Cost and Throughput Analysis for the NASA Ames Arc Jet Modernization Program

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Abstract

NASA Ames Center is currently evaluating alternatives to modernize the Arc Jet Complex, a critical part of testing for NASA's planetary missions. NASA's Arc Jet Complex facilities "are used to simulate the aerothermodynamic heating that a spacecraft endures throughout hypersonic atmospheric entry, and to test candidate thermal protection system (TPS) materials and systems." Because planetary mission schedules often have tight windows due to planetary alignment constraints, a small increase in schedule could result in a two-year delay. Such a delay could increase the cost of a $1 billion mission by hundreds of millions of dollars due to project personnel pay and clean room storage. To avoid these costs, the authors support NASA Ames in evaluating return on investment (ROI) and effectiveness of alternatives for modernizing the complex. The first input into the ROI is the deconstruction and construction cost estimates, which are developed using independent research on highly specialized subsystems, vendor quotes, and Unified Facilities Criteria (UFC), depending on the facility and work package. One of the measures of effectiveness is throughput analysis of the test bays, as a main goal of the modernization is to increase the number of possible test runs per year. This analysis is conducted via a probabilistic simulation and accounts for a variety of stochastic factors that influence the sequence of test runs, such as the facility availability; test complexity; the need to pause to assess test results; test failure; and the possibility of a system failure. The methodologies for both these analyses are discussed, along with the challenges presented due to the unique nature of the highly specialized test equipment.

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Introduction

Arc Jet Complex facilities are “used to simulate the aerothermodynamic heating that a spacecraft endures throughout hypersonic atmospheric entry, and to test candidate TPS materials and systems.” [1] These missions cost a billion dollars or more to develop, build, and launch. When these missions require heat shield testing, the only place they can go is the Arc Jet. Any significant downtime at a critical juncture will cause a schedule slip. Because their schedules often have tight windows due to planetary alignment constraints, a small increase in schedule could result in a two-year delay. Such a delay is quite costly, as it will require project personnel to be assigned to the project for a longer period and could involve expensive clean room storage. A two-year schedule slip for a $1 billion mission could increase the cost of the mission by $300 million or more. Thus, a short amount of Arc Jet downtime could potentially lead to a costly spacecraft delay. Planetary missions that require Arc Jet testing are in development every few years - the cumulative cost impact of these potential slips over two decades is thus large. Note that our estimate of this impact is on the low side as it does not include the impact on human launch system costs, which are even greater. Increasing the availability through modernization of the Arc Jet will help to avoid these costs, which the authors term mission cost avoidance. The impact on mission schedules is likely the largest driver of potential Arc Jet modernization savings to NASA.

Mission Cost Avoidance

Historically, projects of all types - software, dams, roads, bridges, Dept. of Defense weapon systems, and NASA spacecraft, etc. – regularly experience schedule delays. For NASA specifically, nine in ten spacecraft development projects experience schedule slips. The average slip for 98 historical missions is 38%. The impact of schedule delays on cost can be significant. Once a contract is signed, any change to schedule will increase cost, for the reasons mentioned in the preceding paragraph. A variety of studies quantifying the impact of schedule slips on cost have been conducted, and there is general agreement that for each percent increase in schedule, there is a 0.3-0.5% increase in cost, will longer delays have a bigger percentage impact. Thus, a 50% increase in schedule will likely increase cost by 20%, while a 100% increase in the length of a development schedule will increase cost by 50%. [2]

System failures typically follows a bathtub curve, depicted in Figure 1.

