AEROSPACE REPORT NO.
TOR-2010(8591)-16

Space Vehicle Testbeds and Simulators Taxonomy and Development Guide

June 30, 2010

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Computer Science and Technology Subdivision
Computers and Software Division

Prepared for:

Space and Missile Systems Center
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

Contract No. FA8802-09-C-0001

Authorized by: Space System Group

Developed in conjunction with Government and Industry contributions as part of the U.S. Space Programs Mission Assurance Improvement workshop.

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AEROSPACE
Assuring Space Mission Success

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This document was created by multiple authors throughout the government and the aerospace industry. For their content contributions, we thank the following contributing authors for making this collaborative effort possible:

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Executive Summary

The Mission Assurance Improvement Workshop (MAIW) Testbeds & Simulators (Tb&S) Team was established to provide detailed guidance to the unmanned space vehicle and launch vehicle industry by preparing this Space Vehicle Testbeds and Simulators Taxonomy and Development Guide in support of the Mission Assurance Improvement Workshop in May 2010. In this document, the Tb&S team examines the state-of-the-industry and best practices regarding space vehicle Tb&S product capabilities and provides recommendations for lifecycle application of appropriate fidelity simulators and hardware testbeds to best support program needs. The document addresses three primary topic areas concerning Tb&S products:

Effective Communication within an SV Program of the needed Tb&S products (Taxonomy of Different Tb&S products): The document develops a common framework across the Aerospace industry for comparing and contrasting various Tb&S product End Users, End Uses, and characteristics. This leads to timely deployment of capabilities that support program needs.

Tb&S Development Guide: This document describes the complete development and operational lifecycle of a typical SV program Tb&S product that will allow programs to follow standard engineering methodologies to bring these capabilities to the End Users. We also offer specific guidelines based upon industry best practices and lessons-learned that would provide the foundation for Tb&S operations that directly support the mission success of the program.

Guidelines: The document offers specific guidelines based upon industry best practices and lessons learned to provide the foundation for testbeds and simulators operations that directly support the mission success of the program.

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1. Introduction

Space Vehicle (SV) development programs utilize different testbeds and simulators during the SV development lifecycle. The use of testbeds and simulators is critical in ensuring the success of both the SV launch and subsequent mission. However, two primary problems currently exist within many SV programs in the area of testbeds and simulators: first, inadequate types, availabilities, and capabilities of the testbed and simulator products throughout the program's lifecycle have resulted in incomplete Verification and Validation (V&V) of flight hardware with both flight and ground software. This has led to costly reintegration and rework as well as on-orbit operational issues. Second, inadequate emphasis on the planning, development, and efficient use of appropriate testbeds and simulators has led to overutilization of these products and to the development of testbeds and simulators that do not support the growing complexity of spacecraft. Both of these problems significantly increase mission success risk. Table 1-1 shows two recent examples that illustrate this industry-wide problem space and demonstrate the utility of this document.

Table 1-1. Mission Impact Examples

Major Interface Issue Discovery	**Oversubscription of System Testbeds**
Story: Subsystems were delivered for AI&T without being tested within high-fidelity Subsystem Testbeds, leading to late discovery of interface problems.	**Story**: High utilization and over-subscription of the System Testbeds occurred late in the program.
Result: Once the system was integrated, major interface issues were discovered between different subsystems and it took several months and significant added cost before the system could be sold-off.	**Result**: Tests were delayed or deferred to accommodate non-critical users and uses of the testbed since no alternate existed to support their needs. Also, defects were discovered late and verification occurred at a slower pace than required.
Rationale to support need for the Document: Having the appropriate testbed and simulator products ready at the correct development phase would have resolved the encountered integration problems. Also, this identifies the types and characteristics needed for Testbeds & Simulators at each phase of the program.	**Rationale to support need for the Document:** This guidebook provides recommended guidelines for introduction of a variety of simulators and testbeds to meet End User needs. Furthermore, having the ability to offload End Users and their End Uses to an appropriate testbed or simulator helps reserve the high-fidelity, high-cost system testbed for critical uses.

To avoid these issues and to take into account the fact that Space Vehicles (SV) continue to grow in complexity, more emphasis needs to be made in the planning, development, and efficient use of the SV program's testbed and simulator products. We address this problem space by focusing on three key topic areas:

1. **Effective Communication within an SV Program of the needed Testbeds and Simulators (Taxonomy of Different Testbeds and Simulators):** The document develops a common framework across the Aerospace industry for comparing and contrasting various testbed and simulator End Users, End Uses, and physical characteristics. This leads to timely deployment of capabilities that support program needs.
2. **Testbeds and Simulators Development Guide:** This document describes the complete development and operational lifecycle of an SV program testbed or simulator that will allow programs to follow standard engineering methodologies to bring these capabilities to the End Users. We also offer specific guidelines based upon industry best practices and

lessons learned that would provide the foundation for testbed and simulator operations that directly support the mission success of the program.

3. **Guidelines:** The document offers specific guidelines based upon industry best practices and lessons learned to provide the foundation for testbeds and simulators operations that directly support the mission success of the program.

In the context of this guide, we define a Testbed as an environment containing the hardware, instrumentation, simulators, software tools, and any other support elements needed to conduct a test. Similarly, we refer to a simulator as a system whose main function is the execution of a set of behaviors that simulate the presence of external systems or environments. We denote the combined Testbeds and Simulators products of a space program as **Tb&S** products.

As the industry team met to share their experiences, it was quickly recognized that our varied background and experiences had uncovered a communication barrier because we lacked a common terminology in which to describe our Tb&S products. The purpose of putting forth a taxonomy for Tb&S products was in hopes of fostering more communication between various government and industry partners. This taxonomy provides a framework for comparing and contrasting the development and application of different Tb&S products and is guided by the diagram shown in Figure 1-1. The standardized taxonomy is expected to aid in the communication of issues and sharing of solutions between developers, program implementations, and management.

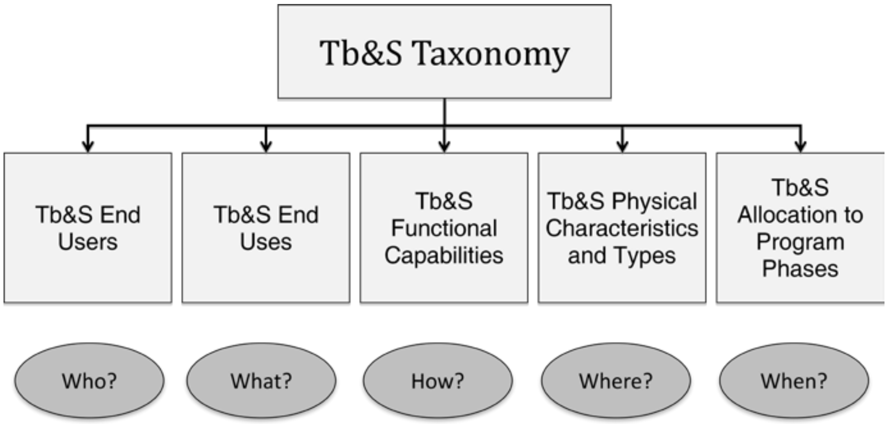


Figure 1-1. Tb&S Taxonomy.

1.1 Scope

This document is primarily focused on new SV development programs, as these programs require new development efforts that require effective communication of program needs matched to Tb&S capabilities. Follow-on programs will also benefit from using this guide’s taxonomy as well as guidelines relating to upgrades due to obsolescence and technology insertion into Tb&S.

1.2 Application of this Guide

This intended audience for this guide is program system engineers, program managers, testbed and simulator users, and testbed and simulator developers. System engineers are responsible for developing the SV program’s V&V plan to coordinate Tb&S requirements and users through the V&V development process. Program Management will benefit by using the common terminology and processes for identifying user needs matched to capabilities. Users of program Testbeds and

Simulator are ultimately the customers of the products developed using this guide, and must clearly communicate the intended use but must also be aware of driving cost, schedule, and technical complexity and risk into the development program. This document also addresses aspects of simulator requirements, development, certification, and operations and recommends development of a Program Tb&S Development Plan (subordinate to Program Test & Evaluation Master Plan). A template of a Program Development Tb&S Plan is provided, which includes a Table of Contents, Scope, Overview, and other critical sections that will serve as a common starting point for the development program. Finally, the guidelines contained within this document should be evaluated for inclusion in U.S. space programs developing and operating Tb&S products. Each guideline is in the format shown in Table 1-2. Guidelines are located throughout the document in the appropriate section, but are also summarized in Section 7 for reference. Overall, the document contains 39 guidelines, however, each SV program may choose to incorporate only a subset of them, depending on the specific program characteristics and goals.

Table 1-2. Guideline Format Example

Guideline XX: text …
Rationale and Example: text …

1.3 Organization of this Guide

This document is organized as follows: In Section 2 (Definitions), we develop a consistent set of definitions associated with the description, development, and use of Tb&S products used across the industry. In Section 3 (Space Vehicle Tb&S Taxonomy), we define a detailed characterization of Tb&S to support their usage classification in a hierarchical structure. In Section 4 (Allocation of Tb&S within the Lifecycle Phases of an SV Program), we describe a sample allocation of Tb&S within a typical development lifecycle described in the *Guidelines for Space Systems Critical Gated Events* document [TOD-2009(8583)-8545]. In Section 5 (Lifecycle Process for Program Tb&S), we describe the entire lifecycle of Tb&S development, from their conception to their operations. In Section 6 (Operational Considerations for Tb&S), we discuss the operational considerations for deploying Tb&S products. In Section 7 (Guidelines Summary), we provide a cross-reference matrix to all guidelines listed in the document. A plan template for Tb&S development is provided in Appendix A. In Appendix B, we provide the results from surveys given to users and developers of Tb&S products from each organization.

2. Definitions

The following definitions provide a framework for common terminology as it applies to the topic of Tb&S. The definitions provided are often specific to the application and use within the testbed and simulator domain. The definitions are divided into two groups—Table 2-1 provides key definitions and Table 2-2 provides other useful supporting definitions.

Table 2-1. Key Definitions

Term	Description
Simulator	A system whose main function is the execution of a set of behaviors that simulate systems or environments not present in the test configuration.
Testbed	An environment containing the hardware, instrumentation, simulators, software tools, and/or other support elements needed to conduct a test.
Dynamics Simulator	A simulator whose main function is the reproduction of dynamics system behavior and often enables closed-loop testing between hardware and the simulator (see Section 3.4.1).
Non Real-Time Simulators (NRT)	This simulator is a purely software simulation of SV components that has few if any constraints on its relative time execution and therefore its timing is nondeterministic. It is typically hosted on a workstation running a non-real-time operating system (e.g., Windows) and includes no flight or EM hardware in the loop. The simulator may include the flight software (FSW) in a closed-loop simulation of Space Vehicle hardware, dynamics, environment, and payload. The implementation includes a command and telemetry interface to the simulation software (see Section 3.4.2.1).
Non Flight-Like Testbed (NFLT)	This testbed has the capability to operate as a subsystem or system testbed but uses lower fidelity (non-flight like) hardware. The dynamics simulator may execute either non real-time or real-time depending on the required capability. The testbed includes an open-loop emulation of the flight interfaces and may include the dynamics models necessary for closed loop testing. The testbed also provides a command and telemetry interface to the operator (see Section 3.4.2.2).
System/Subsystem Testbed (STB)	This testbed is a combination of Engineering Models (EMs) and/or flight units of the Space Vehicle and/or payload subsystems, and may include a Dynamics Simulator that simulates other flight subsystems as well as the orbital and attitude dynamics and the environment. The implementation includes all the electrical ground support equipment required to provide subsystem interfaces including a ground console to provide a command and telemetry interface. A System Testbed differs from a Non Flight-Like Testbed because it includes higher fidelity hardware components (see Section 3.4.2.3).
Integrated Space Vehicle Testbed (ISVT)	This testbed type is a mating of an integrated space vehicle with a Dynamics Simulator to support closed-loop testing. The integrated space vehicle testbed requires components of the AI&T environment (see Section 3.4.2.4).

Table 2-2. Tb&S Supporting Definitions

Term	Description
Attitude Determination and Control Subsystem (ADCS) Software	Software responsible for attitude determination and control of the flight spacecraft. This is often compiled to be a part of the full FSW (see below); but for the purpose of design and development it is frequently handled separately. When FSW is mentioned within this document, it includes the components for ADCS. This is also referred to as Attitude Control Subsystem (ACS).
Build and Test Phase	This is the phase in a program lifecycle that includes all activities associated with building hardware, developing software, integrating systems, and verifying system level requirements. Ref. TOR-2009(8583)-8547
Certification	As applied to Tb&S, certification is the process of ensuring that the testbed/simulator is ready for an intended use. Other interchangeable terms are accreditation, sell-off, or ready-for-use.
Closed Loop	A control system with a feedback loop that is active with the unit under test. This requires external stimulus of inputs that respond to the state of the control outputs.
Command and Telemetry Database	Database that contains detailed information on how commands are built and constructed, and how telemetry is encoded and can be decoded.
Dry Run	A test exercise executed for the purpose of checking out hardware, processes, procedures, and training prior to test runs for the record (formal testing). For example: a script dry run may be a complete execution of the script on the testbed prior to running it on the space vehicle.
Electrical Ground Support Equipment (EGSE)	Electrical non-flight equipment whose purpose is to support or augment the interface to an item under test—especially to provide interfaces or functions required for ground operations that the unit would not require for flight. For example: a Telemetry and Command Test Set to provide a hard-line (vs. RF) interface to the ground system.
Emulator	A system whose main function is the reproduction of a combined hardware and software simulation, so as to perform as a surrogate for said system. An emulator simulates hardware characteristics. For example: a GPS 1 pulse per second (PPS) emulator would drive a physical pulse signal into another electronics box. A GPS 1PPS simulator may just write to the appropriate register of software.
End Use	An End Use is the application for which the end product has been designed.
End User	An End User is the ultimate user of a Tb&S end product.

Term	Description
Engineering Model (EM) Hardware	A non-flight version of a flight hardware unit that utilizes flight design, flight-like components and processes in its manufacturing. This is also referred to as an Engineering Development Unit (EDU).
Fidelity	The accuracy with which the system reproduces the characteristics and behavior of the object of interest. In general, a closer behavior to flight is considered higher fidelity.
Fidelity – Interface Fidelity	Interface fidelity is the accuracy of the electrical, physical, or software boundary between two or more components. For some purposes, the interface fidelity is more important than the overall fidelity of the component. For example, if the UUT only needs to interact with an external box—that external boxes interface fidelity is important; but the complete functionality of that box (those pieces that do not interface with the UUT) is not important.
Fidelity – Hardware Fidelity	Hardware fidelity is the accuracy of the device baseline against the flight unit. Utilizing non-flight parts or other parts substitutions reduces the hardware fidelity.
Fidelity – Simulation Software Fidelity	Simulation Software fidelity is the accuracy of the simulation in behaving like the component/environment it represents. This can be in multiple different regards such as timing, precision, functionality, etc. The baseline measurement for this fidelity is against the real component or environment that is being simulated.
Flight Software (FSW)	Software that executes according to mission requirements on flight hardware or flight-like systems. For the purpose of this document, this term is used generically and is to include all software including subsets like Attitude Determination & Control (ADCS), Command & Data Handling (C&DH), payload, etc.
Ground Console	A user console for performing command, control, and telemetry monitoring of a system/component. Examples include: a computer for commanding the vehicle or a computer console that interfaces with the simulations on a testbed.
Hardware In The Loop (HITL)	A test configuration in which software and hardware are integrated together, including required simulators, to perform a set of dynamics scenarios, often involving state feedback and control. This is also referred to as HWIL. For example: a reaction wheel model that is connected to the avionics hosting the vehicle flight software—the avionics is the hardware in the loop.
Heritage	A product whose design has previously undergone qualification and flown

Term	Description
Models	A mathematical implementation of the understood rules of behavior of the desired system to be simulated. A mathematical or logical representation of a set of system behaviors. For example: a gravity model that defines gravity as a function of position/time.
Non Real-time (NRT)	A system that has few (if any) constraints on its relative time execution.
Open Loop	A system that provides unit under test inputs without utilizing any feedback loop. The Unit Under Test inputs are generally fixed unless altered by an external factor (e.g., a state change by the tester).
Real-time	A system that has timeliness requirements for its execution. Its execution is deterministic within the time domain.
Simulation	The executable implementation of a model, hosted on a simulator.
Simulation Database	A database that contains configurations, parameters, or other data items related to a simulation or group of simulations.
Simulation Engine	Simulation component that controls and orchestrates the overall simulation execution.
Simulation Framework	A software environment for developing and integrating simulation scenarios.
Simulation Modules	A set of software routines or components that together executes the required simulation function.
Simulation Platform	The environment within which the simulation executes (hardware and software infrastructure).
Simulator Console	A user console for configuring and reporting status of a simulator. This is a specific type of a ground console.
Software Item Qualification Testing (SIQT)	Formal testing of the flight software unit level items to validate its functionality meets requirements (e.g., testing of the code modules used for communication across 1553).
Space Vehicle (SV)	The space system compromising the spacecraft bus and payload(s).
Unit Under Test (UUT)	The device(s) that are the target of a set of tests.
Validation	The process of evaluating an item to confirm the product satisfies the system intended use (“build the right product”).
Verification	The process of evaluating an item to confirm the product satisfies the specified requirements. (“build the product right”)

3. Space Vehicle Tb&S Taxonomy

In this section, a common framework is introduced for comparing and contrasting various Testbeds & Simulators (Tb&S) users, uses, functional capabilities, and characteristics that are encountered across Space Vehicle (SV) development programs. A common set of Tb&S End Users is identified in Section 3.1, which drives a set of End Uses (Section 3.2) associated with different Tb&S product types for different SV programs. The End Uses, in turn, drive a set of Tb&S functional capabilities, which are listed in Section 3.3. Using these functional capabilities, we derive four Tb&S types that are common to SV development programs and discuss their physical taxonomy and fidelity in Section 3.4. Since different SV programs have different Tb&S needs at various stages of SV development, the characterization of the Tb&S types presented in this section is not a static taxonomy but allows for the End Users, End Uses, and the functional capabilities to overlap across all four Tb&S types. Furthermore, the characterization takes into account the fact that a particular SV program may not necessarily use all four types that are identified in Section 3.4, but only a subset of them as determined by program-unique technical requirements as well as schedule and cost factors.

3.1 Tb&S End Users Taxonomy

One of the first steps towards adequate planning of the development and the use of Tb&S for any SV development and operations program is to identify who the *End Users* are. An End User is defined as the ultimate user of a Tb&S end product. By identifying the End Users, the End Uses (see Section 3.2) can be identified along with the program phase required for that End Use as well as the Tb&S types (see Section 3.4). A summary of the End User taxonomy is shown in Figure 3-1 and brief description of each End User is given in Table 3-1, followed a more detailed description in the subsequent paragraphs.

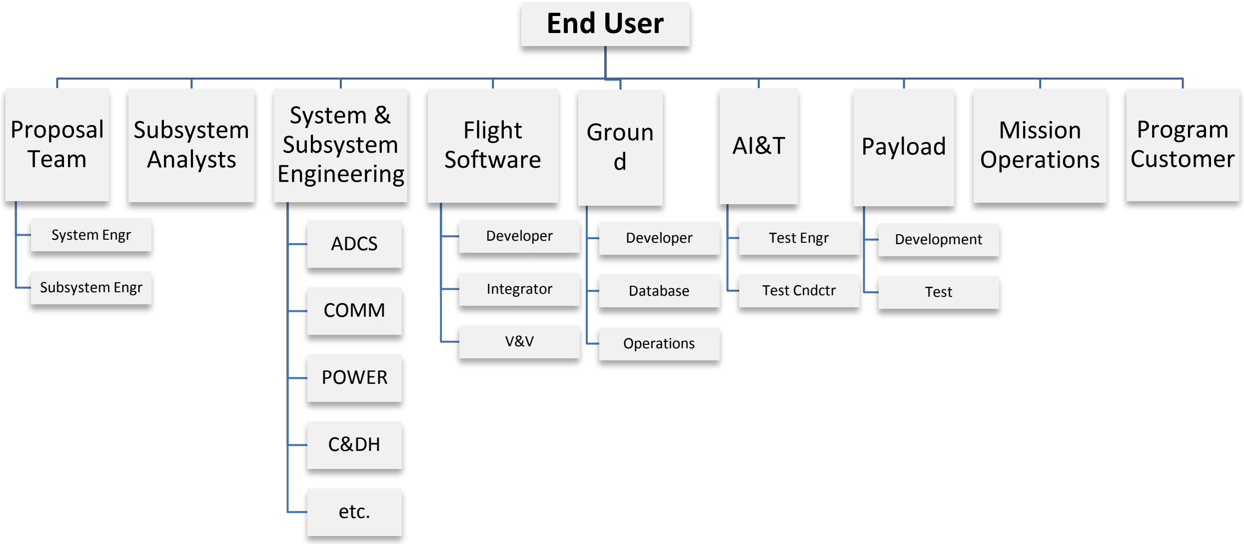


Figure 3-1. End user taxonomy decomposition.

Table 3-1. Tb&S End Users Overview

End User	Description
Proposal Team	Technical proposal staff developing candidate concepts during the pre-Award phase
Subsystem Analysts	Subsystem engineers responsible for concept development and algorithm development.
System & Subsystem Engineers	System and subsystem engineers responsible for analysis, design and performance of space vehicle systems and subsystems.
Flight Software Engineers	Engineers responsible for developing, integrating and testing, qualifying and operating FSW. This category includes both spacecraft bus and spacecraft payload flight software.
Ground Development & Operations	Engineers supporting ground and test functions including C&T database development, ground control hardware and software.
Assembly, Integration, & Test	Test engineers and test conductors responsible for integrating, testing, and configuring the space vehicle prior to launch.
Payload Development & Test	Payload designers, test engineers and test conductors responsible for design and test of the space vehicle payload.
Mission Operations	Operations engineers responsible for controlling the space vehicle after launch.
Program Customer	End customer who may be performing IV&V, training, or integration with other parts of the larger system.

Proposal Team: The proposal team includes system and subsystem (e.g., ADCS, FSW, I&T) engineers who work with the Tb&S development team to validate competing concepts under consideration as candidates for a proposal effort. These proposal users often become End Users under categories defined below during the execution of the program.

Subsystem Analysts: This user category includes analysts responsible for defining and examining the required performance capability during the proposal, refining it during the requirements and design phase, verifying this capability during the test phase of the program, and supporting the operations (including on-orbit operations, failure analysis, and anomaly resolution support). Subsystem Analysts use Tb&S products to develop algorithms prior to releasing the algorithms to FSW engineers.

System and Subsystem Engineers: This user category is comprised of system engineers and subsystem engineers from a variety of subsystems (i.e., ADCS, Communications, Power, Thermal, etc.). The System Engineers require Tb&S to validate and verify requirements. The engineers use Tb&S to run system level tests to validate operation of the Space Vehicle such as orbit-in-the-life tests and scenario-based testing (launch ascent, early orbit, end of life, etc.). Subsystem engineers use simulators to validate or formally verify hardware or software interfaces from their components, perform risk reduction activities, assist with anomaly resolution support (operational or test), and to support many system level activities that may be tested or verified on the testbed or simulator.

Flight Software Engineers: This End User group is composed of Space Vehicle (Bus and Payload) engineers as follows: FSW developers who use Tb&S products to test their software at the unit level in an environment designed to provide realistic timing and inputs for low-level software components; FSW integrators, who use Tb&S products to integrate software units into top level FSW end items in an environment having realistic timing and hardware interfaces to external components; FSW I&T team, which perform dry run testing and debug activities as needed to ensure that FSW is ready for qualification testing; and the FSW V&V team (such as the Software Item Qualification Test (SIQT) team), who use Tb&S products to formally test FSW in an environment designed to provide a realistic flight environment. Activities continue through and beyond launch to include regression testing, FSW upload and patch testing, and anomaly resolution support.

Ground Development and Operations: The ground development and operations user category consists of ground systems, Ground Support Equipment (GSE), ground software and ground database developers. The database developers are responsible for creating and maintaining the Command and Telemetry database. These engineers use Tb&S to test the command and telemetry database in an environment that provides realistic telemetry responses to commands. Ground operators are responsible for Operations & Maintenance O&M of the entire ground segment and may use Tb&S to assist in their duties.

Payload Development and Test: This user group is a subset of the Systems and Subsystem Engineers (described above) specifically assigned to design, build, test, and verify space vehicle payload(s) and/or instrument(s).

Assembly, Integration and Test Team (AI&T): The AI&T team is comprised of test engineers and test conductors. These test personnel use Tb&S to perform initial HW integration validation (risk reduction), dry-run test procedures, investigate test anomalies, perform system-level requirements verification, execute day-in-the-life testing, support ground station end-to-end testing, or to support mission rehearsals.

Mission Operators: This user category includes the System Engineers and operators who comprise the Flight Operations Support Team. These personnel conduct operations against Tb&S for mission rehearsals and operator training activities.

Program Customer: The program customers are the End Users who may be performing V&V, training, integration with other parts of the larger system, anomaly resolution, or FSW patch testing and verification.

3.2 Tb&S End Use Taxonomy

The section details *End Uses* of Tb&S in space vehicle development and operations programs. An End Use is defined as the application for which the end product has been designed. Within this section, each End Use is described along with value to the program and End User. Any risks of omitting or curtailing the End Use during a development program are discussed for each End Use. While each End Use can correspond to a particular End User category, we do not make a direct correlation in our description of the End Uses. We recognize the fact that each program is different and specific correlations will vary between programs. Sample correlations of these End Uses applied within the phases in a risk-constrained program and a resource-constrained program lifecycles are discussed Section 4. As shown in Figure 3-2, we define five primary End Use categories spanning the lifecycle of Tb&S products from Concept Development to Mission Operations.

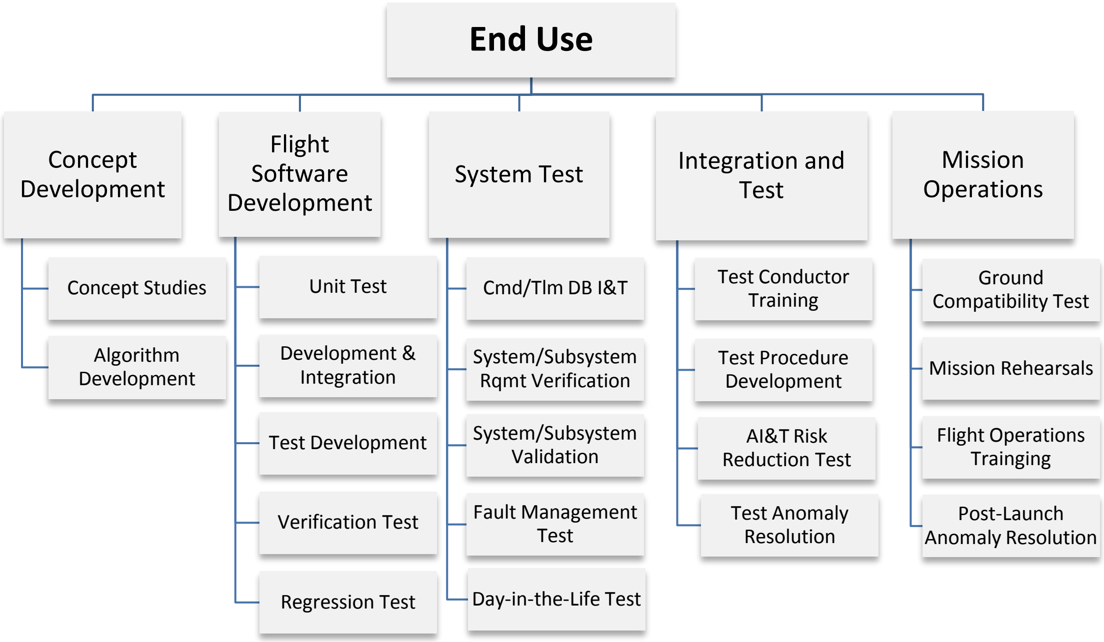


Figure 3-2. End Use Taxonomy Decomposition

The End Uses identified in Figure 3-2 are summarized below in Table 3-2 followed by a detailed description of each End Use in the following sections and paragraphs.

