



Exploring PERFORMANCE IN AIR FORCE SCIENCE and Technology Programs



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Science and technology (S&T) programs serve an important function in the defense acquisition process as the initial phase leading to discovery and development of warfighting technology. The results of these programs impact the larger major defense acquisition programs, which integrate the technologies in subsequent phases of the life cycle. Despite this important role, little prior research has examined the performance of S&T programs. In this study, the authors investigate the impact of technological maturation as a critical success factor in Air Force S&T programs. The results suggest that S&T programs with mature technologies are more likely to experience above average cost growth and larger contract values while less likely to experience schedule growth. Additionally, the authors find the partnership method between the government and contractor matters for both technological maturation and schedule growth. Lastly, the nature of the S&T program is important, with aerospace programs more likely to technologically mature than human systems programs.

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Program management focuses on cost, schedule, and performance as the three key measures of success (Meridith & Mantel, 2003; Pinto & Slevin, 1998). A large body of literature identifies critical factors that lead to program success in both private industry (Nasir & Sahibuddin, 2011; Pinto & Slevin, 1987; Zwikael & Globerson, 2006) and the public sector (Rendon, 2012; Rodriguez-Segura et al., 2016; Tishler et al., 1996). Prior analyses of program performance in defense programs, however, have focused almost exclusively on larger, more mature programs that have reached the Engineering and Manufacturing Development (EMD) phase of the life cycle or beyond. An abundance of studies exploring cost growth or schedule growth can be found for these major defense acquisition programs (MDAPs) (Bolten et al., 2008; Cancian, 2010; Smirnoff & Hicks, 2008). Missing from the literature is an exploration of smaller programs that feed basic science and technologies to subsequent acquisition programs or that develop new systems and technologies on a smaller scale. These are the science and technology (S&T) programs that are undertaken in defense research labs. This article seeks to bridge that gap through an exploratory analysis of program performance in Air Force S&T programs.

To the best of our knowledge, this study is the first to systematically analyze Air Force S&T program performance. While the contributions are novel, they are not intended to be the final word on the subject. Rather, this article seeks to ignite the spark that spawns the intellectual curiosity and research of others in S&T programs. Thus, the purpose of this article is to identify initial insights regarding relationships that may impact cost, schedule, and performance in S&T programs. By lighting the fire, we are optimistic that the findings articulated here will be further explored so that future S&T program decisions can be fully informed.

Importance of Science and Technology

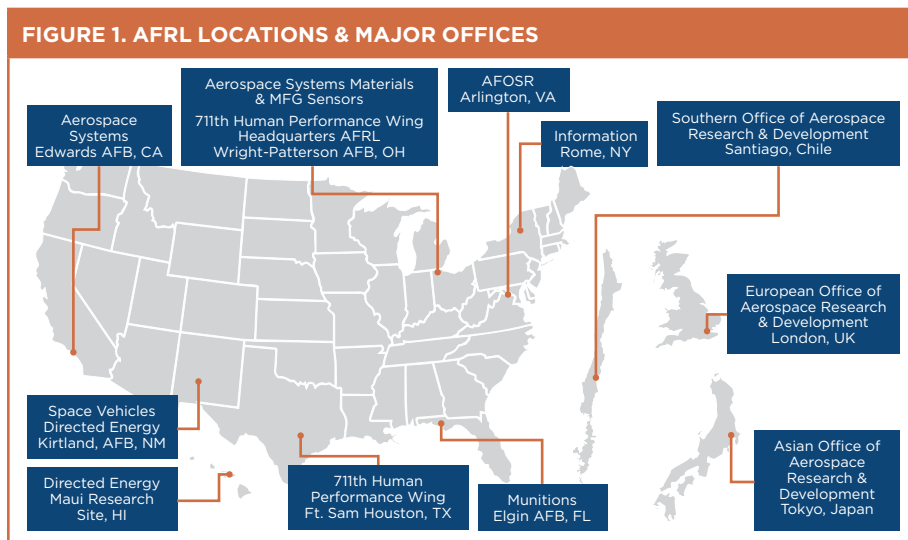
The vision to implement S&T as a centerpiece of our nation's airpower strategy has been around since 1945 (Duffner, 2000). General H. H. "Hap" Arnold, Commanding General of the Army Air Forces, enlisted the aid of top aeronautics scientist Dr. Theodore von Karman to lead the first of these efforts, recommending the creation of an agency devoted exclusively to aeronautical research and development (Gorn, 1988). Over time, that agency has evolved to what is known today as the Air Force Research Laboratory (AFRL) (Duffner, 2000).

S&T's enduring importance is demonstrated in the 2019 publication of the *U.S. Air Force 2030 Science and Technology Strategy*. The 2030 S&T strategy aligns with the National Defense Strategy to empower S&T programs to

develop and deliver warfighting capabilities rapidly and effectively (United States Air Force, 2019). How does S&T fulfill this need? S&T functions as the initial phase of the acquisition process by which technologies are matured and, where appropriate, are transitioned for acquisition by the Air Force (Office of the Chief Scientist of the U.S. Air Force, 2010). Continual advancement in these cutting-edge technologies is crucial, as the Air Force faces ever-changing threats and adversarial advancements in technology.

The Anatomy of Air Force Research Labs

The S&T data analyzed in this article are from AFRL programs. A brief organizational description is provided for those unfamiliar with the laboratory. AFRL is headquartered at Wright-Patterson Air Force Base (AFB) in Ohio. It comprises nine technology directorates in the continental United States and four locations overseas in Hawaii, United Kingdom, Chile, and Japan, as shown in Figure 1.



Note. AFOSR = Air Force Office of Scientific Research; AFRL = Air Force Research Laboratory; MFG = Manufacturing.

TABLE 1. AFRL TECHNOLOGY DIRECTORATES

Technology Directorate	Symbol	Program Descriptions
Air Force Office of Scientific Research	AFOSR	Basic Research Manager for AFRL
711th Human Performance Wing	RH	Aerospace Medicine S&T, Human Systems Integration
Directed Energy Directorate	RD	Laser, Electromagnetics, Electro-Optics

TABLE 1. AFRL TECHNOLOGY DIRECTORATES (CONTINUED)

Technology Directorate	Symbol	Program Descriptions
Information Directorate	RI	Information Fusion, Exploitation, Networking
Aerospace Systems Directorate	RQ	Aerodynamics, Flight Control, Engines, Propulsion
Space Vehicle Directorate	RV	Space-Based Surveillance, Capability Protection
Munitions Directorate	RW	Air-Launched Munitions
Materials & Manufacturing Directorate	RX	Aircraft, Spacecraft, Missiles, Rockets
Sensors Directorate	RY	Sensors for Reconnaissance, Surveillance

Each technology directorate focuses on the development and innovation of leading-edge technologies and is separated by technological capabilities. A list of AFRL's technology directorates, their office symbols, and program descriptions appears in Table 1. The analysis of individual technical directorates will be one of the ways this research segments the data.