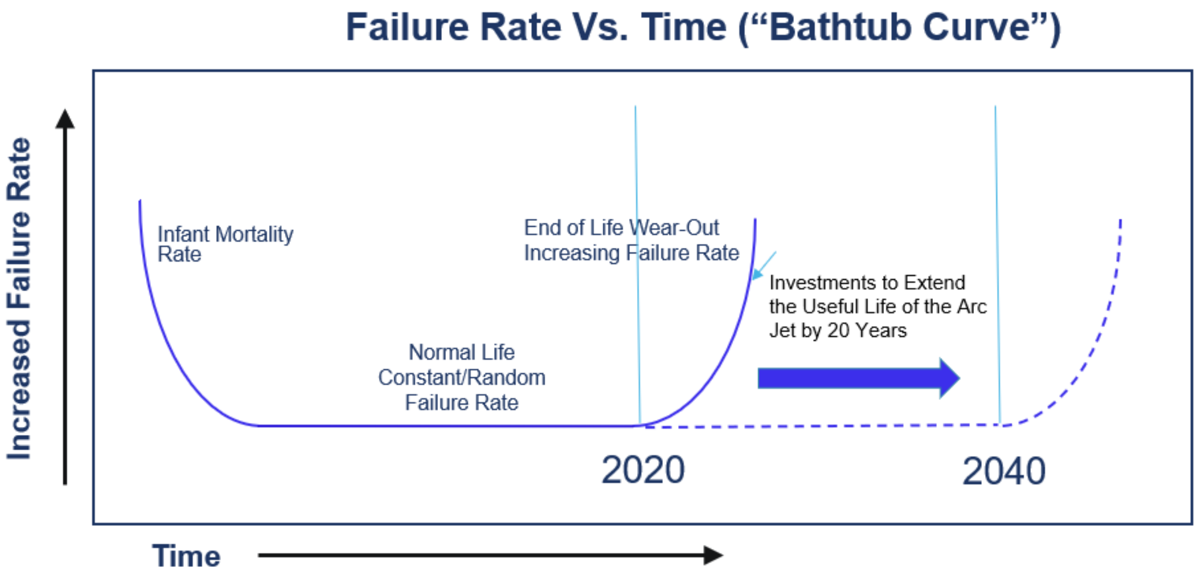


Figure 1: The Bathtub Curve

In the early stages, the higher failure rate is higher due to infant mortality. It then decreases to a steady state, and eventually increases again as wear out occurs. Based on recent experience, the Arc Jet is in the wear out phase, and unless significant investments are made to change this, systems failures will occur at an increasing rate due to a variety of well-documented risks. The downtimes caused by these system failures will lead directly to schedule slips for planetary spacecraft.

The analysis is intentionally not overly conservative so that the mission cost avoidance estimate is credible. The authors developed two cases studies and discuss each in turn. In the first case study, the authors assume that any Arc Jet down time will lead to mission schedule delays and that Arc Jet testing is on the critical path for the Mars Lander and Sample Return missions. The authors assume a relatively short increase in schedule duration, up to one year in length, and that the schedule slip does not impact the launch window. Using this and a schedule penalty model [2], the average impact of the 1,000 simulation trials is $400 million in mission cost avoided if down time can be eliminated through infrastructure investments, with more than 97% of the simulation trials that range from $300-$500 million.

The first case considers the schedule slips as continuous. However, the missions that require Arc Jet testing, such as those going to Mars, have tight launch windows. If this window is missed, the result is a two-year schedule delay. Not all missions that use heat shields will require Arc Jet testing, such as those that re-use vetted shields. The authors assume that for any mission in the 20-year period considered that there is a 50% chance that it will need Arc Jet testing. The average cost avoidance from this more realistic assumption is greater than $800 million. More than 98% of the trials result in at least $200 million in cost avoidance and 82% result in more than $500 million in cost avoidance. Even if 25% of the potential missions considered over the next 20 years require Arc Jet testing, the average cost avoidance is $500 million.

Arc Jet Modernization Objectives

NASA Ames is considering several objectives in modernizing the Arc Jet facilities. They include consolidated assets, smaller footprint, reduced operations and maintenance (O&M) costs, increased test throughput, and research and development (R&D) capability. These objectives are further complicated by the requirement to continuously operate during recapitalization to avoid negatively affecting NASA's planetary missions.

Arc Jet Complex Facilities

The Arc Jet Complex has seven available test bays located in two separate laboratory buildings, N-234 and N238. [3]

Building N-234

- Aerodynamic Heating Facility (AHF): The AHF is designed to simulate the "heating rates of Earth or planetary hypersonic entry to enable the selection, validation, and qualification of TPS and materials." It is connected to a 20MW Power Supply and comprised of three heaters: AHF Constricted, AHF Huels, and TP3. [4]
- Turbulent Flow Duct (TFD): The TFD "provides supersonic turbulent flow over flat surfaces." The TFD has a unique 2x9 nozzle that allows for turbulent flow testing. It is also connected to a 20MW Power Supply. [5]

Building N-238

- Interaction Heating Facility (IHF): The IHF tests the thermal impact resultant from "the interaction of an energetic flow field during a hypersonic entry into a planetary atmosphere." The IHF is connected to a 60MW Power Supply. It has the highest traffic due to the high flow rates / enthalpy that it provides. [6]
- Panel Test Facility (PTF): The PTF tests "spacecraft heat shield material samples in a high enthalpy, high shear boundary layer flow field." The PTF provides panel testing capabilities that can be recreated by the AHF or IHF with semi-elliptical nozzles. It is also connected to a 20MW Power Supply. [7]

These facilities are serviced by common support equipment, which includes two direct current power supplies, a steam ejector vacuum system, a de-ionized (DI) water-cooling system, high pressure gas systems, and controls. The magnitude and capacity of these support systems is a primary reason why the Ames Arc Jet Complex is unique in the aerospace testing. [8]

Steam Vacuum System

The Steam Vacuum System (SVS) is a high-volume, 5-stage steam ejector vacuum-pumping system that in combination with the power supply enables the facility to match high-altitude atmospheric flight conditions with test articles of relatively large size. It is a 300 ft long, and at its widest point, 100 ft wide, network of various-sized ducting that withstands enormous pressure to create these conditions.

<u>De-ionized Cooling Water System</u>

The Arc Jet facilities utilize a closed-loop deionized water system for cooling of the arc jets, test article supports, nozzles, and other facility hardware. Deionized water is required because of the need to have very low electrical conductivity for cooling the arc jets. The deionized water system is located at ground level within the footprint of the SVS and much of the deionized water supply and return piping is in the basements of Buildings N-234 and N-238.
Within these facilities are abandoned structures (e.g., supporting I-beams and pipes) that further complicate the modernization efforts of interdisciplinary facilities. This is one of the major cost drivers in the investment and throughput analysis of each alternative, discussed further in the following sections.