Table 3-2. Tb&S End Uses Overview

End Use	Type of End Use	Description
Concept Development (Section 3.2.1)	Concept Studies and Development	Proposal support: design comparisons, design refinement, trade studies
	Subsystem Algorithm Development	Algorithm development leading to implementation in software
FSW Development (Section 3.2.2)	FSW Unit Test	Low-level SW component testing in a representative environment.
	FSW Development & Software Item (SI) Integration	Integration of SW units into a FSW builds, including limited functional testing and benchmarking HW requirements.
	FSW Test Development	Dry running FSW qualification and verification test scripts.
	FSW Formal Requirements Verification /Software Item Qualification Test (SIQT)	Formal execution of FSW qualification tests to verify FSW requirements, FSW interfaces, and validate FSW algorithms

End Use	Type of End Use	Description
	FSW Regression Test	Regression testing involves the retesting of a software item following the modification of that item or any of its interfacing items.
System/Subsystem Test (Section 3.2.3)	Command and Telemetry Database Integration & Test	Development and testing of the flight command and telemetry database.
	System/Subsystem Requirements Verification	Verify system/subsystem requirements and interfaces.
	System/Subsystem Validation	Validation of system/subsystem intended use.
	Fault Management System Test	Fault detection and response testing, often including fault injection.
	Day-In-The-Life Test	Long duration and mission scenario ConOps V&V testing.
AI&T Support (Section 3.2.4)	Test Conductor Training	Training activities for test engineers and test conductors.
	Test Procedure Development	Dry running AI&T test procedures prior to running against the flight vehicle
	AI&T Risk Reduction Test	Integrating or testing space vehicle systems, subsystems, components and EMs on a testbed prior to use on flight vehicle.
	Test Anomaly Resolution	Investigations of anomalies using a Tb&S product.
Mission Operations Support (Section 3.2.5)	Ground Compatibility Test	Closed loop testing to exercise ground C&T hardware and software as well as activity planning software.
	Mission Rehearsals	Closed loop testing to exercise operations teams, procedures and contingency flow processes.
	Flight Operations Training	Training exercises to familiarize individual operations team members with the use of flight/ground systems.
	Post-Launch Anomaly Resolution	Contingency activity to investigate on-orbit anomalies on a testbed.

3.2.1 Concept Development End Uses

Concept Studies and Development: For concept studies, the Proposal team may explore operational capabilities of the candidate designs in support of the selection of a design path that will be developed for the proposal. In other uses, the proposal team may use Tb&S products to refine the proposal concept. Typical studies would include design comparisons in maneuverability, controllability, stability or line of sight, or design refinements to FSW and ADCS parameters and algorithms. The intent of this “use category” is to ensure that data is available for trade studies used by the proposal team in selecting the basic design concept that will be presented in the team’s proposal. The risk in omitting or curtailing these investigations is that the proposal team risks committing to a poor design path. This may incur added costs if earlier work has to be discarded in a fundamental design change later in the program or if the chosen design path turns out to be more difficult than the proposal bid originally envisioned.

Subsystem Algorithm Development: The purpose of the subsystem algorithm development End Use is for subsystem engineers to finalize algorithms and parameters in preparation for delivering these algorithms to the FSW development team. In this use, Subsystem engineers, like ACS or EPS developers, use Tb&S to validate and debug their algorithms before delivery to FSW. Typically, the ACS development team uses a high-fidelity analysis simulation to prove their algorithms, which is also used to develop open-loop test cases for FSW ACS algorithm verification. The real-world dynamics, environment, disturbance, and hardware models developed for the Tb&S products during this End Use are often (or have the opportunity to be) re-used during later phases of the program. The analyst dynamics test results provide truth data to be used by the Tb&S development team during their dynamics simulator post-test analysis. The intent of this “use category” is to ensure that mature algorithms are passed to FSW. The risk in omitting or curtailing this development work is that inadequate algorithms may be implemented in FSW, and the need for further refinements may not become apparent until later, more costly phases of the program, such as I&T.

3.2.2 Flight Software Development End Uses

Flight Software Unit Test: The FSW development team uses the native development environment for SW unit test and debugging activities including boundary, coverage, and logic paths verification. FSW developers use Tb&S to test FSW components at a unit and component level using inputs and evaluating outputs through flight interfaces. The intent of this “use category” is to ensure that any logical flaws or software design errors at the software component level are caught early. Using a processor that is not exactly flight-like for the FSW unit level testing allows FSW developers to add waypoints and other SW test hooks that the flight processors do not always support. The risk in omitting or curtailing this testing is that errors may not be found until more costly phases of the program and that additional expensive regression testing may be required.

Guideline 01: Ensure that the FSW unit test is performed on a Tb&S product with a realistic FSW environment (but not necessarily on a processor targeted to be used in flight) providing realistic component inputs and interfaces.
Rationale and Example. A worst-case risk scenario that may result from performing FSW unit testing on a platform that is not realistic to the actual operational FSW environment would be one in which the error is not detected at higher levels of testing because all of the component level logical paths are not exercised.

Flight Software Development and Software Item (SI) Integration: The FSW development and integration team uses a Tb&S product with flight-like processors to integrate software components and to test the integrated FSW product in pre-qualification tests. Activities include performance and stress testing of FSW, timing investigations, debug activities, and burn-down of the Discrepancy Reports (DRs) against FSW. The intent of this “use category” is to capture and fix any issues with the integrated FSW prior to the start of qualification testing. The risk in omitting or curtailing this activity is one of both schedule and cost impacts resulting from failed portions of the qualification test and having to reintegrate and retest FSW.

FSW Test Development: In this use, the team performing Software Item verification leading to SI Qualification Test (SIQT)) uses Tb&S products to iterate through development and debug of verification test scenarios. The intent of this “use category” is to capture and resolve defects with the qualification test scripts prior to the start of formal qualification testing. The risk in omitting or curtailing this activity is one of schedule impacts resulting from time spent troubleshooting test scripts during the qualification test.

Flight Software Formal Requirements Verification (SIQT): The FSW formal verification team uses a Tb&S product with Flight-Like hardware to run Qualification/Verification tests. The intent of this “use category” is to verify the software requirements levied on FSW. Software qualification testing may not be skipped and the risk in minimizing this activity is one of schedule impacts resulting from time spent troubleshooting FSW in AI&T, or in a worst case, of launching a Space Vehicle with flaws in FSW.

Guideline 02: Use Flight-Like hardware and configuration as often and as early as possible to verify system requirements (including interfaces) during software-item qualification testing (SIQT).
Rationale and Example: When selling-off lower-level requirements, the use of Flight-Like hardware in a flight configuration will allow for problems to be addressed early in the HW development process rather than late during AI&T. In particular, adequate H/W-S/W debug and dry run enhances the buy-off of lower-level requirements and allows for finding defects early, and retiring of schedule and H/W-S/W risks. From the perspective of flight software, this means that SIQT must be performed with proper flight-like hardware or EDUs to ensure that software works as expected before AI&T.

Flight Software Regression Test: Regression testing involves the retesting of a software item following the modification of that item or any of its interfacing items. This may include modification to the software’s requirements, design, code, interfaces, and documentation. The regression test team uses various Tb&S products to support this activity post-SIQT through launch and completion of the mission.

3.2.3 System/Subsystem Test End Uses

Command & Telemetry (C&T) Database Integration and Test: The database system integration team uses a simulator or a testbed together with a ground system interface for Command and Telemetry database verification. Typical test activities include sending commands to the simulator or testbed, verifying command acceptance, and verifying expected telemetry responses. These activities do not generally require a closed loop orbit/dynamics simulation. The intent of this “use category” is to ensure that the database in use at the start of spacecraft bus integration is valid.

Guideline 03: Use a Tb&S product executing Flight Software to verify Flight Commands and Telemetry.
Rationale and Example. As the FSW goes through various levels of testing and evolution the changes have to be propagated to other parts of the system including the command and telemetry database. The risk of omitting or curtailing this activity is that database errors found during Space Vehicle integration may cause anomalies that impede rapid progress through integration and test. In addition, programs that omit this use must evaluate which commands and telemetry have been exercised during AI&T in order to pass the final program gates prior to launch.

System/Subsystem Requirements Verification: The program test team uses a Tb&S product with Flight-Like hardware to run verification tests. This includes closed loop orbit scenario tests for formal verification of system level requirements and other tests requiring dynamics modeling of the external environment. Typical activities include: ADCS performance testing; fault protection tests of flight hardware systems that require closed loop dynamics or fault injection; Day-In-The-Life tests; and launch simulation tests. For subsystem testing, it is important that all the other subsystems are up and running in their nominal configuration in order to observe subsystem interaction for any design impacts. The intent of this “use category” is to provide the highest fidelity hardware environment (outside of the flight vehicle) for verification of requirements that cannot be verified outside of the testing of final flight hardware configurations. Verifications may not be skipped; however, minimizing testing of these requirements in Tb&S results in added costs associated with the higher level space vehicle tests that would have to replace this testing. Programs with the resources to develop offline simulators and testbeds of the fidelity required to shift these activities off of the space vehicle may be able to minimize or eliminate tests using the space vehicle in closed loop tests from their program timeline.

System/Subsystem Validation: The program test team uses a Tb&S product with flight-equivalent hardware to execute a set of validation tests necessary to demonstrate that the as-built system performs its intended functions (i.e., complies with the documented needs of the stakeholders) in its intended environment. Although most validation is accomplished through simulation and analysis, Tb&S provides an opportunity to perform selected validation using test. Certain testing, like Test Like You Fly (TLYF) can be considered a validation test using Tb&S.

Fault Management System (FMS) Test: Testing of the Space Vehicle fault management system needs to occur for the autonomous on-board fault detection and recovery capabilities implemented in the FSW as well as for the higher-level detection and responses allocated to the Space Vehicle and Ground System. The FMS testing End Use assumes that the developers have the final FSW and that lower level subsystem level tests were successful and complete. Testing includes the validation of all the on-board response and recovery stored command sequences and timing. Testing may use modeled components that can more easily inject test faults (e.g., out-of-range temperatures). Because FMS testing requires use of integrated flight systems, it occurs later in the program lifecycle, and it incurs greater program costs and schedule impacts. Programs may use the flight vehicle augmented with testbed components for fault management testing and combine it with fault protection testing using testbeds or simulators. The intent of this “use category” is to ensure that system level requirements in fault management are verified.

Guideline 04: Perform as much Fault Management testing on the System Testbed as possible.
Rationale and Example: The STB provides greater capability to inject realistic faults, providing greater fidelity and robustness for most type of fault testing. This type of testing should augment tests performed on the space vehicle flight hardware. The risk in omitting or curtailing this activity is that Fault management essential to the safety of the Space Vehicle may contain design or implementation errors that effect on orbit performance and Space Vehicle safety.

Guideline 05: Ensure that at least one Tb&S product can incorporate the required capabilities associated with fault injection and fault detection, with sufficient flexibility available for injecting faults in different ways. This includes not only SW fault injections but also HW/SW timing faults and HW fault injection.

Rationale and Example: One of the most critical capabilities associated with how a Tb&S product incorporates fault-injection is the ability to inject faults while numerous flight tasks are being performed in parallel across all space vehicle processors. Often, during AI&T, commands to exercise the response of each item in the space vehicle are sent in some logical order, which does not reflect the actual operational environment when faults occur during the execution of any given command. A fault may occur at any time during the mission with any number of tasks executing in parallel.

Day-In-The-Life (DITL) Test: In this use a Tb&S product is employed to run mission scenario tests. Typical activities include examinations of sensing/maneuvering CONOPS or ground station interactions in a closed loop orbit scenario. These are typically long duration tests (several hours), intended to exercise the SV subsystems and FSW through a complete cycle as outlined in the CONOPS document. Testing is generally looking for incompatibilities between different operational activities, or for software/processor issues that are either infrequent or require long gestation periods. Testing is also looking for SW/HW issues that are dependent on command sequencing (e.g., forgetting to clear buffers prior to next command). The DITL End Use also includes using a testbed or simulator for executing expected operations sequences that is out of the flow of the more expensive AI&T activities. The intent of this “use category” is to ensure that mission scenarios will properly execute on-orbit. The risk of omitting or curtailing this activity is that conflicts between operational activities may not be detected until the Space Vehicle is on orbit, and the time spent reworking operational scenarios detracts from mission success. In a worse case risk outcome, the on-orbit Space Vehicle may be found to include processor or software issues that cause resets or other loss of function at intervals greater than that tested in all other ground testing. The risk of omitting this activity on a System Testbed and deferring testing to the space vehicle is one of schedule and cost risks, but these risks may be balanced by the benefits of testing the final flight configuration instead the System Testbed configuration.

3.2.4 AI&T Support End Uses

Test Conductor Training: The AI&T Team uses a Tb&S product to develop competencies with the command and telemetry interface, with the Space Vehicle architecture, and with the simulator software. A wide range of activities, from running simple open loop hardware setup operations to running closed loop orbit simulations, are exercised using these Tb&S products. The intent of this “use category” is to provide test conductors an enhanced competency in some of the more technically challenging portions of the test environment prior to the start of flight Space Vehicle AI&T operations. The risk in omitting or curtailing these activities is that subtle test issues encountered in AI&T may be missed or misunderstood by test operators, in a worst case leaving these issues undetected until the Space Vehicle is on orbit.

Test Procedure Development: The Assembly, Integration & Test Team uses a simulator or a testbed to dry run I&T procedures. I&T procedures may be broadly classified as either integration procedures or test procedures. Each classification has different Tb&S needs. Integration procedures are dry run to verify the safety and the validity of the steps used to verify correct and safe electrical interfaces in the flight hardware. Dry runs of this type of procedure require that the simulator has realistic electrical hardware and interfaces at the point that the procedure is executed. Test procedures, on the other hand, are more typically focused on checking the function and performance of integrated systems and subsystems. For this type of dry run, simulators usually only need to realistically respond to commands in the same manner as the flight hardware, and in many cases the relevant spacecraft components may be entirely simulated. The intent of this “use category” is to ensure that the different types of test procedures used in AI&T activities function safely and as expected prior to execution against flight hardware. The risk in omitting or curtailing this activity is two-fold. First, for integration tests, this activity reduces the risk of hardware damage due to incorrect manipulations and excitations of flight hardware. Second, in system-level tests, this activity reduces the added cost and schedule impacts of troubleshooting complicated orbit scenarios or system level behaviors during the more expensive space vehicle AI&T activities.

AI&T Risk Reduction Test: AI&T, subsystem or system engineers require a testbed with an EM or flight components to perform interface verification, initial requirement validation, and pre-integration checkout necessary to reduce the risk associated with initial flight vehicle power-up activities as well as follow-on AI&T activities. The intent of this “use category” is to ensure proper operation of hardware, flight software, ground equipment, or test equipment prior to installation and use on the flight vehicle. The start point for this End Use is the availability of appropriate EM units (or Software components) for testing and generally extends to beginning of system level AI&T.

Test Anomaly Resolution: The AI&T Team or systems and subsystem engineers use a testbed to recreate and examine anomalies found in the execution of test procedures during space vehicle AI&T activities. Typical activities include investigations of ACS attitude errors, unexpected fault detection triggers, signal timing issues, and unexpected HW or SW responses and failures. The intent of this “use category” is to provide a path for troubleshooting that is offline to more expensive AI&T activities. By their nature, these activities are not planned ahead and every program hopes that they will not have to utilize this capability. Nevertheless, planning for these contingency operations is important to smooth program execution and is a logical extension of the capabilities required for the previous “use category”. The ability to quickly interrupt other activities to allow for time on the testbed resource is crucial in maintaining the flow and schedule of AI&T. This is due to the fact that failures on the space vehicle are often desired to be fully understood before any testing may continue (or even powering off the space vehicle), thereby preventing unverified failures. Tb&S have a crucial role in providing this understanding. The risk in omitting or curtailing this function is twofold. First, this activity reduces the risk of hardware damage by reducing the quantity of troubleshooting with flight hardware. Second, this activity reduces the added cost and schedule impacts of troubleshooting complicated orbit scenarios during the more expensive space vehicle AI&T activities.

3.2.5 Mission Operations Support End Uses

Ground Compatibility Test: The Mission Operations Team uses Tb&S products to run orbit scenarios in support of end-to-end testing of ground station command center(s). Activities may include mission scenario tests in closed loop orbit simulations. The intent of this “use category” is to exercise the ground controller’s command and telemetry interfaces and their activity and planning software. The risk in omitting or curtailing these activities is that issues with ground station hardware and software may not be detected until the Space Vehicle is on orbit, and the time spent reworking these resources detracts from mission success.

Mission Rehearsals: The Mission Operations Team runs closed loop orbit simulations in support of operational scenarios run by operations personnel at the ground station command center(s) using Tb&S. Activities include mission scenario tests in closed loop orbit simulations, in both nominal and anomalous configurations. The intent of this “use category” is to exercise the ground staff, their decision-making process, procedures and their procedure flows, in a variety of nominal and off-nominal activities that represent all possible on-orbit conditions. The risk in omitting or curtailing these activities is that issues with personnel availability, procedures and decision-making protocols may not be detected until the Space Vehicle is on orbit, and the time spent reworking these resources detracts from mission success.

Flight Operations Training: In this End Use the Mission Operations Team uses a simulator or testbed to develop competencies with their command and telemetry interface and with the Space Vehicle architecture outside of full mission rehearsals. A wide range of activities from running simple open loop hardware setup operations to running operations in closed loop orbit simulations are executed. The intent of this “use category” is to provide operations personnel with additional experience in controlling and working with their ground systems in response to Space Vehicle operational scenarios. The risk in omitting or curtailing these activities is that operators may be less skillful in using the ground systems to respond to issues on orbit causing unnecessary schedule delays in on orbit activities.

Post-Launch Anomaly Resolution: In this use Mission Operations Team with the help of systems/subsystems engineers (including FSW engineers) use a testbed to recreate and examine anomalies found in on-orbit operations. The intent of this “use category” is to provide a means for troubleshooting that allows access to hardware that is otherwise out of reach. In addition, it allows some types of troubleshooting to take place in parallel with ongoing mission operations. The risk in omitting or curtailing this activity is that any on orbit issues that arise may require more time to setup a suitable surrogate test environment or that testing is done on the space vehicle with much greater risk.

3.3 Tb&S Functional Taxonomy

This section lists a set of common functional capabilities required of the suite of Tb&S associated with space vehicle development and operations programs. These functional capabilities are implemented in direct response to End Uses identified in Section 3.2. As in the previous section, this section does not make a direct correlation in the description of the functional capabilities to specific End Uses since each program is different and specific correlations will vary between programs (see Section 4 for a typical allocation to a risk-constrained program). Table 3-3 provides a list of functions and while it is not comprehensive, it is representative of the types of functions seen in Tb&S products used throughout the Aerospace industry.

Table 3-3. Top-Level Functions Provided by Tb&S Products

Top-Level Function	Summary Description
Process Space Vehicle Uplink Commands	Testbed provides uplink of flight commands from operator workstation.
Provide Space Vehicle Downlink Telemetry	Testbed provides downlink of flight telemetry to operator workstation.
Run Simulation non real-time	Testbed simulation SW may run faster or slower than real-time.

Run Simulation in real-time	Testbed simulation SW runs in real-time.
Simulate Space Vehicle Components	Testbed includes software models of one or more flight components.
Include Hardware EMs	Testbed includes flight or non-flight hardware units of one or more flight components, and a RTOS to control SW interfaces to hardware components.
Simulate Space Vehicle Orbital Dynamics	SW models include integration of force/acceleration, velocity and position of the simulated vehicle.
Simulate Space Vehicle Attitude Dynamics	SW models include integration of torque/angular acceleration, rotations and attitude of the simulated vehicle.
Provide Interfaces to C&DH Subsystem Hardware	Testbed includes C&DH hardware, and all interfaces to this hardware are either simulated or emulated.
Provide Interfaces to FSW	Testbed includes FSW, and all interfaces to FSW are either simulated or emulated.
Provide for Test Planning, Execution, and Post-Test Analysis	Operator interface on testbed includes tools for storage, manipulation and analysis of testbed data.
Provide interface to EM Hardware	Testbed includes physical signal lines with realistic signals at all interfaces for specific test articles.
Provide interface to external EGSE	Testbed provides test interfaces to EGSE including power or test boxes.
Provide interface to external C&C	Testbed includes capacity to select command/telemetry streams from both local and remote operators.
Provide realistic hardware redundancy	Testbed includes both primary and redundant hardware for at least some boxes in some subsystems.

3.4 Tb&S Physical Taxonomy

In this subsection, we take the Tb&S End Users, End Uses, and functional capabilities discussed in Sections 3.1, 3.2, and 3.3 and identify specific Tb&S products that are applicable to space vehicle programs across the Aerospace industry. Depending on the program constraints (i.e., schedule, risk, and cost) the actual uses for each Tb&S type may vary or may not be used at all. What we describe in this section is not a specific allocation of Tb&S products for a particular space vehicle program (see Section 4), but rather a general physical characterization of Tb&S products into four main Tb&S types applicable to all space vehicle programs. The four Tb&S products we consider are as follows:

Section 3.4.2.1: Non-Real-Time Simulator (NRT-Sim)

Section 3.4.2.2: Non-Flight-Like Testbed (NFTB)

Section 3.4.2.3: System/Subsystem Testbed (STB)

Section 3.4.2.4: Integrated Space Vehicle Testbed (ISVT)

A functional decomposition of a space vehicle system testbed is presented followed by a detailed discussion of each of the four Tb&S types. The functional overview provides a high-level illustration of the functional relationship between the Engineering Model (EM) hardware, interface hardware, simulated SV dynamics and environment models within a Tb&S product.

3.4.1 Space Vehicle System Testbed Product Decomposition

The decomposition of a generic Tb&S product is illustrated using several hierarchical tiers. Each successive tier corresponds to a functional decomposition of the Testbeds components from the previous tier. Figure 3-3 shows the first tier (top-level) decomposition of the testbed into four components. The testbed is shown to contain flight-like Engineering Models and Testbed Simulators. The SV Testbed also contains support equipment (i.e., EGSE) and has an Operator Console representing the Ground Command & Control system as well as a Test Conductor console necessary to execute tests.

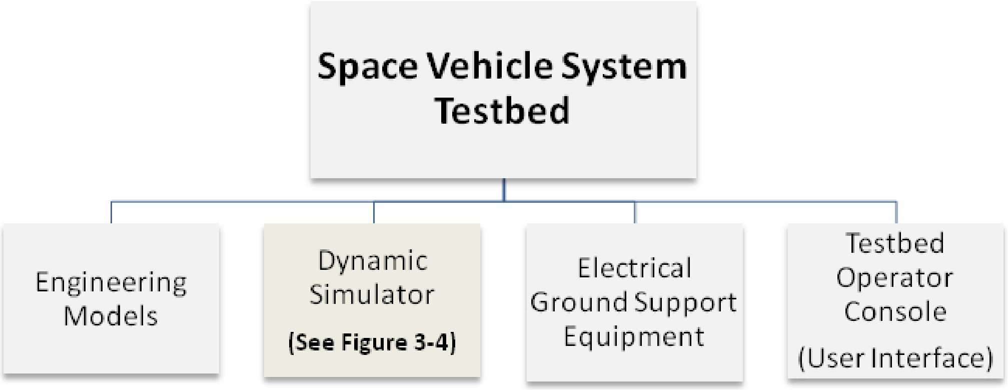


Figure 3-3. First tier decomposition – space vehicle system testbed.

The Dynamics Simulator, shown in Figure 3-4 is comprised of simulations of flight components, hosted on a workstation, running a non real-time or real-time operating system. The simulator includes an operator interface used to start, stop, and configure the dynamics simulator before and during tests. This simulator type is used to provide the either open-loop or closed-loop control capability. This simulator type may also be used to interface to a non-flight-like processor hosting FSW. The Dynamics Simulator consists of six components, including: the Simulator Hardware Platform, which hosts the Simulator Operating System and the computing platform for executing simulator software; the Simulation Framework component, which is a software component used to support Space Vehicle subsystems and components models as well as the Space Environment Models; the Space Vehicle Models component, which consists of software items representing component behavior, interfaces, and timing characteristics; and the Environment Models, which are software representations of real-world space environments such as atmospheric drag.

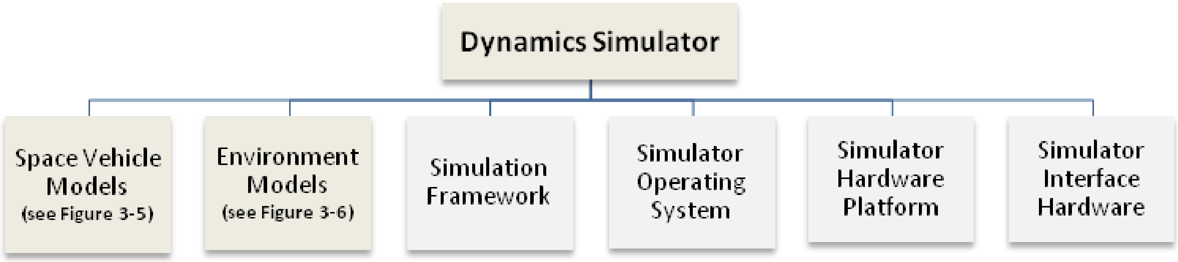


Figure 3-4. Second tier decomposition - dynamics simulator.

At a high level, two distinct types of dynamics simulators are typically developed; Bus Dynamics Simulators and Payload Dynamics Simulators. A Bus Dynamics Simulator is designed to provide simulation of bus flight hardware components and the Space Vehicle environments as well as interfaces to the Space Vehicle's payload(s) and/or instruments. The UUT for a Bus Dynamics Simulator is the set of Bus EMs. Payload Dynamics Simulators are designed to provide simulation of flight hardware components critical to the payload as well as any Space Vehicle environments that impact the payload and/or instrument. The UUT for a Payload Dynamics Simulator is the flight payload or the payload EM.

The Space Vehicle Model decomposition, shown in Figure 3-5, is comprised of Spacecraft Bus Models and the Payload Models. These models are software representing component behavior, interfaces, and timing characteristics. The Environmental Model decomposition, shown in Figure 3-6, is comprised of the forces, torques, and other environmental effects on the vehicle dynamics and sensors. The models are software representations of something in the real-word.