Measures of Success: The Role of Technology Readiness Levels

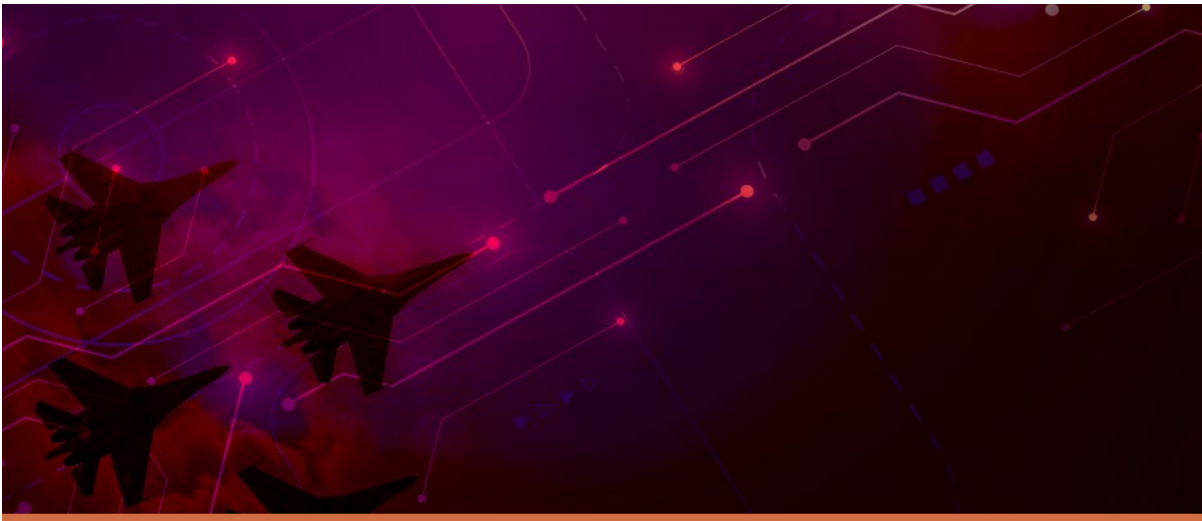
The General Accounting Office (GAO) has identified technology maturation as a critical success factor in product development (GAO, 1999). The DoD's approach to incorporate this critical success factor has been to emphasize Technology Readiness Levels (TRLs) as a measure for selecting mature technologies for inclusion in a program (Department of Defense [DoD], 2011). The TRL concept was developed by NASA (Sadin et al., 1989) and has subsequently been adopted by AFRL. A TRL is a tool to measure the technology maturity of a system or subsystem using a 9-level ordinal scale (DoD, 2011). Detailed TRL definitions and descriptions can be found in Appendix A.

It is believed that "programs that enter the Engineering and Manufacturing Development (EMD) phase of the Defense Acquisition System and have immature technologies will incur cost growth and schedule slippage" (DoD, 2009). To reduce the risk associated with entering the EMD phase of the acquisition life cycle at Milestone B, DoD Instruction 5000.02 requires technologies to be demonstrated in a relevant environment and obtain a TRL of at least 6 (DoD, 2011). AFRL, through the S&T programs they oversee, plays a key role in the creation and maturation of these technologies to reach those thresholds.

Despite TRLs being identified as a critical success factor, the literature has few empirical examinations. The dearth of analysis is particularly acute for S&T-type programs, but even MDAPs have relatively few studies examining TRLs. Dubos et al. (2008) analyzed the relationship between technology uncertainty and schedule slippage in the space industry. Their research resulted in the creation of TRL-schedule-risk curves that are intended to assist program managers in making informed decisions regarding the appropriate TRL to consider when confronted with schedule constraints. The findings suggested a close relationship between technology uncertainty and schedule risk where the more mature a technology is (the higher the TRL), the less potential schedule slippage.

“ The findings suggested a close relationship between technology uncertainty and schedule risk where the more mature a technology is (the higher the TRL), the less potential schedule slippage. ”

Katz et al. (2015) specifically studied the relationship of TRLs to cost and schedule changes during the EMD phase. They found that weapon systems that achieved a TRL of 7 or greater at Milestone B had a lower probability of schedule slippage during the EMD phase than weapons systems that had a TRL of less than 7. While Katz et al. (2015) found evidence to suggest that technology maturity is related to schedule change, they found no relationship with cost changes.



Smoker and Smith (2007), however, found evidence that suggests costs vary exponentially across time as the system's technology progresses through each TRL. Similarly, Linick (2017) found that as the TRL increased throughout the development phase, the percentage of the development cost grew at an increasing rate. As shown by the literature, the extant TRL studies are primarily focused on programs once they reach the EMD stage. To the best of our knowledge, no studies focus solely on S&T programs—a gap this article is designed to fill.

Data

The data for this research were obtained from the AFRL cost and economics division. S&T programs typically fall below the dollar threshold for traditional standardized reporting such as Contract Performance Reports (CPRs). Instead, the S&T programs receive Funds and Man-Hour Expenditure Reports (FMERs). These FMERs provide the procuring activity visibility into the contractor's expenditures for labor, materials and parts, travel, subcontractors, and other charges. Like CPRs, these reports are required on a periodic basis from the contractor—usually monthly. Unlike CPRs, FMERs do not report standardized cost elements like the ones found in MIL-STD-881D. The initial AFRL dataset consisted of 165 S&T programs with contract start dates spanning from 2009 to 2017.

Research Summary Reports were also collected for these programs. These reports are generated at the start of the program (Initial), during the program (Periodic), and at the end of the program (Final). Research Summary Reports include general information such as the program title, lead technical directorate, and start/end dates. They also include DoD-required information such as performance type, joint capability area, Air Force technical capabilities, and TRLs. An example of a Research Summary Report can be found in Appendix B.



TABLE 2. DATASET EXCLUSIONS

Category	Number Removed	Remaining Programs
Programs Obtained from AFRL		165
Missing Elements	64	101
Inadequate TD Sample Size	10	91
Less Than 92.5% Complete	48	43
Final Dataset for Analysis		43

Of the 165 programs obtained from AFRL, 43 are included in the final dataset. Table 2 provides the exclusion criteria and associated number of programs remaining in the analysis.