Investment Cost Estimate Methodology

The aforementioned facilities and support systems are represented in the cost estimate by work packages, which are in varying stages of maturity in both requirements definition and cost management. The authors constructed a standard work breakdown structure (WBS) to structure the work packages for traceability. In general, the Arc Jet Modernization (AJM) project is considered to be at the concept phase, and the cost estimate is a rough order of magnitude (ROM). As there is currently no NASA guidance specific to facility cost estimating, the authors used the methodology recommended by the UFC. [9]

Primary Estimating Methodology

UFC is prescribed by Military Standard 3007 and provides guidance to Military Departments, the Defense Agencies, and the DoD Field Activities for cost estimating military construction projects. It also publishes guidance unit costs (GUCs), which are built up using data from Marshall and Swift, RS Means, and PAX River Newsletters. The authors used one cost database subscription - RS Means. The authors also used the open-source PAX River Newsletters for unit costs in the Arc Jet Modernization ROM. These sources recommend applying contingencies, accommodations, and area cost factors to the unit costs, and because the UFC uses both PAX River Newsletter and RS Means as sources, the UFC methodology was considered appropriate and applied. The UFC recommends the application of the following:

- Area Cost Factor (ACF): The ACF evaluates a market basket of labor, material, and equipment (LME) and normalizes it Then, the LME is modified by 7 Matrix factors that “include weather, seismic, climatic (frost zone, wind load), labor availability, contractor overhead and profit, logistics and mobilization, and local labor productivity versus the United States (US) standard.” [10]
  - Value for AJM: 1.20 (Monterey, CA)
- Historical Factor (HF): This factor accounts for “increased costs for replacement of historical facilities or for construction in a historic district.” [11]
  - This factor is currently not applied in the AJM Cost Model but will be in updates.

- Design Contingency (DC): DC allowance may be included based on the lack of maturity of design data and technical complexity. Its intent "is to cover component items that cannot be analyzed or evaluated at the time the facility cost estimate is prepared; however, such items are susceptible to cost evaluation as engineering and design progresses." This factor is applied on a case-by-case basis using the information in Table 1. [11]

Technical Complexity	Description	Project Maturity	
		Pre-Concept	Concept
LOW	Site adapted, repetitive standard design project involving routine technology	5%	2.5%
MEDIUM	Unique design involving complex technology	10%	5%
HIGH	Unique design involving highly complex technology	15%	10%
ULTRA-HIGH	Unique design involving extremely complex or innovative technology	25%	15%

Table 1: Design Contingencies

- Construction Contingency: This is intended to cover construction requirements that cannot be foreseen before the contract is awarded. This may include issues such as "unforeseeable foundation conditions or encountering utility lines in unforeseeable locations." It is an allowance for work items for which quality or quantity has not yet been determined by specific design. [11]
  - Value for AJM: 1.05 (Default recommendation by UFC)
- Planning and Design: The default value is 1.09 for all facilities that are not medical, and accounts for the "planning and design of a facility" [11]
  - Value for AJM: 1.09
- Supervision, Inspection, and Overhead: Factor to account for the supervision, inspection, and overhead activities associated with the management of a construction project. The current value of the factor is 1.057 for facilities in the continental US (CONUS). [11]
  - Value for AJM: 1.057

In addition to the contingencies above, the authors also applied several factors appropriate for this project. These include:

- Labor Productivity Adjustment: This factor was initiated by the UFC 3-701-01 with Change 2, and accounts for the loss of productivity caused by congested work area. The default recommendation is 3 hours of non-productivity per week. The adjustment factor is found by the following equation:

$$Unproductive\ Hours\ per\ Week\ \div Productivity\ at\ 100\%\ \times Labor\ Cost\ \%\ of\ Total \div Project\ Cost$$

$(3 \div 37) \times (35\% \div 100\%) = 0.028$ [12]

- Additionally, RSMeans data from Gordian shows that infectious disease/COVID precautions can reduce the amount of available work time by up to 10%, thereby increasing labor costs on job sites, especially those with restrictive COVID requirements. Construction work tasks that are associated with high exposure risk levels and publicly funded construction projects will require the most COVID precautions.
- Using the above equation, the updated adjustment factor for the AJM project is 0.074

- Seismic Activity: The ACF for building near Monterey, California already incorporates the requirements reflected in the California Building Code, which is a minimal standard intended to protect life. However, the building code has not been updated in almost 30 years, and NASA Ames engineers were adamant that the structures would not only need to be brought up to code, but that a seismic analysis and additional work for earthquake-resistant construction. To capture this additional work, the authors conducted independent research to find a Cost Analysis and Benefit Study for Earthquake-Resistant Construction of an analogous region according to the U.S. Geographical Survey. This study recommended a 19.6% increase in costs for structural components. [13] The authors apply this factor accordingly in the AJM Cost Model.
- NASA Overhead: NASA Ames provided their overhead rate at 21%. This is applied to every work package to account for the NASA Ames labor in overseeing and executing the AJM project. With this final adjustment, the AJM Cost Estimate provides a total ownership cost (TOC) to decision makers.