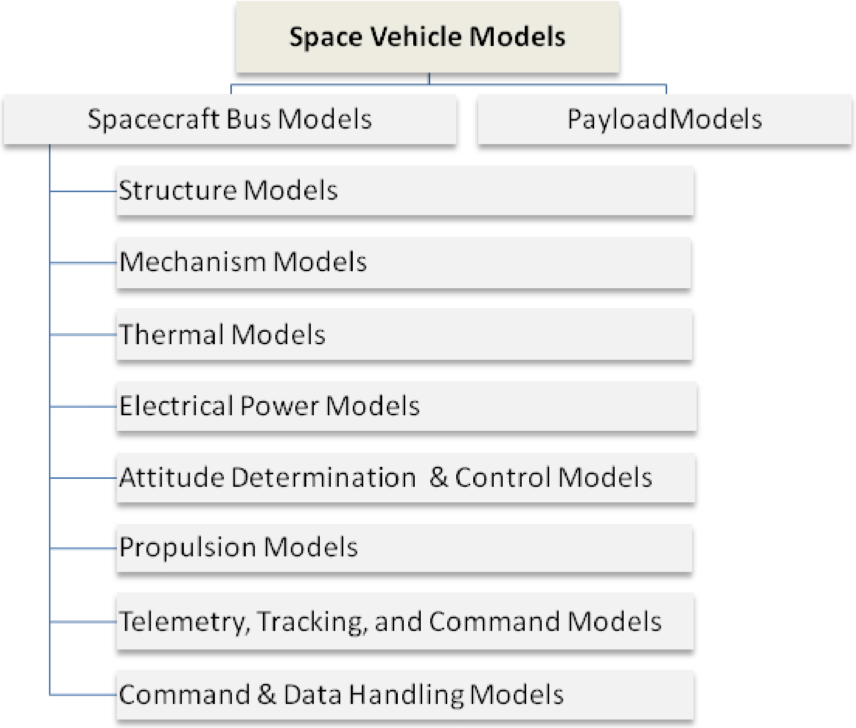


Figure 3-5. Third tier decomposition - space vehicle models.

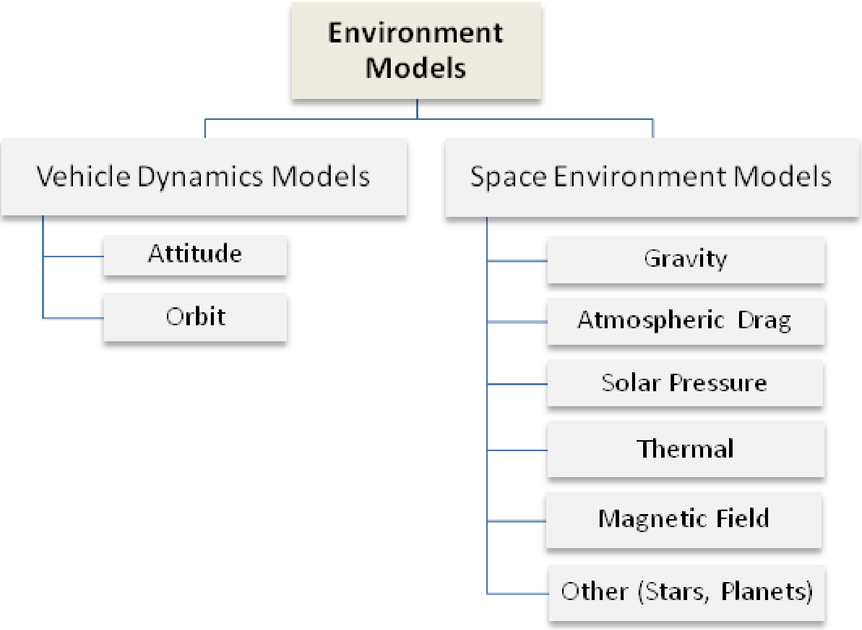


Figure 3-6. Third tier decomposition - environmental models.

All four Tb&S product types, identified here, are composed of a subset of the individual components of the Space Vehicle System Testbed shown above. The differences from one type of testbed or simulator to another lie in the level of fidelity in the implementation of each SV component or subsystem and in how close each simulated or hardware component is to the actual flight configuration.

3.4.2 Tb&S Types and Physical Characteristics

For each Tb&S type we describe its characteristics, assumptions, limitations, and End Uses. These systems vary in terms of their performance and fidelity requirements. The high-performance/high-fidelity Tb&S products are required to execute flight-like scenarios, providing real-time Quality-Of-Service while maintaining stringent timing requirements. These types of Tb&S products also tend to be the most complex and expensive systems to develop and use. The level of fidelity for a Tb&S product could be viewed at two different levels. At the system level, it represents the level of hardware-in-the-loop (HITL) in the configuration of the testbed, while at the modeling level for simulated components it represents the accuracy and precision of the model outputs. Some Tb&S products are designed to maintain real-time performance at lower rates while providing math-intensive operations with high precision model outputs. Others are designed to run at higher rates with lower fidelity model outputs. As noted in Section 6, some Tb&S products typically evolve and improve during the course of the program and therefore separate capabilities of Tb&S products of different levels of maturity are used during various phases of the space vehicle development program. It is expected that in multiple-build SV programs, or programs with a high level of commonality in the designs of consecutive satellites, that the Tb&S product will be at a higher level of maturity than for “one-off” space vehicle builds. When a more mature Tb&S type is available, the End Uses for the more primitive level of Tb&S type listed below may be passed to a higher-fidelity tool.

In our description of each Tb&S product type, we address the notion of the fidelity level required (from the user's perspective) for three aspects relating to Tb&S products: Interface Fidelity, Hardware Fidelity, and Simulation Software Fidelity.

Guideline 06: Identify the fidelity levels required for each Tb&S product capability early in the lifecycle.
Rationale and Example: Fidelity levels for hardware, interfaces, and simulation software models provide the functional and performance capability to satisfy identified End Uses. The fidelity level may significantly drive scope (and therefore cost and schedule) of the end product and may cause significant rework if identified late in the development or operations lifecycle.

Interface fidelity levels (see Table 3-4) describe how closely the interface associated with the simulator or testbed matches the actual flight interface. They vary from physical interfaces over electrical connections between actual hardware components to non-physical interfaces used to support simulator and testbeds. Hardware fidelity levels (see Table 3-5) describe how closely the simulator or testbed hardware matches the actual flight vehicle hardware. Finally, simulation software model fidelity levels (see Table 3-6) describe how closely the dynamics simulator on testbed hardware matches the actual flight vehicle. Simulation software models are developed and deployed on every Tb&S product type as part of the Dynamics Simulator, shown in Figure 3-4. Some simulation software is used to model various physical and non-physical parts of the space system, space vehicle, and the environment in which it operates. Detailed description of the simulation models, including description of the set of attributes having either a qualitative or quantitative description that can be used to specify the level of detail or complexity of a given model is beyond the scope of this document.

Table 3-4. Tb&S Interface Fidelity Levels

Interface Fidelity Level (0-5)	Summary Description
(0) No Interface capability	No interface is provided between two end items
(1) Software Interfaces	Shared memory or other method to connect to systems/components together using software rather than electrical representation of the interface
(2) Simulated Interfaces	An interface is provided that adequately represents the data and general temporal characteristics of the interface
(3) Non Flight-Like Electrical Interface	A commercial equivalent emulation of the flight electrical interface
(4) Flight-Like Electrical Interface	An equivalent electrical interface, but not using flight qualified parts and cables
(5) Flight Electrical Interface	Actual flight electrical interface exists between end items

Table 3-5. Tb&S Hardware Fidelity Levels

Hardware Fidelity Levels (0-4)	Summary Description
(0) No Hardware capability	No hardware capability is provided
(1) Non flight-like Hardware	Commercial hardware capability that has no direct correlation to the flight hardware
(2) Emulated Hardware	Typically a commercial equivalent that has different performance
(3) Flight-Like Hardware	Usually described as an EM present in a testbed. Typically uses non radiation-hardened parts, but has similar performance to the flight hardware present in a testbed or simulator.
(4) Flight Hardware	Flight hardware present in the testbed

Table 3-6. Tb&S Simulator Software Model Fidelity Levels

Simulator Software Model Fidelity Levels (0-3)	Summary Description
(0) No Simulation Software capability	No simulation software model capability is provided
(1) Simple Model	A static representation (e.g. fixed data) of the output of the end item being modeled
(2) Simple Dynamics Model	A simple dynamics model representing input and output of the end item being modeled. This model's input and output data changes during execution, including simple responses to input parameters.
(3) Dynamics Model	A more complex dynamics model representing all required input and output data of the end item being modeled. Dynamics behavior is modeled (usually with algorithms) with ties to other models and the surrounding environment.

3.4.2.1 Non-Real-Time Simulator

A Non-Real-Time Simulator (NRT-Sim) is a purely software simulation, hosted on a workstation, that when implemented includes a command and telemetry interface to both the simulation software and to the hosted flight software. This simulation does not include flight or EM hardware in the loop. At a mature level it typically includes fully integrated FSW, which might be flight qualified as well. An illustration of a typical NRT-Sim example is depicted in Figure 3-7. An NRT-Sim configuration can include a fully integrated FSW or one of the simulation models may be a model of the FSW that can be used as a C&T simulator. Interface fidelity for an NRT-Sim is low and can be anywhere from a level 0 (No Interface Capability) to a level 1 (Software Interfaces). The hardware fidelity level is almost always at level 0: No Hardware Capability. The simulator software model fidelity, however, can vary from level 1 (Simple Model) used for faster-than-real-time Mission Rehearsals and Ground Operations End-to-End Tests to very high-fidelity level 3 (Dynamics Model) that has too much fidelity to operate in a time-constrained environment such as a real-time dynamics simulator, but may be required to support activities associated with access to all aspects of the end item being modeled.

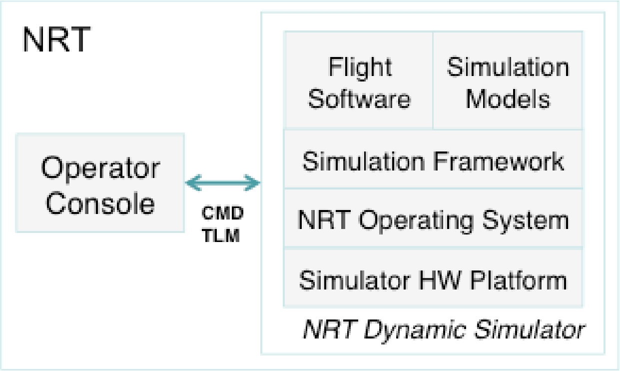


Figure 3-7. Context diagram - non-real-time simulator example.

Generally, NRT-Sims are relatively inexpensive platforms for early flight SW development without HTIL. NRT-Sims are good tools for benchmarking HW requirements for FSW, refining procedure and test script event timing and contents, modeling of Space Vehicle dynamics response to command sequences. They also may be used to provide a realistic interface to the Space Vehicle ground system for C&T database verification to enable early database development without HITL and for use as an Operator training device. Some of the weaknesses of an NRT-Sim include: lack of real-time performance for internal/external interfaces; lack of event-driven flight-like scenario execution and testing; lack of hardware dependent constraints on SW functions; and models of vehicle hardware may have limited scope and capability.

3.4.2.2 Non Flight-Like Testbed

A Non Flight-Like Testbed (NFTB) has the capability to operate as a subsystem or system testbed but uses lower fidelity hardware. It contains a dynamics simulator that can support either simple open-loop or dynamics closed-loop capabilities. The dynamics simulator can execute either non real-time or real-time depending on the required capability. The testbed contains non flight-like units hosting the FSW under test in order to verify the on-board FSW. The testbed includes an open-loop emulation of the flight interfaces and may include the dynamics models necessary for closed loop testing. The testbed also provides a command and telemetry interface to the operator.

An NFTB having a real-time FSW simulator and a real-time dynamics simulator is depicted in Figure 3-8 below. The different fidelity levels for an NFTB are higher than those for an NRT-Sim. Interface fidelity can range from level 3 (Non Flight-Like Electrical Interface) all the way to level 4 (Flight-Like Electrical Interface). Similarly, hardware fidelity levels range from level 1 (Non flight-like Hardware) to level 2 (Emulated Hardware) using a commercial equivalent to the flight hardware. Since the uses of an NFTB are not too different from those for an NRT-Sim, the software simulation models' fidelity levels can be anywhere between level 2 (Simple Model) to a high-fidelity level 3 (Dynamics Model).

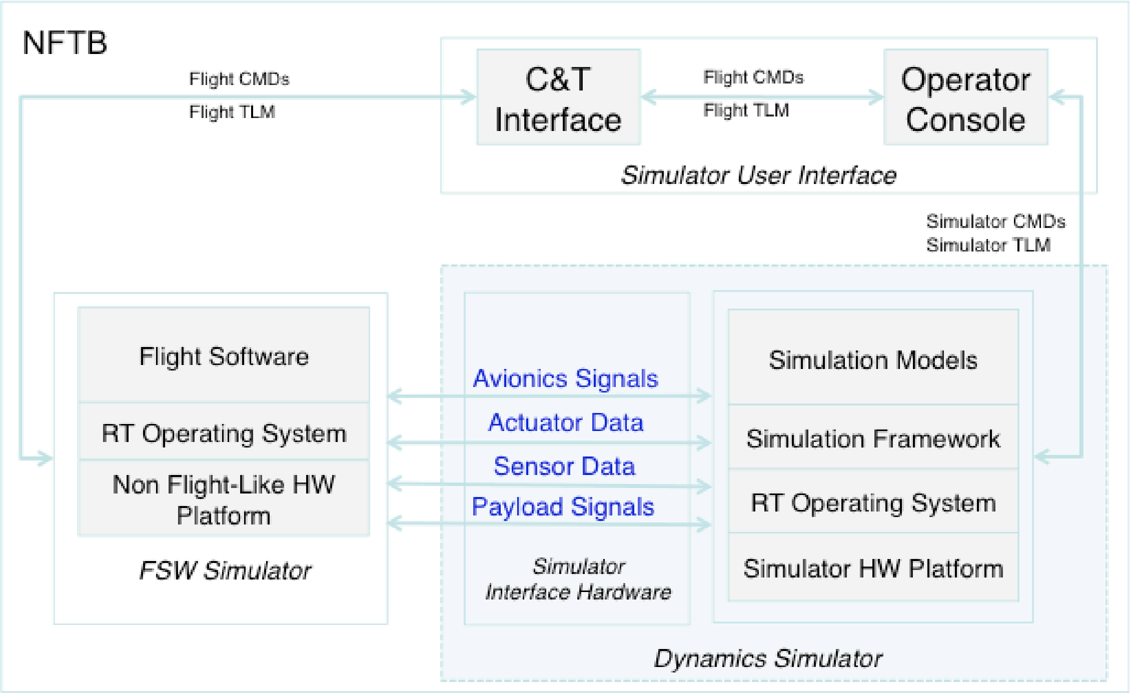


Figure 3-8. Context diagram - non flight-like testbed example.

In cases where an NFTB runs the actual FSW on a hardware platform resembling an emulation of the flight processor, an NFTB may provide a simpler means than an NRT-Sim for porting FSW to a test environment. This Tb&S type may have some limitations, including the lack of event-driven flight-like scenario execution and testing, and limited scope and capabilities of the SV hardware models and host hardware for FSW.

3.4.2.3 System and Subsystem Testbed

A System/Subsystem Testbed (STB) is a combination of Engineering Models (EMs) and/or flight boxes, coupled with a Dynamics Simulator in a Hardware-in-the-Loop (HITL) configuration, which simulates some flight components and also includes the orbital and attitude dynamics models. Subsystem Testbeds may be configured to represent a subsystem such as FSW, EPS, and C&DH. System Testbeds are commonly configured as:

- Space Vehicle Testbed
- Bus System Testbed
- Payload System Testbed

A generic representation of a Subsystem Testbed configuration representing a FSW Subsystem Testbed (i.e., FSW Test Bench) is depicted in Figure 3-9 below. A full System Testbed is illustrated in Figure 3-10, where at a minimum, flight or EM boxes represent most of the C&DH flight components. The hardware fidelity levels range from level 3 (Flight-Like Hardware) all the way to level 4 (Flight Hardware). Each STB also includes a command and telemetry interface to both the simulation software, to the simulated flight components (if any), and to the hardware flight components. Interfaces between simulated and hardware components require dedicated interface hardware. Interface fidelity levels range from level 4 (Flight-Like Electrical Interface) to level 5

(Flight Electrical Interface). In order to interface correctly with the hardware components in the loop, the simulation software must run in a real-time operating system (RTOS) and the software simulation models are at the highest possible fidelity levels compatible with real-time operation: i.e., level 3 (Dynamics Model). In general, the EMs and flight boxes requiring FSW in an STB will typically include fully integrated FSW and a command and telemetry database.

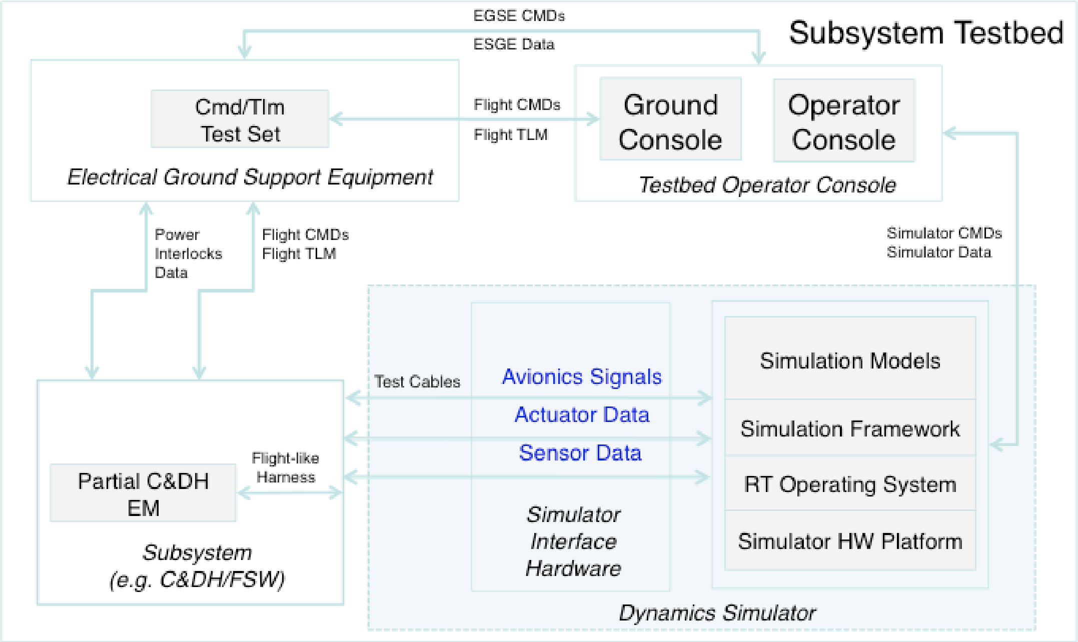


Figure 3-9. Context diagram – subsystem testbed (FSW subsystem testbed).

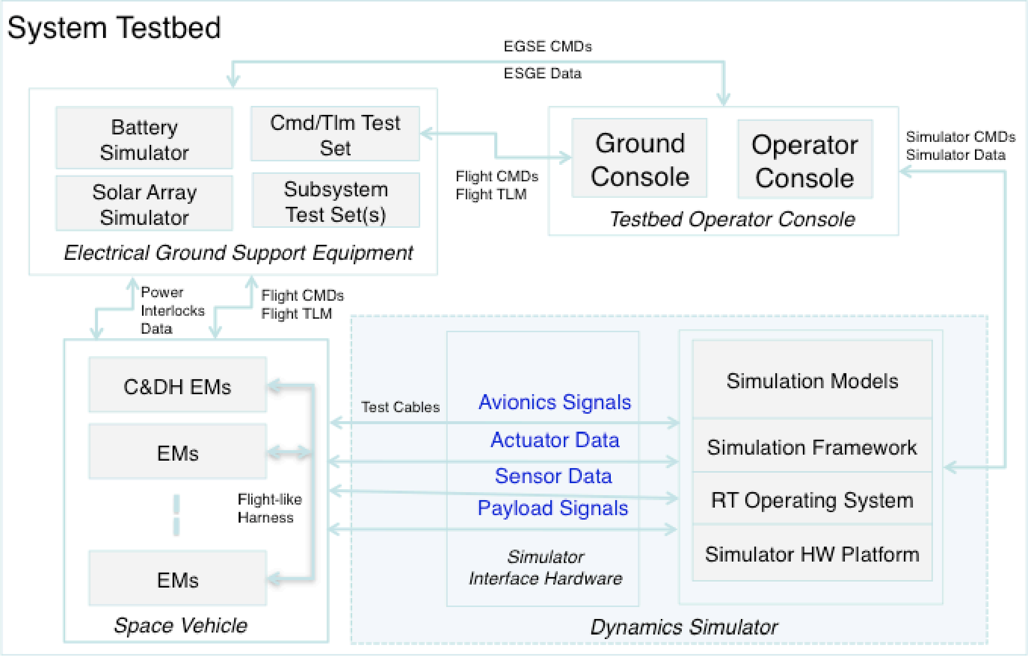


Figure 3-10. Context diagram – system testbed.

Given that an STB is of relatively high fidelity and more accurately represents a full SV or an SV subsystem (such as FSW), an STB is a suitable high-fidelity environment for FSW and hardware testing.

3.4.2.4 Integrated Space Vehicle Testbed (ISVT)

An Integrated Space Vehicle Testbed (ISVT) is a mating of integrated space vehicle hardware with a Dynamics Simulator in a Hardware-in-the-Loop (HITL) configuration. This configuration is depicted in Figure 3-11. The simulator provides the orbital and attitude dynamics models, takes spacecraft actuator information to update the state of these models, and then feeds appropriate sensor signals to the spacecraft. The integrated flight vehicle testbed also requires other components of the AI&T environment, typically a suite of power EGSE/STE components and a command and telemetry interface to both the simulation software and the Space Vehicle. In order to interface correctly with the hardware components in the loop, the simulation software must run in a real-time operating system (RTOS). The ISVT typically has the highest possible fidelity levels compatible with real-time operation for interface fidelity, hardware fidelity, and software simulation models.

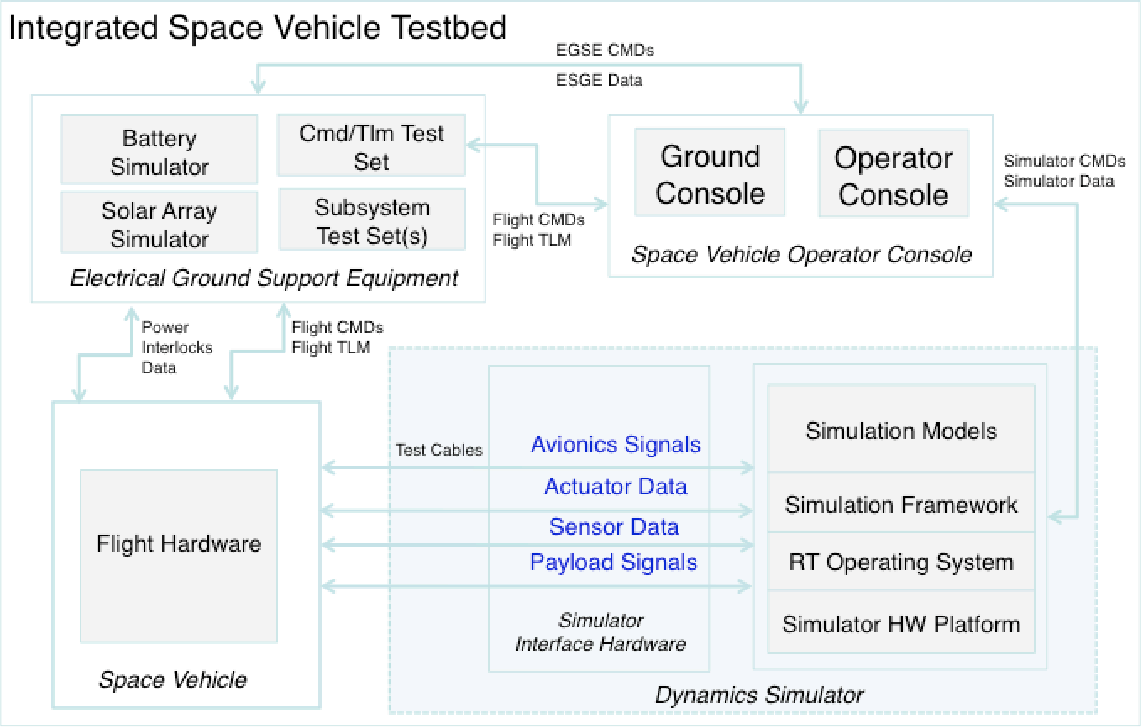


Figure 3-11. Context diagram - integrated space vehicle testbed.

Some of the most important characteristics that distinguish an ISVT from a high-fidelity STB are that an ISVT is most flight-like for software or hardware testing and because of the incorporation of final flight boxes and structures, is the only platform configured for testing that will capture issues in workmanship or in the interaction of control systems with the dynamics of the vehicle structure.

Finally, a summary matrix of how the Functional Capabilities identified in Section 3.3 can be allocated to the four Tb&S types described above is shown in Table 3-7 below. The Functional allocation matrix is defined using three scales for applicability to a particular Tb&S type:

(F)requently, (O)ccasionally, and (R)arely. This allocation scheme represents coupling between the functional capabilities and the physical fidelity characteristics in a particular Tb&S type that was found to be typical among the aerospace companies canvassed in the development of this document.

Table 3-7. Top-Level Functions Mapped to Tb&S Types

	Functional Allocation to Tb&S F=Frequently, O=Occasionally, R=Rarely			
Top-Level Function	**NRT Simulator**	**Non Flight-Like Testbed**	**System/ Subsystem Testbed**	**Integrated Space Vehicle Testbed**
Process Space Vehicle Uplink Commands	O	O	F	F
Provide Space Vehicle Downlink Telemetry	F	F	F	F
Run Simulation non real-time	F	O	R	R
Run Simulation in real-time	R	O	F	F
Simulate Space Vehicle Components	F	F	F	O
Include Hardware EMs	R	O	F	F
Simulate Space Vehicle Orbital Dynamics	F	F	F	F
Simulate Space Vehicle Attitude Dynamics	F	F	F	F
Provide Interfaces to C&DH Subsystem Hardware	R	O	F	F
Provide Interfaces to FSW	O	F	F	F
Provide for Test Planning, Execution, and Post-Test Analysis	O	O	F	F
Provide interface to EM Hardware	R	O	F	F
Provide interface to external EGSE	R	O	F	F
Provide interface to external C&C	O	O	O	O
Provide realistic hardware redundancy	R	O	O	F

4. Allocation of Tb&S Products within the Lifecycle Phases of an SV Program

This section describes the allocation of the Tb&S End Uses and Functional Capabilities identified in Section 3 to the different Tb&S platforms within the lifecycle phases of typical SV programs. Because there is no single “typical SV program” this section confronts the complexity of Tb&S allocations for a broad range of different program types. This is done by presenting an overview of two program types that lie at opposing ends of the spectrum, and by detailing Tb&S allocations for a selected program type as a means of illustrating the sorts of allocation planning that all programs must perform early in the program lifecycle.

4.1 Space Vehicle Development Program Types Overview

As described in Section 5, one of the more difficult tasks in planning the Tb&S development timeline for any program is the determination of the program-specific constraints that will drive the development schedule. Since each program will have a unique set of constraints, the challenge for this document (and Section 4 in particular) is to present an overview of the “problem space” for program level planning of Tb&S product allocations. The “problem space” is bounded by two types of programs defined as follows:

Risk-Constrained Programs: Risk-constrained programs are those that are willing to make cost and schedule flexible to lower risk by allocating the resources and schedule necessary to buy-down risk items early and often.

Resource-Constrained Programs: Resource-constrained programs exhibit strict customer-imposed delivery constraints coupled with stringent cost constraints. In this case, the constrained resource is defined as both schedule and cost.

In between these two extremes is the range of specific individual programs that fill in the middle ground in the problem space. It must be noted, however, that regardless of the program type, cost is an important constraint to any program and there can be cost savings even in risk-constrained programs if the planning of Tb&S product development and allocation is done carefully upfront. It must also be noted that programs are not tolerant of risk to mission success, but rather each program utilizes Tb&S resources differently to retire mission success risk at different points in the program schedule.