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As shown in Table 2, programs that had missing elements are excluded. These 64 programs had their costs reported on the FMER in unique ways, including cost burn rates, earned value management graphs, total costs in phases, or simply an overall total cost or labor hours spent. These reporting methods lack the specific elements needed in this analysis to compute percentages of total cost, which are used to observe the program's behavior. Of the 101 remaining programs, 10 programs fall under four different technical directorates (RD, RI, RX, and RY). Each technical directorate represents unique programs with different characteristics, which precluded aggregation above the technical directorate level. Therefore, the small sample size in these directorates would likely skew the analysis results, especially when observing how these programs behave at the technical directorate level. For these reasons, the programs are excluded from the analysis. Finally, programs with a completion percentage of less than 92.5% are excluded from the dataset. A program's completion percentage is computed using the total cost from the last available FMER to the program's contract value at that time. Previous research determined that a program with a completion percentage of 92.5% or greater accurately predicts the final cost of the program (Tracy & White, 2011). The final number of programs in the dataset is 43, which is sufficient to conduct a robust analysis. See Appendix C for details on the 43 individual programs.

Methods: Contingency Table Analysis

The dataset consists largely of qualitative variables. Therefore, the methodological approach employed is a two-way contingency table analysis. (See McClave et al. [2018, pp. 608–632] for more details on contingency tables.) This type of analysis is used to summarize the relationship between two categorical variables based on the data observed. The contingency table analysis uses a 2 x 2 table to test for independence. For each test, the same type of hypothesis test will be implemented, as shown in Equation 1:

H_o : The two classifications are independent

H_a : The two classifications are dependent (1)

The chi-square distribution is the test statistic used for considering inferences about the category probabilities. If there is a failure to reject the null, the two variables are independent and are not statistically related to one another. If the null is rejected, then the variables are dependent, and a statistical relationship exists between them. The two-way contingency analysis examines the categorical variables (Table 3) with subsequent discussion on the rationale behind variable selection and categorization.

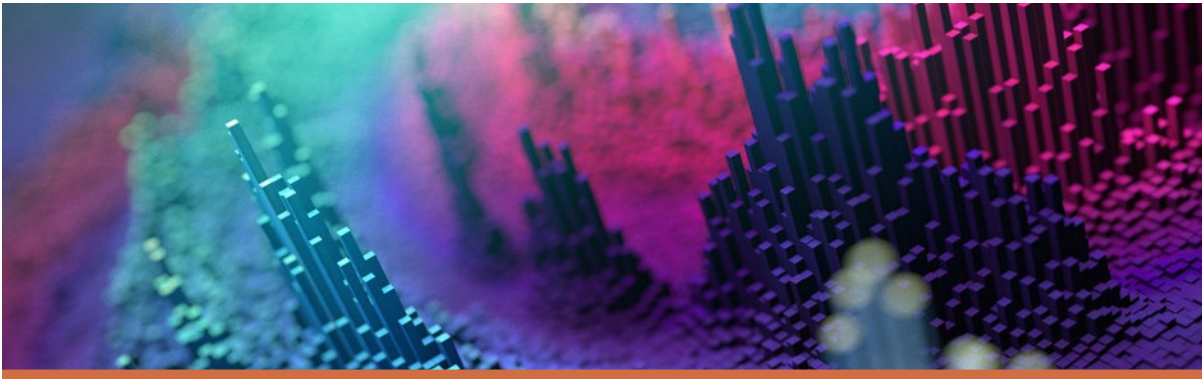
TABLE 3. CATEGORICAL VARIABLES USED IN CONTINGENCY TABLE ANALYSIS

Categorical Variables	
Technical Directorate	Cost Growth > 0%
Performance Type	Cost Growth > 33.7%
TRL Increase	Cost Growth > 44.1%
Last Known TRL \geq 6	Cost Growth > 56.5%
Final TRL \geq 6	Cost Growth > 60.5%
TRL 1 - 3	Cost Growth > 68%
TRL 4 - 5	Contract Value > \$1M
TRL 6 - 7	Contract Value > \$3M
TRL 8 - 9	
Schedule Growth > 0%	
Schedule Growth > 33%	
Schedule Growth > 63%	

An underlying assumption of the chi-square contingency table test is that the sample size should be large enough so that the estimated expected cell count will be equal to five or more. If this assumption is violated, the Fisher's Exact Test can be utilized. The Fisher's Exact Test is based on hypergeometric probabilities, and no statistical assumptions are needed

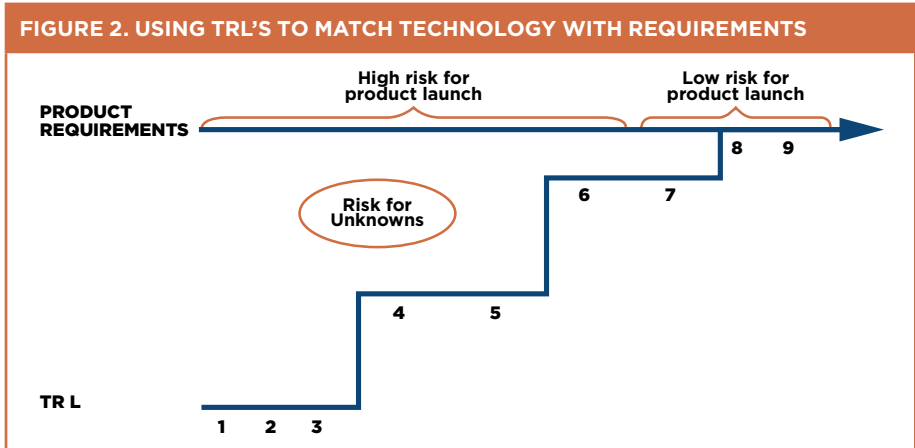
except for computational ability and time. (For more details regarding the use of Fisher's Exact Test, see McDonald [2014, pp. 77–85] or Mehta and Patel [1983].)

When highly significant results are found, one of the benefits of a contingency table is that odds ratios and their associated confidence intervals can be produced. An odds ratio is a measure of association for a two-way contingency table. The ratio is the odds of an event occurring in one group to the odds of the same event occurring in another group. In other words, the odds ratio is the ratio of the probability of a property being present compared to the probability of it being absent. If the odds ratio is 1, the two events are independent.



