aft Closure	1	217	217	0.74	0.389
Nozzle Assembly*Finish Aft Forgings	1	152	152	0.52	0.470
Nozzle Assembly*Aft Closure	1	334	334	1.15	0.284
Nozzle Assembly*Order Forgings	1	92	92	0.32	0.574
Nozzle Assembly*Case Manufacture	1	0	0	0.00	0.989
Nozzle Assembly*Case Preparation	1	6	6	0.02	0.890
Nozzle Assembly*Order Propellant	1	319	319	1.10	0.295
Order Aft Closure*Finish Aft Forgings	1	92	92	0.32	0.573
Order Aft Closure*Aft Closure	1	540	540	1.85	0.173
Order Aft Closure*Order Forgings	1	82	82	0.28	0.596
Order Aft Closure*Case Manufacture	1	488	488	1.67	0.196
Order Aft Closure*Case Preparation	1	75	75	0.26	0.613
Order Aft Closure*Order Propellant	1	118	118	0.40	0.525
Finish Aft Forgings*Aft Closure	1	217	217	0.75	0.388
Finish Aft Forgings*Order Forgings	1	283	283	0.97	0.324
Finish Aft Forgings*Case Manufacture	1	31	31	0.11	0.745
Finish Aft Forgings*Case Preparation	1	248	248	0.85	0.356
Finish Aft Forgings*Order Propellant	1	10	10	0.04	0.850
Aft Closure*Order Forgings	1	162	162	0.56	0.456
Aft Closure*Case Manufacture	1	80	80	0.27	0.600
Aft Closure*Case Preparation	1	467	467	1.60	0.206
Aft Closure*Order Propellant	1	660	660	2.26	0.132
Order Forgings*Case Manufacture	1	1257	1257	4.31	0.038
Order Forgings*Case Preparation	1	1077	1077	3.70	0.055
Order Forgings*Order Propellant	1	1263	1263	4.33	0.037
Case Manufacture*Case Preparation	1	90	90	0.31	0.579
Case Manufacture*Order Propellant	1	309	309	1.06	0.303
Case Preparation*Order Propellant	1	1110	1110	3.81	0.051
Error	61373	17885781	291		
Lack-of-Fit	1981	563747	285	0.98	0.773
Pure Error	59392	17322034	292		
Total	61439	26572687			

Figure 14. ANOVA table (10% reduction)

For better visualization, all statistically significant factors and their combination highlighted in Figure 14 are summarized in Table 5.

Table 5. Statistically significant factors (10% reduction)

Main Effects	P-value	Interaction effects	P-value
Order Nozzle	$<5x10^{-4}$	Order Nozzle*Order Forgings	$<5x10^{-4}$
Order Forgings	$<5x10^{-4}$	Order Forgings*Case manufacture	$<5x10^{-4}$
Case manufacture	$<5x10^{-4}$	Order forgings *Order Propellant	$<5x10^{-4}$
Case Preparation	$<5x10^{-4}$		

Based on the p-values shown in the table, there are four factors and three two-way interaction effects that are statistically significant. Hence, it can be concluded that there is enough evidence to reject the null hypothesis as the mean fabrication time is affected by at least one of the factors shown in Table 5. Based on this understanding of significant factors, the next step is to determine the degree of influence of the individual factors on total fabrication using main effect plots.

The main effect plots, in Figure 15, are graphical representations that illustrate the impact of individual factors on total fabrication time.

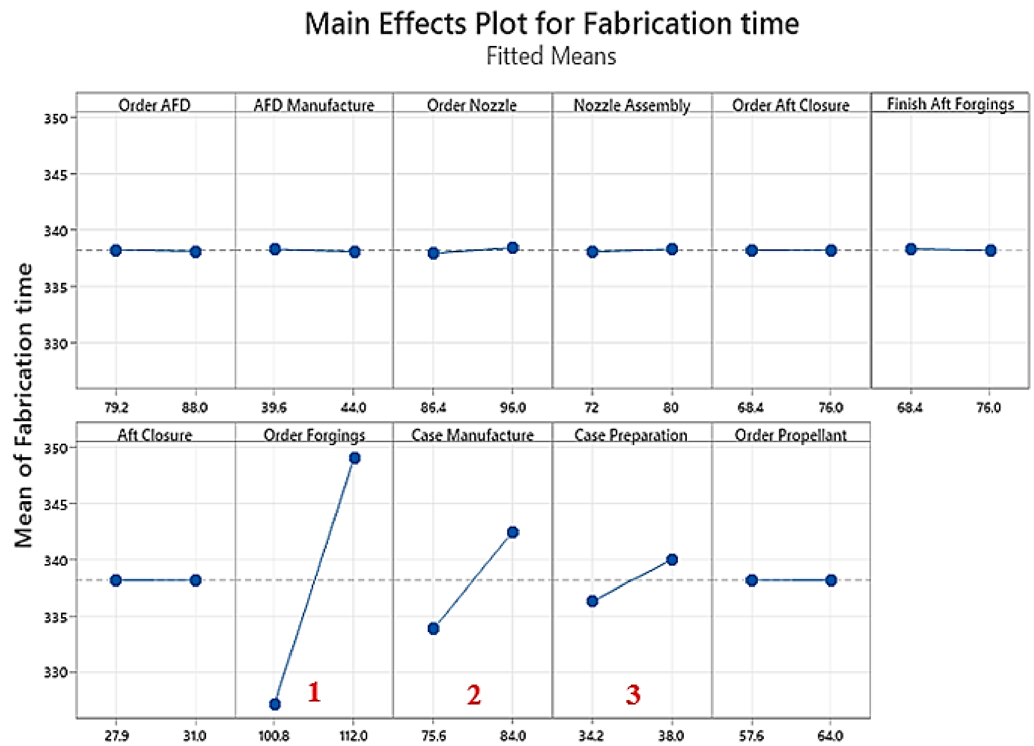

Figure 15. Main effect plot

The slope of the line in the main effects plot determines the level of impact, the steeper the slope the more impactful the factor on the response variable. As annotated, Figure 15 shows the three most influential factors as 1-order forgings, 2-case manufacture, and 3-case preparation, respectively. As a result, when making investments to reduce the fabrication timeline, the contractor should focus on improving the three variables listed as they will make the most impact on reducing the fabrication time. With the main effect analysis completed, the focus shifts to the two-way interaction effects and their sole impact on the response variable.

The two-way interactions highlight the relationship between two independent factors and the level of influence their combined effects exerts on the response variable. To visualize the two-way interactions, the interaction plot in Figure 16 provides a graphical representation of the interactions between the various factors.

On interactions plots, crossed lines indicated strong interactions between the factors whereas parallel lines indicate no interactions between the factors.

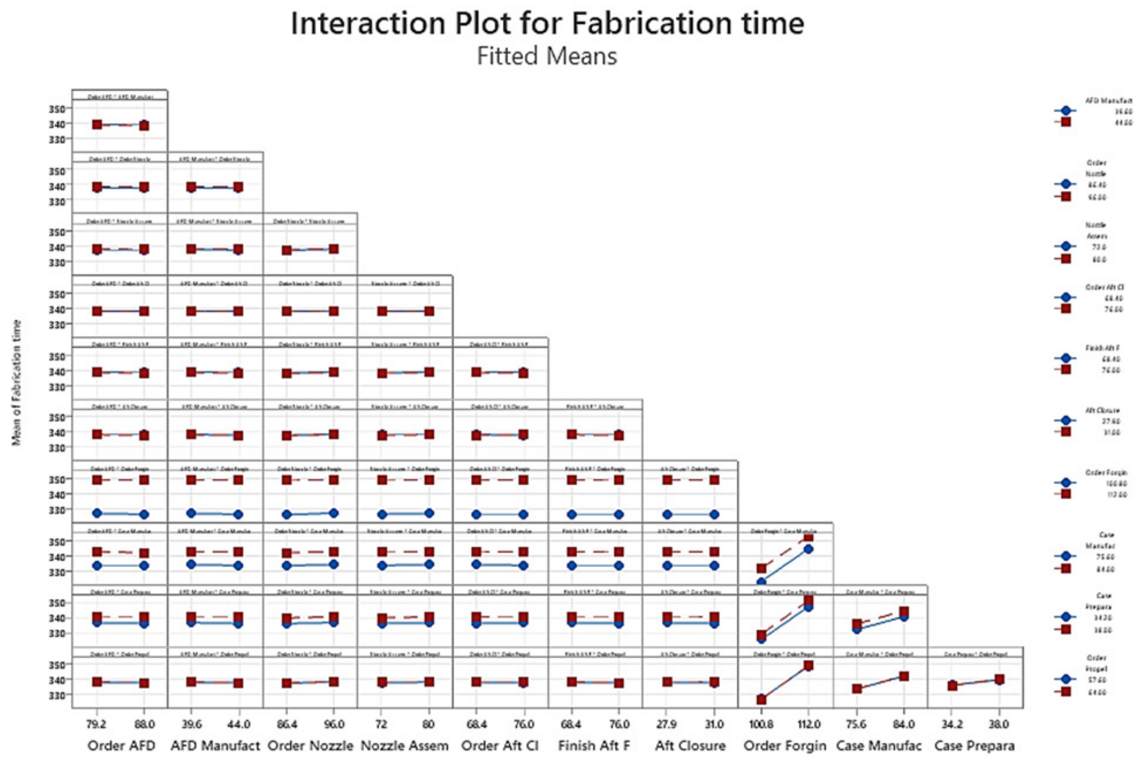

Figure 16. Interaction effect plot (10% reduction)

Figure 16 contains 55 individual plots representing the combinations of two-way interactions. All plots contain lines that are either parallel or are on top of each other thus indicating that there are no significant interactions between any of the two-way interactions in this analysis. To conclude this analysis, it is important to look at the model's R-square value which indicates the model's ability to capture variability. Figure 17 shows the R-squared value, 32.7%, of the ANOVA.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
17.0712	32.69%	32.62%	32.54%

Figure 17. ANOVA R-square (10% reduction)

This low R-square value indicates that the model is not a good fit for the data as only 32.7% of the variability is explained indicating that there is 67.3% of unexplained variability or residuals. Because the residuals are such a large percentage, the next step is to verify their normality. To visually ensure that the residuals conform to a normal distribution, a normal probability plot is generated and shown in Figure 18. Although there are a few outliers at the top right-hand corner of the plot, most of the plotted points follow the straight red line; thus, it can be concluded that the residuals are normally distributed validating the statistical inferences.

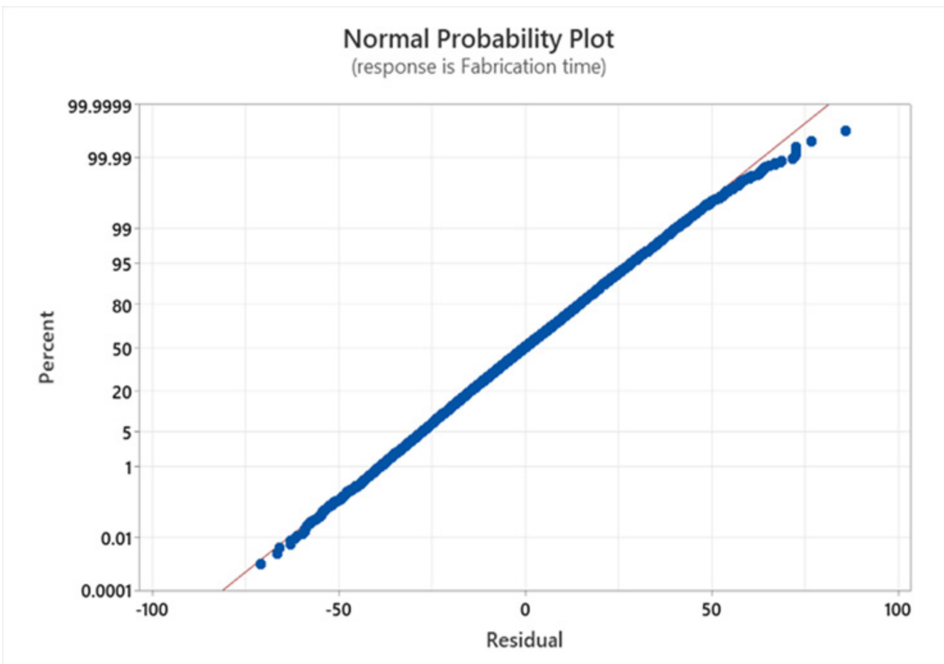

Figure 18. ANOVA residual distribution (10% reduction)

Upon completing an exhaustive and detailed analysis, it is determined that changing the main factors will have the most impact on the response variable. Thorough analysis has shown that applying 10% reductions to all activities only results in a 4.82% reduction of the total fabrication time and that the three main factors that affect fabrication time are 1-order forgings, 2-case manufacture, and 3-case preparations. Supplemental analysis is conducted considering only the effect of the three factors starting with the three factors only ANOVA displayed in Figure 19.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Order Forgings	1	7331919	7331919	25153.09	0.000
Case Manufacture	1	1123877	1123877	3855.60	0.000
Case Preparation	1	208801	208801	716.32	0.000
Error	61436	17908090	291		
Lack-of-Fit	4	2439	610	2.09	0.079
Pure Error	61432	17905651	291		
Total	61439	26572687			

Figure 19. Three factor ANOVA (10% reduction)

Although the ANOVA only includes the three significant factors, the R-squared value of the model remained the same at 32.7% suggesting that the three terms are the main contributors of the regression model and that the additional terms did not contribute much to model improvement. The model's regression equation with the three significant factors is shown in Figure 20. The regression equation is the mathematical representation of the relationship between the three factors and fabrication time.

Regression Equation

Fabrication time = 338.182 - 10.9240 Order Forgings_100.8 + 10.9240 Order Forgings_112.0
- 4.2769 Case Manufacture_75.6 + 4.2769 Case Manufacture_84.0
- 1.8435 Case Preparation_34.2 + 1.8435 Case Preparation_38.0

Figure 20. Minitab output: three factors regression equation

Using the coefficients of order forgings, case manufacture and case preparation, the equation can be represented in the following way:

$$\begin{aligned} \textit{Fabrication time} &= 338.183 + \left(\frac{2\times 10.924}{10\%}\right)(\textit{Order Forgings} - 95\%) \\ &+ \left(\frac{2\times 4.277}{10\%}\right)(\textit{Case Manufacture} - 95\%) \\ &+ \left(\frac{2\times 1.844}{10\%}\right)(\textit{Case Preparation} - 95\%) \end{aligned}$$

Although this model is not 100% accurate for extrapolation as it is missing 67% of the other factor's variability error, it can still be used to predict the reduced fabrication duration for percentages lower than 90%. To verify the validity of the model, Table 6 shows the estimated fabrication time in the case of 5%, 10%, 20% and 40% reduction.

Table 6. Three factor fabrication time prediction

Significant Factor reduction value, %	Estimated Fabrication time (weeks)
no reduction (original values)	355.2
5% reduction (95% of the original time)	338.2
10% reduction (90% of the original time)	321.1
20% reduction (80% of the original time)	287.0
40% reduction (60% of the original time)	218.9

As noted in Table 6, the model's prediction is correct for the values that were explored. For example, the first and second lines, corresponding to original duration and 5% reduction, are the same values, 355 and 338 weeks, as the ones calculated in Table 4. Table 6 also shows the potential benefit of higher reduction percentages for example, a 40% reduction should result in a fabrication time of 287 weeks. The model is not linear and extrapolating the results from the equation will cause some error however as confirmed by Table 6, the equation provides a good predictive tool that can be used for quick and accurate calculations.

3. Realistic Analysis (Aerojet Rocketdyne Reductions)

Upon conducting the initial analysis, the team reached out to Aerojet Rocketdyne to determine the appropriate reduction to be applied for more accurate analysis. With that, the team travelled to Aerojet's Los Angeles office to visit the facilities and get the opportunity for more research focused conversation. At the conclusion of the tour, Aerojet Rocketdyne provided the percentage reductions shown Table 7.

Table 7. Aerojet Rocketdyne reduction percentages

Activity	Duration (Weeks)	% Reduction
1. Order AFD	61.6	30%
2. AFD Manufacture	30.8	
3. AFD/Igniter Assembly	5*(no change)	
4. Booster Final Assembly	3*(no change)	
5. Inspection Pack Out and Ship	1*(no change)	
6. Order Nozzle Exit Cone Material	48	50%
7. Nozzle Assembly	40	
8. Receive TVA from UTAs	10*(no change)	
9. Order Aft Closure Insulation	38	50%
10. Finish Aft closure Forgings	38	
11. Aft Closure Assembly	15.5	
12. Aft Closure/TVA Assembly	5*(no change)	
13. Order Forgings/Extrusions	44.8	60%
14. Case Manufacture-Rollmet	33.6	
15. Case Preparation	15.2	
16. Loaded Case Assembly	5*(no change)	
17. Order Propellant Materials	6.4	90%
18. Propellant Mix/Cast/Cure	6*(no change)	

As noted, the time reductions on the table are much more aggressive than the initial assumption of 10% reduction. Aerojet Rocketdyne explained that they are able to implement much bigger percentage reduction due to the $215 million DOD funding received in April in support of the war in Ukraine. In addition, they were acquired by L3 Harris technologies in July which also provided an influx in funding thus strengthening their SRM production line (Mike Steel, personal communication, September 14, 2023). With the new reduced values, Minitab is once again used to create a two-level multifactorial design with the same 11 factors. Once the DOE is created, the produced values serve as inputs into the ExtendSim model. Upon executing the model, the average fabrication time obtained is 290 weeks as shown in Table 8.

Table 8. Duration comparison

Process	Duration (weeks)	Achieved reduction
Original duration	355.2 weeks	4.8% (original to 10%)
10% reduction	338.2 weeks	14.3% (10% to AR)
AR Reductions	290 weeks	18.4% (original vs. AR)

The applied reduction results in an 18.4% reduction from the original duration values, and a 14.3% reduction from the assumed 10 percent reduced values. Figure 21 is generated to provide visual comparison between reductions.

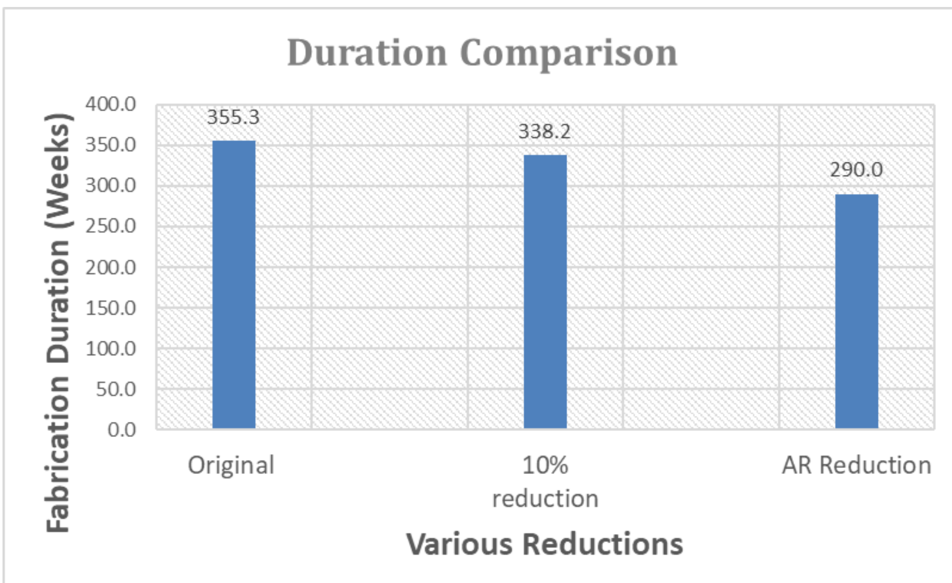

Figure 21. Comparison of various fabrication durations

The total fabrication time generated is added into Minitab for further statistical analysis starting with data visualization.

a. Data Visualization

The reduction duration histogram in Figure 22 captures the variability of the dataset. Fabrication duration shows to be normally distributed with a mean of 290 weeks as mentioned above.

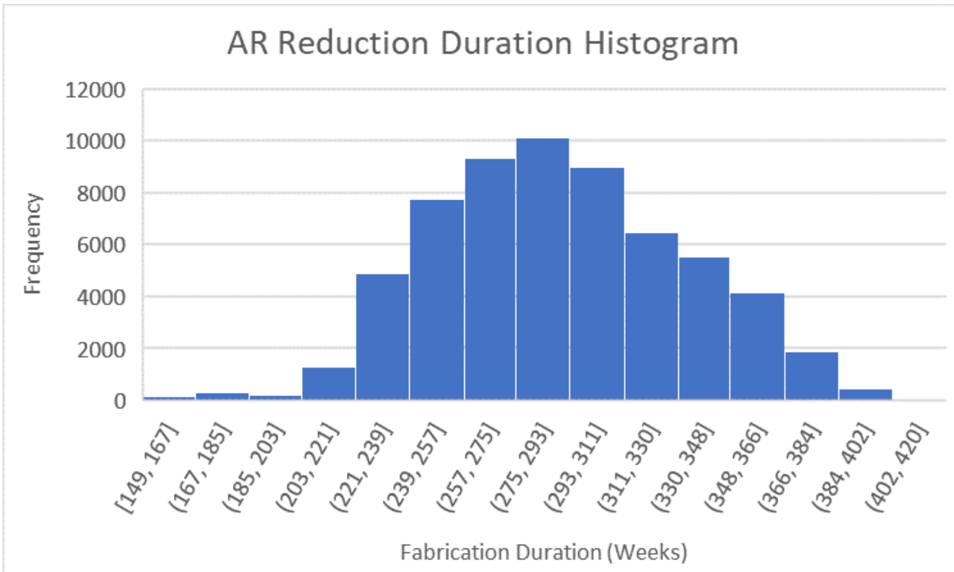

Figure 22. Aerojet Rocketdyne reduction duration histogram

Recall that the regression equation and Table 6 created based on the results from the previous section analysis, predicted 287 weeks which is a good approximation for the achieved results of 290 weeks. Next the pareto chart is generated to visualize the impact of the different factors on total fabrication time.