4.1.1 Risk-Constrained Programs

A typical risk-constrained SV program is characterized by a willingness to provide Tb&S budget early to reduce risk and prevent cost overruns in the back-end of a program’s development lifecycle. Such a program may have a slower vehicle development schedule that does not easily outpace the Tb&S development timeline. Often (but not always) a risk-constrained program is a program composed of non-heritage or modified avionics or avionics that have not previously worked together that require a traditional avionics development cycle before AI&T. Schedule planning for risk-constrained programs must strive to ensure that Tb&S products are available and in use to catch design issues early in order to lessen impacts during AI&T. For this reason, a greater proportion of testing is assigned to System/Subsystem Testbed (STB) activities, as opposed to using the later-developed Integrated Space Vehicle Testbed (ISVT) as shown in Figure 4-1. Sometimes in risk-constrained programs a Tb&S product is on the program’s critical path and there is a willingness to delay SV development schedules if Tb&S products are not delivered on time or at the required maturity level. With proper planning, Tb&S types may be deployed to perform more than one End

Use; such as when the FSW Subsystem Testbed is used for FSW SIQT, regression testing for issues found during Space Vehicle Testbed testing and FSW maintenance post launch. Proactive planning may also streamline Tb&S deployment by assessing fidelity requirements and utilization scheduling in order to reduce the number of Tb&S deployments. For example, if the STB fidelity is assessed to be good enough to perform Fault Management V&V and System Verification, then the program could choose to not implement the ISVT, even though Figure 4-1 allocates the ISVT to those particular End Uses.

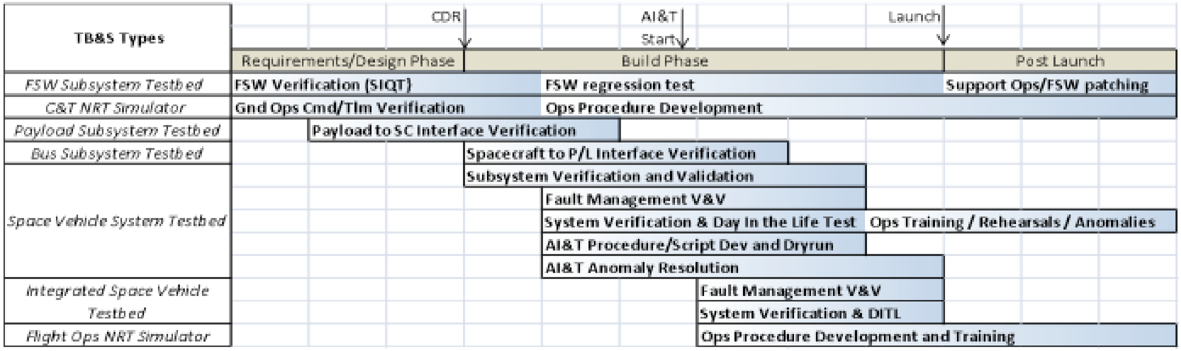


Figure 4-1. Risk-constrained - Tb&S deployment types by program phase.

4.1.2 Resource-Constrained Programs

At other end of the SV program type spectrum are resource-constrained programs. A resource-constrained program is one where rapid progress towards a firm launch date or meeting a strict budget mark has higher priority than an early retirement of risk. Typically, resource-constrained programs exhibit faster and stricter vehicle development schedules, with larger portion of the budget allocated to program activities in proportion to Tb&S activities. Resource-constrained programs may also exhibit relatively smaller cost and schedule vulnerabilities to missteps in early vehicle design. Some organizations consider resource-constrained programs (as defined here) as programs that are based on mostly heritage avionics that may require less Tb&S in the development cycle. It may also be anticipated that the aggressive risk management in this type of program is more often found in fixed-price programs, or programs with customers who may also be under significant schedule pressure.

Regardless of how much heritage avionics is used, however, one common occurrence within resource-constrained programs is that the high-fidelity Tb&S products will not be ready much ahead of the integration of the flight vehicle, making the ISVT more central to the resource-constrained program than in the risk-constrained program. A typical resource-constrained program may exhibit an unwillingness to delay vehicle program level schedules if Tb&S products are not delivered on time or at the required maturity level. This reduces the criticality of the program’s STBs relative to the program’s ISVT and many of the Tb&S End Uses discussed in Section 3.2 can be performed using an ISVT, as shown in Figure 4-2.

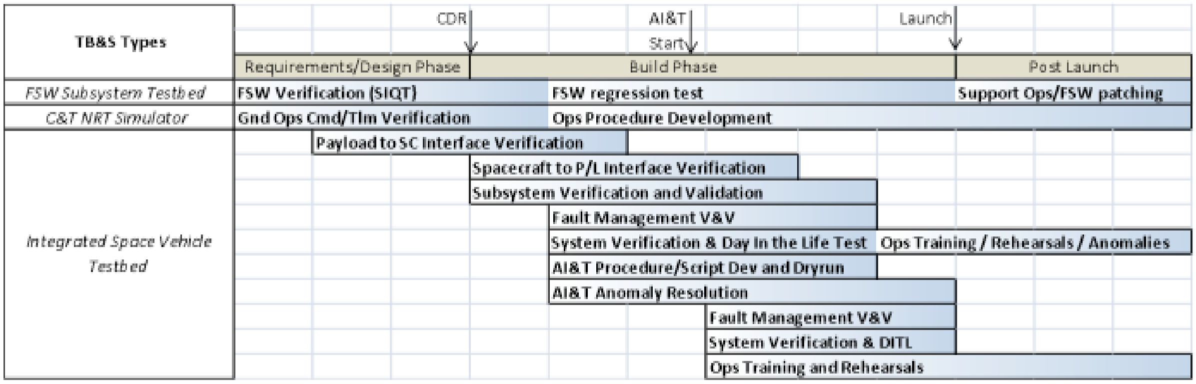


Figure 4-2. Resource-constrained - Tb&S deployment types by program phase.

4.1.3 General Tb&S Allocation to End Uses for Different Program Types

The two “limiting case” programs, discussed above, naturally allocate their Tb&S resources differently for different End Uses. The risk-constrained program will plan for more comprehensive System Testbeds, with higher levels of fidelity. This program will use these high fidelity testbeds to offload significant portions of requirement verifications, risk mitigation, and other Tb&S uses from the single stream AI&T activities later in the program lifecycle. The resource-constrained program on the other hand, will plan for simpler System Testbeds that can be delivered faster while meeting minimal needs (typically focused on FSW development) and will then defer many system level verifications to closed loop testing in AI&T using the ISVT. This type of program will also typically shift some risk management activities to less comprehensive non-simulator resources if this can be done without compromising schedule. Regardless of the program type, however, some of the Tb&S types identified in Section 3 will be more appropriate for some End Uses than others.

Table 4-1 is a matrix of how the Tb&S End Uses identified in Section 3.2 can be allocated to the four Tb&S types for any type of SV program. The End Use allocation matrix is defined using three different labels indicating if a Tb&S is appropriate for each End Use: (F)requently, (O)ccasionally, and (R)arely. This allocation scheme is meant as an allocation that applies to *any* type of program, independent of the program lifecycle phase. It is expected that a program manager responsible for developing a plan for a program’s Tb&S products will be able to use Table 4-1 to allocate each End Use to a particular Tb&S product and program phase as appropriate. In Section 4.3, a specific allocation is done for a risk-constrained program, organized by program phase.

Table 4-1. Tb&S Uses Mapped to Tb&S Products for all SV Program Types

		End Use Allocation to Tb&S F=Frequently, O=Occasionally, R=Rarely			
End Use Category	**End Use**	**NRT-Sim**	**NFTB**	**STB**	**ISVT**
Concept Development	Concept Studies and Development	O	O	R	R
	Subsystem Algorithm Development	F	O	O	R
FSW Development	FSW Unit Test	O	O	R	R
	FSW Development & SI Integration	R	O	O	R
	FSW Test Development	O	O	O	R
	FSW Formal Requirements Verification and Software Item Qualification Test (SIQT)	R	R	F	O
	FSW Regression Testing	R	R	F	O
System / Subsystem Test	Command and Telemetry Database Integration & Test	O	O	F	O
	System/Subsystem Requirements Verification	R	R	F	F
	System/Subsystem Validation	R	R	F	F
	Fault Management System Test	R	R	F	F
	Day-In-The-Life Test	R	R	F	F
	Test Conductor Training	O	O	O	O
AI&T Support	Test Procedure Development	O	R	F	O
	AI&T Risk Reduction Test	R	R	F	O
	Test Anomaly Resolution	R	R	F	R
	Ground Compatibility Test	R	R	O	O
Mission Operations Support	Mission Rehearsals	O	O	F	O
	Flight Operations Training	O	O	F	O
	Post-Launch Anomaly Resolution	O	R	F	R

In order to illustrate a sample case of Tb&S allocations, the remaining paragraphs of this section will first overview the different lifecycle phases (Section 4.2) and then will present the example of Tb&S allocations on a risk-constrained program (Section 4.3). The decision to focus on only one end (risk-constrained) of the "problem space" in Section 4.3 was made to avoid confusing the example with too many program-specific exceptions, however the reader must not take the sample allocations detailed below as an indication that these allocations are typical of all programs. To emphasize this point, the paragraphs below will also include a few references to the most significant top-level differences between the sample risk-constrained program and the resource-constrained program.

4.2 Overview of Space Vehicle Lifecycle Phases

Before an allocation is presented for a risk-constrained program, it is necessary to briefly describe the Space Vehicle Development Lifecycle Phases since the development and use of Tb&S must be coordinated with the spacecraft program lifecycle events. For the purposes of this document, the events of spacecraft lifecycle will be organized as in Aerospace TOR-2009(8583)-8545 "Guidelines for Space Systems Critical Gated Events". Figure 4-3 is from this Aerospace TOR, and shows the critical gated events of a typical program. This top-level timeline shows the program lifecycle broken into five broader categories: Pre-Award, Requirements and Design, Build and Test, Selloff and Mission Preparation, and Operations. Since Tb&S products are typically used in all five of these program phases, the uses typical of each phase and the required simulator maturity typical of each phase are presented in detail in the following sections.

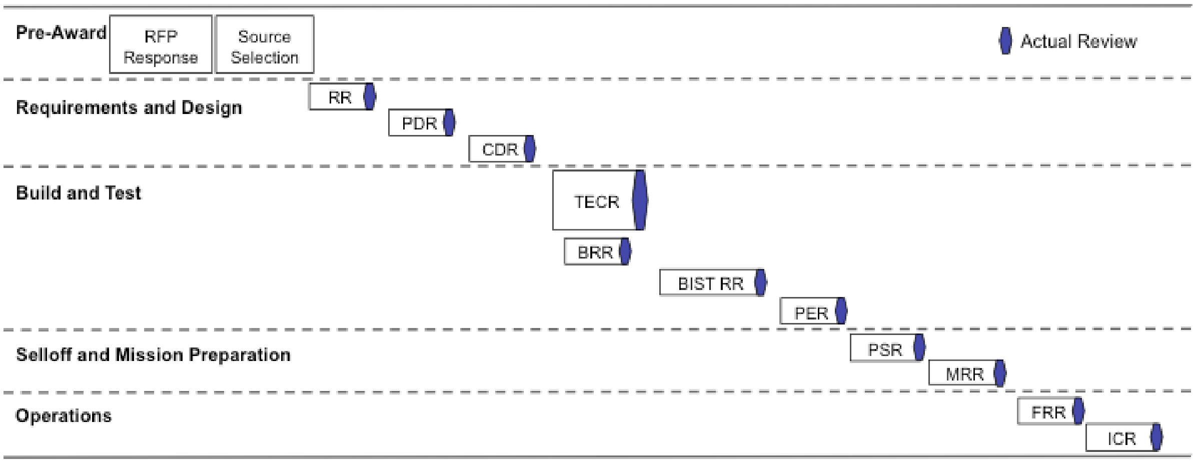


Figure 4-3. Notional gated event sequencing from aerospace TOR-2009(8583)-8545.

1 - Requirements Review (RR)	7 - Pre-Environmental Review (PER)
2 - Preliminary Design Review (PDR)	8 - Pre-Ship Review (PSR)
3 - Critical Design Review (CDR)	9 - Mission Readiness Review (MRR)
4 - Build Readiness Review (BRR)	10 - Flight Initial Readiness Review (FRR)
5 - Test Evaluation Campaign Review (TECR)	11 - Initial Checkout Review (ICR)
6 - Baseline Integrated Test Readiness Review (BISTRR)	

The key program phases are as follows:

- **Pre-Award Phase** – This is the phase in a program lifecycle that includes all activities in support of proposal development
- **Requirements and Design Phase** – This is the phase in a program lifecycle that includes all activities directed at capturing the program's system level requirements and developing a detailed design capable of meeting these requirements.
- **Build and Test Phase** – This is the phase where System and Subsystem engineers are verifying and validating requirements. Typical risk-constrained programs with non-heritage designs benefit from a System Testbed to perform V&V, Fault Management response and recovery scenarios, C&T database validation, AI&T risk reduction and anomaly resolution.

- **Sell-Off and Mission Preparation Phase** – This is the phase in a program lifecycle that includes all activities needed to demonstrate that the flight and ground systems are ready for launch.
- **Operations Phase** – This is the phase in a program lifecycle that includes all activities following launch. Included within this phase are any on-orbit checkouts that are performed.

4.3 Allocation of Program Phases to Tb&S Uses for a Risk-Constrained Program

In this section we allocate the Tb&S End Uses to each of the five program lifecycle phases for a risk-constrained program. Also, a typical Tb&S delivery schedule required to meet the planned Tb&S uses is provided within the detailed description of the allocation to each program phase, suggesting handoffs of Tb&S products between the earlier simulators and the later testbeds for a typical program. We do, however, offer a brief discussion in each subsection that addresses the allocation to a resource-constrained program without going into the details of each use.

4.3.1 Typical Tb&S End Uses during Pre-Award Phase

Tb&S Products Used in a Risk-Constrained Program	*NRT-Sim, NFTB*

The Pre-Award phase of the program is generally conducted outside of customer oversight, and because different programs and different companies vary widely in their practices during this phase, the activities in this phase are somewhat more difficult to categorize. In general, the pre-award phase may benefit from re-use of existing Tb&S products (such as NRT-Sim or STB) for concept studies and concept development in the preliminary system-level design trade studies to support the proposal effort. Also during this phase, Tb&S products are developed or borrowed from previous programs for initial risk-reduction studies and proof of concept studies, especially when the Space Vehicle is new.

The End Uses appropriate here are contained within the Concept Development End Use category, discussed in Section 3.2.1 and the primary Tb&S type used within a risk-constrained program is an NRT-Sim. For these End Uses, the Proposal Team may benefit from reuse of an existing NRT to evaluate candidate design solutions and to define a technical baseline for the next program phase. Depending upon the specifics of the mission described in the Request for Proposal (RFP), the proposal team may elect to borrow a simulator or testbed from a previous program and refine some of the simulator parameters to suit the new concepts under study.

The principal schedule driver in the pre-award phase is the Proposal due date. Working backwards from that date, the Proposal team must have completed design trade studies far enough ahead of the Proposal due date to allow time for any concept development work needed for the selected design, while still leaving time for other proposal data collection and writing activities. Therefore these End Uses will require any simulator or testbed tools before the start of proposal writing, and may continue to need refinements right up to the Proposal Due date, however ideally their use would be completed early in the proposal writing schedule.

Note on Resource-constrained Programs: The Tb&S allocation for a resource-constrained program in this phase should be identical to the allocation for a risk-constrained program, described above. In both program types, the proposal team uses the Tb&S product most convenient to their needs, and with the least development effort required.

4.3.2 Typical Tb&S End Uses during Requirements and Design Phase

For each program step during this phase of the program, Software and Subsystem engineers are using simulators and testbeds to develop and test software algorithms, lower level components, and integrated builds. Since the Requirements and Design phase ends at program CDR, it is usually too early to have an operational STB, but all the components (software and engineering model hardware) should be designed and tested for insertion into an STB.

Figure 4-4 shows the Requirements and Design Phase Tb&S usage schedule for a risk-constrained program. During this phase FSW begins its product development, unit test and integration on NRT/RT simulators and Non Flight-Like Testbeds (before EMs are available) and performs final verification on the FSW Test Bench (see Figure 3-9). Subsystems such as EPS may use a Subsystem Testbed to prove out their algorithms before handoff of algorithms to FSW. Operational Ground Systems (or the STB Ground System if it is different from Operations) need an NRT simulator to check out their operations with the SV Command and Telemetry database.

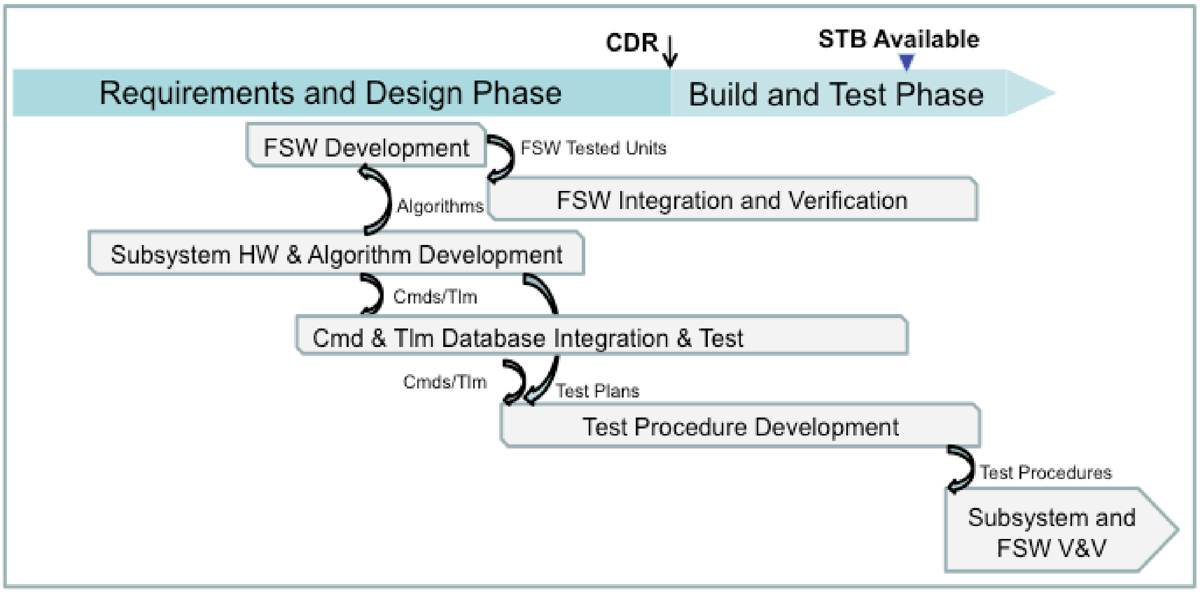


Figure 4-4. Requirements and design phase Tb&S usage schedule.

Note on Resource-constrained Programs: As far as resource-constrained programs are concerned, because of the compressed timetable typical in the resource-constrained program, these programs will typically have trouble completing the development of a System Testbed early enough to allow for the subsequent development and qualification of FSW ahead of the start of AI&T activities. For this reason, resource-constrained programs typically do not complete FSW qualification until just prior to pre-environmental performance testing in AI&T. Since the main use of the System testbed in the Requirements and Design program is the development and test of FSW, all of the boxes with interfaces to the FSW processors will be either modeled or present as EM (or better) hardware. However, it is typical of a resource-constrained program to have less flight-like boxes (and commensurately more simulated or emulated boxes) than in the similar System Testbed used for these activities in the risk-constrained program. Another feature typical of the resource-constrained program is the use of non-simulator tools in checking out the command and telemetry database.

4.3.2.1 Subsystem Algorithm Development End Use

Tb&S Products Used for a Risk-Constrained Program	*NRT-Sim*

In a risk-constrained program, this End Use must start shortly after the proposal win and must be completed early enough to allow time for the development and testing of the FSW units that incorporate these algorithms and then for the integration and verification of FSW before the start of STB activities. In this use, Subsystem engineers, like ACS or EPS, require a method to check out their algorithms before delivery to FSW. Typically, an ACS development team uses a high fidelity analysis simulation to develop their algorithms and open-loop test cases for FSW ACS algorithm verification. The real-world dynamics, environment, disturbance and hardware models are often (or have the opportunity to be) re-used in the STB Dynamics Simulator. The analyst-generated dynamics test results provide truth data to be used by the STB development team for their post-test analysis. EPS engineering model hardware units are typically tested prior to CDR to provide data to backup analyses. Unless the EPS engineer has a comparable analysis simulation to ACS, they are dependent on integrating the EPS units as a subsystem to prove out their EPS algorithms before delivery to FSW. The benefit of having an early EPS subsystem testbed provides an opportunity to integrate it in the post-CDR STB for more closed-loop fidelity.

4.3.2.2 Command and Telemetry Database Integration and Test End Use

Tb&S Products Used for a Risk-Constrained Program	*NRT-Sim, STB*

In this use, the Database System Integration Team (or Ground Systems Team) requires an NRT simulator with adequate realism for command sequences to produce predictable telemetry responses. This use typically starts early in the Requirements and Design phase and must be completed far enough ahead of the Build Readiness Review for the released database to be used in the script and procedure development work that is required before Subsystem and FSW verification testing can begin. Development often continues past the initial release and into the Build and Test phase. As time progresses, the STB becomes available for use as a higher fidelity verification of commands and telemetry.

Guideline 07: For any type of SV program, having a common Ground System during System and Subsystem Testing, AI&T and Operations provides an opportunity to check out and synchronize the Command and Telemetry database early in the SV development process.
Rationale and Example: Use of a common Ground System throughout the phases of the SV development process allows Test Engineers to develop procedures and Telemetry pages to be easily re-used, promotes test-like-you fly and allows the Ground System developer to checkout their database and ground products early.

4.3.2.3 Flight Software Development and Integration End Uses

Tb&S Products Used for a Risk-Constrained Program	*NRT-Sim, NFTB*

This subsection covers the allocation of Tb&S products within a risk-constrained program to two FSW-related End Uses: FSW Unit Test End Use and FSW Development and SI Integration End Use defined in Section 3.2.2. While an NRT simulator is an appropriate test environment during FSW unit development, a realistic environment with a real-time operating system and EM processor hosting the FSW in an open-loop test environment is necessary for FSW integration and verification. During this use, the NFTB includes models of all of the hardware with interfaces to the FSW processor(s). This verification platform may need to be maintained through the life of the SV development cycle to update FSW builds to the STB and AI&T and to maintain the FSW image after launch.

Guideline 08: For a risk-constrained program, to enable timely deliveries of verified FSW to both the STB and AI&T, it is useful for FSW to define a minimum of two FSW builds.
Rationale and Example: The first FSW build should include the C&DH FSW and control of each of the interfaces; such as a wheel controller interface to check out the commands to the wheel corresponding with the tach data from the wheel. This build needs to be completed and delivered to the STB at the start of the Build and Test Phase and needs to be validated in time for AI&T to begin its integration and test. The second FSW build should be the rest of the FSW including the subsystem control algorithms, fault management and payload. Depending on the complexity of the SV, this second FSW build may be divided into even more multiple builds, which support the SV development. Ultimately, the final FSW build needs to be completed in time to be validated on the STB (or ISVT if that's the plan) and before the AI&T comprehensive environmental tests.

4.3.2.4 FSW Test Development End Use

Tb&S Products Used for a Risk-Constrained Program	*NFTB, STB*

For FSW Test Development, test engineers require a platform to develop procedures used in FSW and Subsystem Verification tests. For early preparation, the Test Engineer may draft their procedures on a Non Flight-Like Testbed. This use requires a Command and Telemetry database and Subsystem test plans and must be completed in time to run the procedures on the STB. If planned well, a subset of these procedures (e.g., interface threads and polarity) may be re-run during AI&T on an STB and provides an opportunity to re-use as-run procedures.

4.3.3 Typical Tb&S End Uses during Build and Test Phase

During the Build and Test phase of the program, System and Subsystem engineers are verifying and validating requirements on either the STB or ISVT, depending on their program's resources. Typical risk-constrained programs with non-heritage designs benefit from a System Testbed to perform V&V, Fault Management response and recovery scenarios, C&T database validation, AI&T risk reduction and anomaly resolution.

Figure 4-5 shows the Build and Test Phase Tb&S usage schedule. At the stage when the STB is first available, the Tb&S products from the Requirements and Design Phase need to be mature enough to perform System, Subsystem and Fault Management V&V engineering tests, AI&T procedure development and anomaly resolution. Because of the high cost of AI&T activities, it behooves the risk-constrained program to perform as much of their V&V activities as possible on the STB, relegating only interface, polarity and workmanship type testing to AI&T; thus reducing the AI&T schedule and ultimately reducing costs.

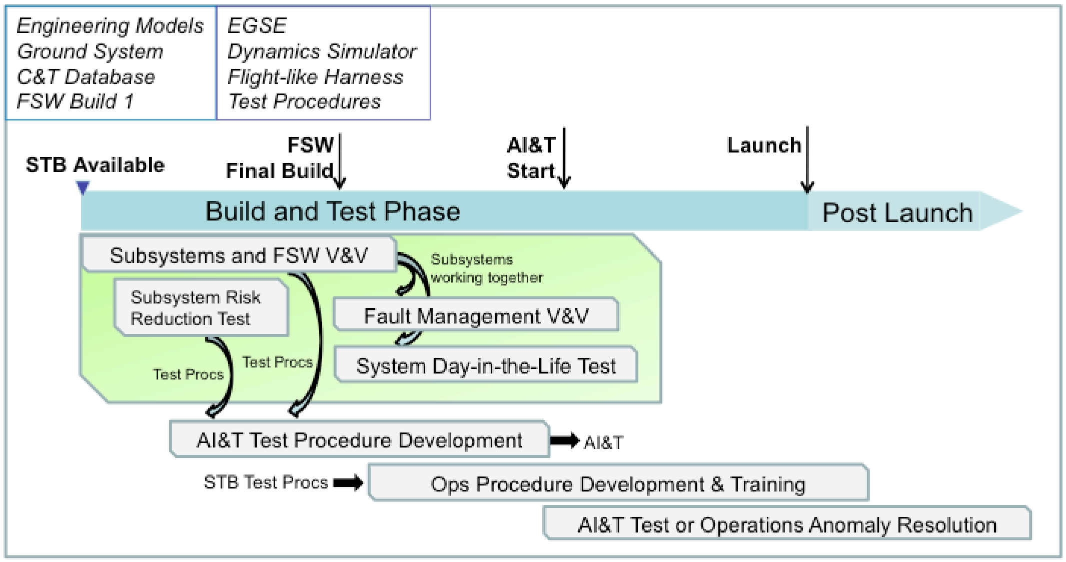


Figure 4-5. Build and test phase Tb&S usage schedule.

Note on Resource-constrained Programs: Simulator use during the Build and Test phase of the program is highly varied, as diverse groups are looking to shift activities off of the flight spacecraft to venues with less cost and schedule penalties. For a typical resource-constrained program, many of the uses appropriate to this lifecycle phase end up getting allocated to the ISVT instead of the STB in order to meet program schedule and cost constraints.

4.3.3.1 System/Subsystem Verification and Validation End Use

Tb&S Products Used for a Risk-Constrained Program	*STB*

This subsection covers the allocation of Tb&S products within a risk-constrained program for several End Uses: FSW Formal Requirements Verification (SIQT) End Use, FSW Regression Testing End Use, System/Subsystem Requirements Verification End Use, and System/Subsystem Validation End Use as defined in Sections 3.2.2 and 3.2.3. These End Uses are typically required to be complete before Fault Management and System level System Testbed (STB) testing and the start of AI&T. Subsystem requirements requiring hardware not present in the STB need to be verified during AI&T.