Adjusted Methodology for Specialized Subsystems

Analogy

NASA Facilities data does exist but is spread across the agency in various places and is often discarded when someone retires or leaves the agency. [9] The authors observed this in every AJM facility, from outdated drawings to a limited understanding of operations and maintenance spending in each facility. However, historical costs and vendor quotes were available from previous upgrade efforts. These were used for especially complex and specialized subsystems, like the IHF Anode Module components.

Vendor Quotes

Vendor Quotes were particularly useful for estimating alternative modernization solutions for Arc Jet work packages, but extremely difficult to come by as the vendors needed defined requirements to give quotes. The authors received vendor quotes through official Requests for

Information (RFIs) to NASA Ames as well as through company and subcontracting relationships. The authors observed that the vendor quotes received had very short time periods for validity, some as short as one week when the quote included steel work. In a single instance, a vendor quote came in for components that were also found in RS Means and independently estimated in the AJM Cost Model. While low estimates had been noted by several subject matter experts (SMEs) throughout the model, this quote showed that the RS Means unit costs were off by a factor 2.5.

Engineering Build-Ups

At discovering this issue, the authors reviewed work packages that relied heavily on RS Means, which was the SVS. The SVS consists of varying diameters of thick steel ducting welded together with flanges and/or stiffening rings and held above ground by structural concrete supports. To operate and maintain the SVS, there is a network of steel walkways, ladders, and entry points, where engineers can access the ducting and, in some areas, walk through it. While the SVS has been consistently maintained, it exhibits rust throughout, in some localized areas worse than others. The maintenance over the years has also included ad hoc upgrades that required their own supports, often connected to other ducting or the structural supports. The result is an enormous, customized structure nestled in a complex web of steel nearly impossible to navigate. The authors worked closely with engineers to develop an informal statement of work (SOW) to upgrade certain portions of the SVS, and mapped hardware and labor descriptions to RS Means line items. The steam ducting listed in RS Means included labor, but the magnitude was not representative of the requirements of the SVS. The authors added additional labor for positioning of the ducting and setting up the site. The authors worked with engineers to determine equipment and additional labor hours for these categories, and the estimate was still considered low in comparison to other estimates. Then, the authors received the vendor quote that showed the large discrepancy between RS Means components and Arc Jet's. Because the vendor quote was analogous to the ducting in that it was large steel piping, the authors applied the complexity factor to the RS Means ducting costs. This methodology moved the estimate into the appropriate ROM based on several independent SMEs.

Parametric

The authors developed many Cost Estimating Relationships (CERs) based on RS Means components to predict the costs for the, usually, much larger components in the Arc Jet Complex. These were primarily linear relationships, with very high R^2, as expected given RS Means uses similar relationships. This was very useful in piping, as vendor quotes were not received for many months after initial estimates were due. Additionally, RS Means did have the required material and schedule piping for estimation.

While water tanks are available in RS Means and PAX River, the size of the tank was not representative of the requirements. The authors applied a size adjustment factor to account for this delta, but also used a proprietary tool called SEER-Manufacturing (MFG) to develop the DI Water tank cost estimate. SEER-MFG uses a comprehensive set of process models ranging from machining, assembly, composites, additive manufacturing, sheet metal, etc. and leverages industry metrics and formulaic cost relationships. This was used until a reliable vendor quote could be obtained.

Cost-Benefit Analysis

How NASA spends the budget for the AJM project will have a significant impact on the effectiveness of the money, especially with inflation at its highest in 30 years in the US. However, the AJM Cost Model has not yet advanced to a full life-cycle cost estimate (LCCE), as the operations and support (O&S) costs are not yet understood on a work package level. Thus, presenting ROI metrics is not yet possible. To inform the decision makers, The authors researched published cost saving percentages of certain materials, labor reduction, and initiated independent estimates of the status quo. The latter methodology is dependent on the stability of the alternative solutions.

To demonstrate how the ROI would look to the decision maker, the authors developed an outlay based on the Saturn phasing and percent of total cost each year represented within each WBS. To present real year (RY) (also known as then year (TY)) costs, the phased constant year (CY) costs are escalated using the NASA new start inflation (NNSI) inflation indices. Again, this was done for demonstration purposes only, as using the NNSI across the WBSs is inconsistent with the CY calculation (discussed further in the following section).

These RY costs are then discounted using the factors published in the Office of Management and Budget (OMB) Circular A-94 to reach a net present value (NPV) by WBS. Again, because cost savings have not yet been identified, the NPV calculation is for demonstration purposes only.

Escalation

NNSI indices are low compared to observed inflation in the construction industry, especially since 2019. While the NNSI is arguably applicable to some subsystems, like the arc heaters themselves, most of the facility upgrade costs primarily use the construction cost index (CCI). The CCI is intended for use in renovations and remodeling projects. It “contains 200 hours of common labor at the 20-city average of common labor rates, plus 25 hundred weight (cwt) of standard structural-steel shapes at the mill price prior to 1996, and the fabricated 20-city price from 1996, plus 1.128 tons of portland cement at the 20-city price, plus 1,088 board-ft of 2 by 4 lumber at the 20-city price.” The CCI contains 79% common labor, 11% Steel, 9% Lumber, and 1% Cement. [14]

The building cost index (BCI) is also available, used only for an alternative for a newly constructed building that would consolidate all test bays. The BCI is intended for use in new construction projects and “contains 66.38 hours of skilled labor at the 20-city average of bricklayers’, carpenters’, and structural ironworkers’ rates, plus 25 cwt of standard structural-steel shapes at the mill price prior to 1996, and the fabricated 20-city price from 1996, plus 1.128 tons of portland cement at the 20-city price, plus 1,088 board-ft of 2 by 4 lumber at the 20-city price.” The BCI contains 63 % Skilled labor, 20% Steel, 15% Lumber, 2% Cement. [14]

Where appropriate, unit costs are escalated using the specific Steel, Lumber, and Concrete rates also published by the Engineering News Record (ENR), meaning that there are six inflation indices that are available for use in the AJM Cost Model. The authors have identified inflation indices as one area of sensitivity analysis that should be conducted as the cost estimate matures from a ROM to a full LCCE.