Figure 23 is a graphical representation of the dataset. At first glance it is noted that the three main contributors to the response variable as order forgings (H), case manufacture (J), and their two-way interaction effect (HJ).

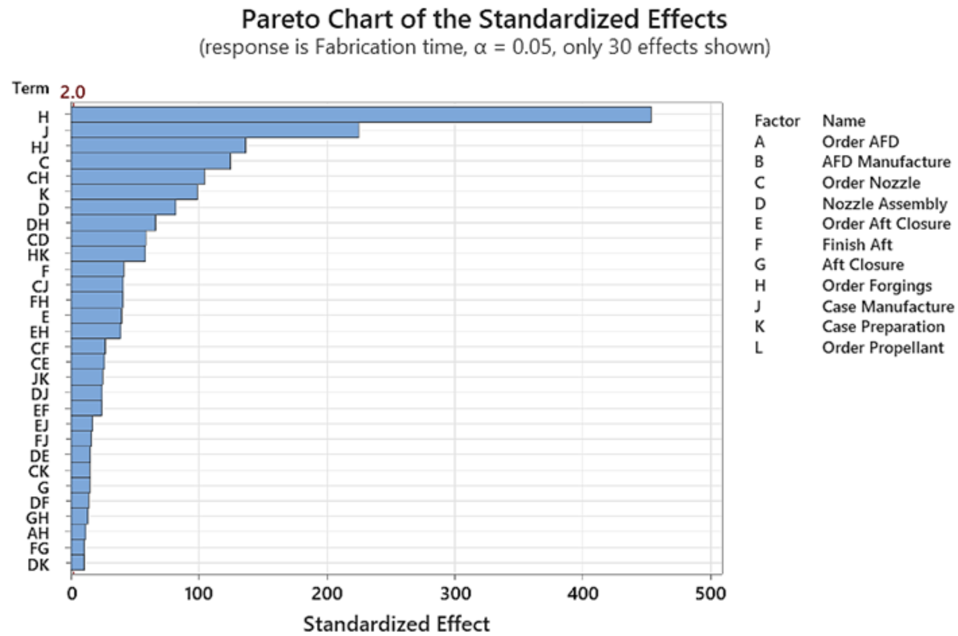

Figure 23. SRM fabrication Pareto chart (AR reductions)

It is also noted that because this is a more balanced process, there are a lot of two-way interactions that could potentially be significant. Although order forging (H) is overwhelmingly impactful, there are also other influential factors such as order nozzle (C), case preparation (K) and numerous two-way interactions effects. More detailed analysis is conducted to determine the factors' statistical significance starting with an ANOVA.

b. ANOVA (AR reductions)

Hypothesis testing is performed using ANOVA at a 95% confidence level. It is stated as follows:

Ho: The mean total fabrication time is not affected by any of the factors.

Ha: The mean total fabrication time is affected by at least one of the factors.

Upon generating the ANOVA, all significant factors and their combinations are those with a p-value ≤ 0.05. The ANOVA table shown in Figure 18 shows all the statistically significant factors in red rectangles.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Order AFD	1	24680	24680	92.04	0.000
AFD Manufacture	1	546	546	2.04	0.154
Order Nozzle	1	4166856	4166856	15539.33	0.000
Nozzle Assembly	1	1812208	1812208	6758.21	0.000
Order Aft Closure	1	422627	422627	1576.09	0.000
Finish Aft	1	458927	458927	1711.46	0.000
Aft Closure	1	58898	58898	219.65	0.000
Order Forgings	1	55151745	55151745	205675.77	0.000
Case Manufacture	1	13563070	13563070	50580.36	0.000
Case Preparation	1	2625430	2625430	9790.94	0.000
Order Propellant	1	1	1	0.00	0.947
Order AFD*AFD Manufacture	1	772	772	2.88	0.090
Order AFD*Order Nozzle	1	29772	29772	111.03	0.000
Order AFD*Nozzle Assembly	1	6343	6343	23.65	0.000
Order AFD*Order Aft Closure	1	11495	11495	42.87	0.000
Order AFD*Finish Aft	1	11587	11587	43.21	0.000
Order AFD*Aft Closure	1	688	688	2.57	0.109
Order AFD*Order Forgings	1	37215	37215	138.79	0.000
Order AFD*Case Manufacture	1	26149	26149	97.52	0.000
Order AFD*Case Preparation	1	134	134	0.50	0.479
Order AFD*Order Propellant	1	50	50	0.18	0.667
AFD Manufacture*Order Nozzle	1	3669	3669	13.68	0.000
AFD Manufacture*Nozzle Assembly	1	127	127	0.47	0.491
AFD Manufacture*Order Aft Closure	1	666	666	2.48	0.115
AFD Manufacture*Finish Aft	1	895	895	3.34	0.068
AFD Manufacture*Aft Closure	1	187	187	0.70	0.404
AFD Manufacture*Order Forgings	1	4218	4218	15.73	0.000
AFD Manufacture*Case Manufacture	1	3385	3385	12.63	0.000
AFD Manufacture*Case Preparation	1	1	1	0.00	0.952
AFD Manufacture*Order Propellant	1	124	124	0.46	0.497
Order Nozzle*Nozzle Assembly	1	918441	918441	3425.11	0.000
Order Nozzle*Order Aft Closure	1	188342	188342	702.38	0.000
Order Nozzle*Finish Aft	1	193694	193694	722.34	0.000
Order Nozzle*Aft Closure	1	17139	17139	63.91	0.000
Order Nozzle*Order Forgings	1	2920182	2920182	10890.15	0.000
Order Nozzle*Case Manufacture	1	452755	452755	1688.44	0.000
Order Nozzle*Case Preparation	1	59930	59930	223.50	0.000
Order Nozzle*Order Propellant	1	439	439	1.64	0.201
Nozzle Assembly*Order Aft Closure	1	61984	61984	231.15	0.000
Nozzle Assembly*Finish Aft	1	51827	51827	193.28	0.000
Nozzle Assembly*Aft Closure	1	3111	3111	11.60	0.001
Nozzle Assembly*Order Forgings	1	1181102	1181102	4404.65	0.000
Nozzle Assembly*Case Manufacture	1	162526	162526	606.10	0.000
Nozzle Assembly*Case Preparation	1	30224	30224	112.71	0.000
Nozzle Assembly*Order Propellant	1	159	159	0.59	0.442
Order Aft Closure*Finish Aft	1	159166	159166	593.57	0.000
Order Aft Closure*Aft Closure	1	21949	21949	81.85	0.000
Order Aft Closure*Order Forgings	1	412987	412987	1540.14	0.000
Order Aft Closure*Case Manufacture	1	79445	79445	296.27	0.000
Order Aft Closure*Case Preparation	1	10984	10984	40.96	0.000
Order Aft Closure*Order Propellant	1	198	198	0.74	0.390
Finish Aft*Aft Closure	1	30596	30596	114.10	0.000
Finish Aft*Order Forgings	1	447057	447057	1667.20	0.000
Finish Aft*Case Manufacture	1	71474	71474	266.55	0.000
Finish Aft*Case Preparation	1	12017	12017	44.81	0.000
Finish Aft*Order Propellant	1	1	1	0.00	0.944
Aft Closure*Order Forgings	1	48314	48314	180.18	0.000
Aft Closure*Case Manufacture	1	8395	8395	31.31	0.000
Aft Closure*Case Preparation	1	2391	2391	8.92	0.003
Aft Closure*Order Propellant	1	235	235	0.88	0.349
Order Forgings*Case Manufacture	1	5006945	5006945	18672.25	0.000
Order Forgings*Case Preparation	1	917001	917001	3419.75	0.000
Order Forgings*Order Propellant	1	321	321	1.20	0.274
Case Manufacture*Case Preparation	1	165728	165728	618.04	0.000
Case Manufacture*Order Propellant	1	1134	1134	4.23	0.040
Case Preparation*Order Propellant	1	30	30	0.11	0.738
Error	61373	16457106	268		
Lack-of-Fit	1981	3217382	1624	7.29	0.000
Pure Error	59392	13239724	223		
Total	61439	108517793			

Figure 24. ANOVA (AR reductions)

As a precautionary measure, the step was verifying was the model's ability to capture variability. The model's R-squared value of 84.8% indicates that the regression model is a good fit for the data as 84.8% of the variability is justified leaving only 15.2% of unexplained variability or residuals thus negating the need for normality verification.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
16.3753	84.83%	84.82%	84.80%

Figure 25. General ANOVA R-squared (AR reduction)

From the ANOVA table in Figure 24 it is noted that there are nine statistically significant main factors and 38 statistically significant two-way interactions. For better visualization, the nine significant factors are summarized in Table 9 along with their p-values.

Table 9. Statistically significant factors (AR reduction)

Main Effects	P-Value
1. Order AFD	$<5x10^{-4}$
2. Order Nozzle	$<5x10^{-4}$
3. Nozzle Assembly	$<5x10^{-4}$
4. Order Aft Closure	$<5x10^{-4}$
5. Finish Aft	$<5x10^{-4}$
6. Aft Closure	$<5x10^{-4}$
7. Order forgings	$<5x10^{-4}$
8. Case Manufacture	$<5x10^{-4}$
9. Case Preparation	$<5x10^{-4}$

Looking at the p-values in Table 9, it can be concluded that there is enough evidence to reject the null hypothesis as the mean fabrication time is affected by at least one of the factors shown on the table. Although p-values are instrumental in determining statistical significance, they do not necessarily show the degree of significance. This means by looking at the p-values alone, one is unable to tell if order AFD has the same effect as finish aft or other factors. In order to determine the actual effect of each factor, main effects plots are generated.

The main effect plots allow for visualization of the individual factors and their effect on the response variable. Figure 26 displays the nine factors and their effect on the total fabrication time.

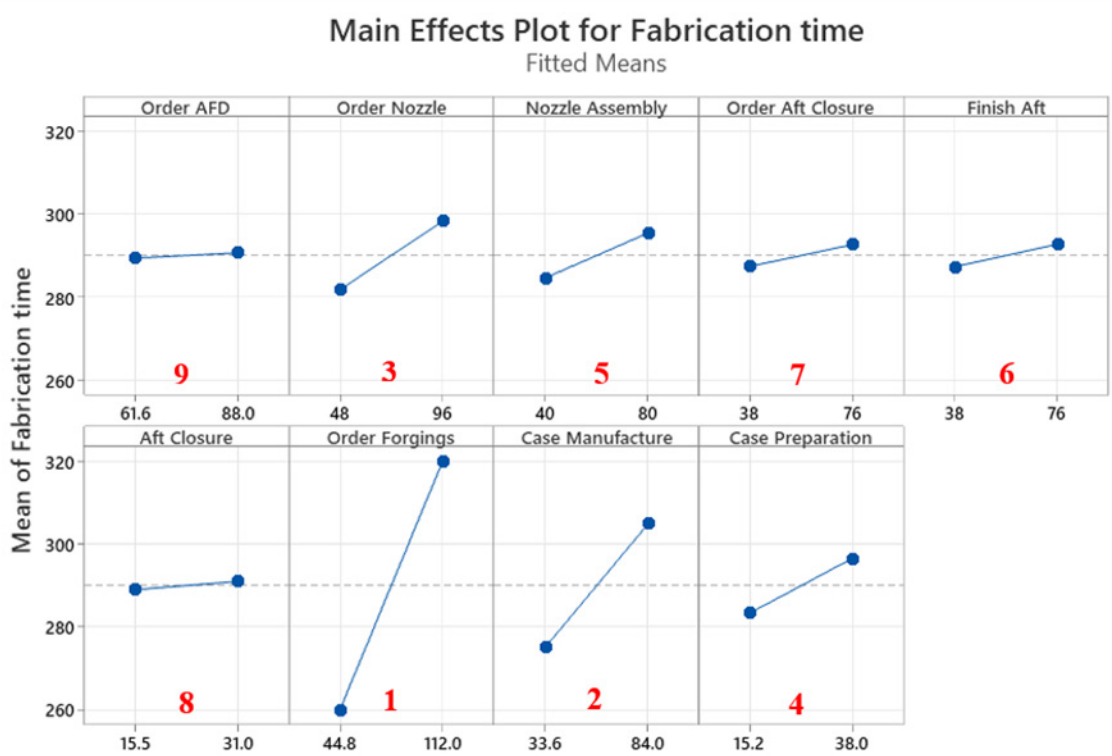

Figure 26. Main effect plot (AR reduction)

As annotated in Figure 26, the nine significant factors are ranked from 1, most influential, to 9 least influential based on their slope. As such, it is apparent that the two factors with the most impact on the response variable are 1-order forgings, 2-case manufacture. This result is consistent with the findings of the experimental analysis section which also highlighted order forgings and case manufacture as the two most influential factors. Now that the main effects have been analysis, the next step is to visualize the interaction effects to determine the degree of interaction between two independent factors and their combined effect on total fabrication time.

The interaction plot, displayed in Figure 27, encompasses 55 figures most of which contain parallel lines indicating no significant two-way interactions except for the six interactions highlighted in the red boxes. The highlighted interactions show the lines crossing indicating that there is a slight significant two-way interaction within the combinations.

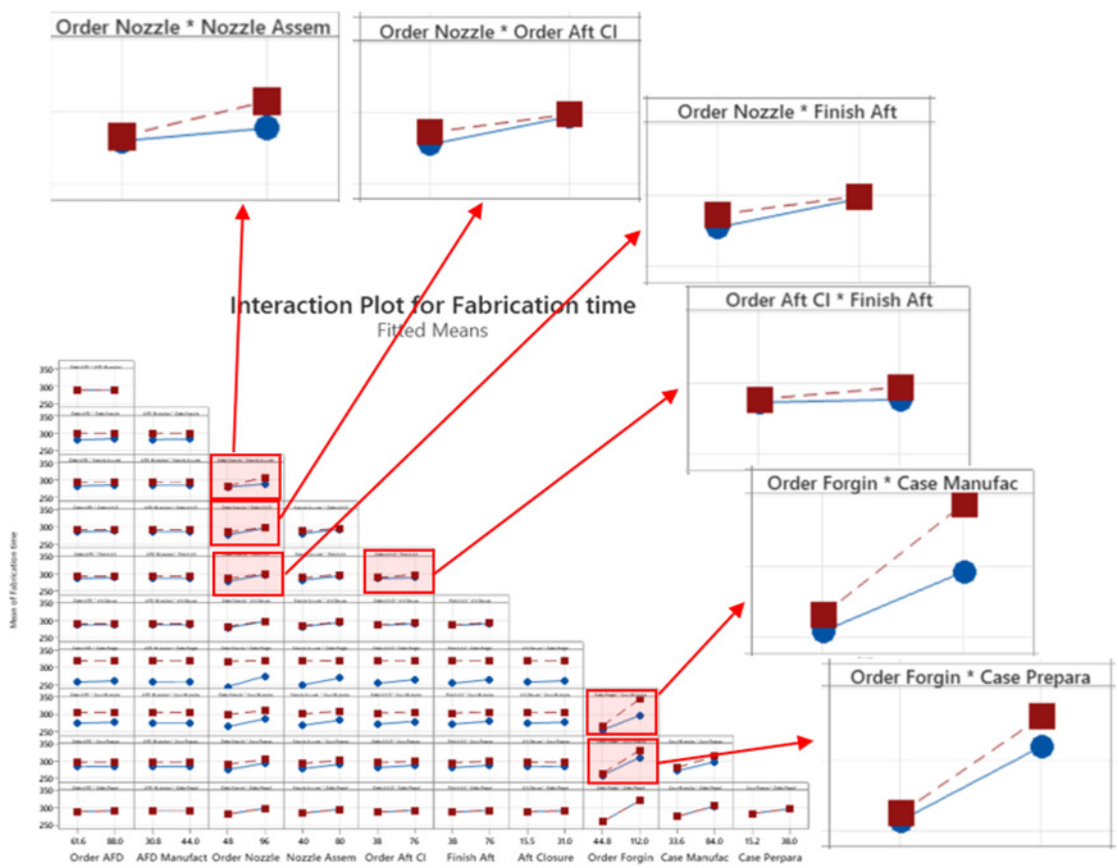

Figure 27. Interaction effects (AR reduction)

Upon determining the five significant factors using ANOVA and the main effect plots, the next step is to conduct supplemental analysis while considering only the five factor effects starting with the ANOVA in Figure 28.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Order Nozzle	1	4166856	4166856	8205.10	0.000
Nozzle Assembly	1	1812208	1812208	3568.48	0.000
Order Forgings	1	55151745	55151745	108601.18	0.000
Case Manufacture	1	13563070	13563070	26707.50	0.000
Case Preparation	1	2625430	2625430	5169.82	0.000
Error	61434	31198484	508		
Lack-of-Fit	26	12672191	487392	1615.53	0.000
Pure Error	61408	18526293	302		
Total	61439	108517793			

Figure 28. Five factor ANOVA (AR reductions)

With the five factors only ANOVA, the model's R-squared value decreased from 84.5%, shown in Figure 25, to 71.3% as noted in Figure 29. As expected, this suggests that the model's ability to capture variability has been reduced. This finding is expected as the model discarded the remaining significant factors and two-way interactions terms that contribute to the model's accuracy.

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
22.5352	71.25%	71.25%	71.24%

Figure 29. Five factor R-squared value (AR reductions)

The five-factor regression equation is shown in Figure 30 representing the mathematical relationship between the five factors and fabrication time.

Regression Equation

```
Fabrication time = 289.985 - 8.2353 Order Nozzle_48 + 8.2353 Order Nozzle_96
                   - 5.4310 Nozzle Assembly_40 + 5.4310 Nozzle Assembly_80
                   - 29.9608 Order Forgings_44.8 + 29.9608 Order Forgings_112.0
                   - 14.8578 Case Manufacture_33.6 + 14.8578 Case Manufacture_84.0
                   - 6.5369 Case Preparation_15.2 + 6.5369 Case Preparation_38.0
```

Figure 30. Minitab output: Five factor regression equation (AR reductions)

Using the coefficients of the five factors and their respective reduction percentages, the regression equation can be represented as follows:

$$\begin{aligned} \textit{Fabrication time} = 289.985 &+ \left(\frac{2\times 8.2353}{50\%}\right)(\textit{Order Nozzle} - 75\%) \\ &+ \left(\frac{2\times 5.431}{50\%}\right)(\textit{Nozzle Assembly} - 75\%) \\ &+ \left(\frac{2\times 29.9608}{40\%}\right)(\textit{Order Forgings} - 80\%) \\ &+ \left(\frac{2\times 14.8578}{40\%}\right)(\textit{Case Manufacture} - 80\%) \\ &+ \left(\frac{2\times 6.5369}{40\%}\right)(\textit{Case Preparation} - 80\%) \end{aligned}$$

Although this model is not 100% accurate for extrapolation as it is missing 29% of the other factor’s variability error, it can still be used to predict the reduced fabrication duration. To verify the validity of the model, the equation was solved by substituting the factor’s values resulting in 237 weeks as shown in Table 10.

Table 10. Five factor fabrication time prediction

Reduction	Estimated Fabrication time (weeks)
Estimated Reduction using Five factor equation	237.0
10% reduction prediction	287.0
Model Reduction	290.0

The model was able to predict the fabrication time with an 18% difference to the fabrication time achieved by the model. As stated previously, the model is not linear and extrapolating the results from the equation will cause some errors. However, the equation is a great predictive tool that can be utilized for quick and accurate calculations and to predict future reductions.

The thorough analysis conducted using Aerojet Rocketdyne reductions revealed that the factors that have the largest impact on total fabrication time are 1-order forgings and 2-order nozzle. This signifies that in a resource restricted environment, reducing those two factors will result in the biggest reduction in overall fabrication time.

4. Conclusion

The SRM fabrication process was modeled using ExtendSim and revealing the initial a total fabrication duration of 352 weeks. The initial analysis was conducted based on the assumption of a 10% duration reduction in individual activities. This analysis was experimental in nature as no further guidance had been provided on duration reductions at the time. The results from this initial analysis indicated that applying a 10% reduction to individual activity duration only results in a 4.82% fabrication time reduction. The factors that impacted the response variable at that reduction rate were order forgings, case manufacture, and case preparation, respectively.

Upon obtaining actual reduction percentages from the Aerojet Rocketdyne team, a second analysis was performed. This analysis revealed a similar finding. Each activity was reduced by somewhere between 30–90% based on contractor input, which still only resulted in an 18.4% reduction in the overall fabrication time. The two most impactful factors with the various reductions were order forgings, and order nozzle, respectively.

It is important to note both analyses highlighted order forgings as the most impactful factor. In fact, the Aerojet Rocketdyne team also stated that forgings procurement has previously caused serious time delay. This aligned with the team's statistical findings and indicated that resources should be allocated towards improving the timeline of forgings procurement marking the conclusion of the analysis of the fabrication process. Once the SRM is built, the next step is to undergo the qualification process. As such, Chapter IV, discussed next, focuses on the analysis of the qualification process.

