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THESIS

**BUILT-IN-TEST EQUIPMENT FOR INTEGRATED
WEAPONS SYSTEMS:
ACHIEVING UTILITY AND USER ACCEPTANCE**

by

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September 2007

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**BUILT-IN-TEST EQUIPMENT FOR INTEGRATED WEAPONS SYSTEMS:
ACHIEVING UTILITY AND USER ACCEPTANCE**

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ABSTRACT

The objective of this work was to determine whether a direct statistical or stochastic relationship between the following systemic characteristics of dedicated built-in-test-equipment (BITE) could be derived and quantified: annual maintenance costs, user acceptance, operational availability, and “complexity” (defined as total number of sensor interfaces per system). Three systems of ascending degrees of complexity from the USAF F-15A/BC/D, O/A-10A, and C-5A/B/C were analyzed, and based upon raw data acquired from field operating units and fleet-wide maintenance data collection a model was constructed to derive constraints on a postulated “best-fit” interdependence between these four characteristics. The chief finding was that BITE reliability and minimal intrinsic system maintenance burden were the prime determinants of user acceptance and therefore system success. A corollary finding was that the number of data interfaces (or sensors) was mathematically irrelevant to user acceptance, suggesting that condition-based monitoring schemas are feasible provided that BITE system-level reliability is maximized with a minimal maintenance burden placed on the user community. Sensor redundancy to achieve this goal was the suggested method. This model may be used as an objective criterion for evaluating future BITE system procurement proposals, a critical concern for the emerging predictive/condition-based maintenance paradigms currently favored by the Department of Defense, NASA, and other Federal and commercial agencies.

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EXECUTIVE SUMMARY

This paper examines the utility and user acceptance of three dedicated aircraft built-in-test equipment (BITE) suites with respect to documented maintenance man-hour expenditures over a twenty-year period as well as a survey of system users. The objective was to determine the factor(s) that influence BITE acceptance by end-users (in this case, aircraft maintainers) and thereby provide design heuristics and other relevant guidance for future system design. BITE effectiveness is a central tenet of the emerging DoD-wide condition-based maintenance (CBM) paradigm, and therefore maximizing the quality and utility of data return from such systems is critical for the initiative's success.

The chief finding was that user acceptance of BITE equipment is inversely related to the amount of effort required by users to maintain the equipment itself. BITE is unusual in that its primary end users are also usually the same people who maintain it, and perceived value of its functionality is critically dependent upon its perceived, more so than empirically determined, reliability. One surprising ancillary finding was that this user trust seemed to be statistically independent of the number of BITE-monitored subsystems, which is encouraging for the future of CBM but also may require greater investment in BITE system physical infrastructure and reliability engineering during system development.

Recommended design heuristics include providing redundant sensors for critical weapon system functions and explicitly requiring that future BITE systems must not require more maintenance than the system(s) that they monitor. Future research may reveal other useful aspects of this issue that will improve operational availability while minimizing sustainment costs for all highly integrated manned and unmanned DoD weapons systems.

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I. INTRODUCTION AND PROBLEM DEFINITION

A. BITE BACKGROUND INFORMATION

Built-in-test-equipment (BITE) as a distinct sub-system design discipline began its most rapid evolutionary phase primarily in the commercial aviation sector during the 1980s, although its roots can be found in the early manual “push to test” functions used by many aircraft systems designed in the 1950s. Early features were designed to provide pre-flight or, occasionally, in-flight equipment confidence checks for aircrews in order to more readily and rapidly discriminate between malfunctions of indicating equipment and mechanical systems, or to identify true abnormal performance. Use of these features by maintenance personnel was an incidental byproduct that later became dominant in aviation as a means to minimize procuring and maintaining ancillary ground test equipment. In the author's opinion, BITE is also perceived by many planners as a means to minimize personnel training requirements by incorporating as much self-diagnostic capability as possible into weapons system design. BITE is also now widely employed in ground, maritime, and space-borne weapons systems (though restricted to ground systems for the latter in its traditional sense) for both operational confidence checks and as a central tool for malfunction isolation and rapid restoration of full functionality.

The Aeronautical Radio Corporation of America, usually referred to as ARINC, published the first standard for airborne BITE, ARINC 604 in 1985 (Spitzer, 2007). In addition to defining specific serial data protocols, this standard for the first time defined a centralized fault display system that would permit aircrews and maintainers to view failure messages from a wide variety of equipment at one location. Prior to this first attempt at standardization, the US Air Force had already developed and fielded several dedicated BITE systems with mixed results, which will be further explored later.

Modern built-in-test (BIT) systems can be broadly placed under two primary categories based on their operational modes and methodologies: active and passive.

Active systems initiate test routines in subsystems or components and report results to operators or maintainers. Active BIT is usually confined to a specific platform

system in order to prevent spurious inputs from otherwise non-function-essential equipment from interfering with (or disabling) the system during normal operations. A prime example of this design philosophy is the extensive built-in-test routine employed by most aircraft autopilots. However, platforms of more recent vintage such as the C-17 do employ multi-system distributed BITE as a consequence of the highly integrated nature of the weapons system. The C-17 flight control system BIT requires several minutes for full execution and tests every critical subsystem related to aircraft control and engine performance on the aircraft.

Passive systems monitor and record the performance of various platform subsystems, and the results are examined after mission execution for evidence of monitored system malfunctions as well as archived for historical trend data analysis. Most passive BITE does not provide a real-time display to operators during mission execution, and consequently its target user community is restricted to maintainers. An exception to this design philosophy is the C-5 MADAR system.

The pioneering C-5A MADAR (Malfunction Analysis, Detection, and Recording) system described by Mash (1968) was an early attempt to implement comprehensive weapons system platform-level condition monitoring. As originally designed, the system consisted of 40 modules, or line replaceable units (LRUs) and periodically sampled nearly 800 test points during flight. Certain critical aircraft performance parameters such as engine vibration were displayed during flight on an oscilloscope and monitored by the flight engineer. Given its large number of components, MADAR was (and still is) arguably the most complex discrete subsystem on the C-5A, and perhaps unsurprisingly also incurred a large number of maintenance actions not only for the systems it monitored, but for its own upkeep. Its overall utility and added value to the C-5A mission was therefore open to question on many levels. Later upgrades to the system were apparently focused on adding additional monitoring capability (currently 2000 test points) and improving the both the reliability of the LRUs which provide the human-machine interface and presentation methods more so than improving user-level confidence in system accuracy.



Figure 1. Avionics technician prepares to troubleshoot a C-5A. (From: G. Wantland, 2007)

This thesis examines dedicated BITE of different types, complexity, and objectives across three USAF weapons systems, and derives a set of boundary conditions and/or figure(s) of merit that may yield the best value for warfighters during future BITE design efforts while simultaneously conserving system acquisition and sustainment costs.

B. RESEARCH QUESTIONS

At what point, and based on which factors, does maintenance of built-in-test and monitoring (BITE) subsystems obviate or negatively impact weapons system life-cycle cost and operational availability? If this question has a quantifiable answer, then the following design heuristic emerges: “BITE must not be more time-consuming or expensive to maintain than the system(s) it monitors.” An analogous statement is frequently used as contractual language for the acquisition of new space systems that replace legacy equipment, which can be paraphrased as follows: new systems must not be

more difficult to maintain than the old. Specifying BITE in this context is a narrowing of this paradigm; however, this improved focus also offers the opportunity to introduce far more rigorous metrics as well as design guidelines, as will be seen later.

Is there an empirical relationship between the overall systemic complexity of BITE subsystems, the analogous complexity of monitored subsystems, and total life-cycle cost for a given integrated weapons system so equipped? This question is designed to determine whether a critical point, or intersection of the stated variables, exists beyond which BITE does not add value to weapons systems maintenance but is either neutral or a burden to sustainment. ('Value' in this context is defined as the system's capability to enable more rapid and accurate repair of monitored systems versus its intrinsic maintenance burden.) Conversely, an insufficiently sophisticated or capable BITE suite may add little if any value whatsoever, and again act as a negative factor for sustainment. Both regions of this potential operational space will be examined.

Can a mathematical model representing interfaces and monitoring capabilities be constructed to optimize BITE infrastructure during the design phase to provide maximum operational availability while minimizing life-cycle costs? The desired end result of this study is a model capable of defining optimal interface levels, methods and operational reliability values framed by measure(s) of effectiveness for user acceptance that can define BITE capabilities within these constraints as a function of total weapons system lifecycle support expenditures. Subjective observations by the author during more than 20 years of direct experience in aircraft maintenance led to the hypothesis that an optimal balance of BITE capabilities as described may be achievable, but that no such analysis has been performed to date that may facilitate development of systems that meet these criteria.