Schedule Analysis

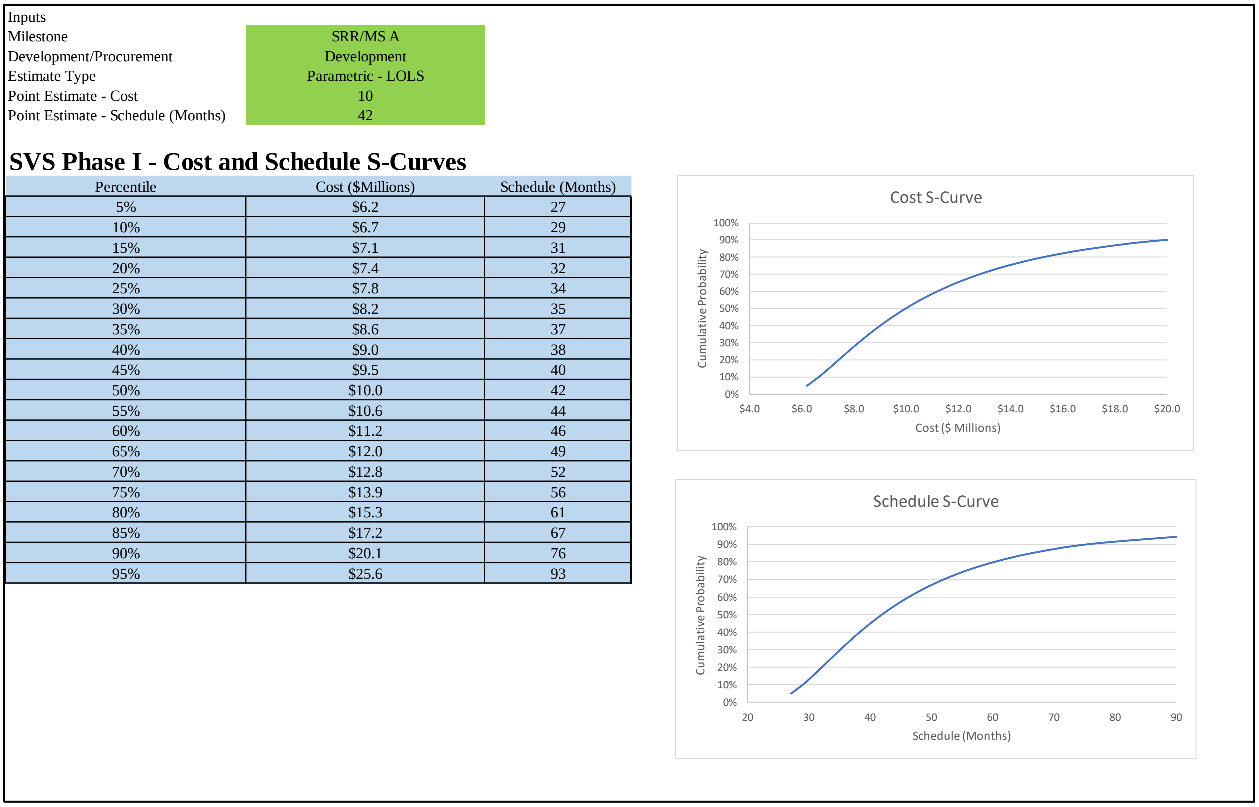
The authors developed schedules for each phase based on the Saturn S-IC Static Test Facility data. Each phase is a period of deconstruction and construction to incrementally build-up the new facility. The effectiveness of the ROM spending profile is currently not required but has been set-up to analyze it at a high level. The source data broke data out into the following categories:

- Design
- Bid and Award
- Design and Procurement
- Construction
- Installation and Checkout

The time between that start of Design and the end of Design and Procurement was categorized and Deconstruction and the Design portion of Deconstructions. The time between the start of Construction and the end of Installation and Checkout was categorized as Construction. Each AJM Phase used these Saturn S-IC durations to develop the spending profile of the project. Then, the authors used schedule estimating relationships (SERs) based on 554 NASA projects collected by Kennedy Space Center to confirm the reasonableness of the developed schedule.