IV. QUALIFICATION PROCESS ANALYSIS

The qualification process is a rigorous and crucial process designed to ensure that the Navy's operational and performance requirements are met. The Navy SRMs are stored onboard ships alongside Sailors hence adding a layer of complexity that is nonexistent for other DOD branches. As such, the PEO IWS 3.0 3.0 qualification process is purposefully extensive and challenging as it demonstrates the SRM's ability to be properly stored and transported onboard ships for an extended period of time. Although the process needs to be rigorous, it should also be expeditious. Given that the recent focus is on rapid missile replenishment, as discussed in Chapter I, a lengthy qualification process means less weapons available to the fleet. As such, the goal of this chapter is to conduct a detailed analysis of the current PEO IWS 3.0 process, along with its derived processes, and evaluate schedule risks impacts on the overall qualification process.

A. QUALIFICATION PROCESSES OVERVIEW

PEO IWS 3.0 provided the team with a generic qualification process used by one of their programs which will be used to derive the two other processes: SpaceX compressed and SpaceX Non-Compressed.

1. PEO IWS 3.0 Qualification Process

Figure 31 highlights the timeline of the rigorous yet lengthy process. The process depicted below is that of a weapon system that requires a booster, first stage, and a Dual thrust rocket motor (DTRM), second stage, both of which are SRMs. The qualification process is explained below.

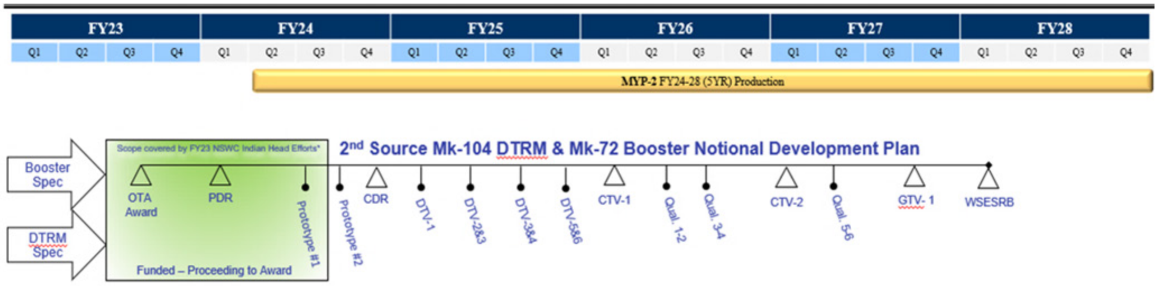

Figure 31. SRM qualification timeline. Adapted from PEO IWS 3.0 (2023).

The process starts with PEO IWS 3.0 setting the specifications for the motor. Once those are set, they proceed to operational test agency award (OTA), which by default is the operational testing and evaluation force (OPTEVFOR). The process then goes through the preliminary design review (PDR) to assess the design maturity and ensure that the system is ready to proceed to detailed design. That is followed by the production of the first prototype by PEO IWS 3.0 and their adjoining entities such as Naval Air Weapon Station China Lake (NAWS). The first four steps are highlighted in green as they are all completed prior to awarding the contract to a specific contractor, which in this case is Aerojet Rocketdyne (AR). It is important for the steps shown in green to be conducted by the PEO IWS 3.0 as this establishes the government's ownership of the technology. Once the contractor is chosen, PEO IWS 3.0 turns the motor over to them for full technology maturation. The second, and improved prototype, is produced and followed by the critical design review (CDR), which ensures that the technology is mature enough to proceed into fabrication and testing while staying on schedule and on budget. The CDR is followed by six development test and verification sets (DTV) which are meant to validate the design under various weather conditions verifying that the preset requirements are still met. After the DTVs, controlled test vehicle one (CTV-1), is conducted focusing on flight simulations and data gathering to further validate the structural design. This is followed by four qualifications tests, conducted in pairs, whose various tests are detailed Figure 32 in accordance with MIL-STD-2105D.

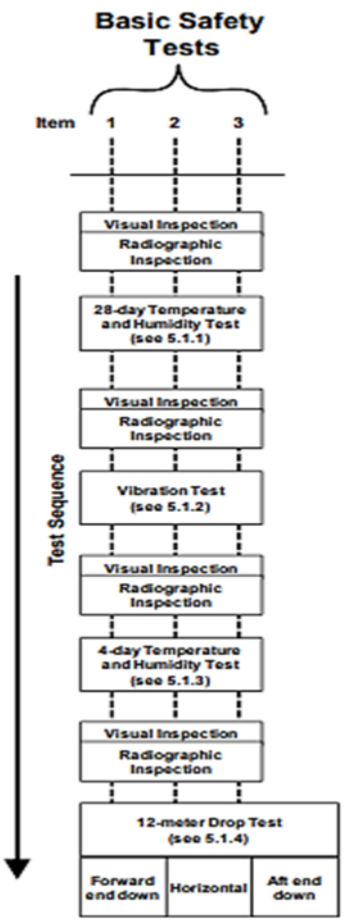

Figure 32. Navy qualification standard. Source: Department of Defense (2011).

The four qualifications tests are followed by CTV-2, further testing and finalizing the structural integrity of the system. This is followed by the last qualification set, 5 and 6, which incorporates the lessons learned from the four previous qualification tests thus proving that the design is ready to be integrated into the weapon system. That leads to ground test vehicle one (GTV-1), which is the first integration of the SRM into the entire weapon system. Once the unit has been integrated, it undergoes the weapon system explosive safety review board, (WSESRB) testing which is shown in Figure 33 in accordance with MIL-STD-2105D. Upon successfully completing this step, the qualification process is completed, the weapon is certified for shipboard storage and usage, and the system can process into low-rate production.

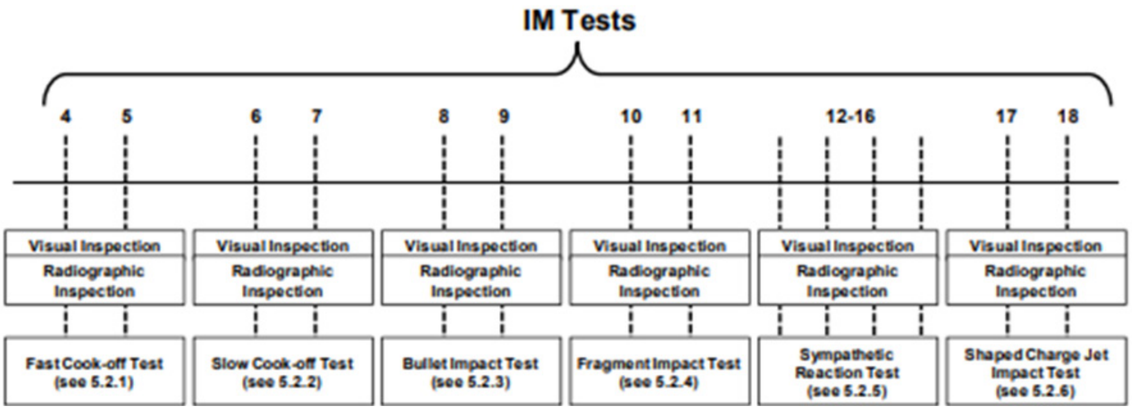

Figure 33. Navy unit testing. Source: Department of Defense (2011)

This meticulous and comprehensive qualification process demonstrates PEO IWS 3.0's commitment to producing weapon systems that are safe and reliable for shipboard applications. The qualification process is represented in ExtendSim to facilitate more in-depth analysis.

2. ExtendSim Model

An ExtendSim model, shown in Figure 34, is created to represent PEO IWS 3.0 qualification process. Although it is a rather simple process, modeling it using ExtendSim is important as it allows for standardization and flexibility when conducting more detailed analysis.

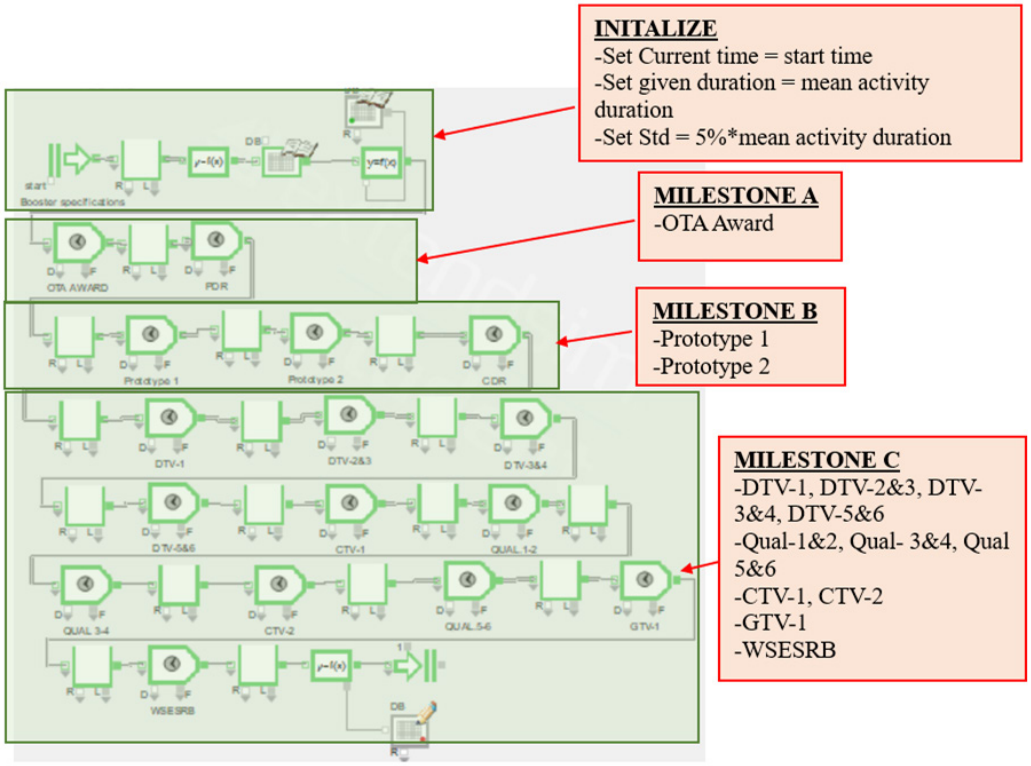

Figure 34. ExtendSim model – Navy qualification process

The model replicates the sequential process in Figure 31 by representing each activity on the timeline with an activity block and an associated queue on the model. It starts with the create block which signals the beginning of the process, then proceeds to the equation block marking the start time of the process as the current time. That is followed by a write-in block allowing each activity duration to be inputted from a database where they will be utilized by the corresponding activity blocks throughout the model. The next block is an equation block calculating each activity duration as a normal distribution with the mean duration, as the time noted in Figure 31 , and a standard deviation of 5% of the mean. The remaining activity blocks in series represent the sequential testing shown in Figure 31. Upon completion of the ExtendSim model, the average total qualification time generated is 52.3 months for the current PEO IWS 3.0 qualification process.

The histogram of the PEO IWS 3.0 qualification duration, shown in Figure 35, is generated to show the variability of the data. The graph indicates that the data set is normally distributed allowing for a normality assumption for the remaining analysis.

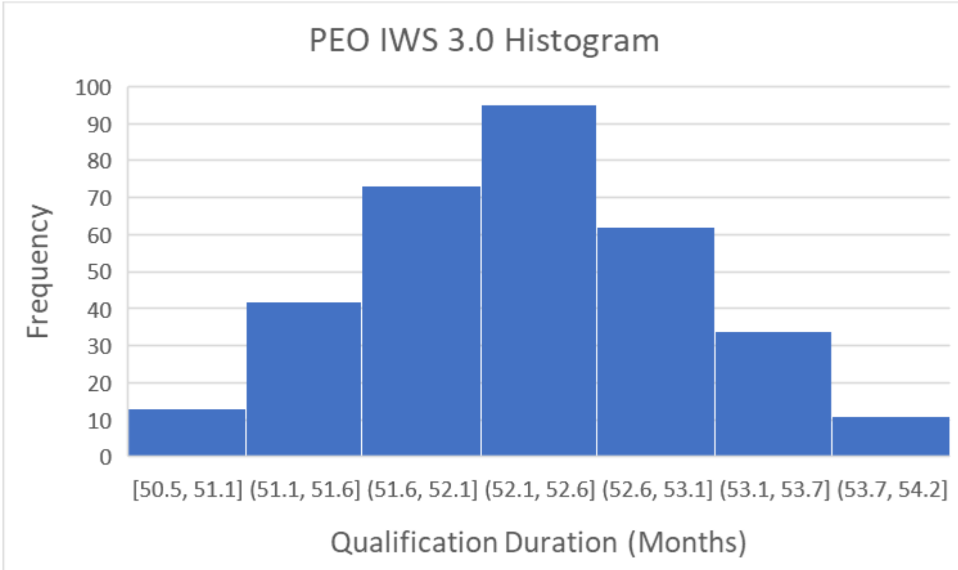

Figure 35. PEO IWS 3.0 qualification duration histogram.

3. SpaceX Compressed Qualification Process

Upon obtaining the PEO IWS 3.0 qualification process, the team reached out to SpaceX to gain perspective on their qualification process resulting in an extended invitation for an in person visit. It is important to recall that SpaceX does not currently participate in the ordnance/weapon industry, nor do they have any intention of participating. On September 15th the team travelled to Segundo, California where they toured SpaceX's facilities and held a conversation about their qualification process. Upon sharing the Navy's qualification process with them, they annotated what their process would look like. Figure 36 shows the tentative SpaceX qualification process according to their notes using the Navy's process as guidance.

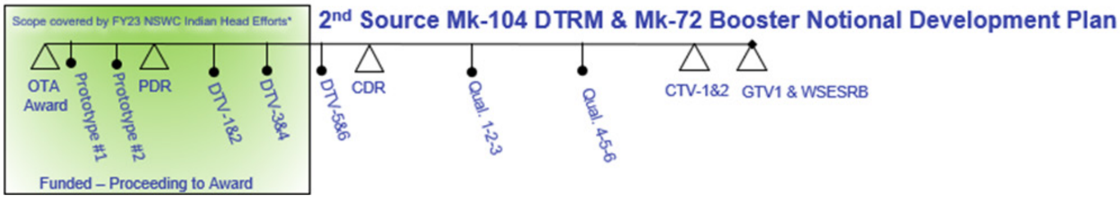

Figure 36. SpaceX qualification timeline – compressed. Adapted from PEO IWS 3.0 (2023).

They started by emphasizing that they spend a lot of time in the beginning of the project focusing on requirement engineering. As discussed in Chapter 2's company engagement section, they believe that it is crucial to conduct effective requirement engineering in the beginning as it guarantees that the system is built upon requirements that align with operational capability and support system performance. As soon as the contract is awarded, the engineers start working on prototypes with the goal of getting to a product that can be fabricated as soon as possible. SpaceX believes in "testing what you fly" which drives them toward assembling engines as fast as possible so they can proceed to testing sooner rather than later (SpaceX, personal communication, September 15, 2023). In this context, the engineers produce the first two prototypes and hold their own mini review to identify design flaws and make improvements prior to the actual PDR. During the PDR, they assess the maturity of the design with an emphasis on providing feedback on models produced thus far. With that feedback, they proceed to complete all six DTVs prior to the CDR. Upon CDR completion, their design is very mature, having undergone numerous iterations, such that it is ready to proceed to qualification testing. During qualification testing, engines are built in excess to facilitate simultaneous testing. SpaceX explained that approach by stating that they are "hardware rich" indicating that they build engines in excess because they possess all the hardware needed on hand consequently, they do not mind destroying engines that do not meet requirements as they can rebuild quickly.

The first set of three qualification tests are accomplished simultaneously assuming that the tests are only for demonstration purposes as all design requirements have already been met. Minor improvements from the first three qualification tests are then applied to the next set of qualification tests, which are also conducted simultaneously. Next, CTV-1 and CTV-2 are combined into one test set, CTV-1&2, as they have high confidence in their design maturity. They conclude with GTV1 and WSESRB qualifications which are also combined into one test set for demonstration purposes at which point engines are produced in large quantities in preparation for low-rate production.

To conduct further analysis on the SpaceX qualification process, an ExtendSim model is created and shown in Figure 37. The SpaceX qualification model is referred to as "SpaceX compressed" for the remaining of the discussion.

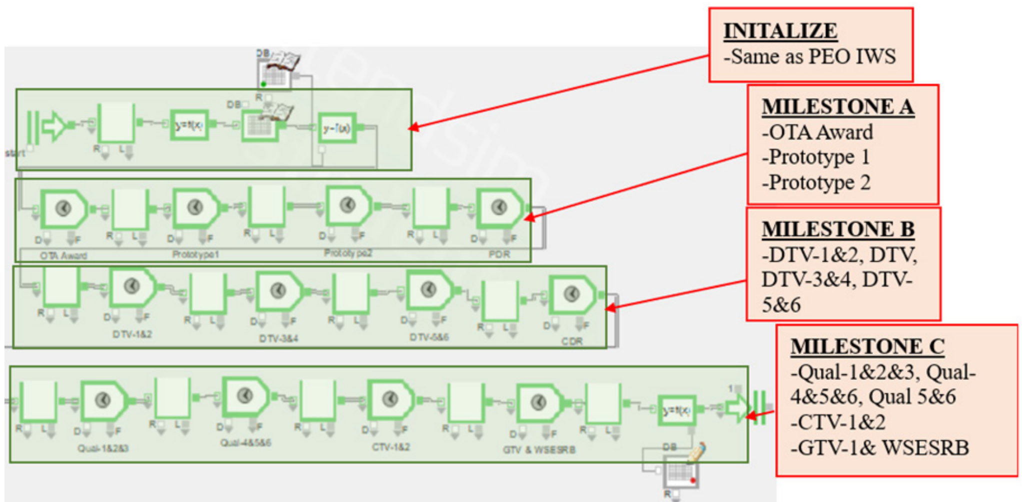

Figure 37. SpaceX qualification model – compressed

Upon creating the model, the average total qualification time generated is approximately 31.5 months. The data variability is captured in the histogram shown in Figure 38.

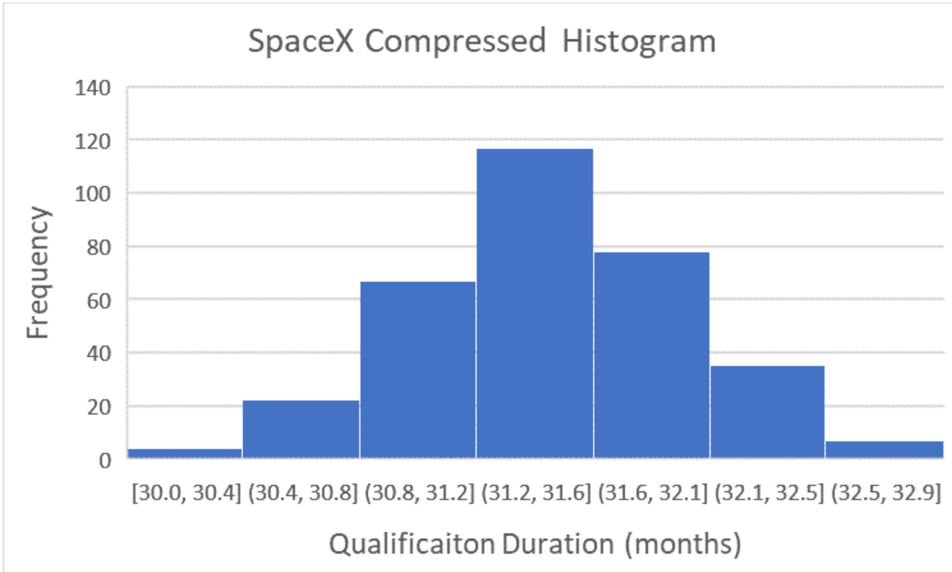

Figure 38. SpaceX compressed qualification duration histogram

4. SpaceX Non-compressed Qualification Process

As noted, the SpaceX and PEO IWS 3.0 processes land on opposing sides. SpaceX conducts intensive requirement engineering, produces prototypes very early, and combines their tests such that they occur in parallel, greatly condensing the timeline. Meanwhile, PEO IWS 3.0 does not start prototyping until after the PDR and conducts all their tests in series which extends an already lengthy timeline. To bridge the gap and allow for more parallel comparison with the PEO IWS 3.0 process, a more moderate option called SpaceX non-compressed is created and shown in Figure 39.

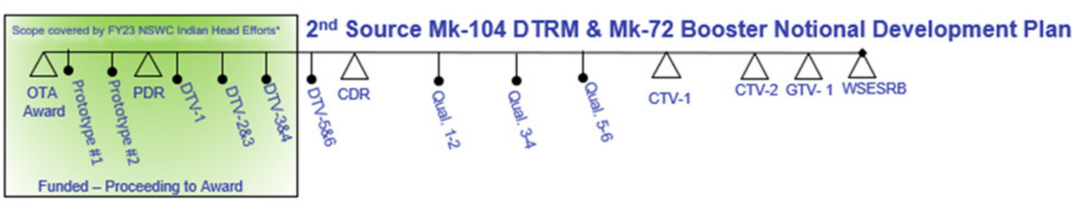

Figure 39. SpaceX qualification timeline – non-compressed. Adapted from PEO IWS 3.0 (2023).