C. RESEARCH METHODOLOGY

After consideration of possible relevant factors, five potential decision variables were selected, with the presumption that interdependencies would be identified between at least some of these factors and provide insight as part of the research. Three Air Force aircraft types were selected as the platforms to be examined since extensive, long-term

detailed statistical maintenance and reliability data was readily available through restricted Internet access. Additionally, the author has had personal experience with all three systems and this fact facilitated acquisition and interpretation of all data. The 'end users' cited are USAF avionics maintenance personnel.

Man-hour ratio. This was defined as the percentage of man-hours expended to maintain a given BITE system divided by the total number of man-hours needed to maintain the entire weapons system avionics suite, or in other words the fraction of direct labor costs directly applied to maintain a system used to improve maintenance of other aircraft systems. Avionics systems identified for determining total workload belonged to the following two-digit work unit code groups: 46, 51, 52, 55 (the group that encompasses dedicated BITE systems), 71, 72, and 74. The metric was obtained by dividing the sum of man-hours expended on maintenance of these systems over a 20-year time span by the man-hours expended on the code 55 group. These systems are maintained by enlisted personnel in a family of career fields generically referred to as aircraft guidance and control. Data was acquired from the USAF Reliability Engineering Management Information System (REMIS) with the assistance of Warner-Robins AFB personnel, and is provided in appendices 1, 2 and 3.

Number of data interfaces. Defined as the total number of sensor/BITE connections as well as BITE LRU-to-LRU connections for a given system. Power and other utility interfaces were not considered since a supporting study objective was to qualitatively assess data return to the user.

Perceived utility by end user. Although subjective in nature, this variable is a vital consideration in BITE system design. 'Perceived utility' in this context is defined as how useful the users believe the subject system to be as a troubleshooting tool. Data was acquired for each subject system via question #2 of a standardized survey (see Appendix 4) that was distributed to members of the A-10, F-15, and C-5 maintenance communities. Please refer to the end of this section for further discussion of the survey methods employed.

Perceived reliability by end user. Again subjective yet critical for application success, this data was also acquired via the aforementioned survey and represents the average of responses to question #3. 'Perceived reliability' is defined as the users' core impression of how frequently the subject system itself malfunctions, which clearly will also affect the users' level of trust in system outputs.

Perceived maintenance burden by end user. This final subjective variable measures level of effort needed to resolve BITE malfunctions relative to the amount of time users spend resolving other aircraft system malfunctions, which is another critical component of operational suitability. Source data was question #4 of the survey.

Questions 1 and 5 of the survey were ultimately not included in the data analysis. Question 1 measured the perceived amount of time spent by technicians maintaining the subject system, but given the availability of objective data from REMIS this information was redundant and less reliable. Likewise, question #5 was originally included to provide a figure of merit for the level of experience of respondents, but the data proved unnecessary for the analytical effort since a core assumption of BITE is that user level of experience is minimal.

Variables 1 and 2 are physical system attributes that can be considered as figures of merit that represent gross systemic complexity. Variables 3, 4 and 5 represent the perceived amount of trust that the end users have in the system's ability to perform its desired function as well as the level of effort needed to maintain its operation. Since BITE is not only used but also maintained by its end users, this variable set measures its user acceptance in terms of its effects on the user's overall workload, a unique, almost recursive characteristic of this equipment class. Question 5 was used as a root measure of the respondent's breadth of experience.

Much of this study is centered on the core issue of user trust of a given system. According to Langford (2007), the concept of 'trust' with respect to weapons system performance can be defined thusly:" ...trust can be considered as follows: Trust factors into four uniquely definable and quantifiable variables. They are *knowledge* (the norms of operation, the expected actions, the rights and permissions granted); *truth* (the

verifiability of data supplied); *belief* (consistency of patterns and standards); and *retribution* (one's stake or ante). Trust is the additive aggregation of knowledge, truth, belief, and retribution. Trustworthiness is the degree to which trust is established." The data acquired was selected in accordance with this definition, and the results of the study are framed in this context.

All survey data was normalized by assigning numerical values to each of the five possible responses, summing the total for each question, and subsequently dividing this number by the number of samples (N), which were 9, 11 and 19 for the A-10, C-5 and F-15 responses respectively.

The C-5 surveys were distributed and collected by the author in person at Travis AFB, CA in November 2006. A-10 surveys were distributed electronically at Pope AFB, NC and Davis-Monthan AFB, AZ to flightline aircraft maintainers by locally assigned members of the Air Force Engineering and Technical Service (AFETS), an independent USAF agency, and returned directly to the author. F-15 surveys were similarly distributed and collected by an AFETS representative at Elmendorf AFB, AK.

All data collected was processed using Microsoft Excel[®] to perform all required calculations and generate graphical data presentations for subsequent analysis of results.

D. STUDIED BITE SYSTEM DESCRIPTIONS

Selected systems were chosen based on their relative complexity and scope of service. Based on the author's experience with approximately 20 types of USAF aircraft, they represent a rough continuum of interface levels and capabilities that accurately reflect the current state of airborne BITE functionality. Additionally, the F-15 ASP design philosophy is extensively emulated on other aircraft, and the A-10 TEMS system is also used on the KC-135R and F-117A aircraft. The least complex system in terms of operations, LRU count, and interfacing is the F-15 Avionics Status Panel (ASP). The A-10 Turbine Engine Monitoring System (TEMS) is an intermediate example for purposes of this analysis, and the C-5 MADAR II was the most complex system examined.

The F-15 ASP provides “go/no-go” indications to ground maintenance personnel for specific aircraft systems via a simple set of black/white magnetically latched ball indicators mounted on the panel itself, which is located in the aircraft’s nose wheel well and therefore not accessible to the aircrew during flight. Dedicated system LRUs are limited to the status panel itself as described and a BIT reset panel in the cockpit. The ASP receives a serial digital data stream from the aircraft central computer (CC), and upon receipt of a failure status word for a given system or aircraft physical region will set the appropriate indicator. The ASP has 72 such indicators, but usage is controlled by CC operational flight program configuration; many are not used or are disabled as nuisance indications (Black, 2007).

The A-10 TEMS continuously acquires and records performance monitoring data for the aircraft’s two TF-34-100A engines as well as selected environmental parameters during flight. The system is also used with an auxiliary real-time ground terminal to perform engine maintenance actions. No indications are provided to the pilot; indeed, no real-time data display exists at all unless the auxiliary terminal is employed during ground maintenance actions. However, stored data is downloaded from each aircraft once per day and input into the USAF Consolidated Engine Management System (CEMS) for trend analysis. CEMS also provides notification to maintenance personnel of potential system or engine discrepancies for specific aircraft during this process. TEMS consists of 21 dedicated LRUs and accepts data from 10 legacy engine indication systems.

C-5 MADAR II is a comprehensive platform status monitoring system that continuously acquires data on nearly every C-5 subsystem and provides a real-time interactive display to the aircrew during flight. MADAR consists of 40 dedicated LRUs that monitor approximately 2000 discrete test points throughout the aircraft. The majority of these LRUs are interface/signal conditioning devices that provide direct connections to the monitored systems and convert analog information into a serial digital data stream for subsequent processing by the recording/display LRU group. Like the A-10 TEMS, data is continuously recorded, retrieved and archived in a ground database which also provides malfunction notifications to maintenance personnel. One major function of the system is to monitor TF-39 engine vibration in real time during flight. Additionally, MADAR

provides most data inputs to the aircraft flight data recorder. Therefore, unlike other BITE systems described thus far, MADAR is essential for safe operation of the aircraft since these particular features are considered flight-critical functions.

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II. ANALYSIS AND INITIAL FINDINGS

A. RESEARCH APPROACH

The gross function of the model is to compare empirical values for the physical attributes of these systems ("objective variables") to measures of user acceptance ("subjective variables"). The objective of the model is to determine relationships, if any, between the physical design attribute of interface quantity, documented reliability, and measures of user acceptance. These variables are defined as follows:

Objective Variables (Units)

M=man-hour ratio (BITE system maintenance hours/total avionics system maintenance hours)

I=total number of data interfaces (positive integer)

Subjective Variables (Units)

U=perceived utility (real number between 1 and 5, large values good, source data was question #2 of survey)

R=perceived reliability (real number between 1 and 5, large values good, source data was question #3 of survey)

B=perceived maintenance burden (real number between 0 and 1, large values good, source data was the average value of question #4 of the survey divided by five to yield a zero to one scaling factor)

For each system, a logarithmic plot of **M** versus **I** was derived. Likewise, **R** versus **U** was plotted, with the additional condition that **B** was used as a coefficient for **U**; actual values examined were **R** versus **B(U)**. The heuristic applied to this action is that perceived utility of a given system for its design function is inversely proportional to the amount of effort required to maintain it. Further investigation also generated plots of **M** versus **R** and **M** versus **B** for comparison.

To establish a baseline for analysis, an "ideal" system was constructed for comparison with the following measured values:

Table 1. BITE system figures of merit.