Risk and Uncertainty Analysis

The authors used a risk calibration method developed by one of the authors [2] to determine the reasonableness of the schedule and the likelihood of achieving it. Risk ranges for the development cost and schedule were conducted for each option using the Systematic Measurement and Analysis of Risk Tool (SMART). This tool uses historical cost growth and schedule delay data to establish realistic, credible risk ranges. It accounts for the heavy right tail of project risk and the skew by modeling cost risk as a lognormal distribution. Inputs include the phase of the project; the type of project (development/production); the estimating methodology used; and the point estimates for cost and schedule. The earlier the phase of the project, the greater the inherent uncertainty and the tool accounts for this. For NASA projects, these phases are delineated by milestones known, respectively, as system readiness review (SRR), preliminary design review (PDR), and critical design review (CDR). For Department of Defense missions, these milestones are often referred to simply as A, B, and C. Projects in development are typically riskier than those in production, so this is also accounted for. The type of estimate has a significant influence on the location of the point estimate on a cost risk cumulative distribution function (aka “S-curve”). Engineering build-up estimates historically are often at the 10-20th percentile, meaning there is an 80% chance or greater of an overrun. Analogy estimates are considered to be the most likely value, that is the mode. Parametric nonlinear analyses that are based on log-linear regression applied at the system level are at the 50th percentile. Other parametric techniques that are unbiased or that use linear regression are at the mean. A notional example of the results of the tool is displayed in Figure 2.



Inputs	
Milestone	SRR/MS A
Development/Procurement	Development
Estimate Type	Parametric - LOLS
Point Estimate - Cost	10
Point Estimate - Schedule (Months)	42

SVS Phase I - Cost and Schedule S-Curves

Percentile	Cost ($Millions)	Schedule (Months)
5%	$6.2	27
10%	$6.7	29
15%	$7.1	31
20%	$7.4	32
25%	$7.8	34
30%	$8.2	35
35%	$8.6	37
40%	$9.0	38
45%	$9.5	40
50%	$10.0	42
55%	$10.6	44
60%	$11.2	46
65%	$12.0	49
70%	$12.8	52
75%	$13.9	56
80%	$15.3	61
85%	$17.2	67
90%	$20.1	76
95%	$25.6	93

Figure 2: Example Risk Analysis Output from SMART

Throughput Analysis

An important metric in a test facility is amount of testing that can be conducted in a year. The authors use the term run to indicate a single test of interest. The authors assess the number of test runs that can be conducted during a calendar year as the facility's throughput. The Arc Jet's first few modernization phases will aim to keep throughput at status quo, while the final phases will aim to increase throughput. In this analysis the authors use only notional values. The testing facility considered in the analysis currently consists of four distinct facilities. Potential improvements for the facilities include a variety of different options. The one the authors focus on involves consolidating the number of individual facilities from four to three.

For the Arc Jet facility, there are a variety of customers, including, among others, planetary spacecraft missions, crewed spacecraft missions, and hypersonics weapons. The number of customers varies over time and the schedule is not deterministic. Rather, they are stochastic in nature. Each customer has its own set of specific test objectives, which determine the number of test runs for a customer. Thus, the number of runs per customers is also stochastic.

For each customer, the type of testing that is required can be classified as simple or complex. Complex testing is slower. With simple testing up to five runs can be conducted in a day versus three for complex testing. Another issue is that a facility may not be available on any given day due to needed repairs. Some tests may require a configuration set up day if a specific piece of equipment needs to be used in the testing. Also, some customers may require a set up day before testing can begin. All these are modeled as stochastic variables.

For the analysis, the authors assume that the testing is conducted during the work week. Accounting for 10 government holidays, there are 250 working days in a year.

To conduct the analysis, the authors performed a 1,000 trial Monte Carlo simulation, which we coded in the R statistical programming language. The process flow is illustrated in Figure 3.