This middle ground option implements practices from both entities to create a feasible and improved model for PEO IWS 3.0. It includes practices such as requirement engineering and early prototyping from SpaceX while maintaining the series testing from the already existent PEO IWS 3.0 model. For the time being, Aerojet Rocketdyne is unable to support building motors in excess at every testing phase, as conducted by SpaceX, because they do not possess the amount of inventory as explained by AR in the company engagement section of Chapter 3. As such, conducting early design and early prototyping is PEO IWS 3.0 best chance at improving their lengthy process. This option also includes all the steps from the PEO IWS 3.0 process thus allowing for a direct comparison between the two processes. This option will be referred to as "SpaceX non-compressed" for the remainder of the discussion.

An ExtendSim model of the SpaceX non-compressed is also built for more thorough analysis as shown in Figure 40.

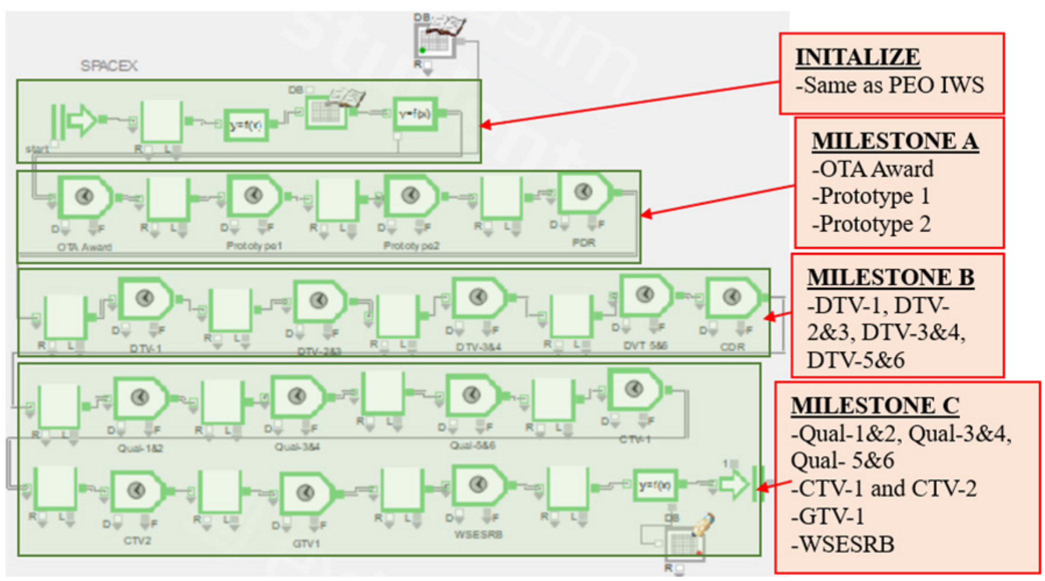

Figure 40. ExtendSim fabrication timeline SpaceX non-compressed

Upon completing the model, the average qualification time generated for SpaceX non-compressed is approximately 39 months. Its histogram, shown in Figure 41, captures the data variability and illustrates a normal distribution.

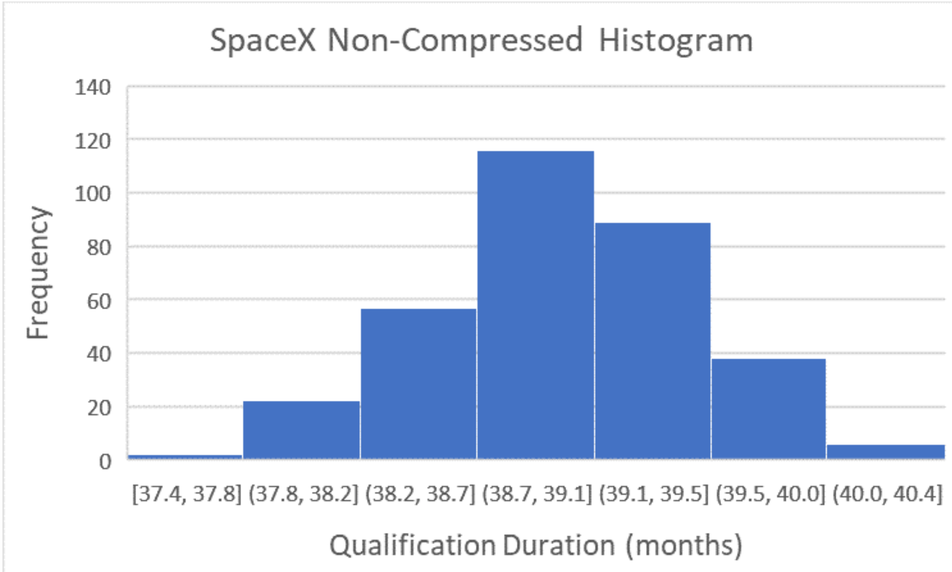

Figure 41. SpaceX non-compressed duration histogram

For visual comparison, the total qualification duration for PEO IWS 3.0, SpaceX non-compressed, and SpaceX compressed is shown in Figure 42.

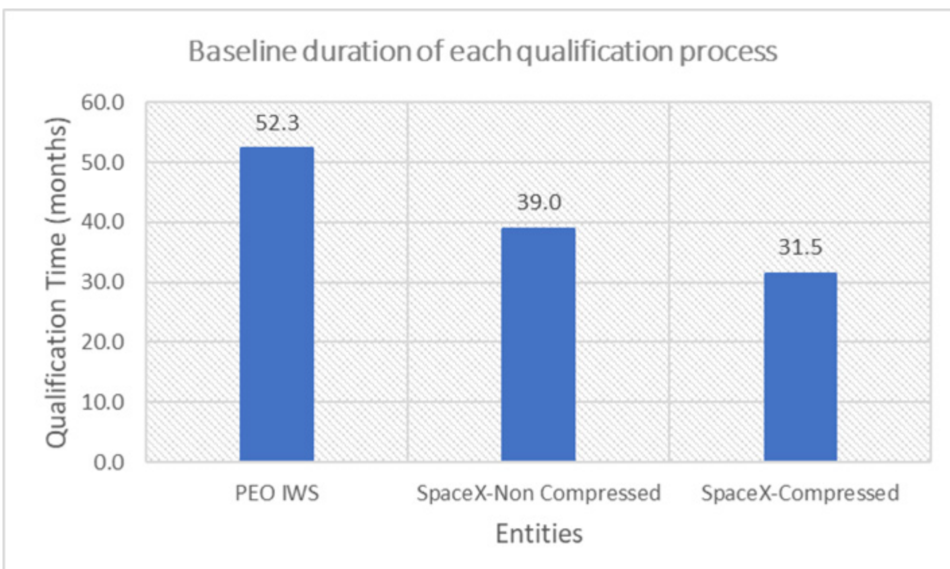

Figure 42. Various models' qualification durations

As noted in Figure 42, PEO IWS 3.0's process takes 52 weeks while SpaceX non compressed takes 39 weeks, and SpaceX compressed takes 31 weeks. For comparison purposes, the reduction percentages between the processes are shown in Table 11.

Table 11. Three process percentage comparison

Process comparison	Percentage difference
PEO-IWS vs. SpaceX compressed	40%
PEO-IWS vs. SpaceX non compressed	26%
SpaceX compressed vs. SpaceX non compressed	19%

The SpaceX compressed process is 40% shorter than the PEO IWS 3.0 process and 19% shorter than the SpaceX non compressed. The Space non-compressed process is 26% shorter than the PEO IWS 3.0 process which is the longest out of all three. All qualification processes, regardless of specific process used, come with schedule risks. The next analysis will focus on the schedule risks highlighted by the 2020 GAO report.

B. SCHEDULE RISK ANALYSIS

Generally, there are three types of risks associated with major programs: cost risk, performance risk, and schedule risk. Cost risk is outside of the scope of this project as stated in Chapter 1. Performance risk is not considered in this research as all DOD programs have safeguards in place so that the program can eventually meet system performance, even if it is at the cost of their schedule. However, schedule risk is a major ongoing battle with DOD major acquisition programs. According to GAO report (2022), more than 50% of the 29 major programs looked at in 2022 were experiencing schedule delays. This makes schedule delays a huge concern for the qualification process thus motivating the team to investigate possible causes. The GAO report (2020) associates schedule risks with lack of implementation of good practices at each knowledge point which are shown in Figure 43.

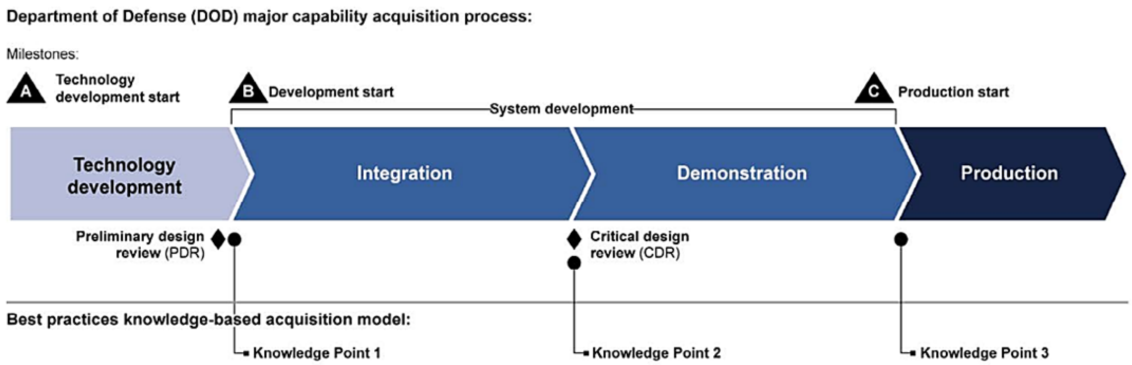

Figure 43. Acquisition milestones points. Source: GAO (2020).

The three knowledge points discussed by the GAO report (2020) and shown in Figure 43 correspond to the major milestones noted in Figure 31 of PEO IWS 3.0 qualification process as follows: knowledge point 1 corresponds to PDR, knowledge point 2 corresponds to CDR and knowledge point 3, which marks the beginning of the low rate production, corresponds to WSESRB. Given that the knowledge points coincide with the major milestones in the PEO IWS 3.0 process, the remaining analysis and discussion will reference the knowledge points.

The 2020 GAO report states that implementing good knowledge practices, detailed on the left side of Figure 44, can lead to limited schedule growth. The percentages noted in Figure 44 were determined based on 21 major programs reviewed.

Knowledge practice	Programs that implemented the practice	Programs that did not implement the practice
Complete a system-level preliminary design review prior to starting system development	• 11.6% schedule growth	• 46.3% schedule growth
Release at least 90 percent of design drawings by critical design review	• 10.3% schedule growth	• 50.3% schedule growth
Test a system-level integrated prototype by critical design review [a]	• 13.3% schedule growth	• 43.2% schedule growth

Figure 44. Knowledge practice impact. Adapted from GAO (2020).

Based on the percentages noted above, it can be inferred that most programs will likely incur a percentage of schedule growth as indicated by the middle column. The middle column suggests that even programs that have implemented good practices at the respective knowledge points are still subjected to a certain level of schedule growth. However, that growth is minimal, 10%–13%, compared to the growth that is experienced by the programs that have not implemented good knowledge practices throughout their process. Given that information, the schedule growth analysis will be broken up into two main categories: low growth analysis, 5%-15%, and high growth analysis, 40–50%.

1. Low Growth Analysis

The section will analyze the effects of low growth, 5%-15% schedule increase, on each of the three qualification processes, PEO IWS 3.0, SpaceX compressed and SpaceX non-compressed individually followed by a comparison analysis between the processes.

a. PEO IWS 3.0 low growth impact analysis

To conduct an analysis of the low growth scenarios, individual durations were extended by 5%–15%. The low schedule growth associated with PEO IWS 3.0 results in a schedule extension shown in Table 12.

Table 12. PEO IWS low growth increase

Process	PEO IWS 3.0 qual time (months)
Original Duration	52.3
5% increase	54.7
15%increase	60.1

PEO IWS 3.0 low growth durations are explored in depth using JMP. Figure 45 shows the data variability for the individual percentages. The red boxes in the image encompass the data spread from the minimum to the maximum values while the green box at the center highlights the mean value of the dataset. Overall, Figure 45 gives a visual representation of the data dispersion at each percentage and provides insight into the difference between the means.

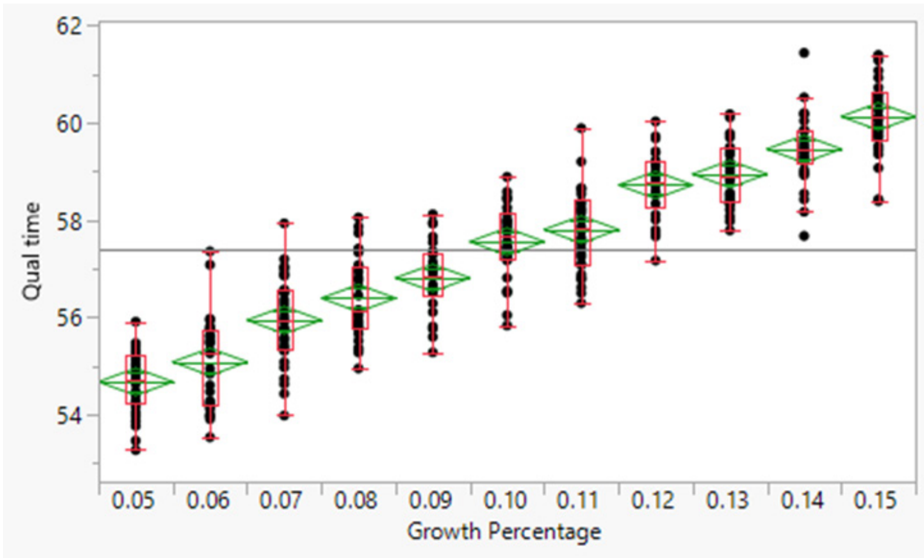

Figure 45. Low growth PEO IWS 3.0 data variability.

For more detailed analysis of the statistical difference between the percentage means, the letter report is generated. Figure 46 shows the letter report detailing each percentage level and their respective mean values. The lettering system works as follows: non-repetitive letters indicate that percentages are statistically significantly different from one another while repetitive letters indicate that two percentages sharing the same letter are not statistically different.

Connecting Letters Report

Level		Mean
0.15	A	60.133036
0.14	B	59.463404
0.13	C	58.947163
0.12	C	58.722240
0.11	D	57.805232
0.10	D	57.558044
0.09	E	56.810402
0.08	F	56.393124
0.07	G	55.941636
0.06	H	55.081950
0.05	I	54.673536

Levels not connected by same letter are significantly different.

Figure 46. Low growth: PEO IWS 3.0 percentage difference.

Analyzing the letter report, all percentages are significantly different from each other except for 10% and 11%, which share the letter D, and 12% and 13%, which share the letter C. This suggests that in almost all cases, a 1% reduction in growth results in a statistically significant reduction to the overall qualification time except for 10 % and 11% and 12 % and 13%. Because 10% and 11% are not significantly different, their impact on qualification duration is the same. The lack of statistical significance indicates that an increase from 10% to 11% on individual activity duration will not have a statistically significant increase on the total process duration. Similarly, a reduction from 10% to 11% in individual activity duration will not have a statistically significant reduction to total qualification duration. This is an important finding as in a resource restricted environment, only 9 different percentages must be considered instead of the original 11. Detailed paired t-test on each percentage pair is conducted and shown in the Appendix. The next analysis will be conducted on SpaceX compressed qualification process.

b. SpaceX compressed low growth impact analysis

The low schedule growth associated with SpaceX compressed process indicates that 5% extension leads to a schedule increase to 33.2 months and a 15% extension leads to a schedule increase to 36.2 months as shown in Table 13.

Table 13. SpaceX compressed low growth increase.

Process	SpaceX Compressed qual time (months)
Original Duration	31.5
5% increase	33.2
15%increase	36.2

JMP is utilized to conduct more in-depth analysis of the SpaceX compressed low growth durations. Figure 47 shows the data dispersion at each percentage which are contained in the red box. As noted, most of the data points lie within the confinement of the red box except for a few extreme observations at 6%, 13% and 15% indicating that the dataset is relatively concise. The means of each percentage duration is shown in green.

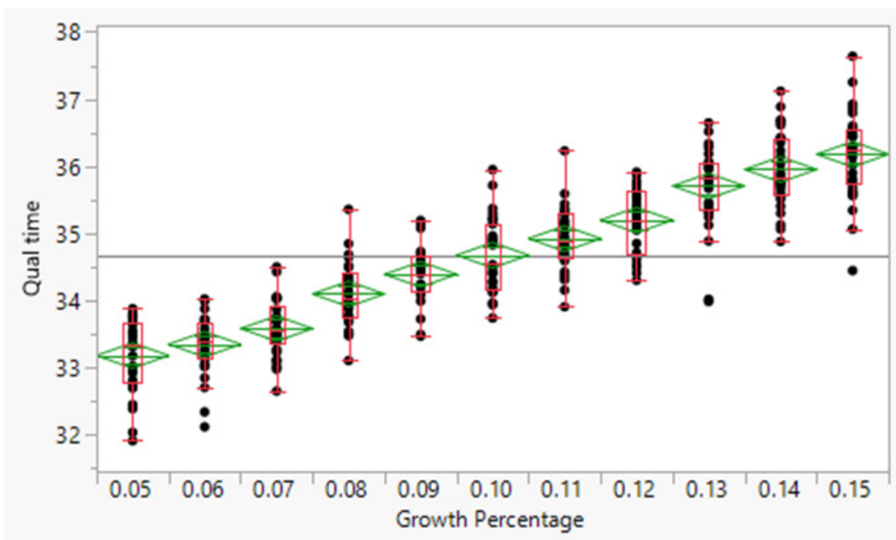

Figure 47. Low growth: SpaceX compressed data variability.

Upon examining the dataset, a letter report is generated and shown in Figure 48 to determine the statistical difference between the percentages.

Connecting Letters Report

Level									Mean
0.15	A								36.173873
0.14	A	B							35.946362
0.13		B							35.699691
0.12			C						35.191105
0.11				D					34.914307
0.10				D					34.666334
0.09					E				34.380168
0.08						F			34.086679
0.07							G		33.571266
0.06							G	H	33.335461
0.05								H	33.167868

Levels not connected by same letter are significantly different.

Figure 48. Low growth: SpaceX compressed percentage difference.

The letter report indicates that there are five percentage pairs that are not significantly different as they share the same letters: 14% and 15% letter A, 13% and 14% letter B, 10% and 11% letter C, 6% and 7% letter G, and 5% and 6% letter H. The lack of significance indicates that an increase from 14% to 15% will not have a statistically significant impact on total qualification duration. Similarly, a reduction from 14% to 15% will not have a statistically significant reduction on total qualification duration. The same finding is true for the remaining four pairs. The next analysis is conducted on the SpaceX non-compressed process.

c. *SpaceX non-compressed low growth impact*

The low schedule growth associated with the SpaceX non-compressed process is shown in Table 14.

Table 14. SpaceX non-compressed low growth increase.

Process	SpaceX Non-Compressed qual time (months)
Original Duration	39.0
5% increase	41.0
15%increase	44.8

The JMP report showing the data dispersion per individual percentage is displayed in Figure 49. The dataset is contained in the red boxes, indicating a concise data set. The means of the data set are indicated by green boxes.

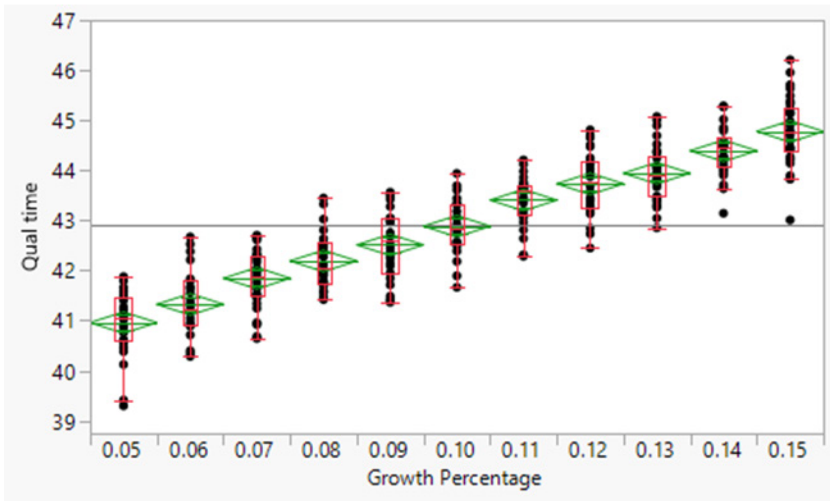

Figure 49. Low growth: SpaceX non-compressed data variability.

The letter report, shown in Figure 50, indicates that all percentages are statistically significantly different except for 12 % and 13%, which are not different.

Connecting Letters Report

Level											Mean
0.15	A										44.780062
0.14		B									44.392846
0.13			C								43.944236
0.12			C								43.732523
0.11				D							43.407604
0.10					E						42.885949
0.09						F					42.512374
0.08							G				42.191670
0.07								H			41.846914
0.06									I		41.324727
0.05										J	40.959292

Levels not connected by same letter are significantly different.

Figure 50. Low growth: SpaceX non-compressed percentage difference.

Given that all the other percentages are statistically significantly different, their impact on total qualification time will be different and must be considered individually. In all cases, a 1% increase in growth results in a statistically significant increase in total qualification time. Similarly, a 1% reduction results in a statistically significant reduction in total qualification time. Detailed paired t-test analysis on the various percentages differences is generated in the Appendix.