Categorical variables for the Technical Directorate (TD), Performance Type, and TRLs are obtained from the Research Summary Reports. The TD variable denotes which AFRL directorate is the lead on the program. Such a variable may capture organizational/managerial/technological differences. For this dataset, the TD variable is either RH (Airman/Human Systems) or RQ (Aerospace Systems). (This limitation is due to the sample size of the other TDs as previously discussed.) The performance type represents the partnership method between AFRL and the contractor. This variable consists of Research, Development, Test and Evaluation (RDT&E) and Small Business Innovative Research (SBIR) relationships. This type of variable may capture differences due to the size, skills, or knowledge of the company types (e.g., small vs. large companies). TRL data for the S&T programs are used in seven different categorical variables. TRL Increase indicates whether the TRL increases at any point during the program's life cycle. Last Known TRL ≥ 6 denotes the last reported TRL of the program, while Final TRL ≥ 6 only analyzes programs that have a Final Research Summary Report. The decision to categorize based on TRL level 6 is due to the role this TRL level fulfills in the defense acquisition process. Specifically, a TRL of 6

is equivalent to demonstration in a relevant environment, which is needed for a program to enter Milestone B (DoD, 2011). Four variables were created by grouping TRLs (Figure 2) based on the maturity of the technology and the product’s requirements, as determined in the literature (GAO, 1999).



Note. Adapted from GAO (1999).

Category	Break Point	Reason	Source
Schedule Growth	0% 33% 63%	Any growth Median Mean	Dataset Dataset Dataset
Cost Growth	0% 33.7% 44.1% 56.5% 60.5% 68%	Any growth DoD Development - Median Air Force Development - Median DoD Development - Mean Air Force Development - Mean Mean	Dataset Bolten et al. (2008) Bolten et al. (2008) Bolten et al. (2008) Bolten et al. (2008) Dataset
Contract Value	\$1M \$3M	Median Mean	Dataset Dataset

Additional variables of interest created from the Research Summary Report contract information include schedule growth, cost growth, and contract value. These attributes are commonly studied for acquisition programs at all phases of their life cycles.

The variables for cost growth, schedule growth, and contract value have been converted from continuous variables to categorical variables for inclusion in the contingency table analysis. Binary (or dummy) variables with methodical break points were created to test the relationships at different locations. These breakpoints were derived either from the literature review or from descriptive statistics of the variable itself in the dataset with its

mean and/or median. For example, the mean cost growth of the dataset was 68%, which led to the creation of a dummy variable (Cost Growth > 68%), separating programs that are above and below the sample mean. Likewise, Bolten et al. (2008) distinguished mean and median percentages of total DoD and Air Force acquisition program development cost percentages. These thresholds from Bolten et al. (2008) are also examined. A summary of the break points can be seen in Table 4.



Results and Discussion

The contingency table results are organized into four sections: technical directorate, performance type, TRL, and growth relationships. Using the chi-square distribution as the test statistic, relationships are identified when Pearson's chi-squared test is significant at a p -value of less than 0.10. For highly significant results (p -value < 0.01), the odds ratio and its associated confidence interval are analyzed. It is important to note the possibility of spurious relationships. Spurious relationships occur when the two variables are associated, but not causally related, possibly due to an unknown mediating variable. With the sheer number of 2×2 tables generated in this analysis, spurious relationships are possible. Therefore, only highly statistically significant results (p -value < 0.01) will be studied in detail (i.e., full contingency table shown) while the other significant variables are observed solely as potential findings.

Technical Directorate

The Technical Directorate (TD) categorical variable denotes which AFRL directorate is the lead on the respective program: either RH (Airman/Human Systems) or RQ (Aerospace Systems). Analyzing the TD variable resulted in 19 contingency tables to be tested for significance. Two variables were significant at an alpha of 0.10 and two were significant at an alpha of 0.05. The full set of test results is provided in Table 5, where the more likely TD is annotated with a + and its name (e.g., +RQ).

TABLE 5. CONTINGENCY TABLE RESULTS FOR TECHNICAL DIRECTORATE	
Variable	TD
Performance Type	
TRL Increase	** (+RQ)
Last Known TRL \geq 6	
Final TRL \geq 6	
TRL 1-3	
TRL 4-5	
TRL 6-7	
TRL 8-9	
Schedule Growth > 0%	
Schedule Growth > 33% (Median)	** (+RQ)
Schedule Growth > 63% (Mean)	* (+RQ)
Contract Value > \$1.0M (Median)	
Contract Value > \$3.0M (Mean)	
Cost Growth > 0%	* (+RQ)
Cost Growth > 33.7% (DoD Dev - Median)	
Cost Growth > 44.1% (AF Dev - Median)	
Cost Growth > 56.5% (DoD Dev - Mean)	
Cost Growth > 60.5% (AF Dev - Mean)	
Cost Growth > 68% (Mean)	
Total Significant Contingency Tables:	4

Note.* p -value < 0.10** p -value < 0.05*** p -value < 0.01

TRL Increase is the only TRL variable with a statistically significant relationship to TD. This test suggests that it is more probable to have a program's TRL increase with RQ (Aerospace Systems) programs compared to RH (Airman/Human Systems) programs. The RQ (Aerospace Systems) programs are composed primarily of engine and propulsion (hardware) system technologies. The ability to transition RQ (Aerospace Systems) through TRL levels may be due to the relationship of hardware versus software



(human systems interactions). It is likely easier to make advancements in hardware technologies as the testing, failures, and efficiencies may be more conclusive.

Similarly, the contingency table results suggest that RQ (Aerospace Systems) programs are more probable to have cost growth as well as schedule growth that is greater than 33% (the dataset’s median) and 63% (the dataset’s mean). This could be related to the maturing technology (increasing the TRL) of RQ (Aerospace Systems) programs. If the technology is maturing, a program office may be more likely to increase funding and schedule to keep the maturation on track. If the technologies do not mature, it could be that the agile nature of S&T programs allows for an early decision to cancel programs. In summary, the TD results suggest that RQ (Aerospace Systems) programs are more likely to technologically mature, have cost growth, and have schedule growth (greater than the dataset mean and median) when compared to RH (Airman/Human Systems) programs.

Performance Type

The performance type variable represents the partnership method between AFRL and the contractor: either Research, Development, Test & Evaluation (RDT&E) or Small Business Innovative Research (SBIR) relationships. This variable formed 19 contingency tables to be tested for significance. One variable was significant at an alpha of 0.10, two variables were significant at an alpha of 0.05, and one variable was significant at an alpha of 0.01. The full set of test results is provided in Table 6 where the more likely performance-type variable is annotated with a + and its name (e.g., +RDT&E).