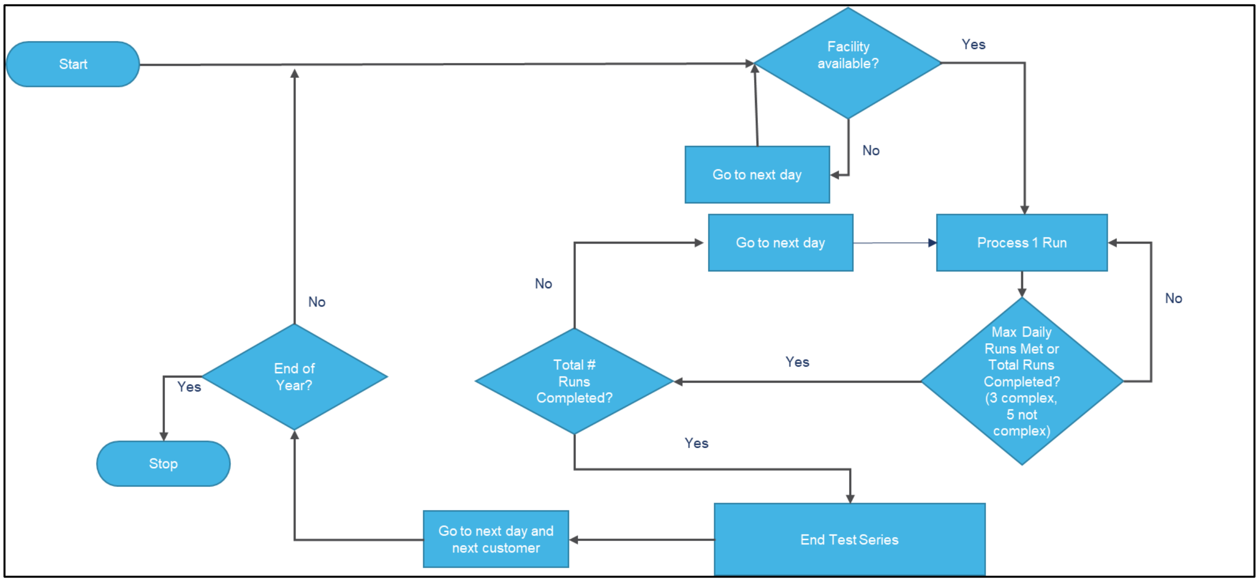


Figure 3: Throughput Analysis Process

For each simulation, the authors calculate the number of test runs conducted per year. The facilities can run in parallel, so the process flow is for each individual facility. The authors first check to see if the facility is available. The status quo is 20% for facility 1, 20% for facility 2, 30% for facility 3, and 40% for facility 4. If the facility is available, a run is processed. For each customer, there is a certain number of runs required. If the testing is complex, up to 3 test runs can be conducted in one day, otherwise 5 can be conducted in one day. The testing continues until the total number of runs required is completed. As the number of test runs varies uniformly from 4 to 12, this could take a few days to complete. The number of customers per year varies uniformly from 50 to 100. The demand for each facility varies significantly. Some facilities are used more often than others. The probability that a customer wants to use facility 1 is 65%; the probability they want to use facility 2 is 15%; the probability they want to use facility 3 is 15%, and the probability that they want to use facility 4 is only 5%. This testing continues for each facility until the number of working days in a year has elapsed.

For the legacy system, the mean number of test runs conducted in a year is 483. A histogram of the various simulation outcomes is displayed in Figure 4.

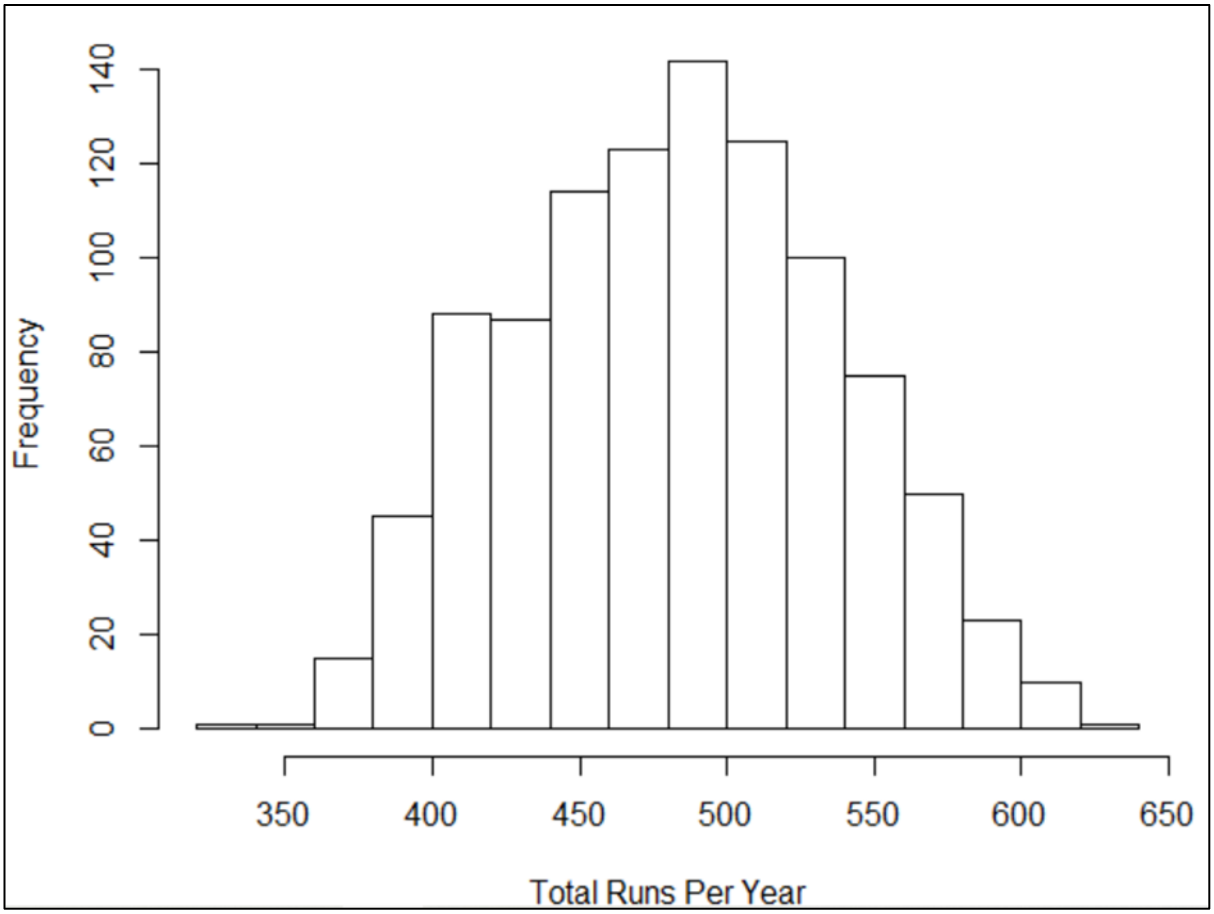


Figure 4: Legacy Arc Jet Complex Test Run Outcomes

Consolidation of three facilities improves availability and shuts down the least-used facility. The availability due to the investments is 80% for each of facility 1 and facility 2, and 60% for facility 3. Based on experience and engineering judgment, the demand for facility 1 is estimated to be 60%; the demand for facility 2 is estimated to be 30%; and the demand for facility 3 is estimated to be 10%. In this case, even though there is one fewer facility, the mean number of runs is increased to 514, with a histogram displayed in Figure 5.