Now that all individual analyses have been completed, the following section will focus on comparison between the three processes discussed above.

d. Low growth: three processes comparison

To concisely demonstrate the differences between each of the three processes in the low growth scenarios, Table 15 summarizes the duration of all three processes at a 5% and 15% schedule growth.

Table 15. Low growth three process comparison

Low Growth percentage	PEO IWS 3.0 duration (months)	SpaceX non-compressed duration (months)	SpaceX compressed duration (months)
5.0%	54.7	41.0	33.2
15.0%	60.1	44.8	36.2

As expected, the percentage differences calculated in Table 11 are noted in Table 15 with a 40% difference between PEO IWS 3.0 and SpaceX compressed, 26% difference between PEO IWS 3.0 and SpaceX non-compressed and 19% difference between SpaceX compressed and SpaceX non-compressed. The numerical values at the table are consistent with the established understanding that regardless of the schedule increase, SpaceX compressed has the shortest duration, followed by SpaceX non-compressed, and PEO IWS 3.0.

The low growth analysis enabled a deep dive into the impact of a schedule increase of 5% to 15% on each of the three qualification processes. The next section will focus on high growth analysis.

2. High Growth Analysis

The high growth refers to a schedule increase of 40% to 50% due to lack of adherence to good knowledge practices at the respective knowledge points discussed in Figure 44. To conduct an analysis of the high growth scenarios, individual activity durations were extended by 40% to 50%. This section will analyze the effects of high schedule growth on each of the three qualification processes, PEO IWS 3.0, SpaceX compressed and SpaceX non-compressed individually followed by a comparison analysis between the processes.

a. PEO IWS 3.0 high growth impact analysis

The high schedule growth associated with PEO IWS 3.0 results in a schedule extension of 72.7 months at 40% and 77.9 months at 50% as shown in Table 16.

Table 16. PEO IWS 3.0 high growth increase

Process	PEO IWS 3.0 qual time (months)
Original Duration	52.3
40% increase	72.7
50%increase	77.9

PEO IWS 3.0 high growth durations are explored in depth using JMP. Figure 51 shows the data variability for the individual percentages providing visual representation of the data dispersion at each percentage and insight into the difference between the means.

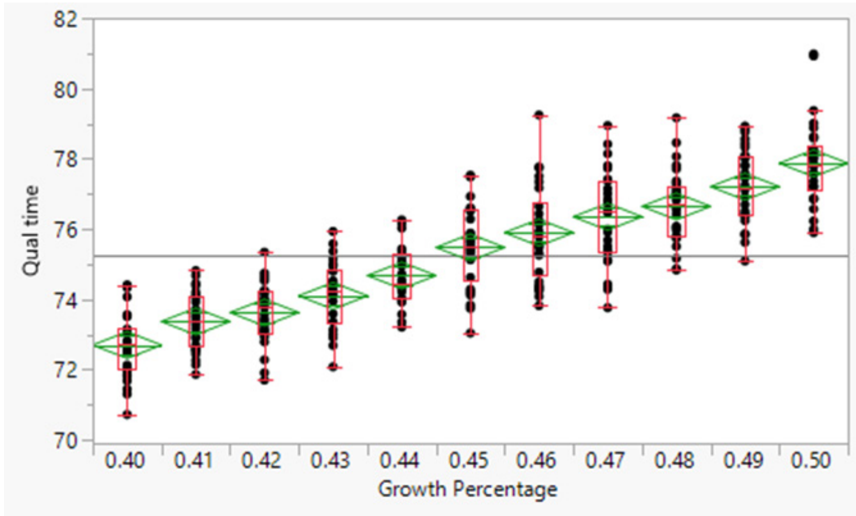

Figure 51. High growth: PEO IWS 3.0 data variability.

For more detailed analysis of the statistical difference between the means, the letter report is generated in Figure 52 detailing each percentage level and their mean values.

Connecting Letters Report

Level										Mean
0.50	A									77.872976
0.49		B								77.208134
0.48			C							76.647011
0.47			C	D						76.352108
0.46				D	E					75.900897
0.45					E					75.479449
0.44						F				74.680912
0.43							G			74.102351
0.42							G	H		73.627002
0.41								H		73.372838
0.40									I	72.703551

Levels not connected by same letter are significantly different.

Figure 52. High growth: PEO IWS 3.0 percentage difference.

The letter report shows five percentage pairs that are not statistically significantly different from one another: 47% and 48%, sharing the letter C, 46% and 47%, sharing the letter D, 45% and 46%, sharing the letter E, 42% and 43%, sharing the letter G, and 41% and 42%, sharing the letter H. Due to their lack of significant difference between the pairs, a 1% growth increase will not result in an significant increase in total qualification time.

Similarly, a 1% reduction will not result in a significant reduction in total qualification duration. More detailed paired t-tests are conducted and shown in the Appendix. The next analysis will be conducted on SpaceX compressed qualification process.

b. SpaceX compressed high growth impact analysis

The high schedule growth of 40% to 50% associated with SpaceX compressed process is shown in Table 17.

Table 17. SpaceX compressed high growth increase.

Process	SpaceX Compressed qual time (months)
Original Duration	31.5
40% increase	44.1
50%increase	47.2

JMP is utilized to conduct more in-depth analysis of the SpaceX compressed high growth durations. Figure 53 shows the data dispersion at each percentage which are contained in the red box. As noted, most of the data points lie within the confinement of the red box except for a couple of extreme observations at 40%, 41% and 43%. The mean of each percentage dataset is shown in green.

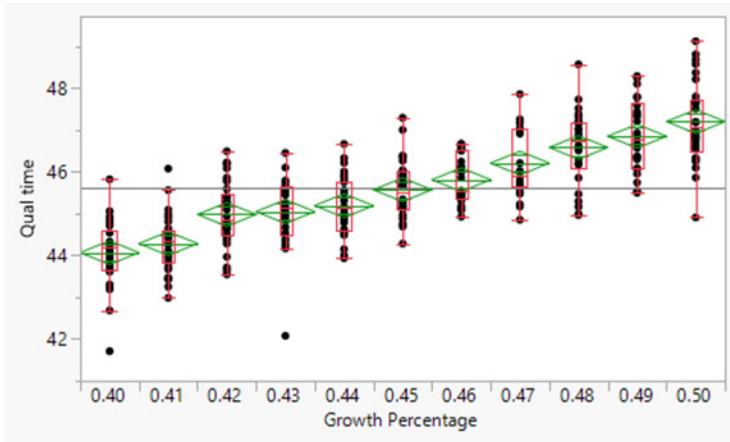

Figure 53. High growth: SpaceX compressed data variability.

Upon examining the dataset, a letter report is generated and shown in Figure 54 to determine the statistical difference between the percentages.

Connecting Letters Report

Level									Mean
0.50	A								47.196689
0.49	A	B							46.845478
0.48		B	C						46.577408
0.47			C	D					46.203277
0.46				D	E				45.806249
0.45					E	F			45.567479
0.44						F	G		45.187302
0.43							G		45.045016
0.42							G		44.977124
0.41								H	44.282516
0.40								H	44.065362

Levels not connected by same letter are significantly different.

Figure 54. High growth: SpaceX compressed percentage difference.

The letter report shows the following seven pairs and one trio as not statistically significantly different: 49% and 50% with the letter A, 48% and 49% with the letter B, 47% and 48% with the letter C, 46% and 47% with the letter D, 45% and 46% with the letter E, 44% and 45% with the letter F, 42% 43% and 44% with the letter G and finally 40% and 41% with the letter H. The primary takeaway is that within the combinations pairs enumerated, a 1% growth reduction does not result in a statistically significant reduction to overall reduction time. Given that percentage pairs are not statistically different, they have the same effect on total fabrication time. Refer to the Appendix for more detailed paired t-test between the various percentages. The next analysis is conducted on the SpaceX non-compressed process.

c. *SpaceX non-compressed high growth impact analysis*

The high schedule growth of 40% and 50% associated with the SpaceX non compressed process is shown in Table 18.

Table 18. SpaceX non-compressed high growth increase

Process	SpaceX Non-Compressed qual time (months)
Original Duration	39.0
40% increase	54.5
50%increase	58.5

The JMP report showing the data dispersion per individual percentage is displayed in Figure 55. The dataset is contained in the red boxes, indicating a concise data set. The means of the data set are indicated by green boxes.

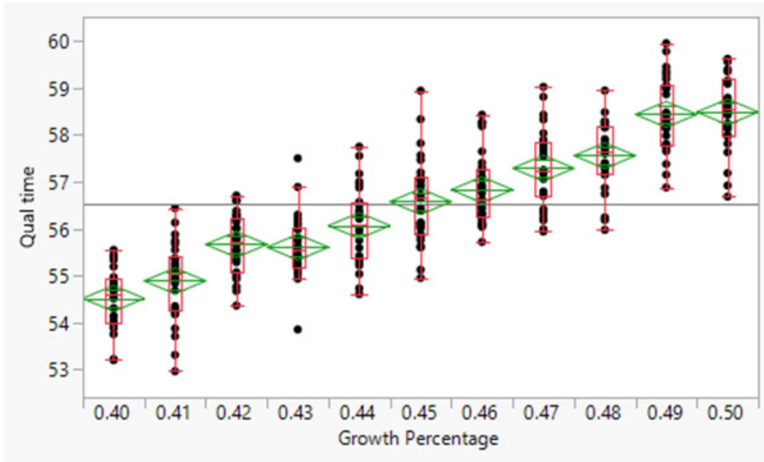

Figure 55. High growth: SpaceX non-compressed data variability.

The letter report, shown in Figure 56, indicates that all percentages are statistically not significantly different except for 44% which is different from all the other percentages.

Connecting Letters Report

Level							Mean
0.50	A						58.491218
0.49	A						58.439126
0.48		B					57.559624
0.47		B					57.289945
0.46			C				56.830102
0.45			C				56.576927
0.44				D			56.064876
0.42					E		55.663072
0.43					E		55.603241
0.41						F	54.884207
0.40						F	54.508953

Levels not connected by same letter are significantly different.

Figure 56. High growth: SpaceX non-compressed percentage difference.

The letters report highlights the following percentage pairs as not significantly different: 49% and 50% with the letter A, 47% and 48% with the letter B, 45% and 46% with the letter C, 42% and 43% with the letter E, 40% and 41% with the letter F. This indicates that a 1% growth reduction does not result in a statistically significant reduction in total qualification time. Now that all individual analyses have been completed, the next section will focus on comparing all three processes.

d. High growth: three process comparison

With high growth percentages of 40–50%, numerical comparison of the three processes is shown in Table 19.

Table 19. High growth three process comparison

High Growth percentage	PEO IWS 3.0 duration (months)	SpaceX non-compressed duration (months)	SpaceX compressed duration (months)
40%	72.7	54.5	44.1
50%	77.9	58.5	47.2

Table 19 illustrates that SpaceX compressed 50% increase yields 47.2 months, while PEO IWS 3.0 40% yields 72.7 months hence making SpaceX compressed 35% shorter in duration. SpaceX compressed at 50% increase is 13.4% shorter than SpaceX non-compressed at 40% with 54.5 months. SpaceX non-compressed at 50% yields 58.5 months while PEO IWS 3.0 40% increase leads to 72.7 months hence making SpaceX non-compressed 19.5% shorter duration. Once again, these findings consistently highlight the lengthy duration of the PEO IWS 3.0, making it longer than any other process even at a lower percentage increase.

The high growth analysis enabled a deep dive into the impact of a schedule increase of 40–50% on each of the three qualification processes and further confirming PEO IWS 3.0 as the longest duration qualification process.

Thus far, the analysis has been conducted in isolation by first analyzing low growth followed by an analysis on high growth. That methodology was helpful in recognizing the trend that SpaceX compressed remain the shortest duration process while PEO IWS 3.0 remains the highest. Shifting gears, the next analysis will focus on analyzing SpaceX compressed at the highest schedule increase of 40% to 50%, while looking at SpaceX non-compressed and PEO IWS 3.0 at the lowest schedule increase of 5% to 15%.

3. Three Process Comparison: High Growth SpaceX Compressed vs. Low Growth PEO IWS 3.0 And Low Growth SpaceX Non-compressed

The Appendix presents multiple perspectives using bar graphs to compare each process at each growth rate. The most important takeaway is that the SpaceX compressed process, even at high growth levels, outperforms both the PEO IWS 3.0 process and the SpaceX non-compressed process at low growth levels. Figure 57 provides a visual comparison of the three processes displaying SpaceX high growth, 40% to 50%, in green and on the right side of the plot, SpaceX non compressed, 5% to 15%, in orange and on the left side of the figure, and PEO IWS 3.0 5% to 15% in blue and on the left side of the figure as well.

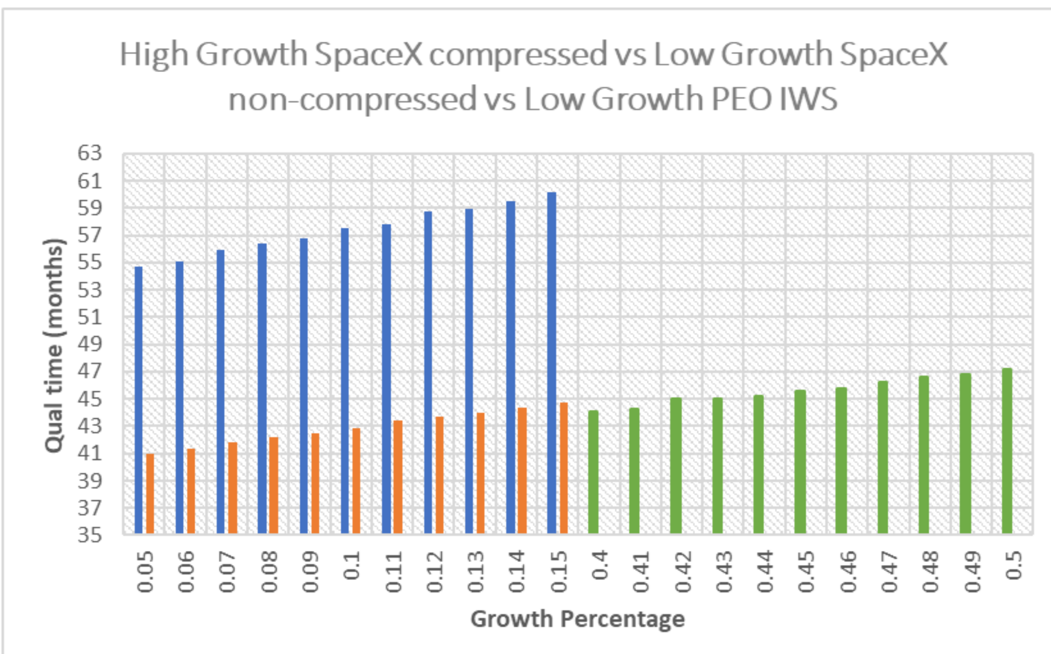

Figure 57. Three-way qualification duration comparison.

Figure 57 aids in emphasizing the disparities between the three processes. It is important to highlight that SpaceX compressed 50% increase leads to a duration of 47.2 months, PEO IWS 3.0 5% increase leads to a duration of 54.7 months, and SpaceX non-compressed 15% increase leads to a duration of 44.8 months. As such, the primary finding is that the SpaceX compressed highest percentage increase of 50%, is still 13.7% shorter than PEO IWS 3.0 and only 5% longer than SpaceX non compressed.

To conclude, the SpaceX model provides the shortest qualification duration regardless of schedule increase. In fact, it incurred a 50% schedule increase and still outperformed the other two processes. Although SpaceX non-compressed provided a middle ground solution and a slight schedule improvement, it was not as impactful as the SpaceX compressed process. Thus, to aid rapid missile replenishment, SpaceX compressed must be embraced as the minimum standard.

C. CONCLUSION

The PEO IWS 3.0 qualification model was modelled using ExtendSim to create a discrete event simulation. Upon modeling the process, the team obtained SpaceX's qualification process based on their LRE production methods which was also modelled via ExtendSim. Given that the SpaceX's process was significantly condensed, it was referred to as SpaceX compressed for the remainder of the discussion. To bridge the gap, a hybrid process called SpaceX non-compressed was created encompassing attributes from both SpaceX compressed and PEO IWS 3.0 processes. The initial durations of all the processes were as follows: PEO IWS 3.0 52.3 months, SpaceX compressed 31.5 months, and SpaceX non compressed 39 months.

Upon creation of the processes, the team analyzed schedule risks associated with DOD programs using GAO 2020 report as guidance. The report highlighted that most programs normally incur a small schedule increase of 5% to 15%. However, programs that do not implement good practices are subjected to a higher schedule increase of 40% to 50%. These two percentages were referred to as low growth, 5% to 15%, and high growth, 40% to 50% throughout the remaining analysis. Henceforth, analyses of PEO IWS 3.0, SpaceX compressed, and SpaceX non-compressed processes were conducted considering low growth and high growth percentages.

Low growth analysis indicated that for PEO IWS 3.0, the 5% increase led to 54.7 months and the 15% increase led to 60.1 months. For SpaceX Compressed, the 5% increase led to 33.2 months and 15% led to 36.2 months. For SpaceX non-compressed, the 5% increase led to 41 months and the 15% led to 44.8 months.

High growth analysis indicated that PEO IWS 3.0, 40% and 50% increase resulted in 72.7 months and 77.9 months respectively. For SpaceX non-compressed, the 40% and 50% increase resulted in 44.1 months and 47.2 months respectively. For SpaceX compressed, 40% and 50% increase led to 54.5 months and 58.5 months respectively. As expected, both low growth and high growth analysis proved that SpaceX compressed had the shortest duration while PEO IWS 3.0 had the longest duration.

For comparison purposes, one last sensitivity analysis was conducted by examining SpaceX compressed at the highest increase of 40% to 50% and the other two processes at the lower increase of 5% to 15%. The analysis shows that even at 50% schedule increase, SpaceX compressed was still 14% shorter than PEO IWS 3.0 and only 5% longer than SpaceX non-compressed.

The analysis demonstrated that SpaceX compressed represents a significant improvement over the existing PEO IWS 3.0 process. Despite the apparent aggressiveness of SpaceX compressed, it still requires 36.2 months, equivalent to three years, accounting for the 15% schedule expansion. This signifies a three-year delay in adequately arming the naval fleet to deter adversaries and safeguard national interests. As such, to curtail the current production time, PEO IWS 3.0 has an opportunity to adopt a more efficient qualification process, akin to SpaceX compressed, as a minimum standard to improve overall schedule. Given the urgency of rapid missile production, the adoption of more streamlined processes becomes crucial for expediting the entire missile production workflow. This concludes Chapter VI analysis, the conclusion in the next section will summarize all work accomplished and provide recommendations for future work.

V. CONCLUSION

This chapter explores the research and analysis conducted within the body of the thesis. This includes the documented engagements with industry companies, analysis conducted on fabrication and qualification processes respectively. The research questions are revisited and answered, and all relevant conclusions are addressed. Additionally, this chapter delineates potential avenues for future research that could contribute to advancing SRM production.

A. SUMMARY OF WORK DONE

The purpose of this thesis was to assess the PEO IWS 3.0 production process by conducting a detailed analysis of their fabrication and qualification processes. The first research question was:

- How can PEO IWS 3.0 improve its current rocket motor fabrication process to impact the production process?

In Chapter III, the initial assessment of the Solid Rocket Motor (SRM) fabrication process involved utilizing ExtendSim to model the entire process, revealing an initial total fabrication duration of 352 weeks. This preliminary analysis was conducted under the assumption of a 10% reduction in the duration of individual activities. As no specific guidance was available on duration reductions at that time, this analysis was experimental. The results from the initial analysis showed that a 10% reduction in individual activity only reduced the fabrication time from 352 to 338.2 weeks. The factors influencing the response variable at this reduction rate were identified as order forgings, case manufacture, and case preparation, respectively. Subsequently, upon obtaining actual reduction percentages from the Aerojet Rocketdyne team, a second analysis was conducted. This secondary analysis demonstrated a similar outcome, with each activity experiencing reductions ranging from 30–90%, resulting in an 18.4% reduction in the overall fabrication time of 290 weeks. Notably, order forgings and order nozzle emerged as the two most impactful factors with varying degrees of reduction. It is crucial to highlight that both analyses found order forgings to be the most influential factor and Aerojet Rocketdyne's acknowledgment of the historical delays caused by forgings procurement aligned with the statistical findings. This emphasized that allocating resources to enhance the timeline of forgings procurement will help improve the fabrication timeline thus also improving the production process.

The second research question was:

- How can PEO IWS 3.0 improve its current rocket motor qualification process to impact the production process?

In Chapter IV, PEO IWS 3.0 qualification process was modelled using ExtendSim. Upon modeling, the team collaborated with SpaceX, incorporating their version of the qualification process based on their streamlined LRE production method. This condensed SpaceX process, referred to as SpaceX compressed, prompted the creation of a hybrid process called SpaceX non-compressed. This hybrid process merged attributes from both SpaceX compressed and PEO IWS 3.0 processes. Initial durations for the three processes were: PEO IWS 3.0 52.3 months, SpaceX compressed 31.5 months, and SpaceX non-compressed 39 months. Schedule risk analysis, guided by the GAO 2020 report, identified low growth percentages as 5% to 15% and high growth percentages as 40% to 50%. Analyses considering these growth rates were conducted for PEO IWS 3.0, SpaceX compressed, and SpaceX non-compressed. The results revealed that SpaceX compressed had the shortest duration in both low and high growth scenarios, while PEO IWS 3.0 exhibited the longest. Even with a 50% schedule increase, SpaceX compressed outperformed both PEO IWS 3.0 and SpaceX non-compressed. This analysis highlights SpaceX compressed as the most efficient process that can be followed to minimize production time and expedite missile production. Considering qualification processes such as SpaceX compressed results in a significant improvement to the PEO IWS 3.0 qualification process which also improves the production process.