TABLE 6. CONTINGENCY TABLE RESULTS FOR PERFORMANCE TYPE	
Variable	Performance Type
TD	
TRL Increase	
Last Known TRL ≥ 6	** (+RDT&E)
Final TRL ≥ 6	** (+RDT&E)
TRL 1-3	
TRL 4-5	
TRL 6-7	
TRL 8-9	
Schedule Growth > 0%	* (+SBIR)
Schedule Growth > 33% (Median)	
Schedule Growth > 63% (Mean)	
Contract Value > \$1.0M (Median)	*** (+RDT&E)

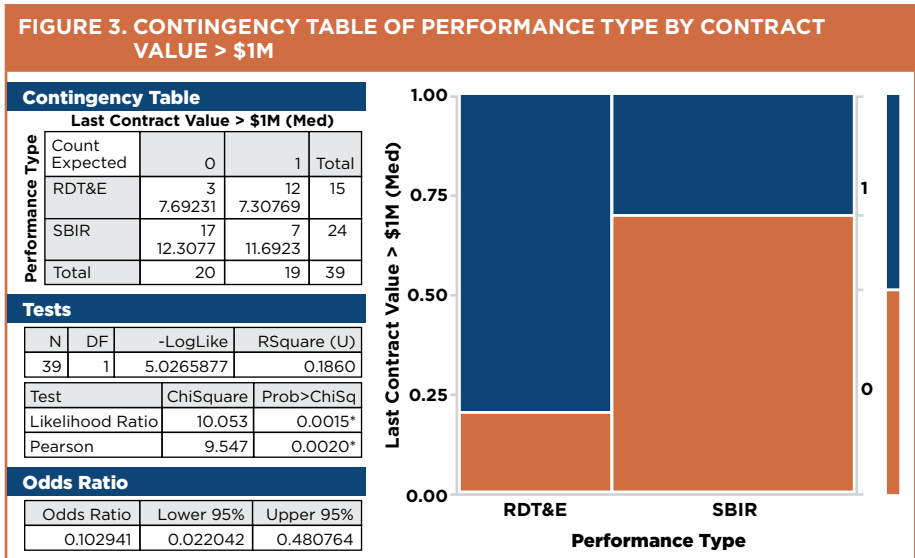
TABLE 6. CONTINGENCY TABLE RESULTS FOR PERFORMANCE TYPE (CONTINUED)

Variable	Performance Type
Cost Growth > 0%	
Cost Growth > 33.7% (DoD Dev - Median)	
Cost Growth > 44.1% (AF Dev - Median)	
Cost Growth > 56.5% (DoD Dev - Mean)	
Cost Growth > 60.5% (AF Dev - Mean)	
Cost Growth > 68% (Mean)	
Total Significant Contingency Tables:	5

Note.

- * p-value <0.10
- ** p-value <0.05
- *** p-value <0.01

Table 6 test results suggest that an S&T program with an RDT&E performance type is more likely to have or end with a TRL of at least 6 than an SBIR-type program. SBIR programs are developed by small domestic businesses, which potentially provide an agile way to stimulate high-tech innovation. But RDT&E programs are dominated by the larger, more experienced defense contractors. These results suggest that the larger defense contractors may obtain contracts with more mature technologies due to their capacity and ability to develop these technologies when compared to SBIR businesses.





Further, as a potential indication of RDT&E and SBIR working different kinds of programs from the start, one can observe that contract values greater than \$1 million (the dataset's median) are more probable with RDT&E performance types, as seen in Figure 3. This result may be an artifact of the policy constraints on SBIR programs. A phase II SBIR contract cannot exceed \$1.73 million without a waiver from the U.S. Small Business Administration. Due to this limitation, one might question the appropriateness of comparing RDT&E and SBIR programs by contract value. But in the dataset analyzed, the average SBIR contract was \$977 thousand, with only one program nearing the waiver cap (Appendix C). At the same time, RDT&E programs have no lower dollar limit, and six of the 17 RDT&E programs are below the \$1.73 million SBIR waiver threshold. Therefore, while comparisons of larger contract values are likely inappropriate, the \$1 million threshold compared here may suggest that the differences are not conclusively a result of the policy limitation, but rather may be highlighting differences in the types of contractors involved in RDT&E and SBIR programs. SBIR programs may target uncertain and risky technologies that small businesses research so that AFRL can evaluate which programs have the potential to develop into mature technologies. The scale of these uncertain programs may contribute to lower contract values. In fact, the odds ratio indicates that given the program has an SBIR performance type, the odds of the contract value being less than \$1 million are 9.7 times higher than when the program has an RDT&E performance type.

“ SBIR programs may target uncertain and risky technologies that small businesses research so that AFRL can evaluate which programs have the potential to develop into mature technologies.

The Table 6 contingency test results also suggest that a program with an SBIR performance type is more likely to have schedule growth. While test results indicate that RDT&E programs are more likely to have higher TRL levels, the opposite could be said that SBIR programs are more likely to have lower TRL levels. Less is known about these immature technologies (where

immature is defined as TRL 1–5), which could lead these small businesses to spend more time developing them, leading to schedule slippage. This result is consistent with the literature findings of Dubos et al. (2008).

In summary, the results suggest that a program that has a performance type of RDT&E is more likely to have a TRL of 6. Furthermore, highly significant results point to evidence that a program that has a performance type of RDT&E is more likely to have a contract value greater than \$1 million. Lastly, the results suggest that SBIR programs are more likely to experience schedule growth.

“As technologies mature, investments are made, which allow costs to grow over their initial estimates. As the technology integrates into a demonstration effort (TRL 6-8), the program is often met with new and unexpected challenges, which tends to increase costs.”

Technology Readiness Level

TRL data were used to create seven different binary variables as previously discussed. These seven TRL variables were tested for significance against the 11 performance variables to produce 77 contingency tables. Seven variables were significant at an alpha of 0.10, four variables were significant at an alpha of 0.05, and one variable was significant at an alpha of 0.01. Despite registering significant Pearson p -values, the contingency table results for the seven significant variables at an alpha of 0.10 were found to be invalid. For all seven tests, the expected counts of two of the four cells were less than five. This violates an assumption for a valid chi-squared contingency table test, which states the sample size should be large enough so that the estimated expected count will be equal to five or more. As a further check, Fisher’s Exact Test—which is a nonparametric test for small samples—found all seven tests to be nonsignificant. This result was largely due to the small number of programs with a TRL of 6–7 (5) and a Final TRL of ≥ 6 (4). The full set of test results is provided in Table 7, with special subscript designators on those test results deemed invalid.



TABLE 7. SIGNIFICANT CONTINGENCY TABLE FOR TECHNOLOGY READINESS LEVEL

Variable	TRL Increase	Last Known TRL ≥ 6	Final TRL ≥ 6	TRL 1-3	TRL 4-5	TRL 6-7	TRL 8-9
Schedule Growth > 0%		**	* ₁			* ₁	
Schedule Growth > 33% (Median)							
Schedule Growth > 63% (Mean)							
Contract Value > \$1.0M (Median)				**			
Contract Value > \$3.0M (Mean)		**				***	
Cost Growth > 0%						* ₁	
Cost Growth > 33.7% (DoD Dev - Median)						* ₁	
Cost Growth > 44.1% (AF Dev - Median)						* ₁	
Cost Growth > 56.5% (DoD Dev - Mean)						* ₁	
Cost Growth > 60.5% (AF Dev - Mean)						* ₁	
Cost Growth > 68% (Mean)						**	
Total Significant Contingency Tables:	0	2	1	1	0	8	0

Note.