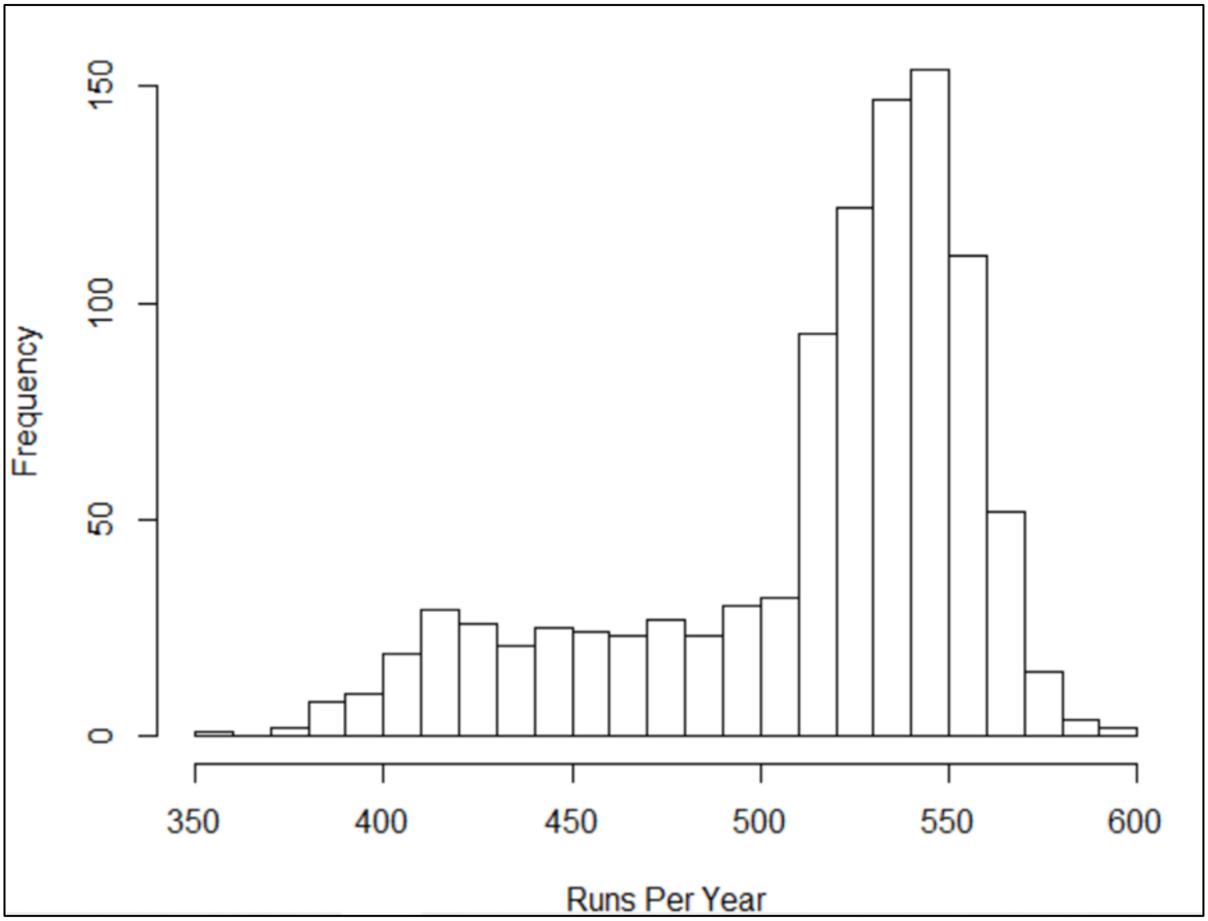


Figure 5: Consolidated Alternative Test Run Simulations

Note that the consolidated case is more skewed than the legacy case. This is due to having three facilities instead of four.

Conclusion

The authors demonstrated the criticality of modernizing the Arc Jet Complex by analyzing the mission costs avoided. Then, they assisted in evaluating the modernization alternatives by capturing investment costs of each work package and the effect on throughput. Capturing the investment costs required a variety of methodologies and sources, as well as risk and uncertainty analysis for reasonableness. As the requirements mature, the cost estimate will capture O&M costs and savings to allow for NPV and ROI metrics for decision-makers. Additionally, the authors will investigate acquisition alternatives such as choosing sustainable design over lowest cost, using existing NASA infrastructure, as well as operations and disposal, as recommended by the NASA Business Case Guide for Facilities Projects. The improvements in testing throughput due to the alternative investments will continue to be updated and presented as a metric of alternative effectiveness.

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