IDEAL	Raw	Log
M =	0.01	-2
I =	5000	3.69897
R =	5	0.69897
B =	1	0
U =	5	0.69897
B(U) =	5	0.69897
A-10 TEMS	Raw	Log
M=	0.063495358	-1.19726
I =	31	1.462398
R =	3.333333333	0.522879
B =	0.666666667	-0.17609
U =	3	0.477121
B(U) =	2	0.30103
C-5 MADAR	Raw	Log
M=	0.190651494	-0.71976
I =	2018	3.304921
R =	2.363636364	0.373581
B =	0.509090909	-0.2932
U =	2.272727273	0.356547
B(U) =	1.157024793	0.063343
F-15 ASP	Raw	Log
M=	0.042565579	-1.37094
I =	74	1.869232
R =	3.210526316	0.506576
B =	0.431578947	-0.36494
U =	3	0.477121
B(U) =	1.294736842	0.112182

M, the fraction of man-hours expended for system maintenance was set at 1% for the ideal case, almost certainly the best possible achievable value under real conditions. DoD weapons system operational requirement documents (ORDs) and the more recent capability development documents (CDD) frequently cite objective operational availability (A_o) targets of 99% for mission-critical systems. Complex 'systems of

systems' such as aircraft and space vehicles require the most accurate and dependable *in situ* BITE capability possible to achieve such goals, which in turn implies that BITE system maintenance expenditures should be absolutely minimal due to its presumed reliability. The number of interfaces (**I**) was arbitrarily and initially set at 5000, more than twice the C-5 MADAR value but reasonable for advanced next-generation equivalent systems. It was later found that the value of **I** was not significant for the model. Perceived reliability (**R**), maintenance burden (**B**), and system utility (**U**) were all set at the greatest possible favorable values.

B. DATA ANALYSIS

Graphical methods were selected as the preferred tool to examine relationships between these data sets. It must be emphasized that, as original research, this data has not been compared against any findings derived from similar studies since no equivalent research was found, and therefore statistical error limits are not known. Initial comparison of the "ideal" system to the A-10, C-5 and F-15 studied BITE systems yielded the following curves (10 x log y-axis used to separate values):

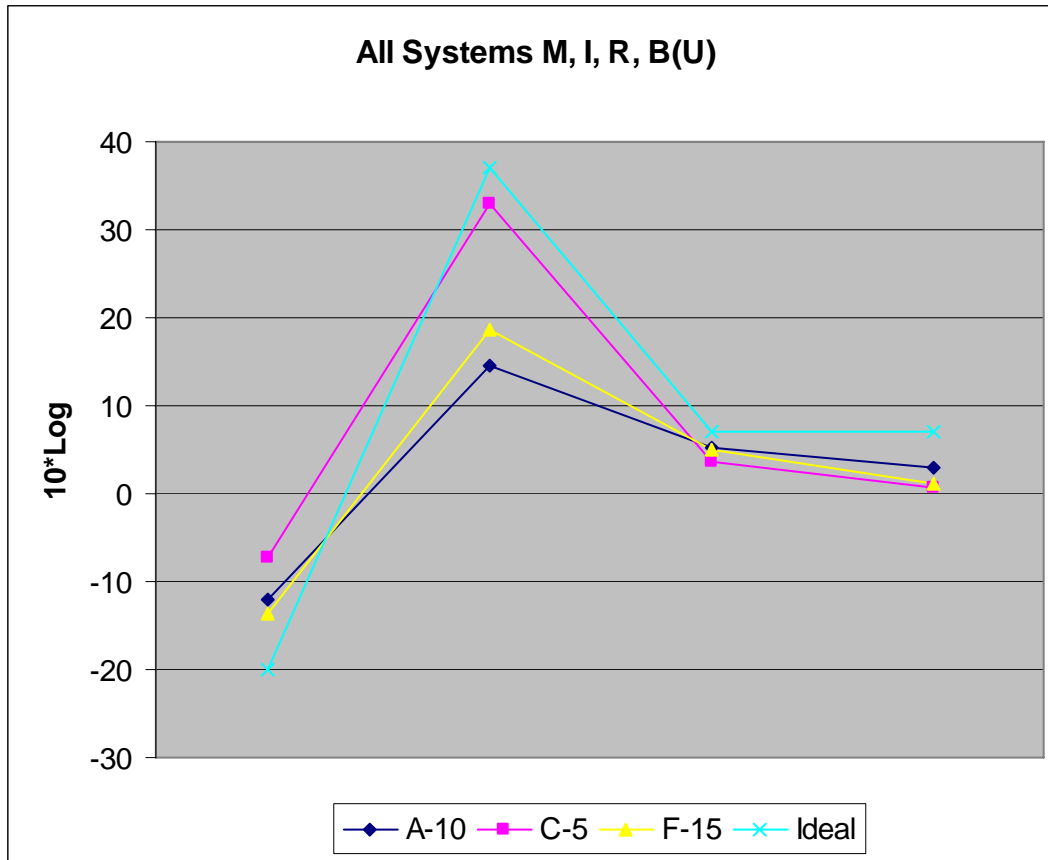


Figure 2. BITE Performance parameters compared to ideal values.

This comparison did not appear to be particularly useful, although it did illustrate two later critical points:

M and **I** (the two left-most data points) should be considered, at least during preliminary analysis, separately from **R** and **B(U)**.

The **R-B(U)** line segment of the ideal system satisfied the equation $y=x$, while the real systems did not, indicating that the relationship between reliability and perceived user utility was not 'simple'.

Since the number of interfaces varied considerably among the systems, a second plot was generated omitting **I** and comparing the remaining three parameters, as shown in Figure 3.

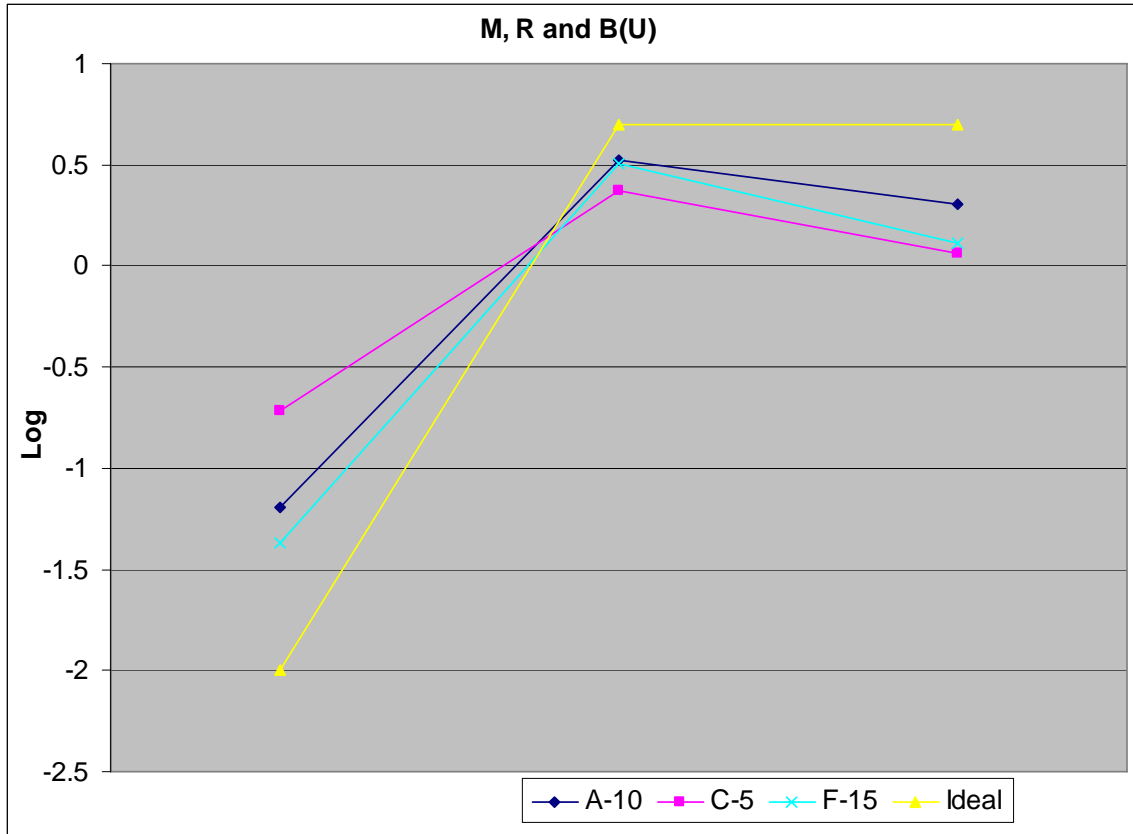


Figure 3. BITE performance parameters compared to ideal values.

This plot suggested the possibility that a significant correlation may exist between **M**, the fraction of man-hours used to maintain BITE and the user acceptance measures **R** and **B(U)**. Further examination of the ideal system's behavior was warranted.