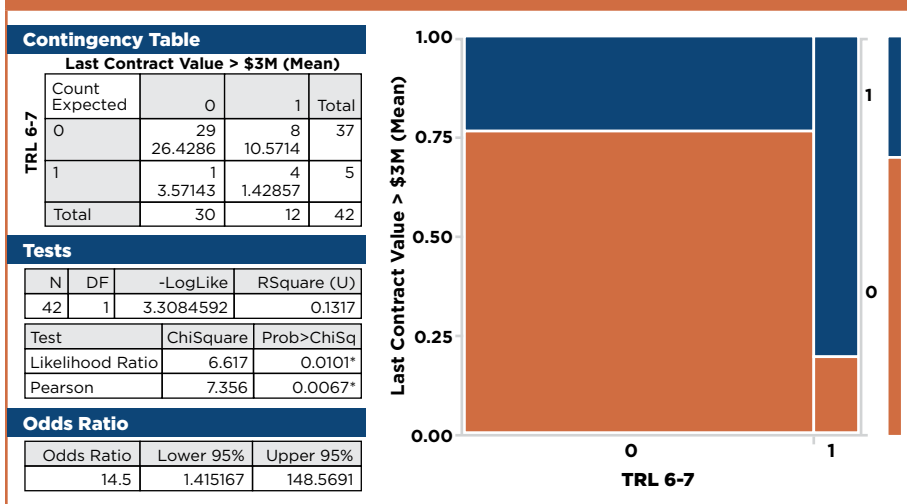
*₁ p-value <0.10, 50% of Expected Counts <5, Non-significant Fisher's Exact Test

* p-value <0.10

** p-value <0.05

*** p-value <0.01

FIGURE 4. CONTINGENCY TABLE OF TRL 6-7 BY CONTRACT VALUE > \$3M



The contingency table results suggest that an S&T program is *more* likely to have cost growth greater than 68% (the dataset's mean) with a TRL of 6 or 7 but *less* likely to have schedule growth with a TRL ≥ 6. Such a finding, perhaps unusual for a development program, is both intuitive and precedent

in an S&T context. With an early TRL (1–5), there is little knowledge of how the technology will mature. This poses a problem to program managers and cost estimators. As technologies mature, investments are made, which allow costs to grow over their initial estimates. As the technology integrates into a demonstration effort (TRL 6–8), the program is often met with new and unexpected challenges, which tends to increase costs. These results support previous research conducted on Air Force programs, which concluded that estimated costs vary exponentially across time with the progression through the various TRLs (Smoker & Smith, 2007). However, for more mature technologies, a broader knowledge base is available for the technology’s development due to more completed research. With a higher TRL, and thus more knowledge of the technology available, the better the chance of meeting schedule requirements (Dubos et al., 2008). This literature finding is also consistent with the results found here.

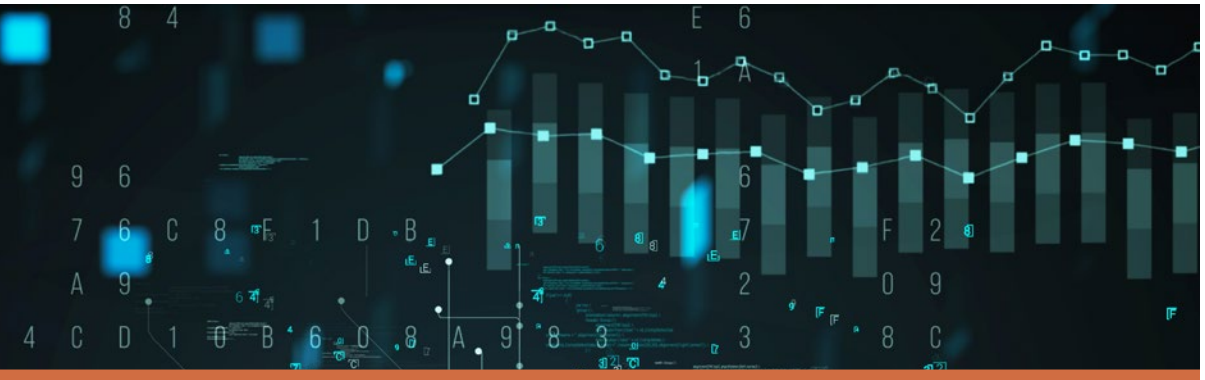


Table 7 results also suggest that an S&T program with a TRL of 6 or greater is *more* likely to have contract values greater than \$3 million (the dataset’s mean). An S&T program with a TRL of 1 through 3 is *less* likely to have contract values greater than \$1 million (the dataset’s median). The explanation is consistent with the aforementioned cost growth finding. As the program’s technology matures, additional investments are made, as shown in the contingency analysis results in Figure 4. In fact, the odds ratio indicates that given the program has a TRL of 6 or 7, the odds of the contract value being greater than \$3 million are 14.5 times higher than a program with a TRL other than 6 or 7.

In summary, the TRL results suggest that programs with mature technologies are more likely to experience larger than average cost growth and larger contract values. Additionally, these programs are less likely to experience schedule growth. Further, the results suggest that programs with immature technologies are less likely to have larger contract values.

Growth Relationships

As previously shown, variables for TD, performance type, and TRL were tested for their relationships with cost growth, schedule growth, and contract value. An analysis was also conducted among these latter variables to analyze their relationships to each other; a total of 63 relationships were tested for significance. Eight tests were significant at an alpha of 0.10, 11 tests were significant at an alpha of 0.05, and 22 tests were significant at an alpha of 0.01. The full set of test results appears in Table 8.

Variable	Schedule Growth > 0%	Schedule Growth > 33% (Med)	Schedule Growth > 63% (Mean)	Contract Value > \$0.9M	Contract Value > \$1.0M (Med)	Contract Value > \$3.0M (Mean)	Contract Value > \$4.0M	Contract Value > \$5.0M	Total Significant Contingency Tables
Contract Value > \$0.9M		**	**						2
Contract Value > \$1.0M (Median)									0
Contract Value > \$3.0M (Mean)									0
Contract Value > \$4.0M									0
Contract Value > \$5.0M									0
Cost Growth > 0%	**	***	***	***	***	**	**	*	8
Cost Growth > 33.7% (DoD Dev - Median)	*	*	***		***	***	***	**	7
Cost Growth > 44.1% (AF Dev - Median)	*	*	***		***	***	***	**	7
Cost Growth > 56.5% (DoD Dev - Mean)	*	**	***			***	***	**	6
Cost Growth > 60.5% (AF Dev - Mean)	*	**	***			***	***	**	6
Cost Growth > 68% (Mean)		*	***			***	***	***	5
Total Significant Contingency Tables:	5	7	7	1	3	6	6	6	41

Note.