4.3.3.2 AI&T Risk Reduction Testing End Use

Tb&S Products Used for a Risk-Constrained Program	*STB*

In this use, AI&T, subsystem or system engineers require a System Testbed with EM or flight components to perform interface verifications, initial requirement validation, and pre-integration checkout. The System Testbed allows a program to verify proper operation of hardware, flight software, ground equipment, or test equipment prior to installation and use on the flight vehicle. The start point for this use is the availability of appropriate EM units (or Software components) for testing and generally extends to beginning of system level AI&T.

4.3.3.3 Fault Management System Testing End Use

Tb&S Products Used for a Risk-Constrained Program	*STB*

In this use, Fault Management engineers use an STB to run tests to verify fault management requirements. In this type of program, the use starts immediately after Subsystem V&V (Section 4.3.3.1) and is ideally completed prior to the AI&T environmental test activities. This testing assumes the flight vehicle is on the final FSW build and the lower level subsystem level tests are successful and complete. Fault Management System testing is primarily conducted on an STB, because it is a safer environment for creating anomalous conditions and because of the ability to inject faults from simulated components. However, a subset of Fault Management tests that exercise critical flight hardware components of the Fault Management system may still need to be re-run during AI&T.

Guideline 09: For any type of SV program, perform as much Fault Management testing on the System Testbed as possible and try to minimize FMS testing against the SV.
Rationale and Example: The STB provides greater capability to inject realistic faults, providing greater fidelity and robustness for most type of fault testing. This type of testing should augment tests performed on the space vehicle flight hardware. The risk in omitting or curtailing this activity is that Fault Management essential to the safety of the Space Vehicle may contain design or implementation errors that effect on orbit performance and Space Vehicle safety.

4.3.3.4 Day-In-The-Life Testing End Use

Tb&S Products Used for a Risk-Constrained Program	*STB*

In this use, System engineers typically require an STB to verify system operational concepts, including autonomous and ground supported operations, as detailed in Section 3.2.3. Realistic nominal and off-nominal scenarios are developed in concert with the Fault Management, Subsystem and Operation Engineers.

4.3.3.5 Flight Operations Training and Mission Rehearsals End Use

Tb&S Products Used for a Risk-Constrained Program	*NRT, STB*

To accommodate these End Uses, an NRT simulator and an STB are required to provide a training tool for developing operational scripts to fly the SV and to respond to anomalies. NRT and Non Flight-Like Testbeds may make an adequate training platform if their fidelity is comparable to or validated against an STB. This use typically starts in the Build and Test phase, and should benefit from the Test Like You Fly procedures utilized by the System and Subsystem engineers.

4.3.3.6 Test Procedure Development End Use

Tb&S Products Used for a Risk-Constrained Program	*NRT, STB*

In this use, AI&T requires an NRT simulator, a FSW Test Bench, or a System Testbed with adequate realism to provide a platform for dry running procedures. For the development of AI&T integration procedures, the hardware realism required is typically more than an NRT can provide, and often the EMs in an STB are also not adequate. For the development of AI&T system-level test procedures, an

NRT or an STB is usually adequate. This use typically starts early in the Build and Test phase. Procedure development for integration procedures should be fundamentally complete before the start of AI&T integration activities, however procedure development work for system-level test procedures is better planned to last until just before the start of pre-environmental performance testing.

4.3.3.7 Test Anomaly Resolution End Use

Tb&S Products Used for a Risk-Constrained Program	*STB*

In this use, AI&T, Subsystem, and System Test Engineers may require a tool to pursue anomaly resolution offline from AI&T spacecraft operations. They benefit from having an STB to resolve anomalies offline to reduce AI&T schedule risk. The required fidelity/maturity of the STB will vary with the nature of the anomaly and benefits from an STB designed with primary and redundant C&DH and EPS hardware in the loop. This use is a contingency activity that may occur any time in the Build and Test phase after the start of AI&T activities and may continue during launch and post launch.

4.3.3.8 Ground Compatibility Test End Use

Tb&S Products Used for a Risk-Constrained Program	*STB, ISVT*

In this use, the STB (or ISVT when ready) is used for database validation during System, Subsystem and FM testing. The STB provides an environment to realistically check out the C&T database between the Ground and the SV, including all the telemetry formats. Hardware commands and telemetry requiring hardware not present in the STB need to be validated during AI&T.

4.3.4 Typical Tb&S End Uses during Selloff and Mission Preparation Phase

Tb&S Products Used for a Risk-Constrained Program	*NRT, STB, ISVT*

During the Sell-off and Mission Preparation Phase, Flight Operations continues to develop procedures, train operators and perform rehearsals. The Tb&S products identified during the Build and Test Phase continue to be used in this Mission Preparation Phase. The initial training activities usually start during the Build and Test Phase and must be completed prior to the Pre-Ship Review. Additional training may continue into the Operations phase of the program. The additional Tb&S End Use that applies to this phase is Mission Rehearsals. In this use, test engineers, working with ground station operators, require a tool to dry run operations activities. Typically an NRT simulator, a System Testbed, or an ISVT is used in the risk-constrained program.

4.3.5 Typical Tb&S End Uses during Operations Phase

Tb&S Products Used for a Risk-Constrained Program	*NRT-Sim, STB*

During the Operations Phase, Operations and Subsystem Engineers require tools to pursue anomaly resolution offline from flight operations. These End Users also require tools to continue Operations procedure development and operator training activities. Typically the Tb&S product developed and used for Mission rehearsals, Day-in-the-life testing, or Test Procedure development are the preferred platforms to maintain post launch. Optimally, two Tb&S platforms are preferred during this phase: 1) The STB is the most useful anomaly resolution platform, due to its hardware in the loop fidelity; and 2) An NRT-Sim (as long as its model fidelity has been validated against the STB) is useful for operators training, due to its ease of use and low maintenance. The Post-Launch Anomaly Resolution End Use may occur any time in the Operations phase after launch, so the Tb&S must be ready by the start of this phase.

5. Lifecycle Process for Program Tb&S Products

This section of the document describes the entire lifecycle of program Tb&S, from the conception to the operations and maintenance phase. Section 5.1 contains the development lifecycle and identifies the common activities for each Tb&S development lifecycle phase along with the entrance and exit criteria for each activity and any required program inputs required during the Tb&S development activity. Section 5.1 also provides a checklist for each activity, containing recommended tasks to be performed and artifacts to be produced. Section 5.2 provides information on Tb&S support of the spacecraft program reviews (i.e., SRR, PDR, CDR). Section 5.3 covers the roles and responsibilities associated with program Tb&S and offers guidelines for improvement.

Guideline 10: Follow a semi-formal to formal Tb&S development process with clear and comprehensive requirements and design documentation.
Rationale and Example: This guideline ensures lower-cost reproducibility of Tb&S components or of an entire Tb&S during later stages in the program when development teams are different or the users must address any issues with the Tb&S operations.

5.1 Tb&S Lifecycle Process Overview

The development and use of Tb&S products on a spacecraft program typically follows a standard system product development process. For the purposes of this document, the Tb&S activities for a spacecraft lifecycle will be organized similar to Aerospace TOR-2009(8583)-8545 “Guidelines for Space Systems Critical Gated Events”, described in Section 4.2. Since Tb&S products are typically developed in this manner (See Figure 4-3), the process description used in this section will follow similar lifecycle phases and corresponding activities organized as follows:

Pre-Award Lifecycle Phase
  - *Tb&S Proposal Activity (Section 5.1.1.1)*

Requirements and Design Lifecycle Phase
  - *Tb&S Architecture and Requirements Development Activity (Section 5.1.2.1)*
  - *Tb&S Design Activity (Section 5.1.2.2)*

Build and Test Lifecycle Phase
  - *Tb&S Build and Integration Activity (Section 5.1.3.1)*

Selloff and Mission Preparation Lifecycle Phase
  - *Tb&S Verification Activity (Section 5.1.4.1)*

Operations Lifecycle Phase
  - *Tb&S Operations and Maintenance Activity (Section 5.1.5.1)*

It should be noted that, since the availability of the Tb&S products constitute a pre-requisite for entry into some program lifecycle phases, i.e., Requirement and Design or Build and test, their development phases are offset and typically lead those of the program.

5.1.1 Pre-Award Lifecycle Phase

The Tb&S activity during this Pre-Award Lifecycle Phase focuses on the development of sufficient Tb&S artifacts to support the Proposal Phase of the program.

5.1.1.1 Tb&S Proposal Activity

Proposal development for Tb&S is tailored for each proposal activity based upon the customer instructions in the Request for Proposal (RFP), Request for Information (RFI), Announcement of Opportunity (AO), or comparable customer directions.

During the Proposal Activity, as shown in Figure 5-1, it is important to create a set of Tb&S artifacts so that trades can be made regarding the quantities and capabilities (e.g., level of fidelity and test-as-you-fly configuration). Using the program's proposed Verification and Validation plan as their guide, Systems Engineering in coordination with Tb&S gathers information from all potential users as discussed within Section 3 of this document. The Tb&S artifacts to be developed during this activity include; Tb&S Development Plan (see Appendix A), Tb&S Schedule, Tb&S Conceptual Architecture, and ultimately the Tb&S Task Descriptions (TDs) and Basis-of-Estimate (BOE). These artifacts will help drive the cost, schedule, and technical proposal decisions that must be made in deciding the number and types of Tb&S products to be utilized for a given program.

Guideline 11: Include a Tb&S Development Plan as part of the standard Tb&S documentation.
Rationale and Example: Creating a Tb&S Development plan, starting in the pre-award phase and baselined at the completion of the Requirements & Architecture phase, is critical to communicating the proposed capability to be developed and deployed. This document can be subordinate to the programs' Test & Evaluation Master Plan, and forms the basis for all activities during the Tb&S lifecycle.

Guideline 12: During the Proposal phase of the program, ensure Tb&S types, quantities, and capabilities are sufficient to support the projected usage during the execution phase of the program.
Rationale and Example: Many programs do not fully consider providing adequate number and types of Tb&S and consequently find that usage is higher than initially assumed. The ensuing resource bottleneck creates costs and schedule impacts far greater than those that would have resulted from the extra cost of building more Tb&S at the appropriate time in the schedule. The usage results will drive the initial Tb&S architecture key requirements and definition.

The Tb&S Proposal Activity's Entry and Exit Criteria are shown in Figure 5-1. The Entry criteria include the Proposal RFP/RFI, the Tb&S Users' needs, the Program's Verification and Validation (V&V) Plan and previous Tb&S lessons learned. The Tb&S Proposal Exit Criteria expects a Tb&S Development Plan, Schedule, Conceptual Architecture and TD/BOEs.

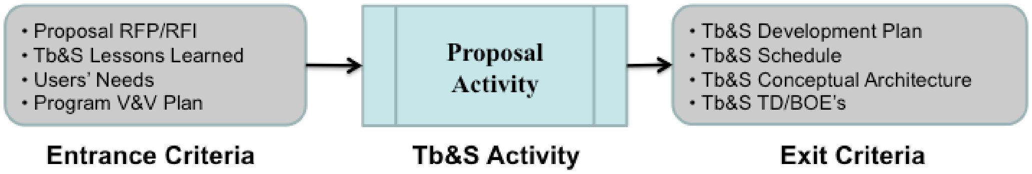


Figure 5-1. Tb&S proposal activity.

Tb&S Development Plan: The development plan identifies all the different Tb&S types required across a Space Vehicle life cycle; including the quantity and fidelity for each type. This plan needs to reflect the Users' needs and support the Program's V&V plan.

Guideline 13: In the initial Tb&S development plan define gates and reviews and ensure that the entry criteria include input from the appropriate users and development teams.

Rationale and Example: This activity addresses the following: 1) It ensures that all users of the various Tb&S are given the chance to specify the capabilities they need from each delivery cycle; 2) It ensures that all appropriate users (such as the Systems Engineering Team) are involved in the development of Testbeds & Simulators; and 3) It ensures that the usage schedule by each user is not underestimated. Underestimating the Tb&S usage schedule affects other users until the schedule slippage propagates to all users.

Tb&S Schedule: The schedule ties all the Tb&S product developments to program life cycle milestones and need dates. High-level Tb&S giver/receivers anchor the Tb&S developments to the Users' needs.

Guideline 14: The Tb&S deployment schedule should satisfy the End User needs during that program phase. The End Users must accurately specify the capabilities they need from each Tb&S delivery and the Tb&S organization must agree that their deployment can satisfy the need.

Rationale and Example: The Space Vehicle and Tb&S development cycles for a typical program share concurrent development cycles. This necessitates staged capability deployment, prioritized based on program level requirements. Underestimating schedule by some users affects other users until the schedule slippage propagates to all users risking critical path impacts. For example, software-only simulators could be deployed in earlier phases providing lower fidelity capabilities, but faster time to market, to support development and risk reduction activities.

Tb&S Conceptual Architecture: The conceptual architecture identifies the physical components of a Tb&S product; namely what's hardware in the loop versus what's modeled, and what ground support equipment and operator console is required. A conceptual architecture needs to be provided for each Tb&S type identified in the Tb&S Development Plan. Tb&S Lessons Learned are extremely helpful in defining the Tb&S Conceptual Architecture.

Tb&S TD/BOE's: Based on the Tb&S Development Plan for Tb&S types across the Space Vehicle life cycle and each Tb&S type's Conceptual Architecture, the TD/BOE's provide the basis for the Tb&S developments and Tb&S labor, material and subcontractor costs.

Table 5-1 provides a Checklist to assess the Tb&S Proposal activities and artifacts during the Pre-Award Lifecycle Phase.

Table 5-1. Tb&S Proposal Checklist

Tb&S Proposal Checklist	Yes	No	N/A
Does the Tb&S development plan support the Proposal's RFP?			
Is the Tb&S Development Plan identified in the Proposal's V&V plan?			
Is the Tb&S conceptual architecture and fidelity defined? Reference Section 3.4.2 to define the fidelity levels.			
Does the Tb&S fidelity and conceptual architecture meet the V&V plan and user needs?			
Does the Tb&S make use of common EGSE and Ground System components?			
Have all the flight-like components (EMs, Cmd/Tlm database, FSW, harness, Ground System, EGSE) fidelity been coordinated and costed?			
Are all the Tb&S givers and receivers identified in Integrated Management Schedule (IMS)?			
Is the Tb&S on a critical schedule path for any of the Program's developments; such as Subsystems, AI&T or Operations?			
If the Tb&S is on the critical schedule path, is appropriate schedule slack identified?			
Are all the Tb&S risks identified, prioritized and with mitigation plans?			
Do the Tb&S TD/BOEs reflect realistic tasks and budget to complete the development and are the costs for the flight like components captured in the current WBS?			

Guideline 15: Tie the Tb&S product and its use to the entry criteria for AI&T.

Rationale and Example: This guideline ensures the early delivery of EMs early so the program gets the value out of their use in a Tb&S product. Often programs do not complete development and qualification of their component hardware in time (causing schedule erosion), which naturally shifts priority away from development hardware to direct development of flight components. This delays delivery of development hardware, rendering it ineffective for troubleshooting and resolving problems found with flight hardware during AI&T.

Guideline 16: Programs must identify early which system requirements (including key risk requirements and functions) they plan to validate on which Tb&S platform or which Tb&S platform they need to collect data for their analyses.

Rationale and Example: The V&V plan should be developed in the earliest phase of the program so that key requirements including test requirements can be identified and flowed down to the testbed level. Often tests are designed and tailored based on the capability of the testbed rather than test requirements driving the testbed requirements. Defining the test requirements early in the program (even during the RFP) will reduce the overall testbed development cycle time and an effective V&V process.

5.1.2 Requirements and Design Lifecycle Phase

The Requirements and Design Phase of the program lifecycle encompasses the activities between program Authorization To Proceed (ATP) and the Critical Design Review (CDR) leading into the Build and Test phase of the lifecycle.

For Program Tb&S products, this activity consists of defining and designing the Tb&S architecture based on key driving requirements and constraints. The Tb&S requirements may be formal or informal, but always come from the standard requirements flow-down for the system. Once the architecture is defined, requirements analysis is performed to derive additional requirements and flow-down lower level requirements. Trade studies are performed and design options are considered to establish a baseline architecture that meets requirements and satisfies the End User for their intended End Uses. The design phase consists of completing a design based on the Tb&S architecture and requirements.

Guideline 17: The Systems Engineering team must be involved during the development of Program Testbeds and Simulators. Defined Tb&S gates and reviews will ensure that the entry and exit criteria include the involvement of the SE team.
Rationale and Example: Since the Tb&S development lifecycle typically involves concurrent design activities with the Program, Systems Engineering's role is to provide requirement updates and to ensure the Tb&S architecture and requirements are aligned with program needs. For example, during the Tb&S requirements and design lifecycle phase, the Space Vehicle goes through reviews resulting in requirement and design changes that impact Tb&S. The Systems Engineering team must have a role in ensuring that impacts to Tb&S are adequately addressed.

5.1.2.1 Tb&S Architecture and Requirements Development Activity

Development of the Tb&S system architecture begins upon ATP and completes with a review establishing the baseline Tb&S system architecture and requirements. Figure 5-2 shows the entrance and exit criteria for the Architecture and Requirements Development Activity as well as the required program inputs during this activity. Entry criteria include the Tb&S Development Plan (draft), the initial Tb&S Schedule, the Tb&S Conceptual Architecture, and the Task Descriptions and BOEs from the proposal activity. If artifacts from the proposal phase are available then they become the starting point for this activity; if they are not available then they must be sufficiently developed in order to begin this activity.

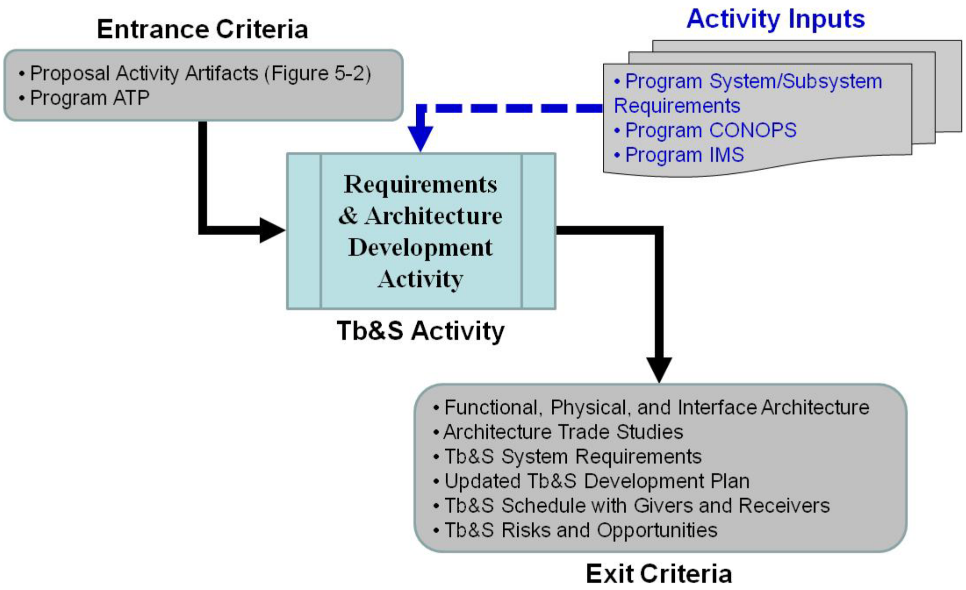


Figure 5-2. Tb&S architecture and requirements activity.

Functional, Physical, and Interface Architecture: A Conceptual Tb&S Architecture should have been developed in the Pre-Award activity, establishing a baseline for the technical, cost, and schedule drivers for Tb&S products. During the Architecture and Requirements Development Activity, a Tb&S Architectural Plan is developed to meet stakeholder (e.g., Tb&S End User) needs and allocated requirements. The Tb&S architecture consists of three elements: functional, physical, and interface.

The process starts with a comprehensive identification of all Tb&S End Users, as described in Section 3.1 and Table 3-1. Once the End Users have been identified, development of the End Uses required of the Tb&S system can be established, as described in Section 3.2 and Table 3-2. These End Uses define the functionality required of Tb&S as detailed in Section 3.3 and Table 3-3. This becomes the basis for the Tb&S Functional Architecture.

The Tb&S Conceptual Architecture should have identified the physical components of the Tb&S end products (i.e., decisions about which components need to be hardware and which can be modeled). During the architecture activity, a baseline is established for the suite of Tb&S products that support the End User. This consists of identifying the types, quantities, and fidelity levels of the Tb&S products that are required for the program (see Section 3.4). The Tb&S Physical Architecture consists of decomposing each identified Tb&S product into their major components as described in Section 3.4.1. The fidelity levels required for the Hardware (Table 3-5) and Software Models (Table 3-6) should be initially defined. At the end of this phase, the decomposition should be sufficiently detailed to begin developing the low-level Tb&S product requirements.

The Tb&S Conceptual Architecture may have identified key interfaces within and external to the Tb&S. During this activity, critical interfaces are defined as necessary to establish capabilities required by the functional architecture. Section 3.4.2 can be used to initial identify the required fidelity levels of the interfaces within the Tb&S system. External interfaces from Tb&S should be established, including facilities, IT infrastructure, and other key external interfaces. This becomes the basis for the Tb&S Interface Architecture.

Architecture Trade Studies: Trade studies of the Tb&S architecture should be performed in order to ensure that the planned Tb&S products not only meets their technical requirements, but can also be deployed on schedule and within the cost constraints of the program.

Tb&S System Requirements: During the Requirements Phase of the program, the requirement analysis and development activity will begin and mature. The purpose of requirements analysis is to perform detailed requirements analysis, including both functional and performance analysis, in order to flow-down appropriate requirements. This process follows the architecture development process that involves trade studies and various design options to establish a baseline architecture with top-level requirements identified ahead of the design activity. The Requirements and functional/performance analysis processes often continue into the Tb&S design activity with updates to the artifacts established in this activity.

The requirements activity is critical to ensuring completeness and accuracy of the final Tb&S products. Effective communication and collaboration with all stakeholders avoids problems with Tb&S functionality and fidelity being under- or over-specified for the identified End Use.

Figure 5-3 shows an example of requirements flow down and specification of program artifacts to the Tb&S System Requirements. The Tb&S requirements are derived from various system and subsystem specifications such as: Ground Requirements (i.e., CMD/TLM); System level functional and performance requirements; Operational scenario and Operations requirements (i.e., training requirements); and direct flow-down from the contractual requirements. The primary purpose of this tree diagram is to identify requirement sources and identify key Tb&S requirements that need to be specified in both system level specifications and component level specifications, if required by Tb&S Development Plan.

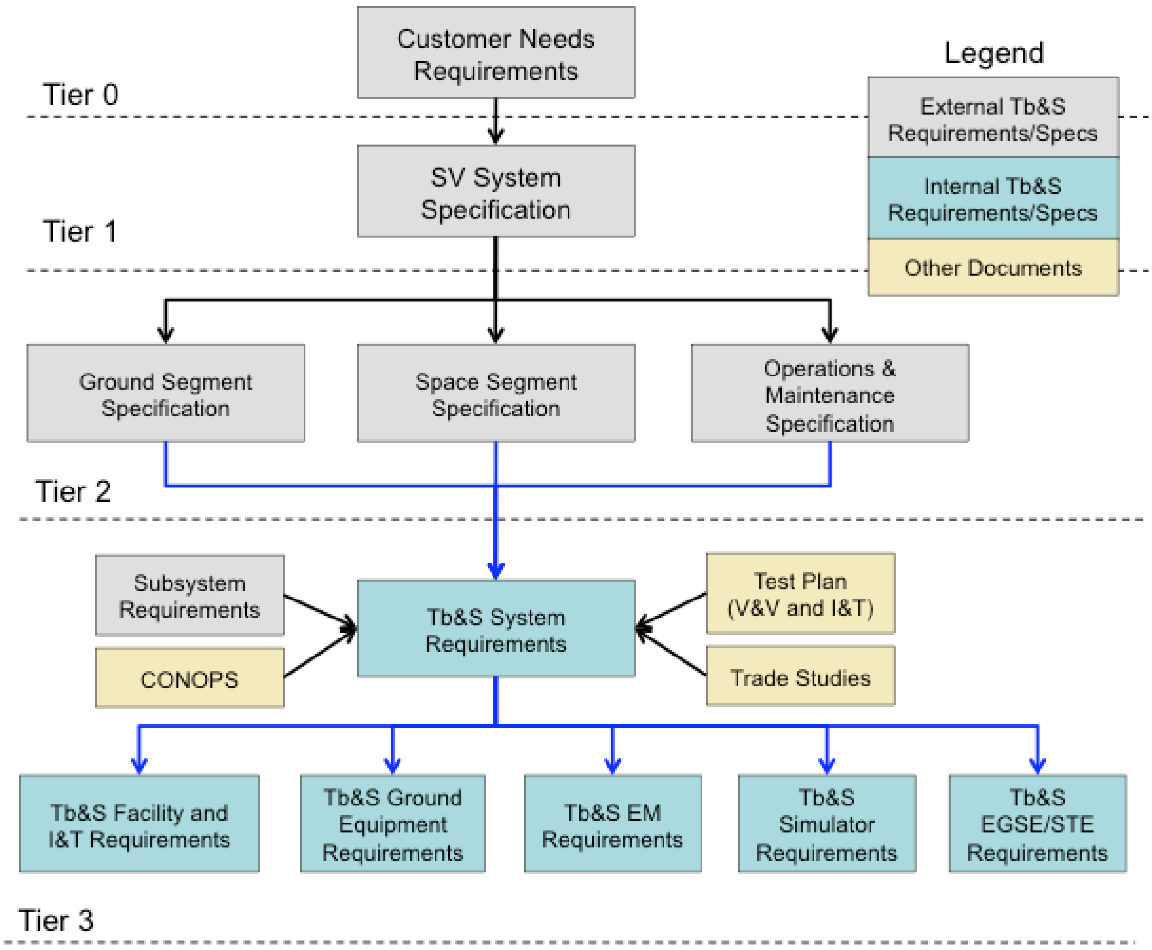


Figure 5-3. Example requirements flow-down and specification tree.

Tb&S Development Plan: The initial Tb&S Development Plan created in the Pre-Award activity should be updated to include all baseline decisions resulting from this activity. At this point the document should be comprehensive and under change control, as it establishes the baseline plan from the completion of the development and deployment of Tb&S to support the program. The development plan may be considered a living document to be updated as the program matures unless other artifacts are planned to support remaining lifecycle activities.

Other Considerations: The Tb&S Top-Level schedule created in the Pre-Award Activity must be refined to adequately define the major Tb&S development activities, Tb&S product deployments, and critical giver-receiver dependencies with other program organizations. This should include key dependencies to EGSE, Subsystem organizations (for EM deliveries), System Analysts, and the I&T organization. Tb&S should identify all top-level risks and develop plans for risk burn-down. Any opportunities associated with Tb&S should be identified for program consideration.

Guideline 18: Hold a Tb&S System Requirements Review (SRR). All findings and action items should be documented and work products should become the Tb&S baseline.

Rationale and Example: It is important that the Tb&S Architecture and Requirements baseline be established and communicated to key program stakeholders. Tb&S End Users must attend this review to ensure that the technical and schedule baseline meets their needs. Program management must be informed as to the importance that the Tb&S products contribute to the overall program development, integration and test, and operations phases of the program.

Guideline 19: Early involvement of System and Subsystem Subject Matter Experts (SME) during the requirement definition phase of Tb&S helps provide domain expertise critical to requirement development.

Rationale and Example: The top level requirements involving system technical performance, Subsystem partitioning and capability definition would benefit greatly with inputs and influence from Subsystem SMEs early on in the architectural phase as they provide foresight into the End Uses, for example providing a modular simulation architecture or a distributed processing would provide for greater system scalability and configurability.

Guideline 20: Ensure the Tb&S system can be controlled from the program ground system.