The relationship between **M** and the other variables was obviously of interest. **M** is a direct indicator of a BITE system's maintenance requirements, and understanding its interaction with other system attributes is important with respect to research question #1. Figures 3 through 5 on the following page depict these relationships:

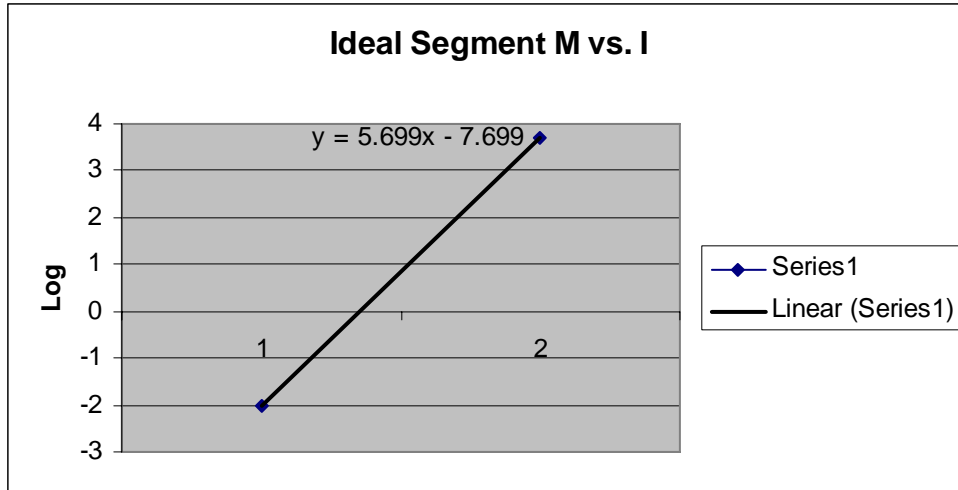


Figure 4. M vs. I for ideal system (I=5000).

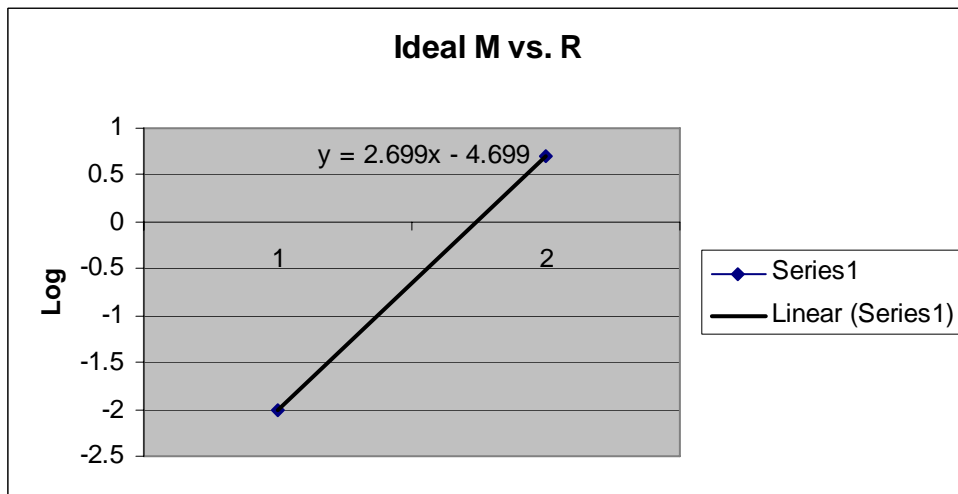


Figure 5. M vs. R for ideal system.

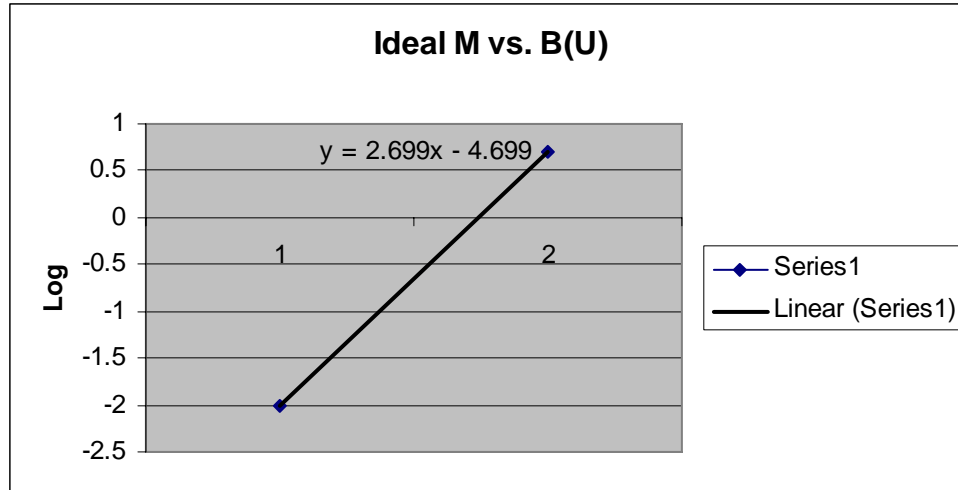


Figure 6. M vs. B(U) for ideal system.

This examination revealed that for $M=0.01$, the relationship between the decimal logarithm of M and those of I , R , and $B(U)$ can be generically expressed as

$$y=kx-(k+2) \text{ (eq. 1)}$$

Interestingly, this relationship remained valid for all values of I , suggesting that the number of data interfaces has no inherent effect on system maintenance time. At first glance that statement seems oxymoronic at best, but later discussion of design implications will illustrate the importance of this finding, which bodes well for future BITE architectures.

As previously described, the second key relationship, R vs. $B(U)$, is trivial in the ideal case ($y=x$), but more complex in real systems. Consider the following tabular comparisons of R and $B(U)$:

Table 2. R and B(U) values for subject systems.

Platform/System	Log(R)	Log(B(U))
A-10/TEMS	3.333333333	2
C-5/MADAR	2.363636364	1.157024793
F-15/ASP	3.210526316	1.294736842

Peak values of \mathbf{R} obviously do not correlate with identical values of $\mathbf{B(U)}$. The manifest reason for this discontinuity is that $\mathbf{B(U)}$ represents user effort required to achieve the highest possible value of \mathbf{R} and therefore an inverse relationship is expected, but the situation is further complicated by the fact that users assign a value judgment to $\mathbf{B(U)}$ based on the utility of data provided. To paraphrase a popular aphorism, 'the pain must be worth the gain', and accurate, reliable, useful data is the expected output of a BITE system. If such a system itself requires a significant amount of maintenance, then users will tend to regard its outputs with justifiable skepticism. The ideal case assumes that \mathbf{R} and $\mathbf{B(U)}$ are maximized; a perfect system would require no maintenance and provide accurate indications at all times. Although unachievable in reality, this standard apparently does provide a meaningful baseline to assess real BITE system performance.

The full data set, including graphics, is presented in Appendices 1 through 3. Unsurprisingly, given the fact that in an ideal system \mathbf{R} and $\mathbf{B(U)}$ are equal, the system with the greatest level of user acceptance (the A-10 TEMS) exhibits the least significant linear slope when these two parameters are graphically compared. What is unexpected from a purely analytical viewpoint is that the least complex system in terms of dedicated LRUs and diagnostic resolution (the F-15 ASP) suffers from the lowest proportional user acceptance (greatest slope) when its perceived reliability and maintenance burden are similarly compared. In other words, the relationship between \mathbf{R} and $\mathbf{B(U)}$ when viewed holistically across the sampled systems is non-linear if intrinsic physical complexity and \mathbf{M} are considered independent variables. Clearly, perception is an integral component of user acceptance.

C. INTERPRETATION AND SIGNIFICANCE

The x-axis in these plots is dimensionless and merely sequential, labeling the parameters in the order in which they are portrayed on the graph. Despite (or perhaps because of) this simplicity, the relationship described by Eq. 1 remains constant, even when \mathbf{I} is included despite its apparent independence from the other parameters. This strongly suggests that \mathbf{K} is merely an artifact of the initial selection of a value of 0.01 for

M, which does not lend any intrinsic significance to the constant or the equation. However, this fact also suggests that the relationship as expressed *is* significant, and worthy of further investigation.

Referring to Figure 3, it is clear that higher values of **M** are correlated with lower values of **R**, which in turn is associated with lower values of **B(U)**. This 'chain of casualty' is difficult to express with true mathematical rigor because the exercise mixes empirical and subjective data. Nevertheless, some tentative heuristics can be derived via examination of the results obtained by this study.

BITE system success depends on perceived system reliability by its end users. The C-5 MADAR system provides a remarkable array of *in situ* troubleshooting capability for its users, yet is not well-received by them due to the fact that a large fraction of their time is spent troubleshooting and repairing the system itself, which tends to introduce skepticism when interpreting MADAR alarms. From a design perspective, it is obvious that the most diverse capabilities are completely secondary to system maintenance reliability.