- * p-value <0.10
- ** p-value <0.05
- *** p-value <0.01

The contingency table results suggest that it is more probable for S&T programs with larger contract values to experience cost growth. Observing cost growth relationships with the original two contract value variables (using the mean and median of the dataset) provided highly significant results. To explore the sensitivity of these relationships relative to the threshold used to

define the binary variables, additional contract value variables were created with lower and higher breakpoints. This additional analysis found contract values greater than \$0.9 million to be the lowest threshold for which a statistically significant relationship could be found with an amount of cost growth (i.e., cost growth > 0%). As the contract value threshold increased, additional cost growth variables displayed statistical significance until all were significant at a contract value of \$3.0 million. The progression is illustrated by the cells with light green shading, as shown in Table 8. This suggests that cost growth and contract value have a positive correlation with each other.

Table 8 results also suggest that it is more probable for S&T programs with contract values greater than \$0.9 million to experience schedule growth above the median and mean (i.e., greater than 33% and 63%, respectively). This was the only contract value variable to result in significant *p*-values when tested with schedule growth variables (see light blue shaded cells in Table 8). These results imply that programs with contract values less than \$0.9 million are less likely to experience schedule growth.

“Analyzing the relationship between cost and schedule growth suggests that programs with schedule growth are more likely to have cost growth as well. The analysis revealed that this schedule growth/cost growth relationship is found in those programs with immature technologies.”

Finally, the results suggest that if S&T programs are experiencing schedule growth, then it is more likely that they're also experiencing cost growth. This seems to contradict the findings that programs with mature technologies are more likely to experience cost growth and less likely to experience schedule growth. But closer analysis of these results suggests that programs with large schedule growth percentages are even more likely to experience cost growth at all amounts. Thus, when this cost and schedule growth relationship is found, it is not in the mature technology programs, but rather in those programs with *immature* technologies.

In summary, the results suggest that S&T programs with larger contract values experience cost growth, while programs with smaller contract values (< \$0.9 million) are less likely to experience schedule growth. Finally, analyzing the relationship between cost and schedule growth suggests that programs with schedule growth are more likely to have cost growth as well. The analysis revealed that this schedule growth/cost growth relationship is found in those programs with immature technologies.

Conclusions

S&T programs serve an important role in the defense acquisition process. They constitute the initial phase of the acquisition process through discovery and development of warfighting technology. The results of these programs impact the larger MDAPs, which integrate the technologies in subsequent phases of the life cycle. Despite this important role, little prior research has examined the performance of S&T programs. Thus, the overarching goal of this article was to discern new insights from an analysis of Air Force S&T program characteristics in relation to their program's performance.



The literature review identified technological maturity as a critical success factor in product development (GAO, 1999). One measure that defense programs use for technological maturity is TRL levels. TRLs, therefore, were an integral component under investigation in this analysis. The objective was to understand how TRLs affect S&T program performance. Several key findings emerged from this analysis.

First, the results suggest that aerospace programs are more likely to technologically mature when compared to human system programs. In other words, the AFRL aerospace programs are more likely to progress through the TRLs in their programs. To the extent that technological maturity is a measure of success, the aerospace programs outperform. However, this technical performance comes at a cost as the aerospace programs were also more likely to experience cost and schedule growth. Intuitively, these results are compatible; with proven success in technology maturation, increases in funding and schedule are likely to keep the maturation on track.

Second, the partnership method between the government and contractor may matter. The partnerships for S&T programs consist of SBIR and RDT&E relationships. The RDT&E programs are more likely to have—and

end—with a TRL of 6 or more in comparison to SBIR programs. The result is not entirely surprising because, by definition, the larger defense companies constitute the RDT&E category. These larger companies have the capacity and resources to mature technology that the smaller SBIR companies may not possess. Additionally, the purpose and limitations of SBIR programs must be acknowledged. SBIR programs are intended to increase private-sector commercialization of innovation and stimulate technology innovation. Funding limits are associated with these programs and, depending on the objectives of the specific SBIR program, they may eventually transition to a funded R&D or procurement contract. These differences are important when comparing SBIR to RDT&E programs.

“ Further analysis of the relationship between cost and schedule growth suggests that if programs have larger schedule growth, then they are more likely to have larger cost growth as well. The analysis revealed that this schedule growth/cost growth relationship is found in those programs with immature technologies. ”

Third, TRLs and program performance are linked. The relationships with TRLs suggest that programs with mature technologies are more likely to experience above average cost growth and larger contract values while less likely to experience schedule growth. Additionally, the results suggest that programs with immature technologies are less likely to have larger contract values. As technologies mature, additional funds for investments are made, which increases costs over their initial contract values. From a practical standpoint, these additional investments may occur due to the need for an increased performance outcome and are not an indictment on the management effort. This is likely to happen when the program is met with new and unexpected challenges as the technology integrates into a demonstration effort (TRLs 6–8). Linick (2017) found that as the TRL increased throughout the development phase, the percentage of the development cost increased at an increasing rate. This literature finding is in agreement with these results. Conversely, as these technologies mature, a broader knowledge base is gained for its development, which increases the chance of meeting schedule requirements.

Lastly, the analysis of “growth” variables (cost growth, schedule growth, and contract value) provides additional insights on S&T programs. Specifically, the analysis suggests that S&T programs with larger contract values

experience larger cost growth at the same time programs with smaller contract values (< \$0.9 million) are less likely to experience schedule growth. Further analysis of the relationship between cost and schedule growth suggests that if programs have larger schedule growth, then they are more likely to have larger cost growth as well. The analysis revealed that this schedule growth/cost growth relationship is found in those programs with immature technologies.

When interpreting the results of this article, it is important to remember that S&T programs are different than MDAPs. As a result, the risk tolerance manifested in cost and schedule performance standards between the two should not be conflated. The research nature of an S&T program inherently makes it more risky. The subtext is that technical failure, or growth in cost and schedule, is often a normal part of the research process and may not be viewed in the same manner as MDAP performance. Rather, the benefit of the current study is the new understanding that arises from depicting the relationship between S&T program characteristics and their performance.