Rationale and Example: This provides users with the capability to have connectivity between the test procedure, the flight commands, and the GSE commands.

Guideline 21: Make Tb&S software configurations flexible by making them parameter-driven so that changing configurations does not require rebuilding the Tb&S software.

Rationale and Example: Enabling parameter-driven reconfiguration of the Tb&S (such as changing the orbit) will significantly reduce the cost of developing and operating Testbeds & Simulators and may protect the Testbed from any cost-cutting measures in cases of schedule erosion.

Table 5-2 provides a Checklist to assess the Tb&S Architecture and Requirements activities and artifacts during the Requirements and Design Lifecycle Phase.

Table 5-2. Tb&S Architecture and Requirements Activity Checklist

Tb&S Architecture and Requirements Activity Checklist	Yes	No	N/A
Are all entrance criteria met for the Architecture and Requirements Development activity?			
Have all Stakeholders and their Needs been identified prioritized?			
Have all the Stakeholders been identified? Note: Refer to Tb&S End User Taxonomy			
Have all stakeholder needs, expectations and constraints been analyzed? Note: Refer to Tb&S End Uses Taxonomy and Functional Taxonomy			
Have the stakeholder needs for each identified End Use been mapped to key Tb&S deployment milestones?			

Tb&S Architecture and Requirements Activity Checklist	Yes	No	N/A
Have the Tb&S limitations and constraints been identified for all phases of the lifecycle?			
Have Tb&S risks been identified and is a preliminary risk analysis complete?			
Have the Tb&S system objectives & Tb&S product deliverables been defined?			
Has a system level functional analysis been conducted to derive key Tb&S system requirements? Note: For each identified use, for each milestone.			
Has a problem statement been developed that succinctly outlines the Tb&S system objectives? Note: For each Tb&S End User.			
Have the Tb&S System Requirements been completed and reviewed?			
Has a Concept of Operations (ConOps) been evaluated for its impacts to Tb&S?			
Have trade studies been conducted and analyzed to further decompose architecture and requirements?			
Have trade studies been conducted to analyze/justify make/buy/re-use decisions?			
Have internal reviews for Tb&S artifacts been conducted to obtain internal Subject Matter Expert (SME) and technical staff feedback?			
Has the Tb&S Functional, Physical, and Interface Architecture been developed and reviewed?			
Have key Architecture drivers been identified? Technical, Schedule & Cost			
Have lessons learned from previous programs been reviewed and implemented? Note: Identify improvements to save cost and schedule			
Has the Tb&S Hardware architecture been developed?			
Has the Simulation architecture been developed?			
Has the Database architecture been developed?			
Has a preliminary Tb&S Data Management architecture been developed? Real-Time Data I/O distribution, Data archiving			
Has Software Configuration Management (SCM) system that supports Tb&S been developed? Note: SCM product identified and reviewed?			
Are all work product packages released and baselined?			
Has there been adequate participation in the architecture and requirements review?			
Are all exit criteria met for this Activity?			

5.1.2.2 Tb&S Design Activity

The Tb&S Design Activity can begin once the baseline system architecture and system requirements have been established. This activity usually occurs in two parts: Preliminary Design, and Detailed Design. The Entry and Exit Criteria for the Design Activity are shown in Figure 5-4.

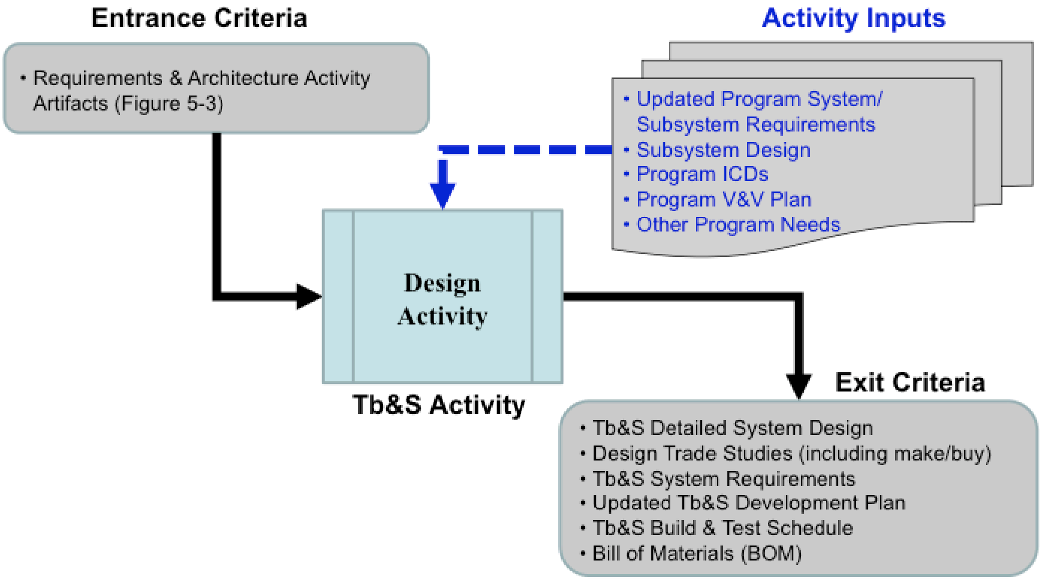


Figure 5-4. Tb&S design activity.

Preliminary Design: During the Preliminary Design, trade studies are performed to determine the optimal solutions for the End Users and End Uses. Given that Tb&S End Uses have been validated and that the physical, functional, and interface architecture has been established, the preliminary design activity includes a decomposition of the architecture and requirements sufficient to perform a more detailed design on each identified component.

A typical Tb&S product consists of both Hardware Configuration Items (HWCI) and Software Configuration Items (SWCI). Tb&S product hardware design consists of Configuration Item (CI) decomposition to lower level components and subsequent design trades necessary to support “make” vs. “buy” decisions. A buy decision can result in a decision to procure a COTS item or a decision to initiate a subcontract to have a third party design and fabricate the component. A make decision will result in a set of preliminary design artifacts sufficient to addresses the high-level Tb&S requirements.

Guideline 22: During trade studies and architectural development phase, considerations must be made for portability and modularity during the design of the software components.
Rationale and Example: In order to maximize reuse of the developed software, i.e., simulation models, it is important to consider an architecture that employs modular design of software simulation models. Software models are developed individually and independently and integrated in the simulation environment to create customized dynamics simulation configurations.

Detailed Design: The Detailed Design process follows the Preliminary Design process to further decompose the design and perform appropriate synthesis to finalize the design. In this stage the high level architecture design and system requirements are translated into the lower level design and requirements. The result of the detailed design process is a collection of artifacts including a set of released design engineering documents for the Tb&S products, the Tb&S requirements, the build and test schedule, and a bill of materials (BOM) for building the Tb&S products. The formality and scope of the engineering documents depends on the requirements of the program and the standards of the contractor. The requirements should be refined and finalized and the corresponding verification plans should be developed. The resulting detailed design will serve as the basis for entry into the Build Phase. A CI design is complete for a procurement decision (e.g., “buy”) after an assessment of the vendor specification is analyzed against the requirements and a Bill of Material (BOM) is produced to identify the vendor name, part number, quantity, and cost. A decision to subcontract the CI design and fabrication requires development of a set of subcontract documents resulting in a contract to design and deliver the product according to a Statement of Work (SOW) and specification. The design process is complete when the subcontractor successfully demonstrates the completion of the design portion of the subcontract. The decision to “make” the component in-house follows standard design processes resulting in hardware and software design artifacts.

Tb&S System Design Artifacts: Facility and Infrastructure requirements should be levied by the Tb&S group to support the build, test, and deployment of all Tb&S products according to the baseline schedule. This typically includes physical space, cooling, power, servers, data storage, and IT network requirements. Engineering drawing of all identified components as to their location and interconnection (e.g., racks, rack elevations, components/modules in racks, SW deployments to computing resource, etc) are released during this activity.

Other Supporting Artifacts: An initial Tb&S Test Plan and O&M plan is developed during this activity. Standard processes outlined in the Tb&S Development Plan are put in place during this activity like configuration management, change management, establishment of any boards (i.e., HW & SW Review Boards, etc), and other processes necessary for the design and build phase.

Not all of the program subsystem specifications are released when the Tb&S is being designed since the Tb&S products are typically designed and built before the flight equipment. Changes to unreleased specifications should be monitored to identify impacts to the Tb&S products.

Guideline 23: Hold Tb&S design reviews conducted with peers and stakeholders and with all findings and action items closed Work products released and baselined.

Rationale and Example: Consider reviews for each Tb&S product; stress the importance of including the stakeholders.

Table 5-3 and Table 5-4 provide Checklists to assess the Tb&S Design activities and artifacts during the Requirements and Design Lifecycle Phase for the Preliminary Design Activity and for the Detailed Design Activity, respectively.

Table 5-3. Tb&S Preliminary Design Activity Checklist

Tb&S Preliminary Design Activity Checklist	Yes	No	N/A
Are all entrance criteria met for the preliminary design phase?			
Have all task inputs been reviewed and analyzed?			
Have relevant lessons learned from previous programs been reviewed and implemented?			
Have trade studies and risk analysis on design approach been performed?			
Has high level design description been created and evaluated?			
Has a preliminary Tb&S design document to capture refined Tb&S product architecture and requirements been created?			
Has there been participation in the Design Review?			
Are all exit criteria met?			

Table 5-4. Tb&S Detailed Design Activity Checklist

Tb&S Detailed Design Activity Checklist	Yes	No	N/A
Are all entrance criteria met for the detailed design phase?			
Have all task inputs been reviewed and analyzed?			
Have relevant lessons learned from previous programs been reviewed and implemented?			
Has make/buy analysis been Performed (Product acquisition analysis)			
Has detail design analysis and evaluation been completed?			
Has Tb&S design document been reviewed and changes been properly incorporated?			
Have all systems and subsystem requirements been reviewed and changes incorporated?			
Are Tb&S system and subsystem specification documents ready for release?			
Is design under configuration control?			
Has there been participation in the Design Review?			
Are all exit criteria met?			
Are Tb&S Verification Cross Reference Matrix (VCRM) and Verification Plan completed?			
Does the detailed design include the necessary descriptions and artifacts for manufacture?			
If the SV is built in-house, are the make/buy decisions for the Tb&S product documented somewhere?			

5.1.3 Build & Test Lifecycle Phase

Once the Tb&S Design Activity has been completed, the Tb&S products are ready for build, integration, and test. The first part of this phase is to ensure the completed design is acquired or built according to the specifications. The Tb&S plan that is developed and matured during the previous Tb&S activities of the program includes Tb&S Verification Plan to drive the Tb&S integration and test process. Having a well-planned system integration activity ensures that each of the system elements comes together and performs as a complete system. Specifically, this activity involves the integration of various components, subsystems or systems that make up the Tb&S product, as well as the integration activities within each of the segments themselves (i.e., subsystem EMs).

The Tb&S integration consists of the methodical assembly or interconnection of system elements into an overall functional system. An element may be a Configuration Item (CI) or a subsystem comprised of two or more integrated CIs. Integration begins with the delivery of an element for integration into a system configuration, and ends with a limited demonstration that provides evidence of the satisfactory operation of each element in the final system. The components or subsystems may have already had their performance characterized or verified through separate test and evaluation.

5.1.3.1 Build & Integration Activity

The Tb&S Build & Integration Activity, shown in Figure 5-5 below, follows the Tb&S Design Activity and involves the acquisition/build of both hardware and software components and subsystems. This build activity could occur in parallel and provide for incremental deliveries for integration and test. Due to this incremental capability of build and integrations, it may be useful for the developer to use portions of the checklist (Table 5-5) provided below at various major phases of the activity to ensure that individual increments of build and integration are on track.

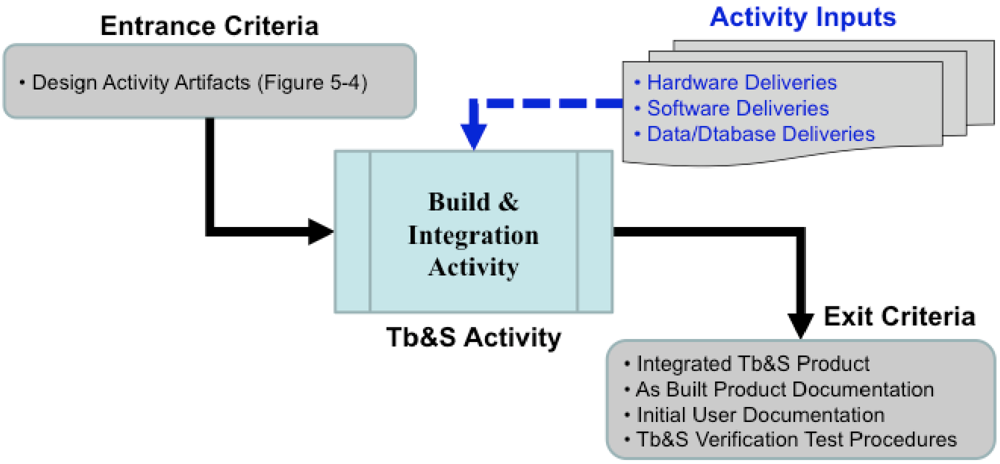


Figure 5-5. Tb&S build and integration activity.

Integrated Tb&S Product and As Built Documentation: During the Tb&S product build, all required hardware and software are purchased or created. As the build proceeds it is important to have a robust configuration control in place and to update, maintain, and/or compile the as-built documentation on the product in the Tb&S system. As-built product documentation is a required exit criterion from this activity to ensure that the next activity of verification has a known, documented baseline.

Guideline 24: Develop and implement an adequate sparing plan.
Rationale and Example: It is during the acquisition of components that the developers will know how many spares are on hand and what items may become spares as the product reaches the end of its life. This information will quickly evaporate if not passed on in a means that preserves the knowledge of where to find spares and how many spares have been produced.

During the Tb&S integration process, pieces of a software or hardware system are integrated to show compliance with requirements, architecture, and design. The integration testing includes combining HW and SW components, COTS, government-off-the-shelf, and subcontracted products for subsequent integration and testing. Integration and integration testing using different or repeated tests may take place multiple times during iterative builds.

Guideline 25: Integration activities should be performed on hardware that is as close as possible to the actual product hardware.
Rationale and Example: Hardware and software integration issues should be identified as early as possible in order to discover and correct them on actual flight hardware and software products. A plan to perform integration and testing on products that closely match the final products will benefit the program in many ways

The focus of integration is verifying new and existing interfaces and functionality such as the following:

- Integrate and test all new software to software interfaces
- Integrate and test all new software to hardware interfaces
- Integrate and test all new hardware to hardware interfaces
- Demonstrate functional capabilities of end item

Guideline 26: Ensure that End Users are involved in the build and integration activity of a Tb&S product.
Rationale and Example: As the integration tests are performed, early involvement of Tb&S End Users with some of the use cases identified in Section 3 will benefit both the Tb&S developers and the users in identifying requirement flaws or potential for requirement growth.

Guideline 27: As part of preparing for the integration and test process, any Tb&S requirements should be reviewed to determine if they must be verified at a low level which may only be available during this integration activity.
Rationale and Example: Although overall verification of the Tb&S product is not performed at this stage, individual pieces of verification may not be available once fully integrated and thus must be performed as part of integration testing.

Initial User Documentation: The details of how the Tb&S is actually operated begin to become realized during this activity. The team performing the integration inherently has to start using portions of the Tb&S and therefore start to generate a method of operations for its hardware and software. It is at this point that some of the initial user documentation is created. This will serve not only as a good starting point for the final user documentation, but as a reference guide to be used during the integration process as inevitably multiple people try to learn how to do the same activities. This user documentation may consist of procedures, manuals, logs, or other such documentation as further defined in Section 5.1.4.2. As an example, one item the user documentation should cover would be the method for how to efficiently switch the configuration of the system between different user environments. The documentation may be generated by the Tb&S developers or it may be provided by external sources. Final user documentation is discussed in more detail in Section 5.1.4.2.

Tb&S Verification Test Procedures: An additional exit criterion for this phase is the Tb&S product verification procedure that will be used in the next phase (see Section 5.1.4). The integration processes used provides a great source for verification procedures. The compilation of the integration test plans and procedures used throughout the iterative integration cycle provides a baseline for what the verification test procedure should contain.

Table 5-5 provides a Checklist to assess the Tb&S Build and Test activities and artifacts during the Build and Test Lifecycle Phase.

Table 5-5. Tb&S Build and Integration Activity Checklist

Develop Build and Integration Plan	Yes	No	N/A
Has the schedule for phased build and deployment been developed?			
Has a review board been formed for Tb&S products? - Tasked with review and approval of change requests to requirement baseline.			
Has a Peer Review Process been defined consistent with program requirements?			
Has a Defect Tracking and Resolution system been defined and deployed?			
Hardware Make/Buy			
Have long lead items been procured?			
Have impacts of long lead items been addressed in the integration and deployment schedules?			
Have COTS products been procured?			
Has test control system been developed or procured?			

Develop Build and Integration Plan	Yes	No	N/A
Are internal/external cable harness assemblies built/ procured?			
Have EGSE or STE hardware subsystems been developed?			
Have the test facilities been identified and built?			
Has IT infrastructure equipment been procured, installed and configured?			
Has simulator hardware equipment been procured?			
Software Make/Buy			
Have STE software and Firmware been developed? – Hardware/Bus interface emulation, Device driver firmware			
Have Simulation models been developed and integrated?			
Have all required data/database items been delivered?			
Documentation and Test Development and Release			
Has as-built documentation been completed?			
Has an integration test plan been developed?			
Have test description documents been created and released?			
Have test procedures/scripts been developed, reviewed and released?			
Has Verification Cross Reference Matrix (VCRM) and/or other requirements documents been reviewed to confirm requirements and their proposed method for verification? T-Test, I–Inspection, D-Documentation, A-Analysis			
Have software or hardware tools required to perform tests been identified and allocated?			
Tb&S Integration Test Execution			
Have End Users been involved in the SW integration and test process?			
Have all Unit Tests been performed and succeeded?			
Have all integration test peer reviews been completed?			
Have Tb&S integration tests been performed?			
Are all post test analysis completed?			
Has an integration test report been created?			
Other Closeout Activities			
Have the verification test procedure(s) been developed?			
Have all problem reports been resolved or dispositioned?			
Has initial user documentation been developed?			
Does the user documentation include a sparing and maintenance plan?			

5.1.4 Sell-off and Mission Preparation Phase

The Tb&S activity during the Sell-off and Mission Preparation Phase focuses on the Tb&S Verification activities and documentation.

5.1.4.1 Tb&S Verification Activity

The last activity in the Tb&S development, as shown is the verification (aka Acceptance, Accreditation, Sell-Off, Certification or Ready-for-Use (RFU)) of the Tb&S. Verification tests may occur throughout the development and maintenance cycles. Since this activity discusses verification against requirements, considerations of when verification tests are performed should be identified in the Tb&S Development Plan. The purpose of the Tb&S Verification activity is to demonstrate the Tb&S meets all its requirements as mapped in the Tb&S VCRM.

The Entry/Exit criteria for the Tb&S Verification Activity are shown in Figure 5-6. The Entry Criteria includes the Build and Integration Activity Artifacts from Section 5.1.3.1. The Exit Criteria includes a

Verified Tb&S Product, Completed Tb&S User Documentation and a Verification Test Report. Section 5.1.4.2 details the Tb&S User Documentation.

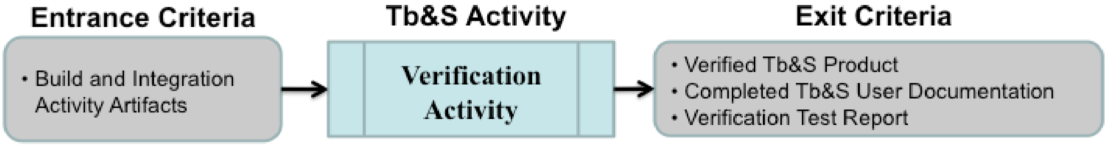


Figure 5-6. Tb&S verification activity entry/exit criteria.

Verified Tb&S Product: Whether the Tb&S is deployed for the first time or redeployed after its use on a given program, the Tb&S typically requires some form of acceptance testing and Verification Test Report at delivery and prior to formal use. Tb&S Verification may be accomplished by analysis and simulation, inspection, demonstration, test, or a combination of these at any level of the design. To ensure the Tb&S meets its requirements, an acceptance test procedure needs to be developed, reviewed and successfully executed to demonstrate that the Tb&S is RFU. This acceptance procedure should verify that the software and hardware interfaces meet requirements specifications (both in format, timing and functionality) and that the Dynamics Simulator software models execute as expected by the analysts and/or the SMEs. This baseline acceptance test, composed of a set of test cases defined to prove the Tb&S is operational, should be completed before the Tb&S is put into operations. The Tb&S acceptance test typically assumes that Tb&S deliverables such as the Dynamics Simulator, EGSE, and all prime hardware and software items, each have executed their own acceptance test to prove their functioning and performing per their design. Once these deliverable items are integrated in the Tb&S, the Tb&S acceptance test is performed as a precursor to performing user dry run and formal V&V tests.

Verification Test Report: The purpose of this document is to provide an overall assessment of the acceptance testing performed on the Tb&S product. The Test Report shall be used to document the acceptance test results; including the as-run acceptance test(s), as-needed data trends and summarized results.

The initial Tb&S use may occur as early as the Tb&S has been integrated to a level wherein it is able to perform some aspects of its intended job. Since a Tb&S may be developed over time with increasing fidelity, there should be continuing verification after any upgrades that the Tb&S functionality still meets the End Users requirements. An example of an early use case is a C&DH test including the command and telemetry database, FSW, C&DH unit(s), and harness; which may not need a Dynamics Simulator. In this instance, the Tb&S may be “delivered” for this use much earlier than it would be ready for a complete closed-loop ACS or fault management test. Due to this flexible definition of delivery, it is important to always ensure that the Tb&S is at its appropriate level of fidelity for a given test. It should be noted that this initial baseline delivery and all subsequent deliveries should be under configuration control. Even though a Tb&S may be in use by a certain user, it may not have the capabilities implemented to function for all intended users. This issue is solved with constant communication between the developers, the users, and the entity managing the Tb&S operation and schedule.

Table 5-6 provides a checklist for the Tb&S Verification activity. This activity includes the preparation for the Tb&S Verification test, the execution of the test and the exit review tasks for a verified Tb&S product during the Sell-off and Mission Preparation Lifecycle Phase.

Table 5-6. Tb&S Verification Activity Checklists

Tb&S Test Readiness Review	Yes	No	N/A
Has a Tb&S Verification Test Plan been released?			
Are the Tb&S requirements mapped to a verification method?			
Have all Tb&S Problem Reports been Dispositioned? Are all Tb&S Liens identified and dispositioned?			
Have all Tb&S Verification test procedures been dry run with all findings addressed?			
Are all Tb&S software and hardware documentation released and under configuration control?			
Has a Test Readiness Review (TRR) package been prepared to be presented at the review?			
Has authorization been obtained from Stakeholders to proceed with Verification Tests (with or without liens)?			
Tb&S Verification Test Execution			
Has Test Conduct been defined and coordinated with Stakeholders? – Test Roles, Audits, Pre &Post-test Reviews			
Are limitations to “Test Like You Fly” understood and approved?			
Have Lessons Learned from previous/similar tasks been reviewed for applicability to the Hardware, Software and/or Facility?			
Are pretest meetings/briefings planned? Are task briefings planned during the Tb&S verification execution?			
Have the engineering support personnel for the test been identified and scheduled?			
Has the Tb&S operations schedule been established? Have shift change policies and handover procedures been identified?			
Has QA participation been coordinated to verify the success of the Tb&S Verification tests?			
Tb&S Post Verification Test			
Are all Post Test Analysis completed?-			
Has a Tb&S Verification Test Report been created?			
Has a Test Exit Review (TER) been scheduled?			
Is the Tb&S certified/signed by the stakeholders?			

5.1.4.2 Tb&S User Documentation

The Tb&S Acceptance documentation includes the deliverable product documentation and the Tb&S Deployment (i.e., operations and maintenance) documentation as shown in Figure 5-7.

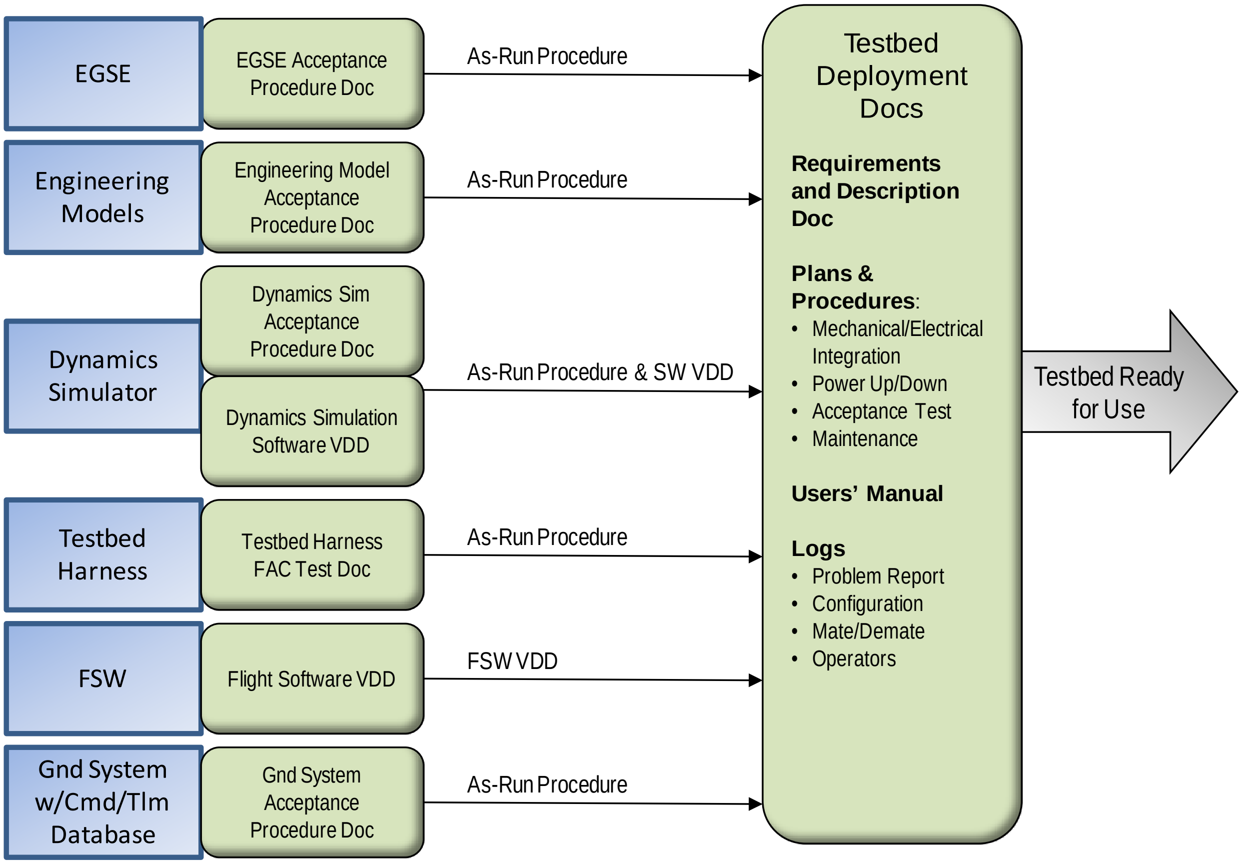


Figure 5-7. Example of Tb&S acceptance document flow-down.

Documentation Deliverable to Tb&S: Each software and hardware item deliverable to the Tb&S is expected to come with a set of documentation containing its description, capabilities and acceptance pedigree.