BITE system success depends on data resolution. At the opposite end of the spectrum, the F-15 ASP is not well-received by its intended users because the information it provides is non-specific. Simple "go/no-go" indications for monitored multi-LRU systems can be easily dismissed as the result of transient conditions such as platform power fluctuations, human error, etc., and if such indications are not accompanied by additional evidence of malfunction such as operator-reported discrepancies then they are usually ignored with long-term damage to BITE credibility. Designers must consider the practical utility of provided data within the context of monitored system's failure mode effects/causes analyses (FMECAs) (Levitt, 2003). Specificity is critical for utility.

The number of BITE data interfaces is irrelevant to user acceptance. This heuristic is predictive, but based on acquired data. User trust is founded on perceived reliability, which is a function of both BITE-provided data quality and the BITE system's

maintenance burden. The ideal system model provides a large number of interfaces, but the model's output does not change for all values of **I**. This characteristic may provide valuable guidance to designers as discussed in the following sections.

D. RESEARCH QUESTION ANSWERS

Although this study is of necessity quite limited in scope, preliminary answers to the stated research questions can be derived from this data:

At what point, and based on which factors, does maintenance of built-in-test and monitoring (BITE) subsystems obviate or negatively impact weapons system life-cycle cost and operational availability? Results strongly indicated that **M** is the primary factor influencing weapons system life-cycle costs associated with BITE. Using a standardized labor cost of \$50.00 per hour yields the following average annual BITE system maintenance expenditures for each weapon system examined:

A-10 TEMS: \$263,000 (200 aircraft, \$1315 per airframe, **M**=6.35%)

C-5 MADAR: \$1,247,293 (94 aircraft, \$13,269 per airframe, **M**=19.07%)

F-15 ASP: \$421,204 (750 aircraft, \$561 per airframe, **M**=4.26%)

It must be noted that these are direct labor costs only and do not reflect LRU repair costs and the corresponding support infrastructure needed to perform this work. Total BITE system support costs may in fact be an order of magnitude (or more) higher for complex systems such as MADAR. Even more importantly, no data exists to quantify direct costs incurred by erroneous LRU replacement (and attendant unnecessary organizational and Depot maintenance) from false BITE results or, conversely, from unnecessary or erroneous troubleshooting and component replacement performed because technicians did not utilize or trust BITE.

Intangible costs that are difficult to quantify may in fact have a greater negative impact. High values of **M** were also associated with low values of **R** and **B(U)**, implying that technicians were not convinced of the system's accuracy as a troubleshooting tool. Based on the author's experience, this paradigm frequently results in extensive additional troubleshooting of monitored aircraft system malfunctions as well as erroneous

component replacement. Therefore, a BITE system **M** value can serve as a reasonably reliable indicator of user acceptance and therefore system effectiveness, and **M** is in turn directly related to total system operational availability. Low values of **M** therefore increase A_o and decrease total life-cycle costs.

Is there an empirical relationship between the overall systemic complexity of BITE subsystems, the analogous complexity of monitored subsystems, and total life-cycle cost for a given integrated weapons system so equipped? Such a relationship does appear to exist, although 'empirical' may be too strong a term within the findings of this study; stochastic is a more accurate description. The most surprising result was that the number of interfaces (**I**) appears to have no effect on **M**, which is counterintuitive. More detailed research efforts are needed to more fully understand and quantify the large number of secondary variables involved. It is tempting to speculate that more effective BITE self-diagnostics would improve **M**, but this conjecture if pursued to its logical extreme might easily devolve into an endless amount of increasingly detailed internal self-monitoring, which at some point would act to increase **M** as even more transient conditions generate operator alarms.

Can a mathematical model representing interfaces and monitoring capabilities be constructed to optimize BITE infrastructure during the design phase to provide maximum operational availability while minimizing life-cycle costs? Optimization in the sense originally envisioned at the beginning of this work does not seem feasible. However, the analysis did define **M** to reveal it as the most critical design parameter for system success due to its direct correlation with measures of user trust and independence from the number of data interfaces.

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III. RESULTS AND RECOMMENDATIONS

A. RECOMMENDATIONS FOR FUTURE DESIGNS

The prime heuristic derived is that dedicated BITE systems must minimize user maintenance burden in order to gain acceptance and fulfill the system's design objectives. Despite the demonstrated independence of the number of interfaces to **M**, it is obvious that most malfunctions will occur at such interfaces, particularly in electrical connectors and other areas of discontinuity in signal paths that are exposed to external environmental effects. Therefore, implementing multi-path and multi-sensor redundancy in a manner similar to that employed for safety-critical systems such as automatic pilots (Branch, 1998) would be a most effective strategy to assure that a given BITE architecture wins user acceptance. For example, the C-5 MADAR engine vibration monitoring suite could be augmented by adding another full set of sensors to each engine, thus providing an inherent "reality check" to sensor readings and preventing or minimizing unnecessary/erroneous maintenance, which in this instance can include full replacement of suspect engines.

An important secondary finding was that data resolution and return was positively correlated with user acceptance, though modulated by perceived system reliability. As previously discussed, the F-15 ASP 'go/no-go' indication method apparently did not yield sufficiently decisive data to win confidence in the veracity of the results. Conversely, the C-5 MADAR provides not only threshold exceedance alarms but also real-time data usually presented in the form of 0 to 5 volt DC conditioned and scaled signal levels. Despite this unusually versatile troubleshooting capability, the system suffers from poor user acceptance; in the author's opinion, the sheer number of MADAR alarms commonly generated leads many technicians to disregard them as transient phenomena in much the same way that the F-15 ASP panel is seen as irrelevant in some respects, and leads to a dismissive attitude towards the system's capabilities.

The most successful system examined, the A-10 TEMS, provides not only recorded in-flight data for later analysis but also (via use of secondary ground support

equipment commonly known as the digital display unit, or DDU) the ability to examine real-time data presented in engineering units. This design philosophy seems to increase user acceptance in two fundamental ways. Since the DDU is portable, its accuracy can be readily checked by connecting the device to another aircraft, or attaching a different unit to a suspect aircraft. Secondly, the DDU's displays closely correspond with those of the systems monitored by TEMS, the aircraft engines; interpolation of TEMS data is greatly minimized thereby.

A corollary to the prime heuristic that dedicated BITE systems must minimize user maintenance burden in order to gain acceptance and fulfill the system's design objectives is that increased development and procurement costs needed to provide the requisite sensor redundancy will yield reduced sustainment costs over the lifetime of the weapons system. Due to highly variable budget environments, most Department of Defense systems across all mission areas usually remain in operational use well beyond their original design lifetimes. Additionally, equipment such as space mission control systems are often designed for "backwards compatibility" with legacy satellite constellations. A recent example is the Advanced Extremely High Frequency (AEHF) Satellite Mission Control System (ASMCS), which will replace the Milstar Satellite Mission Control System (SMCS) (Branham, 2006). Accurate BITE capability *that is trusted implicitly by its users* is urgently needed both due to the nature of the equipment's function and the need to restore it quickly as well as the fact that such a system must interface with two or more generations of technology in terms of spacecraft controlled. In the AEHF example, the need to distinguish latent interface incompatibilities, software problems, and operator errors from genuine equipment malfunctions is overwhelmingly critical and time-sensitive during both peacetime and wartime military operations since potential loss of a strategically essential communications satellite would have a devastating impact on *all* DoD functions.

B. IMPLICATIONS FOR ADVANCED BITE ARCHITECTURES

Condition-based maintenance (CBM) is an emerging concept for most DoD weapons systems. The central concept is to continuously monitor subsystem performance

and execute preventative maintenance actions prior to the occurrence of non-mission-capable failures (US Department of Defense, 2006). Aircraft engine trend monitoring in the commercial sector is an early implementation of CBM, and USAF is deploying a more comprehensive architecture known as CFRS (computerized fault reporting system) which will monitor the F-15 and C-130 fleets. Clearly, the goals of CBM cannot be realized if platform BITE lacks reliability and incurs a large maintenance burden, or, in other words, exhibits a high value of **M**. Not only would consequent low levels of user acceptance eventually drive such systems into limited use, but overall sustainment costs would increase disproportionately, especially if ancillary technical data is not procured due to mandates to use perceived--at least at higher echelons--infallible BITE systems, and consequently lower levels of training are provided to end users in a misguided belief that a given weapon system "can troubleshoot itself".

Arguably, this situation is the case with the C-5 MADAR. Despite troubleshooting trees that can stretch into literally hundreds of steps, the system if used mechanistically as intended in accordance with published technical data absent of inherent experience and judgment rarely produces decisive conclusions. Indeed, the sheer magnitude of effort required to perform these procedures verbatim frequently discourages technicians from performing them in their entirety, and therefore again defeats the functional utility of the system.