Prior examinations of S&T programs are scarce. Thus, the possibilities for future research are vast. The exploratory analysis conducted here focused solely on AFRL programs. S&T programs in the other military services warrant examination. Additionally, one of the more surprising aspects of the data obtained from S&T programs was the reported TRL at various stages of the program's life cycle. In order for a program to advance past Milestone B into the EMD phase, a program must have a TRL of 6 or greater. Further research into those S&T programs whose technology matured (TRL increased) could identify common characteristics, which indicates a higher probability of technological maturation. Lastly, future research should investigate the reasons or root causes behind the correlations found in this article. The aim of that research would be to expound upon the interpretation of the data. The contribution from that research is important to arming leadership with the necessary information upon which to base decisions. The exploratory analysis provided here was just the first step of the journey. Through future research and discoveries, we can gain the knowledge needed to increase the odds of successful S&T programs.



Appendix A

TRL Definitions, Descriptions, and Supporting Information

TRL	Definition	Description	Supporting Information
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5	Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?

TRL	Definition	Description	Supporting Information
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	

Note. Adapted from DoD (2011).

Appendix B

Sample Research Summary Report

Research Summary Report

General Information											
Work Unit Title:	Program Title										
Work Unit (WU) #:		Accession #:	XXXX								
Start Date:	MMDDYYYY	End Date:	MMDDYYYY								
Local ID:	RD	Fifair Security:	Unclassified								
Literature Search Order #:	XXXXX	Lit Search Date:	MMDDYYYY								
Work Phase Code:		WU Category:									
Responsible Organization:	Aerospace Systems Directorate (AFRL/RQ) WRIGHT-PATTERSON AFB, OH										
Parent Program:	Parent Program Title										
Work Unit Manager											
Name:	XXXX.XXXX		Phone:	(XXX) XXX-XXXX							
Office Symbol:	RQTE		Email:	xxxx.xxxxx@us.af.mil							
DoD Required Information											
Performance Method:	PROCUREMENT/ACQUISITION AWARD Contract			Lab Core Technical Competency:	Power, Propulsion, Energy & Alternative Fuels						
Performance Type:	RDTE - Research, Development, Test, & Evaluation Work			Technology Readiness Level:	2 Technology Concept						
Fields of Science & Engineering:				Data Management Plan Exist:	No						
Joint Capability Area:	Force Application										
Communities of Interest:	1.1 Aircraft Propulsion, Power and Thermal										
Technology Transition Opportunities:	None at this time Follow on contract will progress TRI of key components to enable future transition										
Principal Investigator											
Name:	XXXX.XXXXXX		Phone:	(XXX) XXX-XXXX							
Office Symbol:	XX		Email:	xxxx.xxxxx@us.af.mil							
Performing Mechanism											
Contract #:	FAXXXX-XX-X-XXXX-XXXX			Contract Status:	Complete						
Contract Face Value	\$XX,XXX,XXX			TR Due DTIC Date:	MMDDYYYY						
Award Date:	MMDDYYYY			TR Draft Due Date:	MMDDYYYY						
Tech End Date:	MMDDYYYY			Terminate Date:	WAWF /DD2562						
End Date:	MMDDYYYY			Date:	MMDDYYYY						
Performing Organization											
Performer:	NAME OF COMPANY			Address:							
Division:	XX										
CAGE Code:	XXXXXX										
Performing Org Type:	Industrial Firm										
WU Funding (\$K)											
PE / BPAC	Source	Funding	Prior	FY18	FY19	FY20	FY21	FY22	FY23	To Complete	Total
		Appropriated									
		Obligations									
		Appropriated									
		Obligations									
Descriptive and Progress/Status											
Objective/Restricted											

MMDD, YYYY
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Appendix C

Dataset

Last Performance					Last Performance				
Program ID	TD	TRL	Type	Total Cost	Program ID	TD	TRL	Type	Total Cost
Program 1	RH	7	RDT&E	\$2,660,154	Program 22	RQ	4	CRDA*	\$5,648,405
Program 2	RH	5	RDT&E	\$1,224,259	Program 23	RQ	4	CRDA*	\$3,595,076
Program 3	RH	6	RDT&E	\$4,815,251	Program 24	RQ	2	CSAE*	\$7,166,910
Program 4	RH	5	RDT&E	\$1,640,552	Program 25	RQ	6	RDT&E	\$4,428,565
Program 5	RH	4	RDT&E	\$2,424,100	Program 26	RQ	2	RDT&E	\$974,340
Program 6	RH	6	RDT&E	\$4,856,299	Program 27	RQ	5	RDT&E	\$10,086,064
Program 7	RH	4	RDT&E	\$747,541	Program 28	RQ	3	RDT&E	\$4,781,200
Program 8	RH	3	RDT&E	\$8,437,990	Program 29	RQ	6	RDT&E	\$892,110
Program 9	RH	4	SBIR	\$705,525	Program 30	RQ	5	RDT&E	\$749,489
Program 10	RH	4	SBIR	\$719,187	Program 31	RQ	3	RDT&E	\$18,922,869
Program 11	RH	3	SBIR	\$1,475,528	Program 32	RQ	6	RDT&E	\$14,897,568
Program 12	RH	5	SBIR	\$728,021	Program 33	RQ	5	RDT&E	\$5,236,777
Program 13	RH	4	SBIR	\$727,783	Program 34	RQ	5	SBIR	\$1,698,117
Program 14	RH	3	SBIR	\$737,907	Program 35	RQ	4	SBIR	\$742,919
Program 15	RH	3	SBIR	\$733,454	Program 36	RQ	8	SBIR	\$1,234,988
Program 16	RH	2	SBIR	\$1,110,133	Program 37	RQ	3	SBIR	\$747,185
Program 17	RH	5	SBIR	\$1,442,603	Program 38	RQ	3	SBIR	\$758,161
Program 18	RH	4	SBIR	\$1,428,715	Program 39	RQ	2	SBIR	\$748,685
Program 19	RH	4	SBIR	\$1,246,712	Program 40	RQ	4	SBIR	\$748,172
Program 20	RH	4	SBIR	\$739,001	Program 41	RQ	3	SBIR	\$998,582
Program 21	RH			\$5,958,377	Program 42	RQ	2	SBIR	\$941,116
					Program 43	RQ	2	SBIR	\$1,085,073

Note. *Not included in TD analysis due to small sample size

Performance Type	
CRDA	Cooperative Research and Development Agreements
CSAE	Contracted Studies, Analysis and Evaluations
RDT&E	Research, Development, Test and Evaluation
SBIR	Small Business Innovative Research

Technical Directorate	
RH	Aerospace Medicine, Human Systems Integration
RQ	Aerodynamics, Flight Control, Engines, Propulsion

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