The EGSE documentation should include an as-run acceptance test, which records the configuration of the hardware and software. Any EGSE changes need to be tracked and evaluated to determine whether the acceptance tests need to be repeated.

The Dynamics Simulator documentation should include an as-run acceptance test and identify software required for the simulator to function. The acceptance test records the configuration of the hardware and the version of the software it was tested against. A list all the software components, in a form of a Version Description Document (VDD) or equivalent, and how the software was tested, linked and compiled should be included. Hardware and software changes need to be tracked and evaluated to determine whether the acceptance tests need to be repeated for future delivery updates.

Engineering Model (EM) hardware documentation is to include the EM as-run acceptance test. There should be a goal to keep the EMs up-to-date with the flight hardware; especially if timing and interfaces are impacted by the change. Any EM changes need to be tracked and evaluated to determine whether EM or full Tb&S acceptance tests need to be repeated. Depending on the work structure of the program, this may not be the responsibility of the Tb&S users or developers (especially if it is assumed to be of no impact to the Tb&S); however the users and developers should be provided information on the change and what testing will be repeated. This will help ensure that that any potential impact to Tb&S operations is uncovered.

Tb&S Harness documentation should include an as-run acceptance tests. Examples of tests include; high voltage pin-to-pin continuity and isolation test to ensure there are no harness manufacturing flaws and shorts.

The Flight Software documentation should include the software listing (VDD or equivalent) all the software components and how the software was tested, linked and compiled. The documentation should also include the command and telemetry database list.

The Ground System documentation should include an as-run acceptance procedure identifying the version of ground software and command and telemetry database it was tested against.

Tb&S Deployment Documentation: As shown Figure 5-7, a Tb&S Requirements and Description document, a set of procedures (Power Up/Down procedures, and Special Configuration Utilities), Maintenance Plan, Users' Manual, as-built drawings, and Tb&S Logs (Problem Report, Configuration and Operators) are necessary to successfully operate the Tb&S. These procedures, plans, manuals and logs are necessary to power up and down, operate, and maintain configuration of the Tb&S. The level of formality for the Tb&S documentation type, release process and standard format is an important consideration that needs to be addressed at the start of the program by consulting program management and customers (internal and/or external users). Required deliverable documentations and level of formality during the Tb&S operations should be determined based on the end user needs.

The Tb&S Users' Manual should describe all the Tb&S features, initialization and configuration options, including the Tb&S Critical Item Control Plan and any operational constraints. It should provide operators all the steps they need to take to develop and run their specific procedure. Furthermore, a standard procedure to power up and down the Tb&S is necessary to maintain a known test configuration. Options in the procedure should be provided to power up and initialize the Tb&S to the Users' needs. This procedure may be provided by the simulator developer, or developed by the end users.

The Tb&S Maintenance Plan should define the process for the maintenance of the hardware and software (HW/SW) components, including the type of regression testing required to preserve the Tb&S Ready For Use certification. This plan should also address the Tb&S sparing and obsolescence strategy.

The Tb&S logs developed and maintained by the users are necessary to track daily operations and to provide a record of activities on the Tb&S. These records act as a journal for test events, provide troubleshooting information, and allow test operators to track problems and system configuration. In a program with a formal handoff structure the operator's responsibilities for logging should be clearly stated in the operating guidelines or Users' Manual. The Operators log is used to track all the events of the day; including what procedures are run, any issues observed, changes in configuration and any successes and failures. The Operators log entries are usually the precursor to identifying problem reports and configuration issues. There may be different levels of formality when developing and maintaining Tb&S logs that must be considered and defined ahead of time.

Guideline 28: The Tb&S developers should determine the formality of deliverable User Documents (Requirements, Manuals, User's Guides) at the start of the program by coordinating with the customer or the program office or with the program Tb&S product End Users.
Rationale and Example: Having a formal documentation flow-down and deliverable requirements during the Tb&S operations phase may not be suitable for every program. For example, smaller programs with less complex Tb&S, may not require formal documentation deliverables delaying their Tb&S deployment.

Section 6 provides more details to the type of operational considerations and documentation necessary for Tb&S operations.

5.1.5 Operations Phase

The Operations Phase consists of the Tb&S Operations and Maintenance Activity after the Tb&S is verified and deployed. Tb&S Operational Considerations are discussed in detail in Section 6.

5.1.5.1 Tb&S Operation and Maintenance Activity

The Tb&S Operation and Maintenance Activity, as shown in Figure 5-8, assumes the Tb&S is verified (certified, operational and ready for use). The Tb&S Operations activity includes performing scheduling, problem tracking and reporting, and other standard operational processes in support of higher-level program phases (e.g., I&T, V&V, launch, and on-orbit operations, etc). The Tb&S Maintenance activity follows the Tb&S Maintenance Plan to keep the Tb&S operational and deal with obsolescence concerns during its lifecycle.

The Tb&S Operations and Maintenance Activity's Entry Criteria includes the Certified Tb&S with Stakeholders concurrence, Users Manual and Maintenance Plan. The Tb&S Operations and Maintenance Activity Exit Criteria is a Tb&S in Operation and actively maintained.

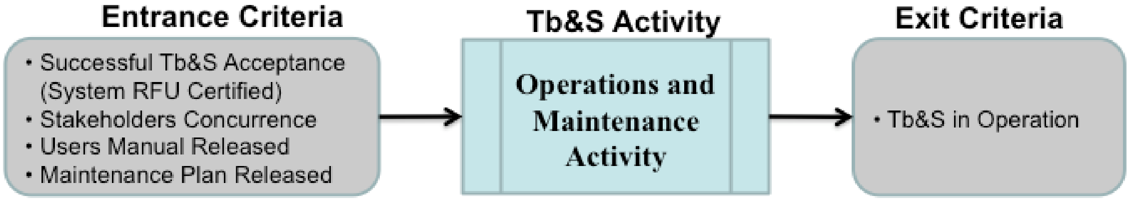


Figure 5-8. Tb&S operations and maintenance activity.

Tb&S in Operation: The extent of this activity depends on the Program contract or if the company is the owner, its next use (deployment on another program, storage or surplus). Section 6 provides operational and maintenance considerations.

Table 5-7 provides a Checklist to assess the Tb&S Operations and Maintenance activities and artifacts during the Operations Phase.

Table 5-7: Tb&S Operations and Maintenance Activity Checklist

Tb&S Operations and Maintenance Checklist	Yes	No	N/A
Are the program and user needs for the Tb&S Operations & Maintenance phase identified?			
Has a Sparing and Obsolescence Strategy been identified? Is there a list identifying all hardware spares?			
Has a Tb&S Maintenance Plan been developed? Does it include a plan for addressing EM and software modifications and updates? Does it include a standard and readiness maintenance plan?			
Has a well-defined regression test strategy been developed?			
Is there a Tb&S Users' Manual?			
Is there a Tb&S User Log book?			
Is there documentation for the Tb&S hardware and software components including (if applicable), EM End Item Data Packages, drawings, acceptance data?			
Has a Point Of Contact list been compiled and posted in the Tb&S area?			
Have all test personnel been made aware of what to do and not to do in the event of a problem or failure in test?			
Has the proper training been identified for a test engineer to be approved to run tests on the Tb&S?			
Have specific personnel assignments been made and are responsibilities understood?			
Is the chain of command established and understood by all stakeholder organizations (i.e., facility, project personnel, contractors, etc.)?			
Has a Tb&S utilization schedule and user prioritization method been identified?			
Does the Configuration Management log identify all the Tb&S hardware and software configured items in the Tb&S?			
Is there a common Problem Reporting tool to disposition problems found during Tb&S testing?			
Is instrumentation calibrated and are the test equipment calibration stickers intact? Is there a plan in the Tb&S Maintenance Plan to keep the equipment calibrated for the duration of the Tb&S use?			
Is there a mate/de=mate log? Has the mate/de-mate log and status of all connectors been reviewed and the impact to test understood?			
Are the Tb&S security, safety and training guidelines identified and followed?			
Is there a plan and schedule to perform special hardware and software tests; such as one-time hardware compatibility tests?			

5.2 Tb&S Support of Program-Level Reviews

The development and use of Tb&S on a spacecraft program requires a coordination of the development schedule for Tb&S with the spacecraft program lifecycle events. During the Tb&S development process, critical program milestone reviews will be conducted (i.e., SRR, PDR, and CDR) that require support as defined in this section. These program-level reviews are as described in Aerospace TOR-2009(8583)-8545, "Guidelines for Space Systems Critical Gated Events". The maturity of the Tb&S based on Section 5.1 drives the content that is presented at the actual development phases of the program itself.

5.2.1 Tb&S Support to Program SRR

This review is the first major review in the program following the proposal phase, and is an opportunity for the Tb&S team to present their overall concept to the program and customer. The Tb&S Conceptual Architecture should be presented along with the top-level schedule including major Tb&S development and deployment milestones.

5.2.2 Tb&S Support to Program PDR

This review is the opportunity for the Tb&S team to present their design for the baseline program Tb&S to the customer. The current Tb&S architecture (functional, physical, and interface) and baseline system requirements should be presented along with the top-level schedule, major Tb&S milestones, and all significant risks or potential opportunities. If possible, the Tb&S team should present their preliminary design products including trade results, requirements trace to Tb&S end products, and plans for V&V of the identified products. Program presentations for other products that require Tb&S capabilities should be reviewed to ensure that any dependencies are properly communicated.

5.2.3 Tb&S Support to Program CDR

At this review, the Tb&S team will present their completed design for the baseline program Tb&S to the customer. The Tb&S architecture, requirements, schedule, upcoming Tb&S milestones, and remaining risks should be presented. The Tb&S team should present their detailed design products including specifications and interface documents for lower-level Tb&S components, make/buy plans, final V&V plans and schedule, and transition plan for deploying the Tb&S products. Program presentations for other products that require Tb&S capabilities should be reviewed to ensure that any dependencies are properly communicated.

5.2.4 Tb&S Support to Program TRR

This review does not directly map to a particular Gated Event, and is intended to include any program-level reviews that require any Tb&S products for formal V&V efforts. The Tb&S presentation should include required artifacts to support the review.

5.2.5 Tb&S Support to Program PSR

At this review, the Tb&S team will present the current capability and status of program Tb&S supporting final closeout activities as well as planned support for launch and early operations. Program presentations for other products that require Tb&S capabilities should be reviewed to ensure that any dependencies are properly communicated.

5.3 Tb&S Roles and Responsibilities

As set of individuals with certain skills is required to plan, develop, deploy, and operate the suite of Tb&S associated with a space vehicle development program. The Tb&S organization has been found to live in a variety of places within the program organization as shown in Figure 5-9, as found in a survey of industry organizations responsible for Tb&S.

Guideline 29: Establish a well-defined set of roles and responsibilities for individuals and organizations tasked with delivery of Tb&S end products.

Rationale and Example. The Tb&S organization for any particular program may be centralized (e.g., Tb&S organizational chart controlling a majority of the management and development personnel) or distributed (e.g., Core Tb&S organizational chart with significant dependencies of other organizations for development of certain aspects of the end product(s)), but roles and responsibilities must be clearly established and communicated in order to ensure timely delivery of end products.

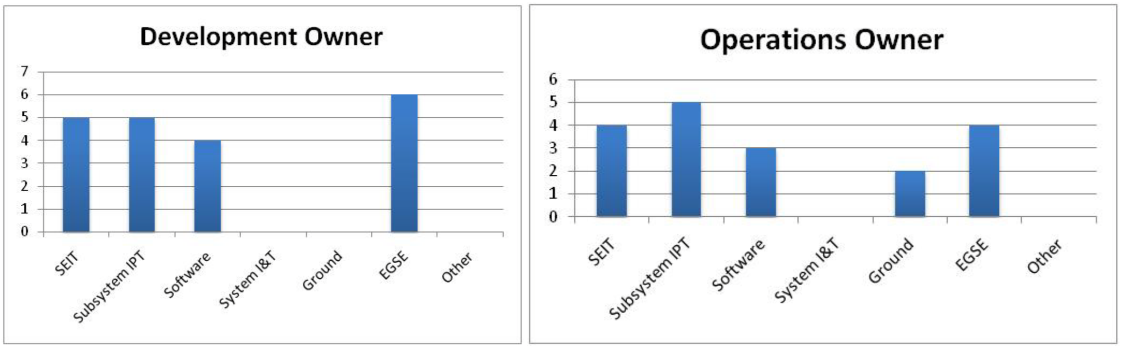


Figure 5-9. Tb&S development and operations organizational owners.

Tb&S management includes responsibility for the overall cost and schedule, technical planning and status, and overall decision-making authority necessary to delivery all Tb&S products within the program constraints.

Guideline 30: An SV program should have an organizational construct having an accountability and responsibility for their Tb&S products.

Rationale and Example: Usually, Tb&S development is owned by the FSW subsystem but in reality it must be elevated upward and be its own subsystem. Elevating Tb&S products as part of their own subsystem allows them to be more critical to the SV program schedule and allows for more formal documentation and development process.

Guideline 31: Ensure the Tb&S costs are collected in a Work Break-down Structure (WBS).

Rationale and Example: Grouping the Tb&S cost within a WBS allows for the allocation of sufficient, and, most importantly, dedicated funds to complete Tb&S development.

Tb&S development consists of engineers and technicians with skills in systems engineering, electrical design, software, mission operations, and test. Due to the fact that Tb&S products can be complicated systems, it is the responsibility of the development team to ensure that they have expertise from potentially all subsystems of the space vehicle in addition to those areas that are unique to the Tb&S architecture and design. This expertise may reside within the development team, or the development team may contain technical liaisons that are responsible for communicating with outside experts. The scope of expertise required is based on the overall scope of the specific Tb&S product. Also, the Tb&S development team may provide continued support of the Tb&S product after deployment for problem resolution, upgrades, etc. (unless this responsibility is delegated to another functional area).

Tb&S operational management has the responsibility for scheduling of resources, enforcing use and disposition of problem reports, ensuring maintenance of test logs, and maintaining Tb&S configuration information. Operational management also has the responsibility to provide the technical expertise on Tb&S usage in support of End Users. This technical expertise should direct the End Users on how to safely use the Tb&S, how to effectively configure the Tb&S product for their specific use, and how to use any special tools or utilities in association with the Tb&S product. In short, the technical expertise provided by operational management will provide answers to questions and training for all End Users.

Supporting functions are typically provided by organizations outside of Tb&S and can include hardware and software quality, facilities, information technology, and others.

Guideline 32: Ensure the Tb&S is staffed with individuals that have prior knowledge of the Tb&S lifecycle
Rationale and Example. Staffing the initial organization with key personnel with prior experience of developing program Tb&S can ensure that sufficient knowledge is available to execute the project in an efficient manner. Also consider needs for recruitment and training of people.

6. Operational Considerations for Tb&S Products

This section discusses guidelines for deploying Tb&S products with a focus on HITL testbeds, such as the System/Subsystem Testbed (STB) or the Integrated Space Vehicle Testbed (ISVT). For simplicity, this section refers to these Tb&S products as Testbeds. These types of Testbeds are key program assets that usually have a life after their initial target use. It is therefore important to consider all the Testbed user requirements and needs across the Tb&S lifecycle as defined in Section 5. The operational considerations include the following Tb&S activities:

- Deployment
- Scheduling and Utilization
- Configuration Management
- Problem Tracking and Reporting
- Obsolescence and Maintenance
- Special Hardware and Software Testing
- Security, Safety and Training Guidelines

A checklist to aid the user to assess the Tb&S operational considerations is provided in Section 5.1.5.

6.1 Deployment

If the Testbed is moved or delivered to another site, a functional test needs to be performed to ensure that overall functionality is compliant with delivered capabilities. The functional test may be a subset of the original acceptance test, or it may be a separate test used only for recertification following moves and simple changes to the testbed configuration. Deciding if a full or partial acceptance test needs to be repeated depends on the testbed implementation and intended use. For example, if a testbed is designed to be “mobile”, then considerations should be made in the design of the functional test that makes it easier to repeat, thus resulting in reduced testbed downtime. If a testbed moves rarely, then a more comprehensive functional test may be planned. The Testbed Maintenance Plan (see Section 6.5.2) needs to identify the guidelines to maintain the Testbed after delivery and define the subset of regression tests necessary for recertification.

6.2 Scheduling and Utilization

The Testbed ownership and utilization priorities may change depending on the Space Vehicle development phase (see Section 5). Scheduling and de-conflicting End Users competing for use of Tb&S products, setting priorities and providing Testbed oversight is the job of Tb&S operational management. Proper planning and management of testbed usage and maintenance are necessary to ensure satisfaction of the End Users and to minimize schedule delays. This becomes more important if there are multiple testbeds and multiple groups of users needing testbed time.

For a full discussion of the different Tb&S End Uses that will have to be scheduled and prioritized by the Testbed owner, see Section 3.

Guideline 33: In planning the use schedule for Tb&S, do not neglect or underestimate AI&T uses of the Tb&S.
Rationale and Example: In many settings, Testbed user groups are heavily Flight-software-centric. In these user groups it is common to forget that even relatively simple AI&T activities (e.g., procedure refinement or operator training) should carry extra weight in schedule planning decisions because of the excessive hourly costs and severe program risks associated with running these activities on the flight vehicle without adequate preparation time in the cheaper, safer simulator environment.

Guideline 34: Create a Testbed Scheduling process to adjudicate needs for all End Users.
Rationale and Example: After deployment of the Testbed, many users will compete for time on the testbed. Although some are regular, heavy users, others may infrequently use the testbed for time-critical activities. The existence of a defined process for collecting, allocating, and resolving conflicting and ever-changing user needs is critical to the operational effectiveness of the testbed.

Guideline 35: During the testbed cycle, a testbed will be recertified many times. It is important to come up with an efficient, standardize recertification process to minimize the testbed downtime and reduced cycle time for making testbed operational.
Rationale and Example: Once a testbed is fully sold-off via a full-up acceptance testing, in most likely scenario, a testbed will not go through another full-up acceptance. It is important to identify a set of recertification requirements early on and develop the recertification test plan accordingly. Also, it is important to minimize the overall recertification time so the test process should be streamlined, including (if possible) such activities as test dry runs, test automation, and simplified data review, in order to reduce the testbed downtime.

6.3 Configuration Management

At the start of testbed integration, all software, hardware, and databases should follow a configuration management plan. The overall testbed configuration goes beyond the software version numbers used in test—it is a record of the state of the testbed including how the software and hardware are configured.

Each user may have different needs for the same testbed, so it will inherently have different configurations. A Configuration Log should be kept that tracks the FSW versions, the Command & Telemetry database versions, the EM hardware (or other HITL) serial numbers and design, and other important configuration items specific to that testbed; such as the EGSE and Dynamics Simulator. It is important that each user understands the testbed configuration and its reconfigure capability. Improper configurations may result in incorrect testing and unnecessary debugging.

Proper configuration management procedures and tools need to be identified to accommodate FSW updates; these procedures should include provisions for verifying FSW images and/or patches in both RAM and Non-Volatile Memory. The goal should be to manage FSW updates in the same way as they are managed after launch using the ground system procedures and tools. In addition to FSW, there should also be audit procedures in place to verify the Testbed software images against a gold copy to ensure integrity of the installed software and system configuration.

Command and telemetry database versions need to be carefully synchronized with the Ground System software and On-Board FSW and captured in the Testbed Configuration Log.

HITL Hardware Configuration Items (HWCI), especially testbed EMs, need to be tracked via serial numbers and end item data packages that identify their configuration and any design exceptions to the flight hardware.

Guideline 36: Due to the complexity of testbed configurations, it is recommended that an easy-to-understand display be available that provides information on the current state of components that compromise the testbed.

Rationale and Example: Either in a notebook (i.e. Log) or on-line display, provide the current configuration of the hardware interconnects (what's connected or disconnected), software versions (EGSE, Dynamics Simulator and FSW), command and telemetry database version, and any applicable operating mode(s). Clearly identifying the Testbed configuration prevents users from inappropriately operating the testbed.

6.4 Problem Tracking and Reporting

During Tb&S operations, it is important to track problems and disposition the cause as testbed or flight. Within these two categories, the problem should note whether it is database, hardware or software related. The goal should be to use the same problem-reporting tool as AI&T or at least to correlate the problem reports. The problem reports should be reviewed and resolved in a timely way. It is also important that the problem resolution process includes steps to refer flight anomalies (hardware, software, database or EGSE) back to the flight program for resolution. A common PR tool can make the referral of flight anomalies to the program easier.

Guideline 37: Utilize a common Problem Reporting tool between Testbed and AI&T to better track issues.

Rationale and Example: Using one database to track problems is helpful in correcting problems. Hardware, software, EGSE, or database issues found on the testbed that effect flight may be dispositioned easier with a common PR tool.

6.5 Obsolescence & Maintenance

Testbed obsolescence needs to be addressed in terms of spares and test availability. The Testbed availability needs and lifetime duration necessitates identifying obsolescence and maintenance options for all the Testbed components, including EMs, EGSE and the Dynamics Simulator. Testbed availability usually means defining or limiting the acceptable downtime for working hardware problems, which may require EM or supporting test hardware (i.e. EGSE) to be reworked or replaced. Planning for obsolescence and maintenance should be included early in the Testbed development process.

6.5.1 Testbed Sparing and Obsolescence Strategy

The Testbed lifetime duration influences the amount of spare hardware that should be purchased according to projected unit Mean Time Between Failure (MTBF), or based on perceived risk of unit failure, as well as impact of the failure on operability of the testbed. One large issue in using the Testbed lifetime duration to determine sparing and obsolescence strategy is the fact that the program development contract may only state that the testbed will be used through launch or initial operational capability. The Tb&S products may need development funds to support the full future O&M lifecycle, but funding this capability could detract from development funds. The full O&M lifecycle (i.e., life of the mission) is often contracted as a minimum resulting in long term planning issues when, for example, a five year mission continues on for decades. So even though a program may get more funding to support the extra years, if the original planning did not allow for likely extensions, then it usually becomes more expensive to replace obsolete hardware. Unfortunately, even with good planning the overall ability to purchase enough spares to avoid costly obsolescence issues is often driven by customer funding during the early development phase of the program. Lack of funding for this purpose early in the program may lead to unavoidable redesign late in life if commercial parts can no longer be purchased when funding becomes available.

Other major Testbed obsolescence components that need to be addressed are Testbed software, operating systems, hardware platforms and programming languages. For the operating system and hardware platform, usually commercial operating systems are more likely to provide long-term support than open-source operating systems. One important recommendation that can be made here is to look for deprecation flags when compiling the Testbed software during development. Deprecated flags usually indicate obsolescence in the programming language or the implementation of some of the operating system functions and calls. Ensuring that there is no deprecation during development will help ensure longer support for the Testbed software.

Guideline 38: Whether a program has a short (0-7 years) or long (0-20 years) Testbed lifespan, make a list that identifies and tracks the types and locations of EGSE, Dynamics Simulators and Testbed hardware in the loop (e.g., EMs) that may be used as spares in contingency situations.
Rationale and Example: By identifying early where there is common hardware being used across the program, one can plan to use this hardware for sparing during the Testbed lifespan. For example, if the Testbed uses the same EGSE as AI&T, then after launch, the AI&T EGSE may be used as spares on the testbed. Another example: if the program procured flight spares for the space vehicle development, these spares may be used for the Testbed after launch.

6.5.2 Testbed Maintenance

Maintenance of a testbed is needed to ensure its proper working order and reduce hardware degradation and failed parts. The Testbed maintenance plan should identify the organization(s) that provide on-going support for both hardware repair/replacement and software updates and address the resources required (including staffing) to keep the Testbed operating smoothly. There are two general categories of maintenance—Standard Maintenance and Readiness Maintenance.

Guideline 39: A Maintenance Plan for the Tb&S system should be developed to provide guidelines and the process to service and maintain the system after the delivery and during the Operations and Maintenance phase.
Rationale and Example: The Tb&S Maintenance Plan is a document that defines the process to be followed to maintain the System and to preserve certification status. It outlines a series of regression tests to be conducted to provide verification of system level functionality. Successful completion of these regression tests will establish that required functionalities are verified and that the system is ready for operational use by test personnel.

6.5.2.1 Standard Maintenance

Standard maintenance is conducted to ensure proper Testbed operation and includes support equipment such as computers and power supplies required to keep the Testbed running within its specifications. Some examples of standard maintenance items include:

Equipment Calibration: Includes performance of standard calibration of power supplies, sensors, or other units at pre-determined intervals to ensure the equipment is still performing within its tolerances. This may entail removal of equipment from the Testbed. If an item fails calibration, it may prevent use of the testbed. Therefore, it is recommended that backup equipment be available if needed to prevent any extended downtime of the Testbed.

Software Updates: Includes tracking anti-virus updates, software application bug fixes to software license upkeep.

General Computer Maintenance: Includes performing maintenance to keep the computers running well such as test archive maintenance (to free up hard drive space), defragmentation, etc. This maintenance may be performed autonomous or require user intervention.

The goal of standard maintenance is to keep the testbed performing well without interrupting the flow of events. A Testbed that is operating well will be less likely to fail resulting in schedule delays or poor quality of testing.

6.5.2.2 Readiness Maintenance

Readiness maintenance refers to the post launch activities required to ensure a Testbed is ready for use when needed. This consideration is primarily required during times when the Testbed may not be used frequently. In particular, if the Testbed is used solely for debug of issues while the Space Vehicle is on-orbit, it may not be used for years and then suddenly have a critical need to be brought up and used immediately. Readiness maintenance is designed to keep the hardware and software operable as well as to maintain a limited user base for proficiency. The required timelines between maintenance activities will be based upon the specific missions needs for the Testbed. Durations may be as short as a week (if the Testbed is used at semi-regular intervals spanning a couple of months) to several months if the Testbed is used rarely or only for anomalies. Again, also depending on the program and the Testbed usage; Testbed proficiency training may occur more frequently. An example of simple readiness maintenance would be to configure a Testbed to a fully operational state and run an aliveness test on it. The aliveness test should go through enough interfaces to verify that they are operational within desired specifications. Readiness maintenance requires ongoing support of personnel able to operate the Testbed and support as required from the developers whom would fix any issues discovered.

6.6 Support for Special Hardware and Software Testing

Testbeds may need to accommodate one-time hardware compatibility interface testing. EMs not selected for the testbed may be interfaced to the testbed via a flight-like harness and tested. For example, wheel drive electronics (WDE) EM driving a reaction wheel assembly (RWA) EM may be exercised on the testbed. This reduces risk to AI&T and also verifies the Dynamics Simulator model by comparing its wheel model data to the RWA spin-up and spin-down results. Generally, considerations must be put in-place during the development phase to allow “hooks” to connect hardware items and insert new software into the testbed. An important aspect of this capability is to conduct a safe-to-mate test, whenever there is high value hardware involved, during integration with the Testbed.

6.7 Security, Safety and Training Guidelines

Prior to deployment/delivery of the operational Testbed, operating guidelines should be put in place to address the Testbed security control policy, safety and training.

The security and control policy guidelines should address the Testbed physical hardware, systems software, computing networks, and supporting hardware/software used to interconnect computers and users. For example, physical hardware guidelines may specify that all computers have removable hard disks, software guidelines may specify that all software applications are security approved, and network guidelines may specify which networks are closed and which networks are open. The intended purpose of a security control policy is to clearly address compliance with the company’s security policy and the Tb&S computing access control management plan and to make sure that access is controlled appropriately.

The safety guidelines should address the Tb&S operating environment (temperature and humidity), ESD/RF precaution/protection, and any other safety precautions.

The training guidelines should address ESD and other certification type training needs; such as mate/de-mate connector processes. These guidelines should be referenced in the Tb&S Users’ Guide to ensure that all end users of the Tb&S are aware of the operating guidelines.