Sensor redundancy in proportion to monitored function criticality combined with parsimonious selection of other subsidiary monitored subsystems is therefore the only reasonable design strategy apparent to avoid these highly undesirable circumstances and consequences.

These design observations may yield significant improvement in future BITE architectures. However, one of the most intractable problems revealed by the study was the fact that users and maintainers of BITE are often the very same individuals, which conceivably can incur a lack of oversight or objective evaluation in terms of system utilization and performance. It would be absurd to establish a completely distinct Air Force Specialty Code (AFSC) or Military Occupational Specialty (MOS) for other services dedicated to BITE system maintenance, but some level of separation must be

achieved between the user and operator roles in order to decouple them and prevent undesirable negative feedback loops to become established. One means of doing so would be to dedicate selected maintenance personnel to BITE maintenance only for limited periods. This method would both concentrate system knowledge for the detailed personnel and provide objective, rather than subjective, analysis of malfunctions, hopefully resulting in improved user confidence and subsequently better BITE system utilization.

The only practical alternative to BITE is specialized test equipment, from the perspective of system maintainers. Such devices themselves require extensive logistics support throughout their life-cycle, and therefore military acquisition efforts generally tend to minimize development of this equipment. Furthermore, test equipment can be cumbersome to use, and this characteristic therefore may tend to discourage its employment.

From the perspective of system operators such as aircrew members and satellite controllers, the unique ability of BITE to provide immediate verification of system status is invaluable, and cannot be replaced by any other schema. It is essential for users to have some indication of system status before committing to operational decisions, and external test equipment cannot satisfy this requirement.

C. CONCLUSION

Although passive stand-alone BITE may eventually prove to be a transient phase in weapon system design, BITE capability as a paradigm is here to stay, and the lessons learned in this study are equally applicable to such alternative architectures. There is a relatively fine line between truly adding value and merely adding unnecessary labor and sustainment expense through employment of such systems, defined almost exclusively by the derived indicator **M**.

Methods for obtaining lower values of **M** must include both physical design considerations and development/adoption of user policies intended to minimize the field-level maintenance burden. As previously discussed, redundant sensors for critical platform data acquisition would allow cross-checking of indicated malfunctions and

thereby improve user confidence in BITE results. However, adding interfaces and equipment must also increase the potential for local system malfunctions and increase the system's maintenance burden.

From a policy perspective, if critical sensors are triple or quadruple-redundant then repairs of single or double sensor failures could be deferred until the next periodic Depot maintenance period. Removing this additional **M** contribution from the field user's area of responsibility would facilitate a refocus on the subject BITE system's core functionality and therefore improve overall platform maintenance.

For applications such as unmanned spacecraft ground control, redundant fault detection architectures (software or hardware based) are even more critical. Restoring functionality as rapidly as possible is of paramount importance and is operationally equivalent to an aircrew reacting to an in-flight emergency. Despite the fact that there is no potential for direct loss of life in these situations, loss of a space vehicle usually cannot easily or rapidly be redressed, and such losses invariably incur a large negative impact on the system's user community.

Additionally, simplifying troubleshooting procedures to the greatest degree possible would again make a significant contribution to BITE employment. Onerous, lengthy procedures are obviously non-quantifiable but important negative influences on system acceptance that may act to increase **M** based on the author's experience, since 'collateral' findings of BITE anomalies frequently occur during such efforts.

These suggestions are only some of the possible applications of the findings of this research. Further investigation is likely to reveal additional methods to refine BITE system performance from a holistic perspective. The main conclusion of this study is that obtaining values of **M** as close as possible (or ideally lower) than 0.01 will provide truly useful BITE performance and greatly reduce sustainment costs over the operational lifetime of DoD weapon systems.

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APPENDIX A. A-10 TEMS DATA

Table 3. A-10 REMIS data(April 1987-April 2007).

System	Maintenance Hours
01	0.0
02	0.0
03	0.0
04	0.0
05	0.0
06	0.0
07	0.0
09	0.0
11	721433.6
12	250983.1
13	689904.7
14	757789.8
23	647693.9
24	84716.0
41	176759.6
42	259270.7
44	121131.8
45	125130.5
46	576997.6
47	67975.1
49	30740.3
51	301701.3
52	58629.1
55	105201.3
62	98719.7
63	98126.5
64	28226.4
65	69180.3
69	24081.2
71	108180.9
72	10109.8
74	496014.5
75	764069.6
76	346090.7
91	16935.6
96	938.7
97	62197.5
99	121.9
AA	47.6
AP	13.0
XX	32.0

Appendix A. A-10 data (continued).

Table 4. TEMS survey results.

N=9

	A	B	C	D	E
Question 1	4	2	1	1	1
Question 2		4	1	4	
Question 3	1	2	5	1	
Question 4	1	3	4		1
Question 5	6	2	1		

Normalization (A=5, B=4, C=3, D=2, E=1)

					Averages	Comments
A	B	C	D	E		
20	8	3	2	1	3.78	>20% time resolving TEMS discrepancies
0	16	3	8	0	3.00	Sometimes use TEMS to troubleshoot other systems
5	8	15	2	0	3.33	Medium trust in system accuracy
5	12	12	0	1	3.33	Medium repair difficulty
30	8	3	0	0	4.56	Most respondents have no experience on other acft types

Appendix A. A-10 data (continued).

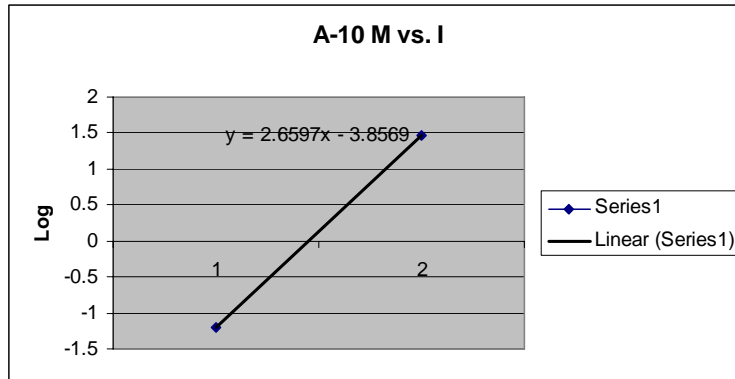


Figure 7. A-10 M vs. I.

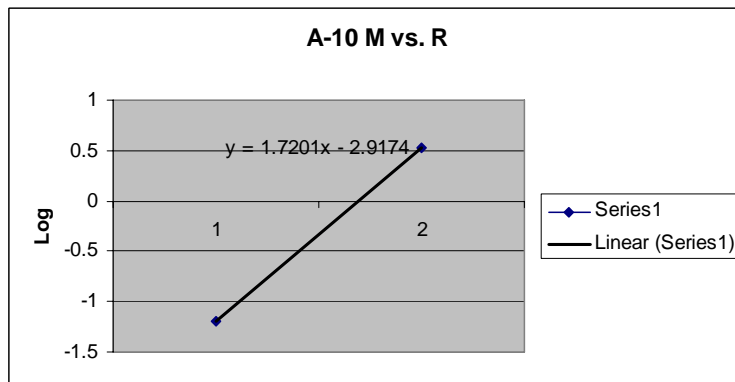


Figure 8. A-10 M vs. R.

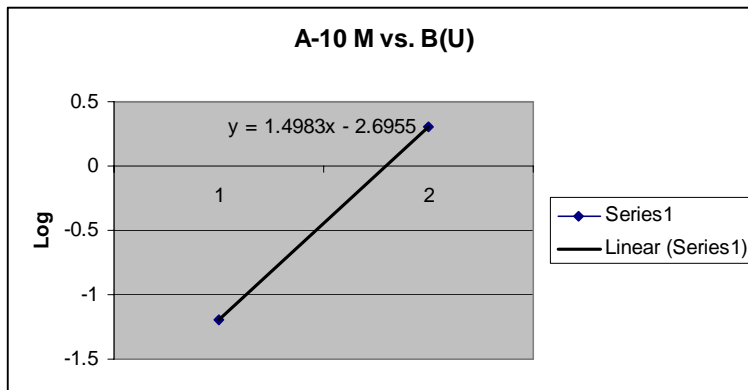


Figure 9. A-10 M vs. B(U).

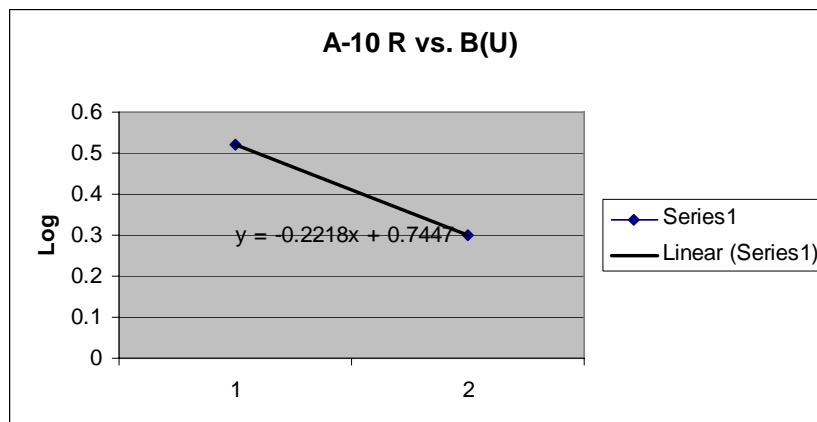


Figure 10. A-10 R vs. B(U).