B. FUTURE WORK

One of the goals of this thesis was to integrate the fabrication process and the qualification process to produce the overall production process. However, data procurement from various entities took longer than expected and was not as informational as the team had hoped. Thus, future research efforts should be concentrated towards obtaining more detailed data on the fabrication process which will aid in conducting more accurate and in-depth analysis of the fabrication process thus aiding in determining the tangible impact of the fabrication process on the production process. Research efforts should also be allocated towards obtaining more detailed data on the qualification process which will aid in conducting more accurate and in-depth analysis on the qualification process thus aiding determining the tangible impact of the qualification process on the production process. Future research should also investigate new technological advances and how they can be used to improve the SRM production process.

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APPENDIX. DATA

The low schedule growth associated with PEO IWS 3.0 results in a schedule extension of 52.8 months at 5% and 60.1 months at 15% as depicted in the figure.

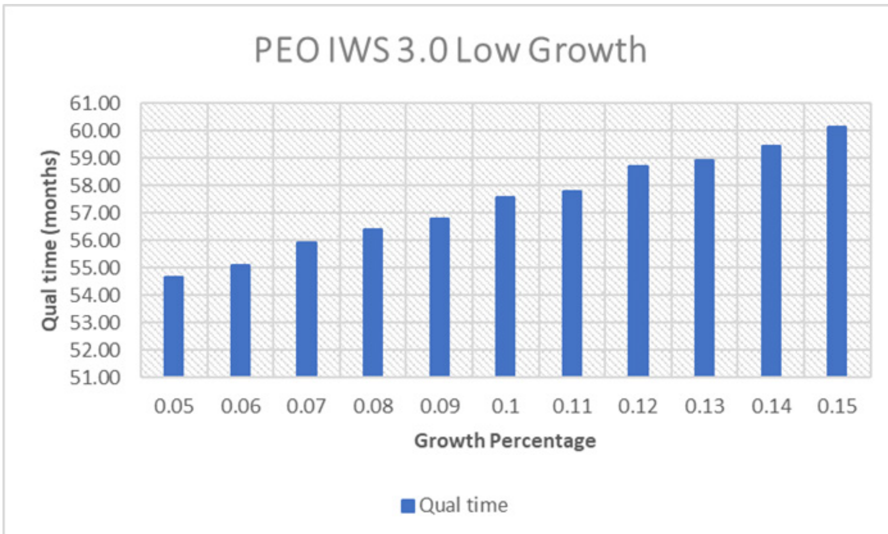

Figure 58. Low growth: PEO IWS 3.0 qualification duration

The low schedule growth associated with SpaceX compressed process indicates that in the best case of 5% extension, the schedule will increase to 33.2 months. While with the worst case of 15% extension, the schedule will increase to 36.2 months.

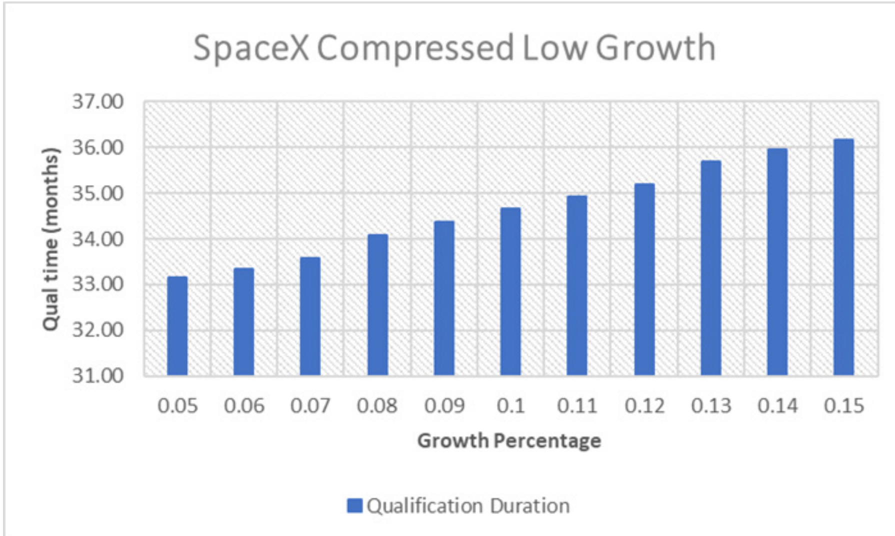

Figure 59. Low growth: SpaceX compressed qualification duration.

The low schedule growth associated with the SpaceX non compressed process is displayed in the figure The 5% schedule increase results in 41 months and the 15% schedule increase results in 44.8 months qualification duration.

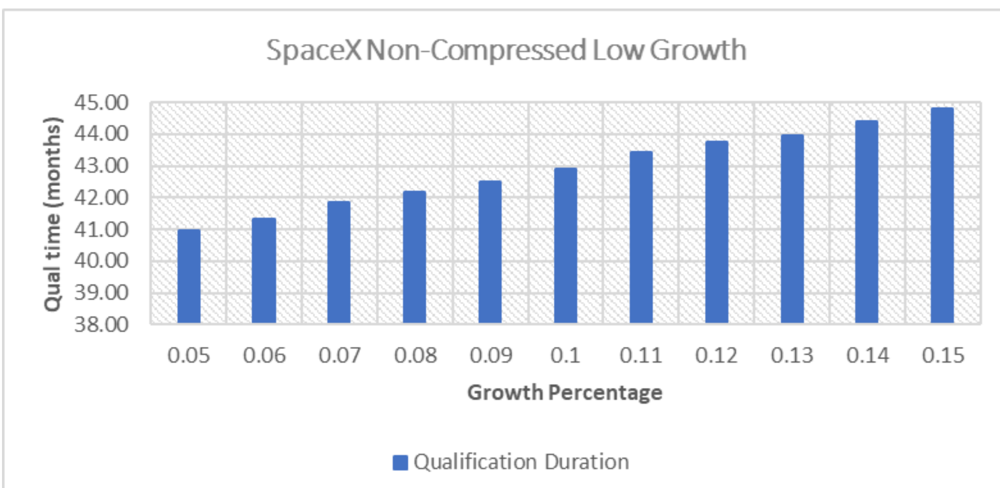

Figure 60. Low growth: SpaceX non-compressed qualification duration

Detailed paired t-test for low growth analysis on the three processes is shown as follows:

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
0.15	0.05	5.459500	0.2009870	5.06407	5.854928	<.0001*
0.15	0.06	5.051086	0.2009870	4.65566	5.446513	<.0001*
0.14	0.05	4.789868	0.2009870	4.39444	5.185296	<.0001*
0.14	0.06	4.381454	0.2009870	3.98603	4.776881	<.0001*
0.13	0.05	4.273627	0.2009870	3.87820	4.669055	<.0001*
0.15	0.07	4.191400	0.2009870	3.79597	4.586828	<.0001*
0.12	0.05	4.048704	0.2009870	3.65328	4.444132	<.0001*
0.13	0.06	3.865213	0.2009870	3.46979	4.260641	<.0001*
0.15	0.08	3.739912	0.2009870	3.34448	4.135340	<.0001*
0.12	0.06	3.640290	0.2009870	3.24486	4.035717	<.0001*
0.14	0.07	3.521768	0.2009870	3.12634	3.917196	<.0001*
0.15	0.09	3.322634	0.2009870	2.92721	3.718061	<.0001*
0.11	0.05	3.131696	0.2009870	2.73627	3.527123	<.0001*
0.14	0.08	3.070280	0.2009870	2.67485	3.465708	<.0001*
0.13	0.07	3.005528	0.2009870	2.61010	3.400955	<.0001*
0.10	0.05	2.884508	0.2009870	2.48908	3.279936	<.0001*
0.12	0.07	2.780604	0.2009870	2.38518	3.176032	<.0001*
0.11	0.06	2.723282	0.2009870	2.32785	3.118709	<.0001*
0.14	0.09	2.653002	0.2009870	2.25757	3.048429	<.0001*
0.15	0.10	2.574992	0.2009870	2.17956	2.970419	<.0001*
0.13	0.08	2.554039	0.2009870	2.15861	2.949467	<.0001*
0.10	0.06	2.476094	0.2009870	2.08067	2.871522	<.0001*
0.12	0.08	2.329116	0.2009870	1.93369	2.724543	<.0001*
0.15	0.11	2.327804	0.2009870	1.93238	2.723232	<.0001*
0.09	0.05	2.136866	0.2009870	1.74144	2.532294	<.0001*
0.13	0.09	2.136761	0.2009870	1.74133	2.532188	<.0001*
0.12	0.09	1.911838	0.2009870	1.51641	2.307265	<.0001*
0.14	0.10	1.905360	0.2009870	1.50993	2.300787	<.0001*
0.11	0.07	1.863596	0.2009870	1.46817	2.259024	<.0001*
0.09	0.06	1.728452	0.2009870	1.33302	2.123880	<.0001*
0.08	0.05	1.719588	0.2009870	1.32416	2.115016	<.0001*
0.14	0.11	1.658172	0.2009870	1.26274	2.053600	<.0001*
0.10	0.07	1.616409	0.2009870	1.22098	2.011836	<.0001*
0.11	0.08	1.412108	0.2009870	1.01668	1.807535	<.0001*
0.15	0.12	1.410796	0.2009870	1.01537	1.806224	<.0001*
0.13	0.10	1.389119	0.2009870	0.99369	1.784546	<.0001*
0.08	0.06	1.311174	0.2009870	0.91575	1.706601	<.0001*
0.07	0.05	1.268100	0.2009870	0.87267	1.663527	<.0001*
0.15	0.13	1.185873	0.2009870	0.79045	1.581300	<.0001*
0.10	0.08	1.164920	0.2009870	0.76949	1.560348	<.0001*
0.12	0.10	1.164196	0.2009870	0.76877	1.559623	<.0001*
0.13	0.11	1.141931	0.2009870	0.74650	1.537359	<.0001*
0.11	0.09	0.994830	0.2009870	0.59940	1.390257	<.0001*
0.12	0.11	0.917008	0.2009870	0.52158	1.312436	<.0001*
0.09	0.07	0.868767	0.2009870	0.47334	1.264194	<.0001*
0.07	0.06	0.859685	0.2009870	0.46426	1.255113	<.0001*
0.10	0.09	0.747642	0.2009870	0.35221	1.143069	0.0002*
0.14	0.12	0.741164	0.2009870	0.34574	1.136592	0.0003*
0.15	0.14	0.669632	0.2009870	0.27420	1.065059	0.0010*
0.14	0.13	0.516241	0.2009870	0.12081	0.911668	0.0107*
0.08	0.07	0.451488	0.2009870	0.05606	0.846916	0.0254*
0.09	0.08	0.417278	0.2009870	0.02185	0.812706	0.0387*
0.06	0.05	0.408414	0.2009870	0.01299	0.803842	0.0430*
0.11	0.10	0.247188	0.2009870	-0.14824	0.642615	0.2197
0.13	0.12	0.224923	0.2009870	-0.17050	0.620351	0.2639

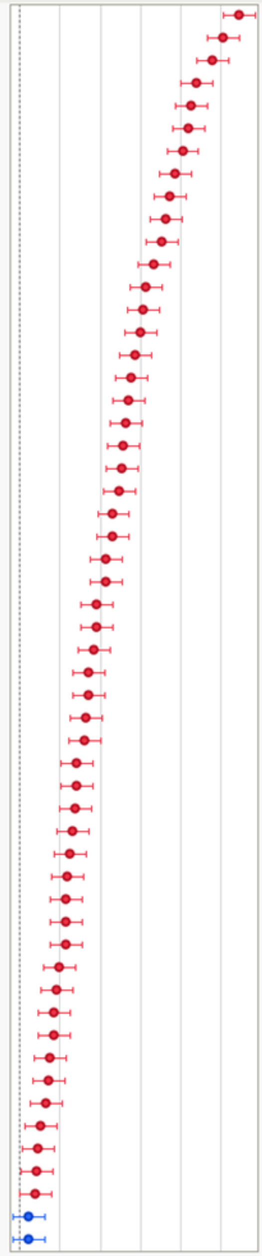

Figure 61. PEO IWS 3.0 low growth statistical difference

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
0.15	0.05	3.006005	0.1358051	2.73882	3.273192	<.0001*
0.15	0.06	2.838412	0.1358051	2.57123	3.105599	<.0001*
0.14	0.05	2.778494	0.1358051	2.51131	3.045681	<.0001*
0.14	0.06	2.610901	0.1358051	2.34371	2.878088	<.0001*
0.15	0.07	2.602607	0.1358051	2.33542	2.869793	<.0001*
0.13	0.05	2.531823	0.1358051	2.26464	2.799010	<.0001*
0.14	0.07	2.375096	0.1358051	2.10791	2.642283	<.0001*
0.13	0.06	2.364230	0.1358051	2.09704	2.631417	<.0001*
0.13	0.07	2.128425	0.1358051	1.86124	2.395612	<.0001*
0.15	0.08	2.087194	0.1358051	1.82001	2.354380	<.0001*
0.12	0.05	2.023237	0.1358051	1.75605	2.290424	<.0001*
0.14	0.08	1.859683	0.1358051	1.59250	2.126870	<.0001*
0.12	0.06	1.855644	0.1358051	1.58846	2.122831	<.0001*
0.15	0.09	1.793705	0.1358051	1.52652	2.060891	<.0001*
0.11	0.05	1.746439	0.1358051	1.47925	2.013625	<.0001*
0.12	0.07	1.619838	0.1358051	1.35265	1.887025	<.0001*
0.13	0.08	1.613012	0.1358051	1.34583	1.880199	<.0001*
0.11	0.06	1.578846	0.1358051	1.31166	1.846032	<.0001*
0.14	0.09	1.566194	0.1358051	1.29901	1.833381	<.0001*
0.15	0.10	1.507539	0.1358051	1.24035	1.774726	<.0001*
0.10	0.05	1.498466	0.1358051	1.23128	1.765653	<.0001*
0.11	0.07	1.343040	0.1358051	1.07585	1.610227	<.0001*
0.10	0.06	1.330873	0.1358051	1.06369	1.598060	<.0001*
0.13	0.09	1.319523	0.1358051	1.05234	1.586710	<.0001*
0.14	0.10	1.280028	0.1358051	1.01284	1.547215	<.0001*
0.15	0.11	1.259566	0.1358051	0.99238	1.526753	<.0001*
0.09	0.05	1.212300	0.1358051	0.94511	1.479487	<.0001*
0.12	0.08	1.104426	0.1358051	0.83724	1.371612	<.0001*
0.10	0.07	1.095067	0.1358051	0.82788	1.362254	<.0001*
0.09	0.06	1.044708	0.1358051	0.77752	1.311894	<.0001*
0.13	0.10	1.033357	0.1358051	0.76617	1.300544	<.0001*
0.14	0.11	1.032056	0.1358051	0.76487	1.299242	<.0001*
0.15	0.12	0.982768	0.1358051	0.71558	1.249955	<.0001*
0.08	0.05	0.918811	0.1358051	0.65162	1.185998	<.0001*
0.11	0.08	0.827627	0.1358051	0.56044	1.094814	<.0001*
0.12	0.09	0.810936	0.1358051	0.54375	1.078123	<.0001*
0.09	0.07	0.808902	0.1358051	0.54172	1.076089	<.0001*
0.13	0.11	0.785385	0.1358051	0.51820	1.052571	<.0001*
0.14	0.12	0.755257	0.1358051	0.48807	1.022444	<.0001*
0.08	0.06	0.751218	0.1358051	0.48403	1.018405	<.0001*
0.10	0.08	0.579655	0.1358051	0.31247	0.846841	<.0001*
0.11	0.09	0.534138	0.1358051	0.26695	0.801325	0.0001*
0.12	0.10	0.524771	0.1358051	0.25758	0.791958	0.0001*
0.08	0.07	0.515413	0.1358051	0.24823	0.782600	0.0002*
0.13	0.12	0.508586	0.1358051	0.24140	0.775773	0.0002*
0.15	0.13	0.474182	0.1358051	0.20700	0.741368	0.0005*
0.07	0.05	0.403399	0.1358051	0.13621	0.670585	0.0032*
0.09	0.08	0.293489	0.1358051	0.02630	0.560676	0.0314*
0.10	0.09	0.286165	0.1358051	0.01898	0.553352	0.0359*
0.12	0.11	0.276798	0.1358051	0.00961	0.543985	0.0424*
0.11	0.10	0.247973	0.1358051	-0.01921	0.515159	0.0688
0.14	0.13	0.246671	0.1358051	-0.02052	0.513858	0.0703
0.07	0.06	0.235806	0.1358051	-0.03138	0.502992	0.0835
0.15	0.14	0.227511	0.1358051	-0.03968	0.494697	0.0949
0.06	0.05	0.167593	0.1358051	-0.09959	0.434780	0.2181

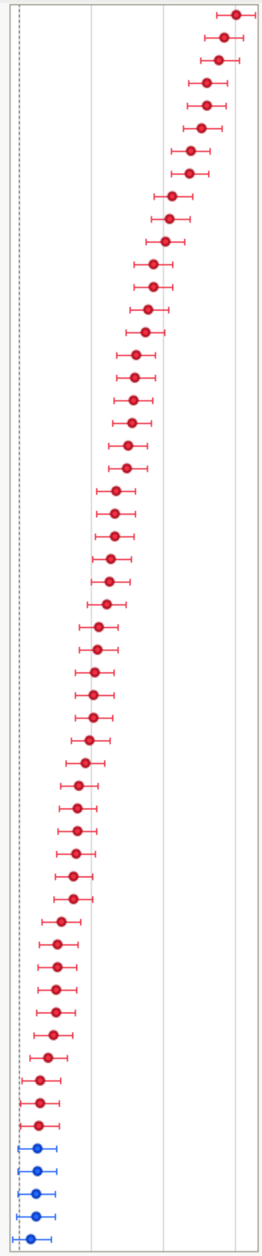

Figure 62. SpaceX compressed low growth statistical difference.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
0.15	0.05	3.820771	0.1536502	3.51847	4.123066	<.0001*
0.15	0.06	3.455335	0.1536502	3.15304	3.757631	<.0001*
0.14	0.05	3.433554	0.1536502	3.13126	3.735850	<.0001*
0.14	0.06	3.068118	0.1536502	2.76582	3.370414	<.0001*
0.13	0.05	2.984944	0.1536502	2.68265	3.287240	<.0001*
0.15	0.07	2.933149	0.1536502	2.63085	3.235444	<.0001*
0.12	0.05	2.773231	0.1536502	2.47094	3.075527	<.0001*
0.13	0.06	2.619509	0.1536502	2.31721	2.921804	<.0001*
0.15	0.08	2.588392	0.1536502	2.28610	2.890688	<.0001*
0.14	0.07	2.545932	0.1536502	2.24364	2.848228	<.0001*
0.11	0.05	2.448313	0.1536502	2.14602	2.750609	<.0001*
0.12	0.06	2.407796	0.1536502	2.10550	2.710091	<.0001*
0.15	0.09	2.267688	0.1536502	1.96539	2.569984	<.0001*
0.14	0.08	2.201176	0.1536502	1.89888	2.503471	<.0001*
0.13	0.07	2.097322	0.1536502	1.79503	2.399618	<.0001*
0.11	0.06	2.082877	0.1536502	1.78058	2.385173	<.0001*
0.10	0.05	1.926657	0.1536502	1.62436	2.228953	<.0001*
0.15	0.10	1.894113	0.1536502	1.59182	2.196409	<.0001*
0.12	0.07	1.885609	0.1536502	1.58331	2.187905	<.0001*
0.14	0.09	1.880472	0.1536502	1.57818	2.182768	<.0001*
0.13	0.08	1.752566	0.1536502	1.45027	2.054862	<.0001*
0.10	0.06	1.561222	0.1536502	1.25893	1.863517	<.0001*
0.11	0.07	1.560691	0.1536502	1.25839	1.862986	<.0001*
0.09	0.05	1.553082	0.1536502	1.25079	1.855378	<.0001*
0.12	0.08	1.540853	0.1536502	1.23856	1.843148	<.0001*
0.14	0.10	1.506897	0.1536502	1.20460	1.809193	<.0001*
0.13	0.09	1.431862	0.1536502	1.12957	1.734158	<.0001*
0.15	0.11	1.372458	0.1536502	1.07016	1.674754	<.0001*
0.08	0.05	1.232379	0.1536502	0.93008	1.534674	<.0001*
0.12	0.09	1.220149	0.1536502	0.91785	1.522445	<.0001*
0.11	0.08	1.215934	0.1536502	0.91364	1.518230	<.0001*
0.09	0.06	1.187647	0.1536502	0.88535	1.489942	<.0001*
0.13	0.10	1.058287	0.1536502	0.75599	1.360583	<.0001*
0.15	0.12	1.047539	0.1536502	0.74524	1.349835	<.0001*
0.10	0.07	1.039035	0.1536502	0.73674	1.341331	<.0001*
0.14	0.11	0.985241	0.1536502	0.68295	1.287537	<.0001*
0.11	0.09	0.895230	0.1536502	0.59293	1.197526	<.0001*
0.07	0.05	0.887622	0.1536502	0.58533	1.189918	<.0001*
0.08	0.06	0.866943	0.1536502	0.56465	1.169239	<.0001*
0.12	0.10	0.846574	0.1536502	0.54428	1.148870	<.0001*
0.15	0.13	0.835826	0.1536502	0.53353	1.138122	<.0001*
0.10	0.08	0.694279	0.1536502	0.39198	0.996574	<.0001*
0.09	0.07	0.665460	0.1536502	0.36316	0.967756	<.0001*
0.14	0.12	0.660323	0.1536502	0.35803	0.962619	<.0001*
0.13	0.11	0.536632	0.1536502	0.23434	0.838927	0.0005*
0.07	0.06	0.522186	0.1536502	0.21989	0.824482	0.0008*
0.11	0.10	0.521656	0.1536502	0.21936	0.823951	0.0008*
0.14	0.13	0.448610	0.1536502	0.14631	0.750906	0.0038*
0.15	0.14	0.387217	0.1536502	0.08492	0.689512	0.0122*
0.10	0.09	0.373575	0.1536502	0.07128	0.675871	0.0156*
0.06	0.05	0.365436	0.1536502	0.06314	0.667731	0.0180*
0.08	0.07	0.344756	0.1536502	0.04246	0.647052	0.0255*
0.12	0.11	0.324918	0.1536502	0.02262	0.627214	0.0352*
0.09	0.08	0.320704	0.1536502	0.01841	0.623000	0.0377*
0.13	0.12	0.211713	0.1536502	-0.09058	0.514009	0.1692

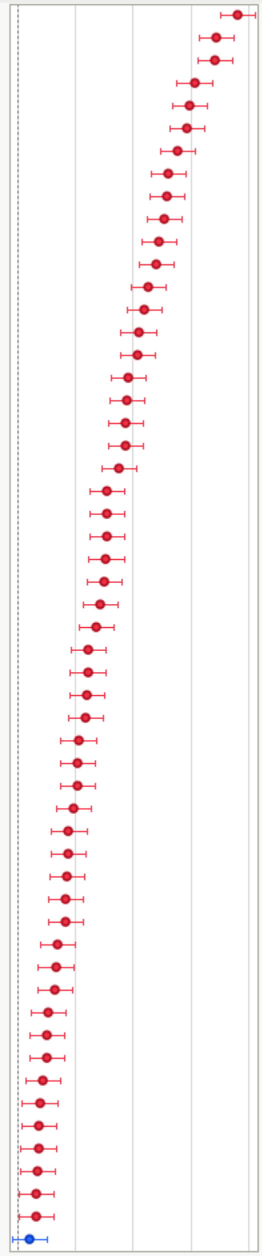

Figure 63. SpaceX non compressed low growth – percentage statistical difference.