APPENDIX B. C-5 MADAR DATA

Table 5. C-5 REMIS data (April 1987-April 2007).

C-5A		C-5B		C-5C	
System	Maint. Hrs.	System	Maint. Hrs.	System	Maint. Hrs.
01	0.0	01	0.0	01	0.0
02	0.0	02	0.0	02	0.0
03	0.0	03	0.0	03	0.0
04	0.0	04	0.0	04	0.0
05	0.0	05	0.0	06	0.0
06	0.0	06	0.0	07	0.0
07	0.0	07	0.0	09	0.0
09	0.0	09	0.0	11	34914.7
11	1581203.5	11	721828.6	12	6452.4
12	518756.8	12	226380.1	13	30347.3
13	1155500.8	13	697184.1	14	17146.7
14	681976.2	14	425145.3	23	29783.0
23	1249294.8	23	725908.0	24	3213.1
24	129121.0	24	85663.0	41	7602.4
41	424502.6	41	213185.1	42	5305.5
42	263791.5	42	172091.0	44	6240.1
44	333337.4	44	185115.7	45	5585.9
45	346273.0	45	177092.4	46	9005.6
46	545152.0	46	273657.3	47	820.0
47	84449.3	47	36360.2	49	5852.7
49	256473.0	49	151935.0	51	5454.8
51	265483.3	51	164570.0	52	4648.0
52	276178.7	52	161455.0	55	5885.0
55	332546.6	55	160485.8	57	21.3
57	121.8	57	1794.5	59	1001.7
59	28623.0	59	25107.7	61	716.8
61	52808.6	61	27420.7	62	193.6
62	26729.5	62	18124.0	63	440.4
63	27685.5	63	14981.8	64	1773.5
64	122614.7	64	72570.2	65	919.5
65	37205.0	65	20948.4	66	927.4
66	54177.5	66	20528.9	68	6.0
68	559.8	68	512.7	69	17.8
69	3226.4	69	1850.6	71	1010.2
71	44173.3	71	22238.4	72	3793.9
72	209716.5	72	142205.4	76	22.3
76	607.2	76	27082.0	82	149.1
82	26.2	82	3316.8	91	652.8
91	103918.9	91	51981.5	97	416.3
97	24730.7	97	9356.4		
AA	1.0	Y5	433.0		
Y5	18.8	ZZ	2.0		

Appendix B. C-5 data (continued).

Table 6. MADAR survey results.

N=11						
	A	B	C	D	E	
Question 1	2	6	1	2		
Question 2		1	3	5	2	
Question 3			5	5	1	
Question 4	1		3	7		
Question 5	2	2	1	4	2	
Normalization (A=5, B=4, C=3, D=2, E=1)						
				Averages	Comments	
A	B	C	D	E		
10	24	3	4	0	3.73	>20% time resolving MADAR discrepancies
0	4	9	10	2	2.27	Often use MADAR to troubleshoot other systems
0	0	15	10	1	2.36	Medium/low trust in system accuracy
5	0	9	14	0	2.55	Medium/low repair difficulty
10	8	3	8	2	2.82	Most respondents have experience on at least 2 other acft types

Appendix B. C-5 data (continued).

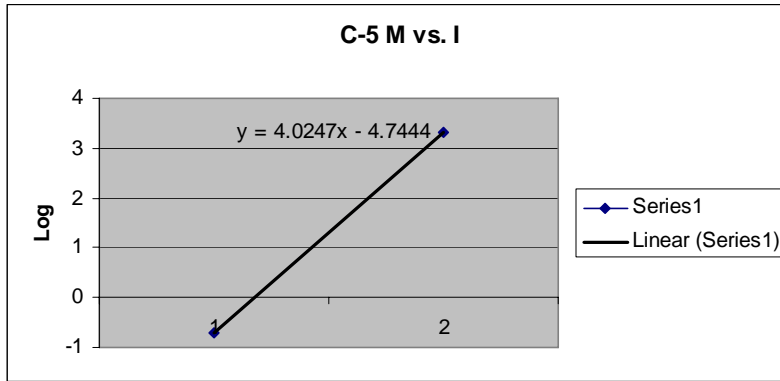


Figure 11. C-5 M vs. I

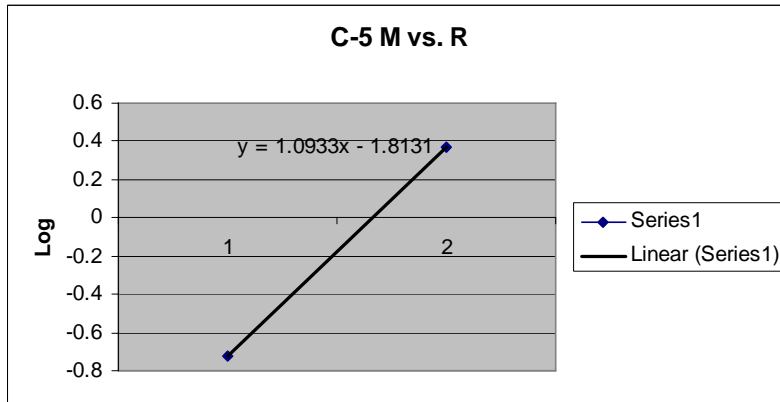


Figure 12. C-5 M vs. R.

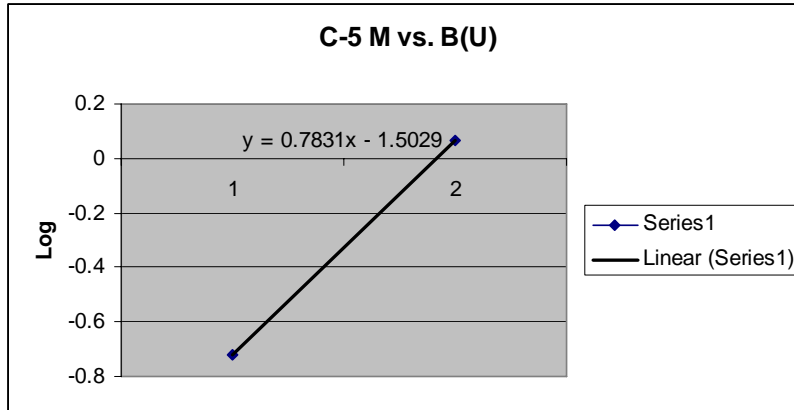


Figure 13. C-5 M vs. B(U).

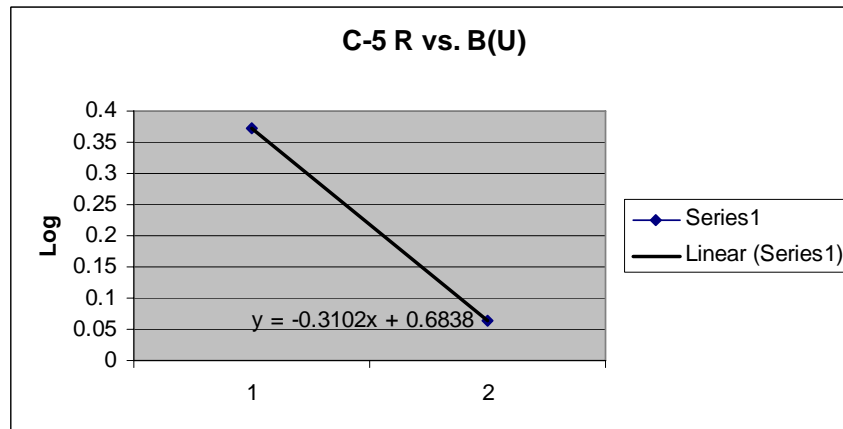


Figure 14. C-5 R vs. B(U).

APPENDIX C. F-15 ASP DATA

Table 7. F-15 REMIS data (April 1987-April 2007).