PEO IWS 3.0 vs. SpaceX Compressed

With low growth percentages of 5–15%, visual comparison of the two process is generated in the figure.

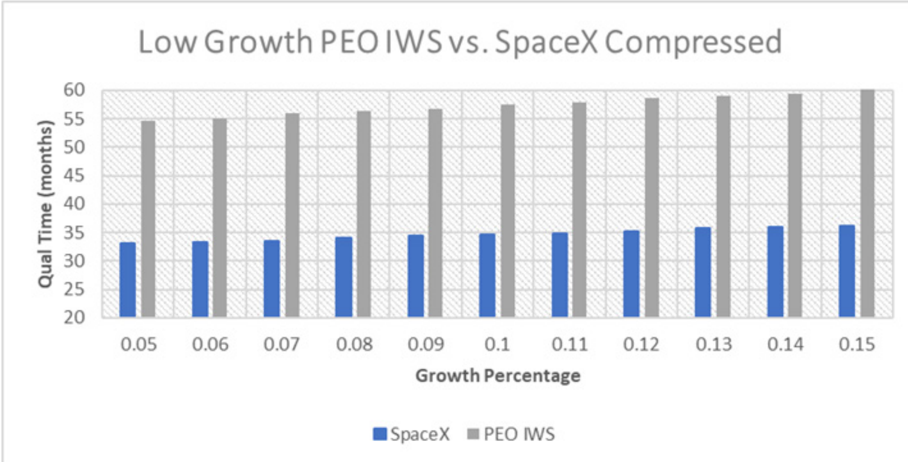

Figure 64. Low growth: PEO IWS 3.0 vs. SpaceX compressed qualification duration.

As expected, a large difference of 40% is noted between the two processes throughout the various percentages. It is important to highlight that SpaceX's highest percentage of 15% yields 36.2 months which is 33.8% shorter than PEO IWS 3.0 smallest percentage of 5% which yields 54.7 months. It is no surprise that SpaceX compressed process is a much shorter duration. The next analysis will be comparing PEO IWS 3.0 to SpaceX non-compressed.

PEO IWS 3.0 vs. SpaceX Non-Compressed

The figure provides visual comparison between the two processes, also shows a significant difference between PEO IWS 3.0 and SpaceX non-compressed.

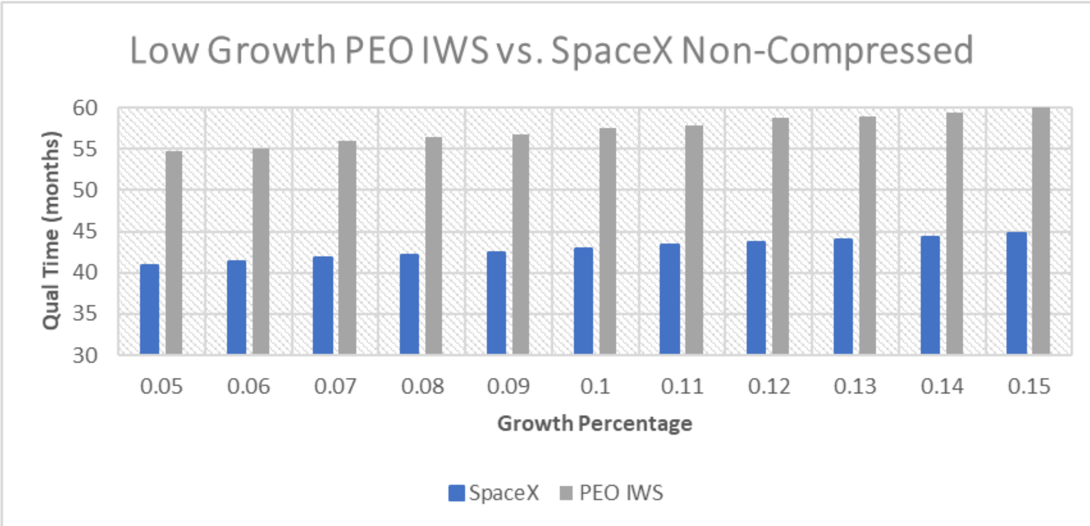

Figure 65. Low growth: PEO IWS 3.0 vs. SpaceX Non-compressed qualification duration

As expected, a 26% difference is noted between the two processes throughout the various percentages. Analyzing both processes, is important to note that SpaceX non-compressed with the highest percentage of 15% yields 44.8 months which is still 18.1% shorter than PEO IWS 3.0 smallest percentage of 5% which yields 54.7 months. Once again, it is noted that PEO IWS 3.0 process is severely lagging compared to both SpaceX compressed and SpaceX non-compressed. The next analysis will be a comparison between the two derived processes SpaceX compressed and SpaceX non-compressed.

SpaceX Compressed vs. SpaceX Non-Compressed

The qualification duration between the two processes at various percentages is shown in the figure highlights a relatively large difference.

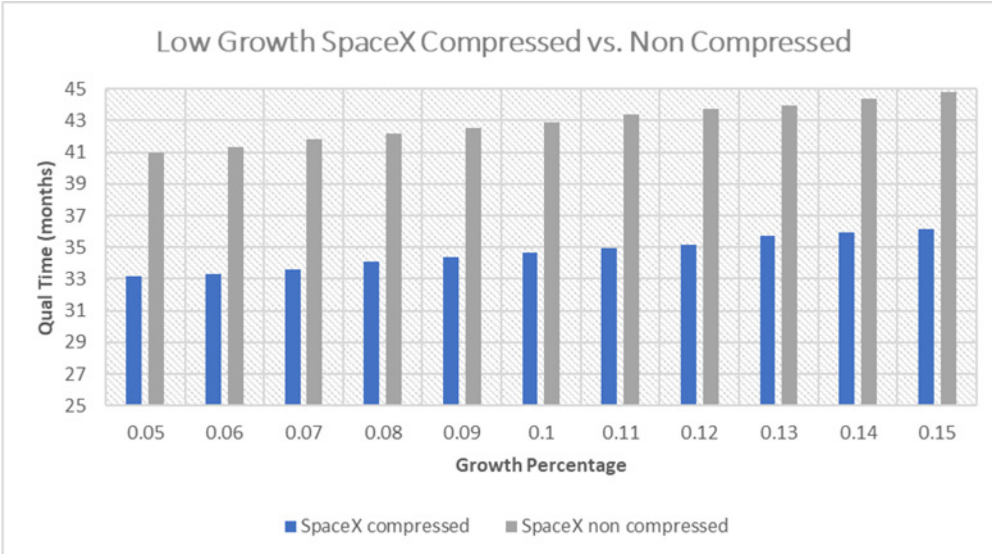

Figure 66. Low growth: SpaceX compressed vs. non compressed qualification duration

As expected from Table 1, a 19% difference is noted between the two processes at the various percentages. It is important to note that SpaceX compressed with the highest percentage of 15% yields 36.2 months which is still 11.7% shorter than PEO IWS 3.0 smallest percentage of 5% which yields 41 months. The low growth analysis enabled a deep dive into the impact of a schedule increase of 5–15% on each of the three qualification processes. The next section will focus on high growth analysis.

High Growth Analysis

The high schedule growth associated with PEO IWS 3.0 3.0 results in a schedule extension of 72.7 months at 40% and 77.9 months at 50%.

Figure 67. High growth: PEO IWS 3.0 qualification duration

The high schedule growth associated with SpaceX compressed process are displayed in the figure indicating that in the best case of 40% extension, the schedule will increase to 44.1 months. While with the worst case of 50% extension, the schedule will increase to 47.2 months.

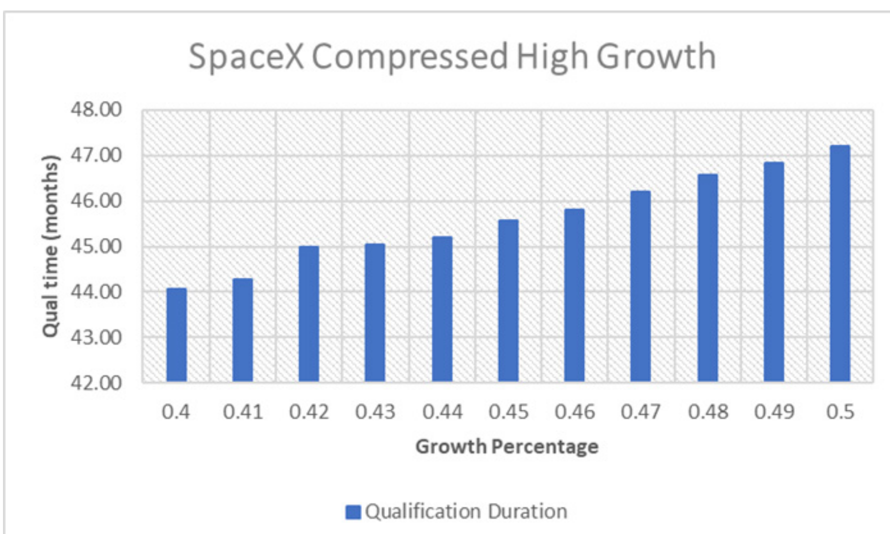

Figure 68. High growth: SpaceX compressed qualification duration.

The low schedule growth associated with the SpaceX non compressed process is displayed in Figure 33. The 40% schedule increase results in 54.5 months qualification duration, and the 50% schedule increase results in 58.5 months qualification duration.

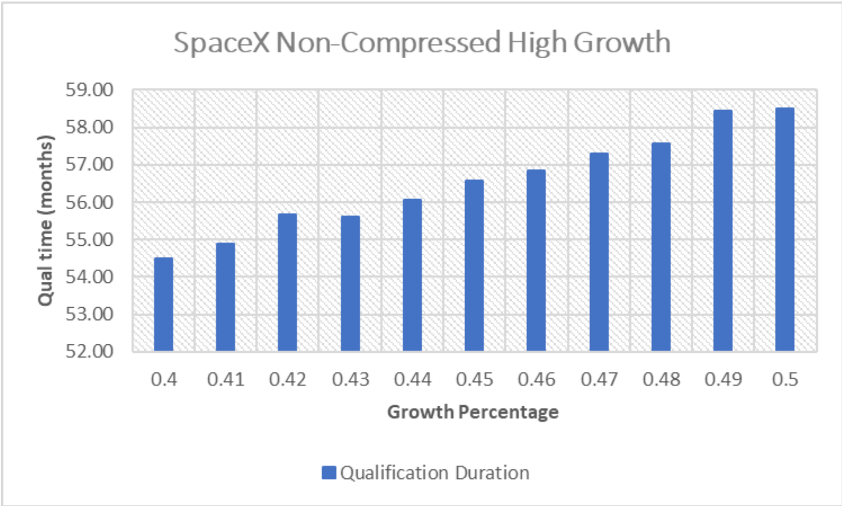

Figure 69. High growth: SpaceX non-compressed qualification duration

Detailed paired t-test for high growth analysis on the three processes is shown as follows:

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
0.50	0.40	5.169426	0.2733232	4.63168	5.707170	<.0001*
0.49	0.40	4.504583	0.2733232	3.96684	5.042327	<.0001*
0.50	0.41	4.500139	0.2733232	3.96239	5.037883	<.0001*
0.50	0.42	4.245975	0.2733232	3.70823	4.783718	<.0001*
0.48	0.40	3.943460	0.2733232	3.40572	4.481204	<.0001*
0.49	0.41	3.835296	0.2733232	3.29755	4.373040	<.0001*
0.50	0.43	3.770625	0.2733232	3.23288	4.308369	<.0001*
0.47	0.40	3.648557	0.2733232	3.11081	4.186301	<.0001*
0.49	0.42	3.581132	0.2733232	3.04339	4.118876	<.0001*
0.48	0.41	3.274173	0.2733232	2.73643	3.811917	<.0001*
0.46	0.40	3.197346	0.2733232	2.65960	3.735090	<.0001*
0.50	0.44	3.192065	0.2733232	2.65432	3.729808	<.0001*
0.49	0.43	3.105782	0.2733232	2.56804	3.643526	<.0001*
0.48	0.42	3.020009	0.2733232	2.48227	3.557753	<.0001*
0.47	0.41	2.979270	0.2733232	2.44153	3.517014	<.0001*
0.45	0.40	2.775898	0.2733232	2.23815	3.313642	<.0001*
0.47	0.42	2.725106	0.2733232	2.18736	3.262850	<.0001*
0.48	0.43	2.544659	0.2733232	2.00692	3.082403	<.0001*
0.46	0.41	2.528059	0.2733232	1.99032	3.065803	<.0001*
0.49	0.44	2.527222	0.2733232	1.98948	3.064966	<.0001*
0.50	0.45	2.393528	0.2733232	1.85578	2.931272	<.0001*
0.46	0.42	2.273895	0.2733232	1.73615	2.811639	<.0001*
0.47	0.43	2.249756	0.2733232	1.71201	2.787500	<.0001*
0.45	0.41	2.106611	0.2733232	1.56887	2.644355	<.0001*
0.44	0.40	1.977361	0.2733232	1.43962	2.515105	<.0001*
0.50	0.46	1.972080	0.2733232	1.43434	2.509824	<.0001*
0.48	0.44	1.966099	0.2733232	1.42836	2.503843	<.0001*
0.45	0.42	1.852447	0.2733232	1.31470	2.390191	<.0001*
0.46	0.43	1.798545	0.2733232	1.26080	2.336289	<.0001*
0.49	0.45	1.728685	0.2733232	1.19094	2.266429	<.0001*
0.47	0.44	1.671196	0.2733232	1.13345	2.208940	<.0001*
0.50	0.47	1.520869	0.2733232	0.98312	2.058613	<.0001*
0.43	0.40	1.398801	0.2733232	0.86106	1.936545	<.0001*
0.45	0.43	1.377097	0.2733232	0.83935	1.914841	<.0001*
0.44	0.41	1.308074	0.2733232	0.77033	1.845818	<.0001*
0.49	0.46	1.307237	0.2733232	0.76949	1.844981	<.0001*
0.50	0.48	1.225966	0.2733232	0.68822	1.763710	<.0001*
0.46	0.44	1.219985	0.2733232	0.68224	1.757729	<.0001*
0.48	0.45	1.167562	0.2733232	0.62982	1.705306	<.0001*
0.44	0.42	1.053910	0.2733232	0.51617	1.591654	0.0001*
0.42	0.40	0.923451	0.2733232	0.38571	1.461195	0.0008*
0.47	0.45	0.872659	0.2733232	0.33492	1.410403	0.0015*
0.49	0.47	0.856026	0.2733232	0.31828	1.393770	0.0019*
0.45	0.44	0.798537	0.2733232	0.26079	1.336281	0.0037*
0.48	0.46	0.746114	0.2733232	0.20837	1.283858	0.0067*
0.43	0.41	0.729514	0.2733232	0.19177	1.267258	0.0080*
0.41	0.40	0.669287	0.2733232	0.13154	1.207031	0.0149*
0.50	0.49	0.664843	0.2733232	0.12710	1.202587	0.0155*
0.44	0.43	0.578561	0.2733232	0.04082	1.116304	0.0351*
0.49	0.48	0.561123	0.2733232	0.02338	1.098867	0.0409*
0.43	0.42	0.475350	0.2733232	-0.06239	1.013093	0.0830
0.47	0.46	0.451211	0.2733232	-0.08653	0.988955	0.0998
0.46	0.45	0.421448	0.2733232	-0.11630	0.959192	0.1241
0.48	0.47	0.294903	0.2733232	-0.24284	0.832647	0.2814
0.42	0.41	0.254164	0.2733232	-0.28358	0.791908	0.3531

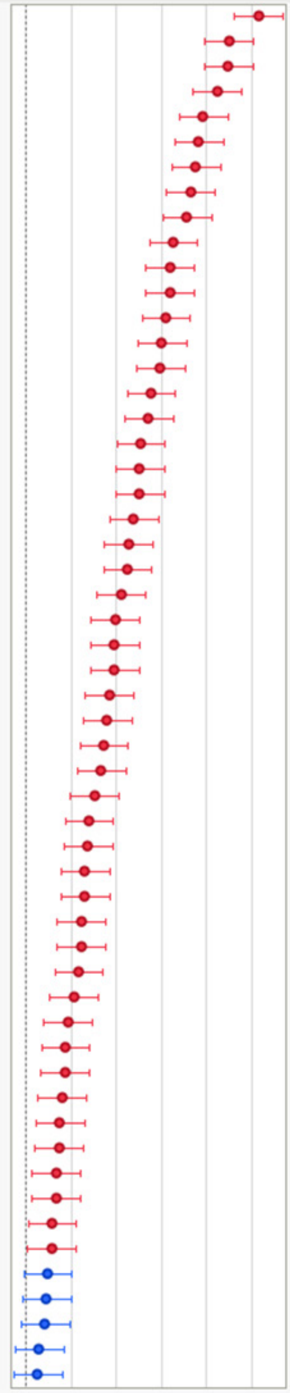

Figure 70. High growth: PEO IWS 3.0 percentage difference

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
0.50	0.40	3.131328	0.2032030	2.73154	3.531115	<.0001*
0.50	0.41	2.914174	0.2032030	2.51439	3.313961	<.0001*
0.49	0.40	2.780116	0.2032030	2.38033	3.179904	<.0001*
0.49	0.41	2.562962	0.2032030	2.16317	2.962750	<.0001*
0.48	0.40	2.512047	0.2032030	2.11226	2.911834	<.0001*
0.48	0.41	2.294893	0.2032030	1.89511	2.694680	<.0001*
0.50	0.42	2.219565	0.2032030	1.81978	2.619353	<.0001*
0.50	0.43	2.151674	0.2032030	1.75189	2.551461	<.0001*
0.47	0.40	2.137915	0.2032030	1.73813	2.537703	<.0001*
0.50	0.44	2.009387	0.2032030	1.60960	2.409174	<.0001*
0.47	0.41	1.920761	0.2032030	1.52097	2.320549	<.0001*
0.49	0.42	1.868354	0.2032030	1.46857	2.268141	<.0001*
0.49	0.43	1.800462	0.2032030	1.40067	2.200250	<.0001*
0.46	0.40	1.740888	0.2032030	1.34110	2.140675	<.0001*
0.49	0.44	1.658175	0.2032030	1.25839	2.057963	<.0001*
0.50	0.45	1.629211	0.2032030	1.22942	2.028998	<.0001*
0.48	0.42	1.600284	0.2032030	1.20050	2.000072	<.0001*
0.48	0.43	1.532393	0.2032030	1.13261	1.932180	<.0001*
0.46	0.41	1.523734	0.2032030	1.12395	1.923521	<.0001*
0.45	0.40	1.502117	0.2032030	1.10233	1.901905	<.0001*
0.50	0.46	1.390440	0.2032030	0.99065	1.790227	<.0001*
0.48	0.44	1.390106	0.2032030	0.99032	1.789893	<.0001*
0.45	0.41	1.284963	0.2032030	0.88518	1.684751	<.0001*
0.49	0.45	1.277999	0.2032030	0.87821	1.677786	<.0001*
0.47	0.42	1.226153	0.2032030	0.82637	1.625940	<.0001*
0.47	0.43	1.158261	0.2032030	0.75847	1.558049	<.0001*
0.44	0.40	1.121941	0.2032030	0.72215	1.521728	<.0001*
0.49	0.46	1.039228	0.2032030	0.63944	1.439016	<.0001*
0.47	0.44	1.015975	0.2032030	0.61619	1.415762	<.0001*
0.48	0.45	1.009930	0.2032030	0.61014	1.409717	<.0001*
0.50	0.47	0.993412	0.2032030	0.59363	1.393200	<.0001*
0.43	0.40	0.979654	0.2032030	0.57987	1.379441	<.0001*
0.42	0.40	0.911762	0.2032030	0.51197	1.311550	<.0001*
0.44	0.41	0.904787	0.2032030	0.50500	1.304574	<.0001*
0.46	0.42	0.829125	0.2032030	0.42934	1.228913	<.0001*
0.48	0.46	0.771159	0.2032030	0.37137	1.170946	0.0002*
0.43	0.41	0.762500	0.2032030	0.36271	1.162287	0.0002*
0.46	0.43	0.761234	0.2032030	0.36145	1.161021	0.0002*
0.42	0.41	0.694608	0.2032030	0.29482	1.094396	0.0007*
0.49	0.47	0.642201	0.2032030	0.24241	1.041988	0.0017*
0.47	0.45	0.635798	0.2032030	0.23601	1.035586	0.0019*
0.50	0.48	0.619281	0.2032030	0.21949	1.019068	0.0025*
0.46	0.44	0.618947	0.2032030	0.21916	1.018734	0.0025*
0.45	0.42	0.590355	0.2032030	0.19057	0.990142	0.0039*
0.45	0.43	0.522463	0.2032030	0.12268	0.922251	0.0106*
0.47	0.46	0.397028	0.2032030	-0.00276	0.796815	0.0516
0.45	0.44	0.380176	0.2032030	-0.01961	0.779964	0.0623
0.48	0.47	0.374131	0.2032030	-0.02566	0.773919	0.0665
0.50	0.49	0.351212	0.2032030	-0.04858	0.750999	0.0849
0.49	0.48	0.268069	0.2032030	-0.13172	0.667857	0.1880
0.46	0.45	0.238771	0.2032030	-0.16102	0.638558	0.2409
0.41	0.40	0.217154	0.2032030	-0.18263	0.616941	0.2860
0.44	0.42	0.210178	0.2032030	-0.18961	0.609966	0.3018
0.44	0.43	0.142287	0.2032030	-0.25750	0.542074	0.4843
0.43	0.42	0.067892	0.2032030	-0.33190	0.467679	0.7385