F-15A		F-15B	
01	0.0	01	0.0
02	0.0	02	0.0
03	0.0	03	0.0
04	0.0	04	0.0
05	0.0	05	0.0
06	0.0	06	0.0
07	0.0	07	0.0
09	0.0	09	0.0
11	484804.8	11	123312.9
12	127919.6	12	50569.3
13	314846.8	13	89792.7
14	233442.8	14	60132.3
1A	0.0	23	127040.5
23	697271.8	24	50023.6
24	258583.1	41	37188.0
28	7.3	42	26040.3
41	160550.3	44	17876.6
42	110542.7	45	36551.8
44	69525.8	46	73099.6
45	152660.3	47	8517.8
46	366771.8	49	6575.8
47	25327.1	51	37275.5
49	43579.9	52	18160.8
51	146351.6	53	0.2
52	86688.8	55	5592.3
55	30628.9	57	13258.9
57	52963.1	61	400.9
61	1891.9	63	30845.3
63	113995.4	65	16743.4
65	86388.3	71	27455.5
71	130026.8	72	92.0
72	8.5	74	135221.0
74	679123.4	75	54599.1
75	240319.7	76	28122.3
76	351390.4	91	1865.8
91	2774.7	92	239.1
92	605.4	97	16680.3
97	39918.6	99	3388.0
99	1828.5		

Appendix C. F-15 data (continued).

F-15C	
01	0.0
02	0.0
03	0.0
04	0.0
05	0.0
06	0.0
07	0.0
08	0.0
09	0.0
11	1702360.9
12	431346.1
13	1173499.4
14	825112.9
23	1313987.9
24	831837.4
28	186.1
41	524290.7
42	495251.2
44	321795.9
45	466743.7
46	1156392.7
47	140682.4
49	70847.8
51	408060.6
52	281959.1
53	87.8
55	111710.6
57	128623.4
61	181.8
63	413791.1
65	272157.7
71	449134.2
72	134.2
74	2573993.1
75	1060629.4
76	1954716.7
77	24.2
82	185.8
91	16204.9
92	504.6
97	77904.9
99	625.5
AA	22.5
ZZ	107.2

F-15D	
01	0.0
02	0.0
03	0.0
04	0.0
05	0.0
06	0.0
07	0.0
09	0.0
11	352467.8
12	134693.5
13	228223.5
14	157345.1
21	0.0
23	240091.7
24	134408.3
28	7.0
41	81740.1
42	84566.7
44	57066.6
45	77931.9
46	183126.5
47	28119.4
49	9854.1
51	80349.1
52	48232.3
53	436.9
55	20549.9
57	23518.1
61	104.8
63	95276.3
65	41720.4
71	77712.7
72	15.0
74	413003.9
75	168492.6
76	157290.0
77	38.0
82	12.0
91	4993.2
92	445.3
97	23750.1
99	911.1
AA	0.0
ZZ	61.2

Appendix C. F-15 data (continued).

Table 8. ASP survey results.

N=19						
	A	B	C	D	E	
Question 1	11	4	2	1	1	
Question 2	2	2	10	4	1	
Question 3	1	6	8	4		
Question 4		1	8	3	7	
Question 5	7	9	1		2	
Normalization (A=5, B=4, C=3, D=2, E=1)						
					Averages	Result
55	16	6	2	1	4.21	<20% time resolving ASP discrepancies
10	8	30	8	1	3.00	Sometimes use ASP to troubleshoot other systems
5	24	24	8	0	3.21	Low/medium trust in system accuracy
0	4	24	6	7	2.16	Low repair difficulty
35	36	3	0	2	4.00	Most respondents have experience on at least one other acft type

Appendix C. F-15 data (continued).

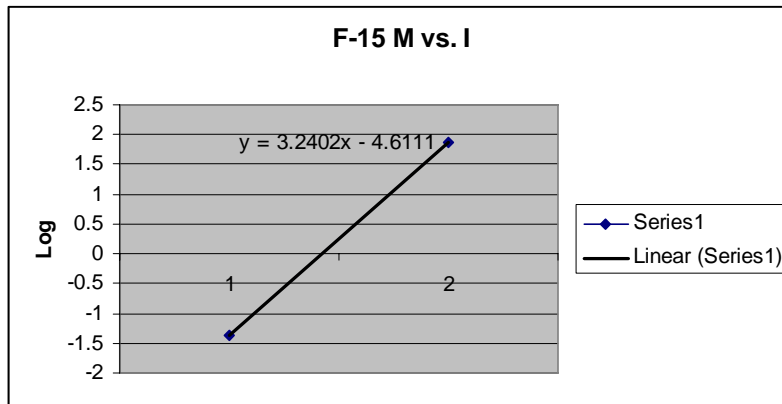


Figure 15. F-15 M vs. I.

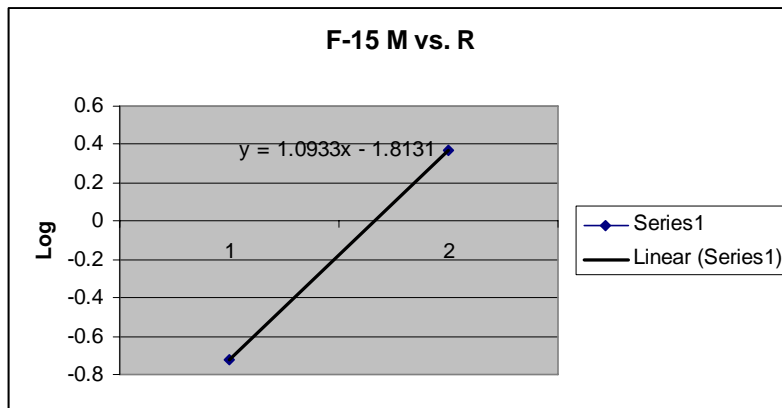


Figure 16. F-15 M vs. R.

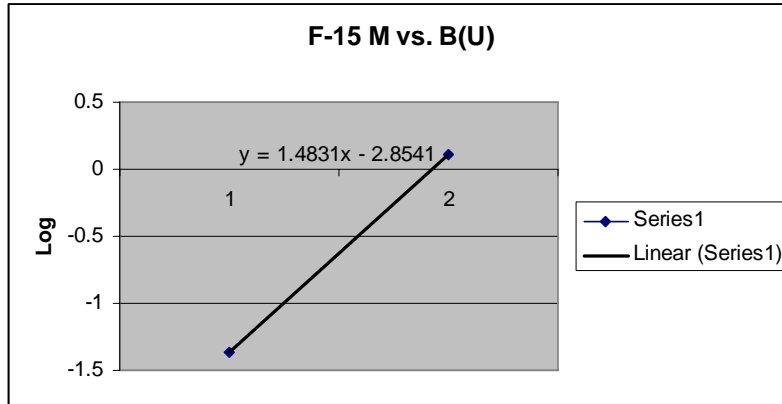


Figure 17. F-15 M vs. B(U).

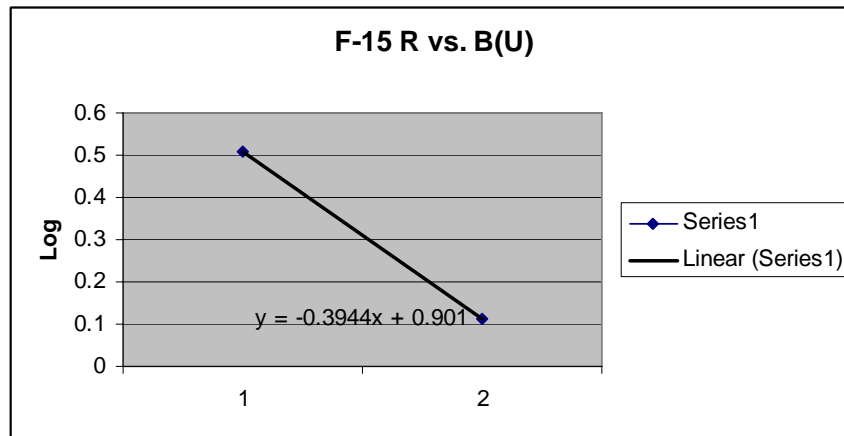


Figure 18. F-15 R vs. B(U).

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APPENDIX D. SYSTEM SURVEY

[SUBJECT AIRCRAFT/SYSTEM] QUESTIONNAIRE

Ver 2- 24 Apr 07

1. If you are an avionics technician, how much of your time doing avionics work is/was spent on [subject system] discrepancies?
 - a. 0%-20%
 - b. 20%-40%
 - c. 40%-60%
 - d. 60%-80%
 - e. 80%-100%

2. How often do you use [subject system] to troubleshoot other aircraft systems?
 - a. Never
 - b. Rarely
 - c. Sometimes
 - d. Often
 - e. Very often

3. How much do you trust [subject system] readings when troubleshooting other systems?
 - a. Not at all
 - b. A little
 - c. Somewhat
 - d. Quite a bit
 - e. Completely

4. Compared to other [subject aircraft] avionics systems, how difficult is [subject system] to troubleshoot & repair?
 - a. Much more
 - b. A little more
 - c. Medium/no difference
 - d. Not as bad as some others
 - e. Easy

5. How many other types of aircraft have you worked?
 - a. Zero
 - b. One
 - c. Two
 - d. Three
 - e. Four or more

Please write your rank and AFSC, including skill level (3, 5, 7)- names aren't needed-and return this to Nick Previsich. Thanks!

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