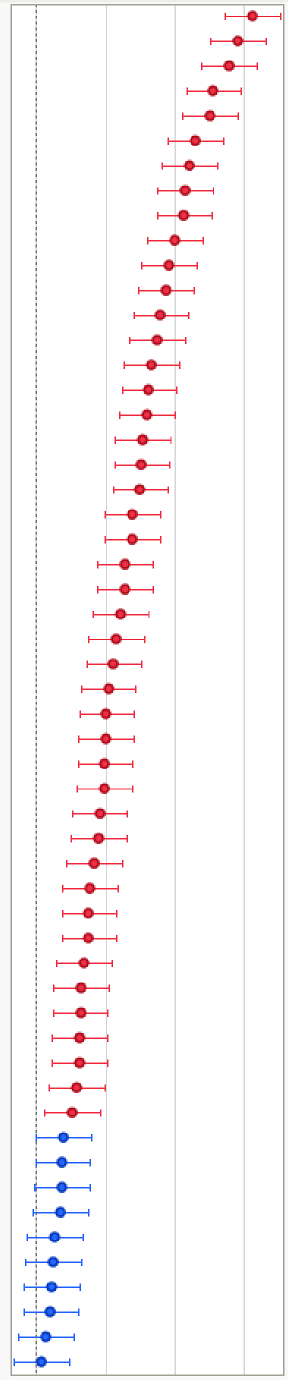

Figure 71. High growth: SpaceX compressed percentage difference

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
0.50	0.40	3.982265	0.1979419	3.59283	4.371702	<.0001*
0.49	0.40	3.930173	0.1979419	3.54074	4.319609	<.0001*
0.50	0.41	3.607012	0.1979419	3.21758	3.996448	<.0001*
0.49	0.41	3.554919	0.1979419	3.16548	3.944356	<.0001*
0.48	0.40	3.050671	0.1979419	2.66123	3.440108	<.0001*
0.50	0.43	2.887977	0.1979419	2.49854	3.277414	<.0001*
0.49	0.43	2.835885	0.1979419	2.44645	3.225321	<.0001*
0.50	0.42	2.828146	0.1979419	2.43871	3.217582	<.0001*
0.47	0.40	2.780992	0.1979419	2.39156	3.170429	<.0001*
0.49	0.42	2.776053	0.1979419	2.38662	3.165490	<.0001*
0.48	0.41	2.675418	0.1979419	2.28598	3.064854	<.0001*
0.50	0.44	2.426343	0.1979419	2.03691	2.815779	<.0001*
0.47	0.41	2.405739	0.1979419	2.01630	2.795175	<.0001*
0.49	0.44	2.374250	0.1979419	1.98481	2.763687	<.0001*
0.46	0.40	2.321149	0.1979419	1.93171	2.710586	<.0001*
0.45	0.40	2.067974	0.1979419	1.67854	2.457411	<.0001*
0.48	0.43	1.956383	0.1979419	1.56695	2.345820	<.0001*
0.46	0.41	1.945896	0.1979419	1.55646	2.335332	<.0001*
0.50	0.45	1.914291	0.1979419	1.52485	2.303728	<.0001*
0.48	0.42	1.896552	0.1979419	1.50712	2.285988	<.0001*
0.49	0.45	1.862198	0.1979419	1.47276	2.251635	<.0001*
0.45	0.41	1.692721	0.1979419	1.30328	2.082157	<.0001*
0.47	0.43	1.686705	0.1979419	1.29727	2.076141	<.0001*
0.50	0.46	1.661116	0.1979419	1.27168	2.050552	<.0001*
0.47	0.42	1.626873	0.1979419	1.23744	2.016310	<.0001*
0.49	0.46	1.609023	0.1979419	1.21959	1.998460	<.0001*
0.44	0.40	1.555923	0.1979419	1.16649	1.945359	<.0001*
0.48	0.44	1.494749	0.1979419	1.10531	1.884185	<.0001*
0.46	0.43	1.226862	0.1979419	0.83743	1.616298	<.0001*
0.47	0.44	1.225070	0.1979419	0.83563	1.614506	<.0001*
0.50	0.47	1.201273	0.1979419	0.81184	1.590709	<.0001*
0.44	0.41	1.180669	0.1979419	0.79123	1.570106	<.0001*
0.46	0.42	1.167030	0.1979419	0.77759	1.556467	<.0001*
0.42	0.40	1.154119	0.1979419	0.76468	1.543556	<.0001*
0.49	0.47	1.149180	0.1979419	0.75974	1.538617	<.0001*
0.43	0.40	1.094288	0.1979419	0.70485	1.483724	<.0001*
0.48	0.45	0.982697	0.1979419	0.59326	1.372133	<.0001*
0.45	0.43	0.973686	0.1979419	0.58425	1.363123	<.0001*
0.50	0.48	0.931594	0.1979419	0.54216	1.321031	<.0001*
0.45	0.42	0.913855	0.1979419	0.52442	1.303291	<.0001*
0.49	0.48	0.879502	0.1979419	0.49006	1.268938	<.0001*
0.42	0.41	0.778866	0.1979419	0.38943	1.168302	0.0001*
0.46	0.44	0.765227	0.1979419	0.37579	1.154663	0.0001*
0.48	0.46	0.729522	0.1979419	0.34009	1.118958	0.0003*
0.43	0.41	0.719034	0.1979419	0.32960	1.108471	0.0003*
0.47	0.45	0.713018	0.1979419	0.32358	1.102455	0.0004*
0.45	0.44	0.512052	0.1979419	0.12262	0.901488	0.0101*
0.44	0.43	0.461635	0.1979419	0.07220	0.851071	0.0203*
0.47	0.46	0.459843	0.1979419	0.07041	0.849280	0.0208*
0.44	0.42	0.401803	0.1979419	0.01237	0.791240	0.0432*
0.41	0.40	0.375254	0.1979419	-0.01418	0.764690	0.0589
0.48	0.47	0.269679	0.1979419	-0.11976	0.659115	0.1740
0.46	0.45	0.253175	0.1979419	-0.13626	0.642612	0.2018
0.42	0.43	0.059832	0.1979419	-0.32961	0.449268	0.7626
0.50	0.49	0.052093	0.1979419	-0.33734	0.441529	0.7926

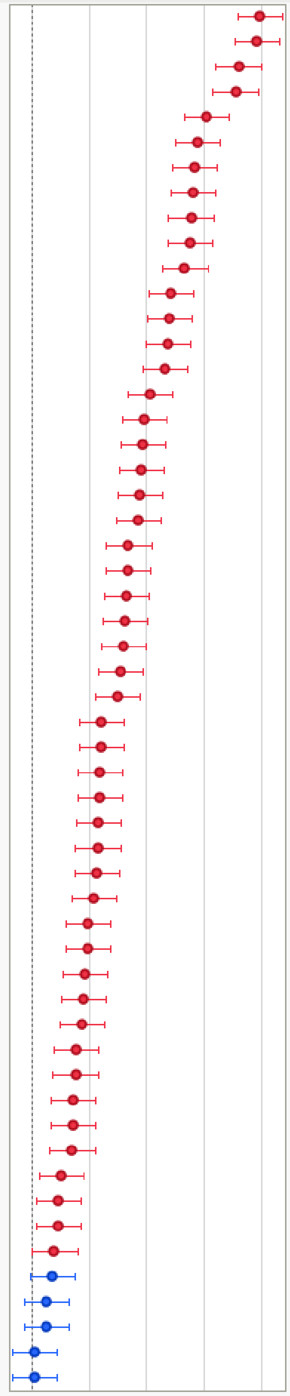

Figure 72. High growth: SpaceX non-compressed percentage difference

PEO IWS 3.0 vs. SpaceX Compressed

With high growth percentages of 40–50%, visual comparison of the two processes is shown in the figure.

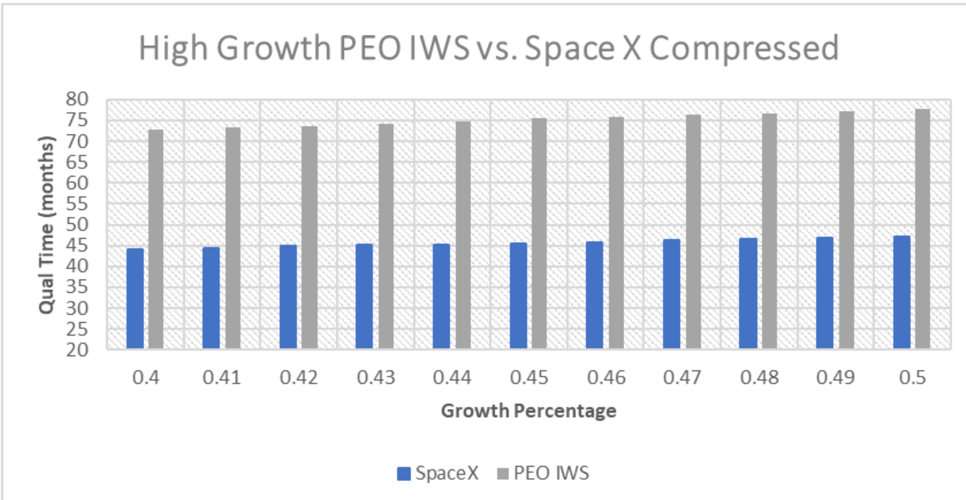

Figure 73. High growth: PEO IWS 3.0 vs. SpaceX compressed qualification duration

As expected, a large difference of 40% is noted between the two processes throughout the various percentages. It is important to highlight that SpaceX's highest percentage of 50% yields 47.2 months which is still 35% shorter than PEO IWS 3.0 smallest percentage of 40% which yields 72.7 months. It is no surprise that SpaceX compressed process is much more beneficial. The next analysis will be comparing PEO IWS 3.0 to SpaceX non-compressed.

PEO IWS 3.0 vs. SpaceX Non-Compressed

The figure provides visual comparison between the two processes, shows a significant difference between PEO IWS 3.0 and SpaceX non-compressed.

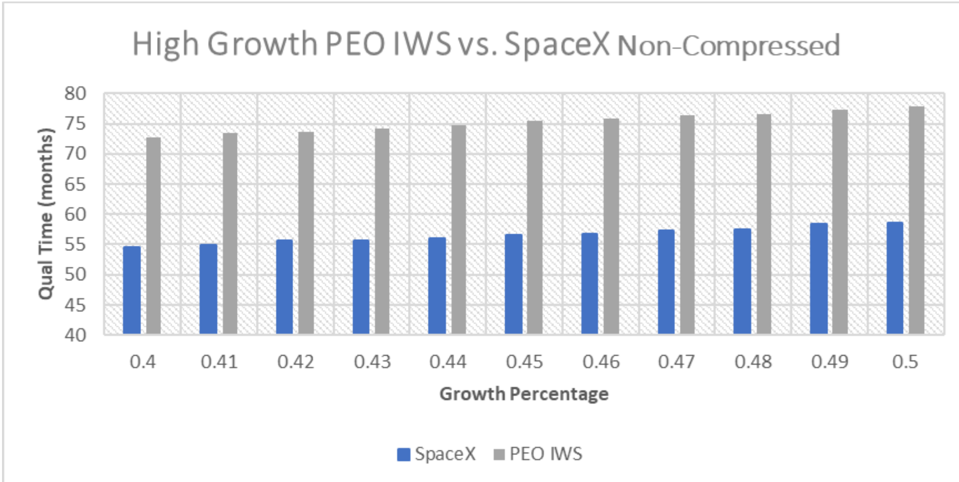

Figure 74. High growth: PEO IWS 3.0 vs. SpaceX non-compressed qualification duration

As expected, a 26% difference is noted between the two processes throughout the various percentages. Analyzing both processes, is important to note that SpaceX non-compressed with the highest percentage of 50% yields 58.5 months which is still 19.5% shorter than PEO IWS 3.0 smallest percentage of 40% which yields 72.7 months. Once again, it is noted that PEO IWS 3.0 process is severely lagging behind both SpaceX compressed and SpaceX non-compressed. The next analysis will be a comparison between SpaceX compressed and SpaceX non-compressed.

SpaceX Compressed vs. SpaceX Non-Compressed

The qualification duration between the two processes at various percentages is shown in the figure.

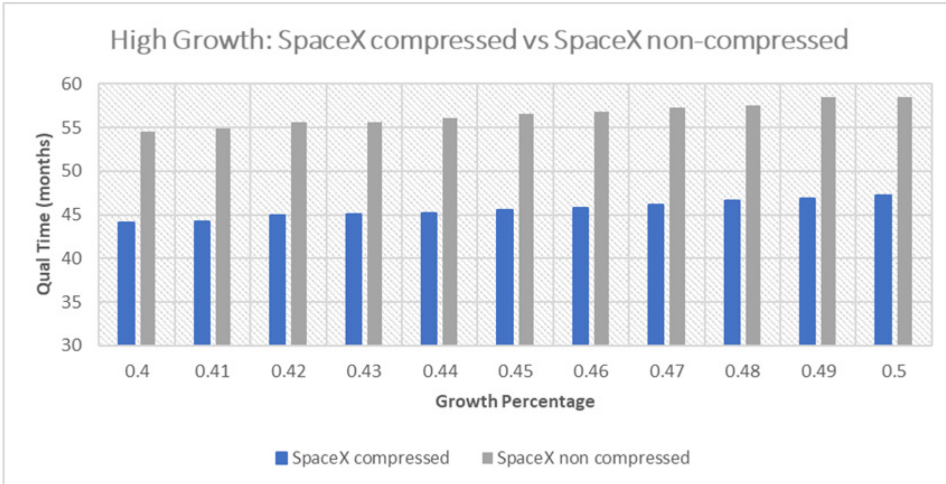

Figure 75. High growth: SpaceX compressed vs. non-compressed qualification duration

As expected, a 19% difference is noted between the two processes at the various percentages. Analyzing Figure 26, it is important to note that SpaceX compressed with the highest percentage of 50% yields 47.2 months which is still 13.4% shorter than SpaceX non-compressed smallest percentage of 40% which yields 54.5 months.

Paired Comparison for low and high growth scenarios are shown in the figure.

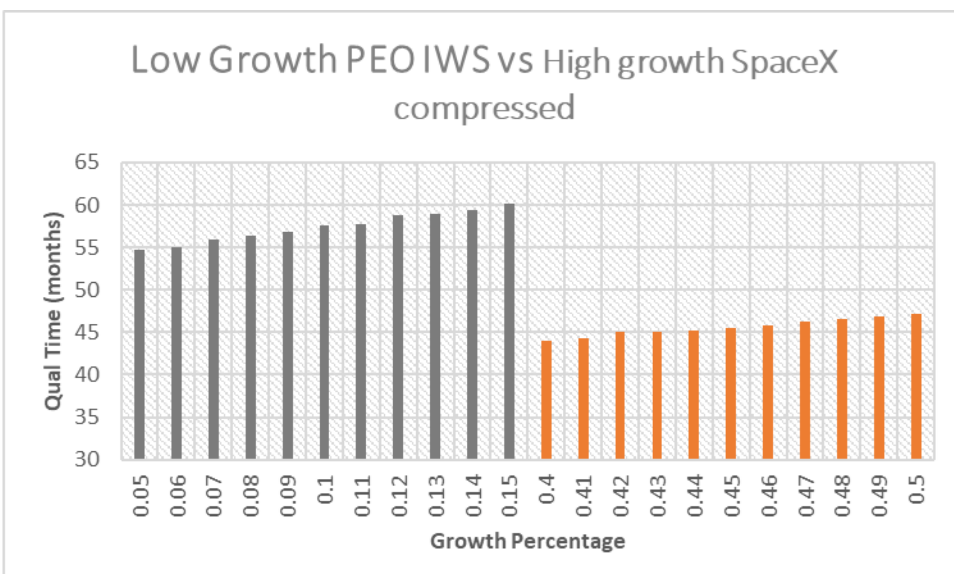

Figure 76. Low growth: PEO IWS 3.0 vs. high growth SpaceX compressed

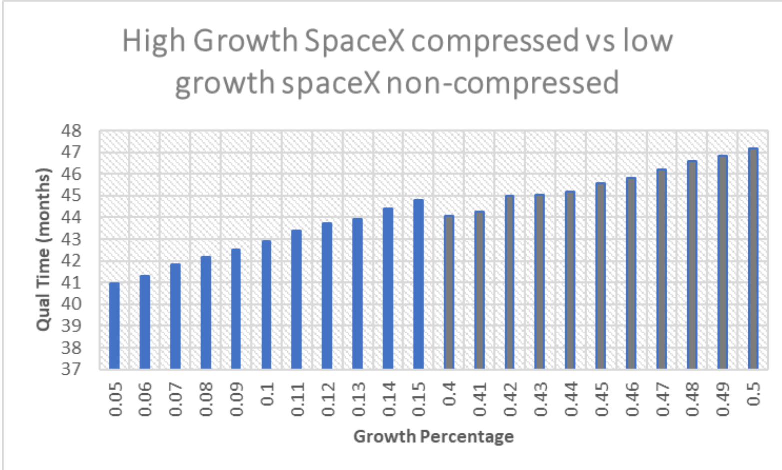

Figure 77. High growth: SpaceX compressed vs. SpaceX non-compressed

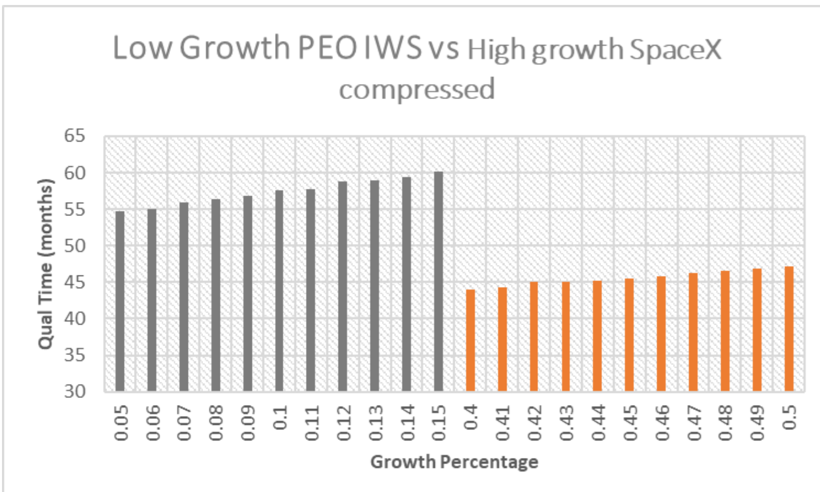

Figure 78. Low growth PEO IWS 3.0 high growth SpaceX compressed

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