7. Guidelines Summary

In this section, we summarize the guidelines listed throughout the document and provide a cross reference for each guideline to its location in the document. The guidelines can be grouped as follows:

- General Tb&S Usage Guidelines – Guidelines 01 through 09 (Sections 3 and 4)
- Tb&S Development Process Guidelines – Guidelines 10 through 32 (Section 5)
- Tb&S Operational Considerations Guidelines – Guidelines 33 through 39 (Section 6)

Table 7-1. Guidelines Reference Matrix

Number	Guideline Text	Section Reference
01	Ensure that the FSW unit test is performed on a Tb&S product with a realistic FSW environment (but not necessarily on a processor targeted to be used in flight) providing realistic component inputs and interfaces.	3.2.2 - Flight Software Development End Uses
02	Use Flight-Like hardware and configuration as often and as early as possible to verify system requirements (including interfaces) during software-item qualification testing (SIQT).	3.2.2 - Flight Software Development End Uses
03	Use a Tb&S product executing Flight Software to verify Flight Commands and Telemetry.	3.2.3 - System/Subsystem Test End Uses
04	Perform as much Fault Management testing on the System Testbed as possible.	3.2.3 - System/Subsystem Test End Uses
05	Ensure that at least one Tb&S product can incorporate the required capabilities associated with fault injection and fault detection, with sufficient flexibility available for injecting faults in different ways. This includes not only SW fault injections but also HW/SW timing faults and HW fault injection.	3.2.3 - System/Subsystem Test End Uses
06	Identify the fidelity levels required for each Tb&S product capability early in the lifecycle.	3.4.2 - Tb&S Types and Physical Characteristics
07	For any type of SV program, having a common Ground System during System and Subsystem Testing, AI&T and Operations provides an opportunity to check out and synchronize the Command and Telemetry database early in the SV development process.	4.3.2.2 - Command and Telemetry Database Integration and Test End Use
08	For a risk-constrained program, to enable timely deliveries of verified FSW to both the STB and AI&T, it is useful for FSW to define a minimum of two FSW builds.	4.3.2.3 - Flight Software Development and Integration End Uses
09	For any type of SV program, perform as much Fault Management testing on the System Testbed as possible and try to minimize FMS testing against the SV (i.e., using the ISVT).	4.3.3.3 - Fault Management System Testing End Use
10	Follow a semi-formal to formal Tb&S development process with clear and comprehensive requirements and design documentation.	5 - Lifecycle Process for Program Tb&S Products

Number	Guideline Text	Section Reference
11	Include a Tb&S Development Plan as part of the standard Tb&S documentation.	5.1.1.1 - Tb&S Proposal Activity
12	During the Proposal phase of the program, ensure Tb&S types, quantities, and capabilities are sufficient to support the projected usage during the execution phase of the program.	5.1.1.1 - Tb&S Proposal Activity
13	In the initial Tb&S development plan define gates and reviews and ensure that the entry criteria include input from the appropriate users and development teams.	5.1.1.1 - Tb&S Proposal Activity
14	The Tb&S deployment schedule should satisfy the End User needs during that program phase. The End Users must accurately specify the capabilities they need from each Tb&S delivery and the Tb&S organization must agree that their deployment can satisfy the need.	5.1.1.1 - Tb&S Proposal Activity
15	Tie the Tb&S product and its use to the entry criteria for AI&T.	5.1.1.1 - Tb&S Proposal Activity
16	Programs must identify early which system requirements (including key risk requirements and functions) they plan to validate on which Tb&S platform or which Tb&S platform they need to collect data for their analyses.	5.1.1.1 - Tb&S Proposal Activity
17	The Systems Engineering team must be involved during the development of Program Tb&S products. Defined Tb&S gates and reviews will ensure that the entry and exit criteria include the involvement of the SE team.	5.1.2 - Requirements and Design Lifecycle Phase
18	Hold a Tb&S System Requirements Review (SRR). All findings and action items should be documented and work products should become the Tb&S baseline.	5.1.2.1 - Tb&S Architecture and Requirements Development Activity
19	Early involvement of System and Subsystem Subject Matter Experts (SME) during the requirement definition phase of Tb&S helps provide domain expertise critical to requirement development.	5.1.2.1 - Tb&S Architecture and Requirements Development Activity
20	Ensure the Tb&S system can be controlled from the program ground system.	5.1.2.1 - Tb&S Architecture and Requirements Development Activity
21	Make Tb&S software configurations flexible by making them parameter-driven so that changing configurations does not require rebuilding the Tb&S software.	5.1.2.1 - Tb&S Architecture and Requirements Development Activity
22	During trade studies and architectural development phase, considerations must be made for portability and modularity during the design of the software components.	5.1.2.2 - Tb&S Design Activity
23	Hold Tb&S design reviews conducted with peers and stakeholders and with all findings and action items closed Work products released and baselined.	5.1.2.2 - Tb&S Design Activity

Number	Guideline Text	Section Reference
24	Develop and implement an adequate sparing plan.	5.1.3.1 - Build & Integration Activity
25	Integration activities should be performed on hardware that is as close as possible to the actual product hardware.	5.1.3.1 - Build & Integration Activity
26	Ensure that End Users are involved in the build and integration activity of a Tb&S product.	5.1.3.1 - Build & Integration Activity
27	As part of preparing for the integration and test process, any Tb&S requirements should be reviewed to determine if they must be verified at a low level, which may only be available during this integration activity.	5.1.3.1 - Build & Integration Activity
28	The Tb&S developers should determine the formality of deliverable User Documents (Requirements, Manuals, User's Guides) at the start of the program by coordinating with the customer or the program office or with the program Tb&S product End Users.	5.1.4.1 - Tb&S Verification Activity
29	Establish a well-defined set of roles and responsibilities for individuals and organizations tasked with delivery of Tb&S end products.	5.3 - Tb&S Roles and Responsibilities
30	An SV program should have an organizational construct having an accountability and responsibility for their Tb&S products.	5.3 - Tb&S Roles and Responsibilities
31	Ensure the Tb&S costs are collected in a Work Break-down Structure (WBS).	5.3 - Tb&S Roles and Responsibilities
32	Ensure the Tb&S is staffed with individuals that have prior knowledge of the Tb&S lifecycle.	5.3 - Tb&S Roles and Responsibilities
33	In planning the use schedule for Tb&S, do not neglect or underestimate AI&T uses of the Tb&S.	6.2 - Scheduling and Utilization
34	Create a Testbed Scheduling process to adjudicate needs for all End Users.	6.2 - Scheduling and Utilization
35	During the testbed cycle, a testbed will be recertified many times. It is important to come up with an efficient, standardize recertification process to minimize the testbed downtime and reduced cycle time for making testbed operational.	6.2 - Scheduling and Utilization
36	Due to the complexity of testbed configurations, it is recommended that a simple to understand display be available that provides information on the current state of components that compromise the testbed.	6.3 - Configuration Management
37	Utilize a common Problem Reporting tool between Testbed and AI&T to better track issues.	6.4 - Problem Tracking and Reporting

Number	Guideline Text	Section Reference
38	Whether a program has a short (0-7 years) or long (0-20 years) Testbed lifespan, make a list that identifies and tracks the types and locations of EGSE, Dynamics Simulators and Testbed hardware in the loop (e.g. EMs) that may be used as spares in contingency situations.	6.5.1 - Testbed Sparing and Obsolescence Strategy
39	A Maintenance Plan for the Tb&S system should be developed to provide guidelines and the process to service and maintain the system after the delivery and during the Operations and Maintenance phase.	6.5.2 - Testbed Maintenance

8. Conclusion

In this Space Vehicle Testbeds and Simulators Taxonomy and Development Guide, we have provided three key topic areas necessary to improve the Mission Assurance associated with US Space Program Tb&S.

The first Tb&S-related Mission Assurance key topic is the effective communication of the end product produced by the Tb&S development organization that is necessary for the timely deployment that support program needs. This is referred to as the Tb&S taxonomy (Section 3), which provides a common framework for comparing and contrasting various testbeds and simulator users, uses, functional capabilities, and characteristics across the Aerospace industry. One of the most important contributions of the Tb&S taxonomy is the identification and description of four Tb&S types (NRT-Sim, NFTB, STB, and ISVT) a variation (or subset) of which is applicable to any type of SV development program. An example allocation of Tb&S types to End Uses is shown in Section 4.

The second Tb&S-related Mission Assurance key topic is an industry best practice overview presented as a development and operation guide in this document (Sections 5 and 6). The overview provides for a standard process along with maturing product artifacts necessary to develop and deploy successful Tb&S products. As we describe the development and operational processes, we are guided by the principle that cost is an important constraint to any program, regardless of the other program constraints (i.e., risk, schedule, etc.) and there can be significant cost savings if the planning is done upfront. Within each section, we have provided a set of guidelines that adhere to the above stated principle and to the problem statement in our charter.

Finally, we have provided a set of lessons and guidelines that provide the foundation for testbeds and simulators operations that directly support the mission success of the program. We recommend that these guidelines be evaluated for inclusion in all future SV development programs that employ Tb&S products to buy-down mission success risks (technical risks or programmatic risks).

In closing, this document provides a variety of program personnel and end customers with a resource to guide the efficient planning, development, and use of the Space Vehicle program’s testbed and simulator products. The distribution, dissemination, and direct use by practitioners will provide an opportunity for improving mission assurance in the future.

9. Acronym List

ADCS	Attitude Determination and Control
AI&T	Assembly Integration and Test
AO	Announcement of Opportunity
ATP	Authority to Proceed
BISTRR	Baseline Integrated Test Readiness Review
BOE	Basis of Estimate
BOM	Bill of Materials
BRR	Build Readiness Review
C&C	Command and Control
C&DH	Command and Data Handling
C&T	Command and Telemetry
CDR	Critical Design Review
CI	Configuration Item
CONOPS	Concept of Operations
COTS	Commercial Off the Shelf
CS	Control System
DB	Database
DITL	Day it the Life
DR	Discrepancy Report
EDU	Engineering Development Unit
EEPROM	Electronically Erasable Programmable Read Only Memory
EGSE	Electrical Ground Support Equipment
EM	Engineering Model Hardware
EPS	Electrical Power Subsystem
FM	Fault Management
FQT	Flight Software Qualification Test
FRR	Flight Readiness Review
FSW	Flight Software
GSE	Ground Support Equipment
HITL	Hardware-in-the-Loop
HW	Hardware
HWCI	Hardware Configuration Item
I/F	Interface
ICR	Initial Checkout Review
IDR	Internal Design Review
IMS	Integrated Master Schedule
ISVT	Integrated Space Vehicle Testbed
IV&V	Independent Verification and Validation
MAIW	Mission Assurance Improvement Workshop

MRR	Mission Readiness Review
M&S	Modeling and Simulations
NFTB	Non Flight-like Testbed
NRT	Non-Real Time
OS	Operating System
O&M	Operations and Maintenance
PC	Personal Computer
PDR	Preliminary Design Review
PER	Pre-Environmental Review
PSR	Pre-Ship Review
RAM	Random Access Memory
REP	Request for Proposal
RFI	Request for Information
RFR	Run for Record
RFU	Ready for Use
RR	Requirements Review
RT	Real Time
RTOS	Real Time Operating System
RWA	Reaction Wheel Assembly
SCM	Software Configuration Management
SDD	Software Design Document
SDP	Software Development Plan
SI	Software Item
SIQT	Software Item Qualification Testing
SME	Subject Matter Expert
SOW	Statement of Work
SRR	System Requirements Review
SRS	Software Requirements Specification
STB	System/Subsystem Testbed
STD	Software Test Description
STE	Special Test Equipment
STR	Software Test Report
SVTP	System Verification Test Plan
SW	Software
SW	Software Configuration Item
Tb&S	Testbeds and Simulators
TER	Test Exit Review
TD	Task Description
TECR	Test Evaluation Campaign Review
TOR	Technical Operating Report

TRR	Test Readiness Review
UUT	Unit Under Test
VCRM	Verification Cross Reference Matrix
VDD	Version Description Document
V&V	Verification and Validation
WDE	Wheel Drive Electronics

Appendix A: Tb&S Development Plan Template

This appendix contains a template to be used for development of a *Program Tb&S Development Plan template* with a Table of Contents, Scope, Overview, and other critical sections. This plan is intended to be a living document during the program. When it is first developed, many of the details will be high level or non-existent. This document should have the capability (if desired) to have these details added as the program matures such that this document becomes a good reference for the Tb&S.

Title: Program X Testbed and Simulator Development Plan

1.0 Program Overview

1.1 Type and Quantity of Testbeds and Simulators

- Define the top-level view of the program resources. Include details/rational as to why the quantities were chosen. Identify if the Tb&S product will be made in house or purchased as a final product.

1.2 Schedule Overview

- Place top-level schedule information for all Tb&S products here. Focus on major milestones like start of development, start of equipment acquisition, and delivery milestones. This information will need refinement as the program continues, but placing initial assumptions down will help to get them refined later. The goal is to have a view of how the developments of different Tb&S products interact with each other and the program. Program milestones should be included as a method of anchoring the details to the remainder of the program. Later sections will provide more schedule detail—this should be a good executive overview.

1.3 Key Usage

- Identify some of the most important items for the Tb&S. Particularly detail any items that are of high priority, high risk, or program critical. This area is a good place to briefly mention how the different quantities are used (e.g., if there are two system testbeds and one of them is for FSW development and the other for hardware development)

Note: The following sections begin to detail each individual testbed and simulator. The general sections will repeat for each type or unit (whichever best fits).

2.0 Tb&S Product Type/Name (e.g., System Testbed)

2.1 Scope and Tb&S Product Type Overview

- Provide functional diagrams of what is contained within the system testbed (may be high level or immature during development of this document, but it will lay the foundation for future updates). A summarized scope of the Tb&S (e.g., capabilities, performance, usage, etc.) will help provide direction for later paragraphs within this section.

2.2 Modeling, Simulation and Analysis Objectives

- Example: facilitate integration testing of subsystems
- Example: validation of system/subsystem performance and internal interfaces
- Other Examples …

2.3 Required hardware and software

- EMs, support hardware, etc.
- This section should tie together with the overview and objectives above. This will detail the HW and SW that are required. This can be as simple as a list, or it can provide more detail specifying why the hardware and software is needed and how it meets the objectives of the testbed listed above.

2.4 Lifecycle and Program Support

- This section is used to detail the lifecycle and the program support and corresponds with the different program phases identified in Section 5. As a part of this section there should be a schedule for this particular Tb&S. It is a more detailed version of the program schedule overview. For example, if the delivery of a particular flight unit is important (because it will require the testbed or the testbed will require it), having this on the schedule overview will help ensure both are available when necessary. Additionally, the subsections below will identify how the testbed will be used during each phase. Include information about security considerations (program, IT, physical, etc.) necessary for the testbed or simulator. This information should be combined to create a cohesive design and release cycle for both users and developers.

2.4.1 Proposal Phase

2.4.2 Requirements and Design Phase

2.4.3 Build and Test Phase

2.4.4 Assembly Integration &Test Phase

2.4.5 Transition and Support Operations

2.5 Applicability to mission capability elements

- Identify capabilities that the Tb&S will or will not perform when compared to the mission capabilities.
- Example: verify SV commanding capabilities
- Example: platform for on-orbit anomaly resolution, etc.
- Example: will not include payload mission data simulation

2.6 Applicability to interfaces

- If the Tb&S type discussed (for example) is a System Testbed, then some of the interfaces that it applies to include:
- Interface Document YYY: Communications with Command using Baseband
- Interface Document YYZ: Communications with User using Laser Communications
- Other examples …(include all items that are intended to physically/electrically interface even if the details are TBD)

2.7 Facility Interfaces

- Power interfaces (conditioning, backup, etc.),

- Grounding system (e.g., single point ground)
- Environmental requirements (temperature, humidity, purge, etc.)
- Unique requirements
- Necessary mitigation steps to correct/compensate for facility interfaces that are undesirable; such as no separate technical ground

2.8 Models and Simulation Planned for each capability

- Provide a mapping of all models and simulations by their functional need/requirement. Identify items that can be re-used and those that must be created.
- Provide information on a software development plan (may be an existing program or company plan)

2.9 Verification and Validation of the Simulation/Testbed

- Define how the requirements will be defined for the simulator/testbed (see section 5.1.2)
- Guideline the intended principles in how the verification and validation of the Tb&S is performed. For example, include the level of formality of the process and details of the process. Include details as to the level at which V&V will be performed (system, subsystem). Also include a plan for when this occurs in as it relates to the lifecycle. Is the test performed only once? Every x months? Whenever a new HW/SW configuration arrives?

2.10 Outputs and Metrics

- Identify technical performance measures or Tb&S product metrics to be collected during Tb&S development phase.

2.11 Configuration Control and Management

- Provide overview of how the configuration control of the testbed is going to be maintained. There are several areas that are worth considering here, such as modeling, simulation, analysis tools, ground equipment, etc.

2.12 Maintenance and Operations support

- Specify the intended support activities for the testbed and simulator, identifying the duration of this support that is required and how this influences the design. It is also worth postulating if the Tb&S product is potentially going to be used past its lifetime and provide any recommendations, requirements, or concerns that may apply in the future to allow this extended life (this may not be within the scope of the current contract, but applying the rational early will help if it is likely to become in scope at some point in the future).

3.0 Tb&S Product Type/Name (e.g., Integrated Space Vehicle Testbed)

- Continue with the above template for additional Testbeds or Simulator types

Appendix B: Tb&S Surveys

Two surveys were developed to assess the current state of Tb&S product development and use. The surveys were conducted in person by the MAIW Tb&S team members to ensure consistency between results. The developer survey had twenty-one responses and the user survey had eighteen responses.

For each survey, the original questions are listed and then results are presented in both graphical and tabular form. Note that some of the names and acronyms used for Tb&S product types changed between when the surveys were developed and final release of the paper; all results use the final names while the survey questions use the original names.

Appendix B1.1: Survey Questionnaire for Tb&S Product Developers

The following is the survey developed to solicit feedback from Testbed and Simulator development organizations in industry.

MAIW Testbeds and Simulators (Tb&S) Survey for Developers

A. Background Information

1. Please indicate your years of experience as follows:

	Year in Aerospace	Years working on Tb&S
A. <5	______	______
B. 6-10	______	______
C. 11-15	______	______
D. 16-20	______	______
E. >20	______	______

2. Number of programs that you have worked on performing development/operations of Testbed & Simulators?

A. _____ 1
B. _____ 2
C. _____ 3-5
D. _____ 5-10
E. _____ > 10

B. Program Questions

3. Who was the program customer?

A. _____ Civil
B. _____ Commercial
C. _____ National Defense

The MAIW Tb&S Team has categorized program testbeds and simulators into four generalized categories as follows:

Non-Real-time Simulators (NRT): This simulator is a purely software simulation, hosted on a workstation, and includes no flight or EM hardware in the loop. The simulator includes the flight software (FSW) - ported and running on the host environment - in a closed-loop simulation with spacecraft hardware, dynamics and environment models and/or payload simulation models. The implementation includes a command and telemetry interface to the simulation software.

FSW RT Simulator: This simulator is almost a purely software simulation, hosted on a workstation, but includes non-flightlike processors to host FSW in the loop. These simulators are often run without orbital and attitude dynamics in the loop. This implementation requires a Realtime Operating System. The implementation also includes a command and telemetry interface to the simulation software.

System Testbed: This testbed provides a Hardware-in-the-Loop test environment that includes a combination of Engineering Models (EMs) and/or flight units for some of the vehicle boxes, coupled with a Real-Time Simulator that simulates other flight subsystems as well as the orbital and attitude dynamics and the environment. The implementation includes all the supporting ground support equipment including a ground console to provide a command and telemetry interface. The System Testbed category includes:

- FlatSats (most boxes and harnessing represented in flightlike hardware)
- Software Testbeds (for testing FSW in EM processors)
- Vehicle Simulators (for payload interface testing)
- Payload Simulators (for spacecraft bus interface testing).

Integrated Space Vehicle Testbed: This testbed type is a mating of an integrated flight spacecraft with a Hardware-in-the-Loop (HITL) Simulator providing orbital and attitude dynamics models. The integrated space vehicle testbed also requires other components of the AI&T environment, typically a suite of power STE components and a command and telemetry interface to the spacecraft.

4. How many testbeds and simulators were developed for the program, and were any of them deliverable?

	Number	Deliverable (yes/no)
A. NRT Simulator(s)	______	______
B. FSW RT Sim(s)	______	______
C. System Testbed(s)	______	______
D. Integrated Space Vehicle Testbed(s)	______	______

5. What was the primary use of the system testbed(s) identified in Question #4?

A. _____ SV testing
B. _____ Payload testing
C. _____ Bus testing

6. What was the date of completing development of the testbed for this program?

A. _____ Prior to 1995
B. _____ 1995-1999
C. _____ 2000-2004
D. _____ 2005 to present

7. When were the testbeds and simulators available for scheduled use?

	NRT	FSWRTS	STB	ISVT
A. Prior to SDR	______	______	______	______
B. Prior to PDR	______	______	______	______

C. Prior to CDR ______ ______ ______ ______
D. Prior to AI&T Start ______ ______ ______ ______
E. Prior to Launch ______ ______ ______ ______
F. After Launch ______ ______ ______ ______

8. How much schedule time did it take for development and verification of the testbeds and simulators?

NRT FSWRTS STB ISVT

A. under 3 months ______ ______ ______ ______
B. up to 6 months ______ ______ ______ ______
C. up to 12 months ______ ______ ______ ______
D. up to 3 years ______ ______ ______ ______
E. up to 5 years ______ ______ ______ ______
F. over 5 years ______ ______ ______ ______

9. What was the size of the aggregated development team(s) (number of equivalent people over the development schedule listed in Question #8)?

______ EP over ______ Months

C. Testbed Questions

Answer the following questions for the highest fidelity system testbed or integrated Space Vehicle testbed for the program:

10. How much schedule time was the testbed used operationally prior to launch (end of development until launch)?

A. _____ under 3 months
B. _____ up to 6 months
C. _____ up to 12 months
D. _____ up to 3 years
E. _____ up to 5 years
F. _____ over 5 years

11. What was the size of the testbed operations team (number of equivalent people over the operations schedule listed in Question #10)?

______ EP over ______ Months

12. After launch, how long was the testbed scheduled for operational use and support?
_____ years

13. What was the documentation process associated with the testbed?

A. _____ Formal (review process, controlled document)
B. _____ Informal (not officially released)
C. _____ Ad-hoc (sparse documentation)

14. What was the review process associated with the testbed?

A. _____ Formal (program-level reviews, stakeholder attendance)
D. _____ Informal (peer reviews)
E. _____ Ad-hoc or absent

15. What was the sell-off process associated with the testbed?

A. _____ Formal (e.g., test plan and procedure, QA involvement, review gate)
B. _____ Informal (functional demonstration)
C. _____ Ad-hoc or none

16. Which organization owned the testbed during development?

A. _____ System Engineering (SEIT)
B. _____ Subsystem Integrated Product Team
C. _____ Software
D. _____ System I&T (includes AI&T)
E. _____ Ground
F. _____ EGSE
G. _____ Other

17. Which organization owned the testbed after development (deployed simulator operations)?

A. _____ System Engineering (SEIT)
B. _____ Subsystem Integrated Product Team
C. _____ Software
D. _____ System I&T (includes AI&T)
E. _____ Ground
F. _____ EGSE
G. _____ Other

18. Can you estimate the total development & maintenance cost (ATP through Launch) of the aggregate of all testbeds (including HW, developed simulator SW, labor, etc)?

A. _____ under $100K
B. _____ up to $500K
C. _____ up to $1M
D. _____ up to $5M
E. _____ up to $10M
F. _____ up to $20M
G. _____ over $20M

19. Can you estimate the total cost of duplicating the system testbed, at the time when the original testbed was developed (i.e., excepting obsolescence issues)?

A. _____ under $100K
B. _____ up to $500K
C. _____ up to $1M
D. _____ up to $5M
E. _____ up to $10M
F. _____ up to $20M
G. _____ over $20M

20. What is the distribution of users for the highest fidelity testbed after initial deployment during the following phases? (Approximate, must add up to 100%)

	Prior to AI&T start	Prior to Launch	After Launch
A. Testbed/Simulator Developers	_______	_______	_______
B. FSW (including FQT)	_______	_______	_______
C. Ground SW, Cmd+Ctrl, EGSE	_______	_______	_______
D. AI&T	_______	_______	_______
E. System and Subsystem Engineers	_______	_______	_______
F. Mission Ops	_______	_______	_______

21. What was the approximate operation schedule for the testbed for each of the program phases?

	Pre-CDR	CDR to AI&T Start	AI&T to Launch	Operations
A. N/A	_______	_______	_______	_______
B. 0-20 Hours/wk	_______	_______	_______	_______
C. 21-40 Hours/wk	_______	_______	_______	_______
D. 41-60 Hours/wk	_______	_______	_______	_______
E. 61-80 Hours/wk	_______	_______	_______	_______
F. 81-120 Hours/wk	_______	_______	_______	_______
G. > 120 Hours/wk	_______	_______	_______	_______

22. What percentage of space vehicle hardware components in your system testbed were EM/EDU units or better?

A. ______ under 10%
B. ______ up to 25%
C. ______ up to 50%
D. ______ up to 75%
E. ______ over 75%

23. How well does your testbed match the redundancy of the flight system?

A. _____ Fully
B. _____ Partially
C. _____ Not at all

24. Rate the following obstacles and challenges in successfully developing and deploying the testbed? (1=Significant, 5 = No impact)

A. _____ Program Management
B. _____ Technical
C. _____ Budget
D. _____ Schedule
E. _____ Customer
F. _____ Other (list) ________________________

25. What percent of the testbed models (hardware models and dynamics/environment models) were used as both analyst’s models and testbed models, as opposed to custom developed for the testbed?

A. _____ under 10%
B. _____ up to 25%

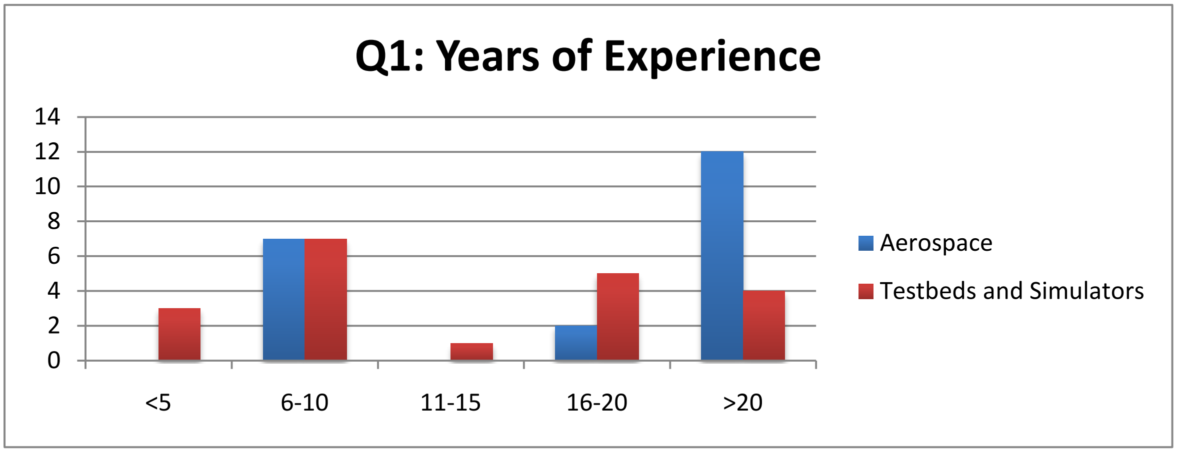
C. _____ up to 50%
D. _____ over 50%

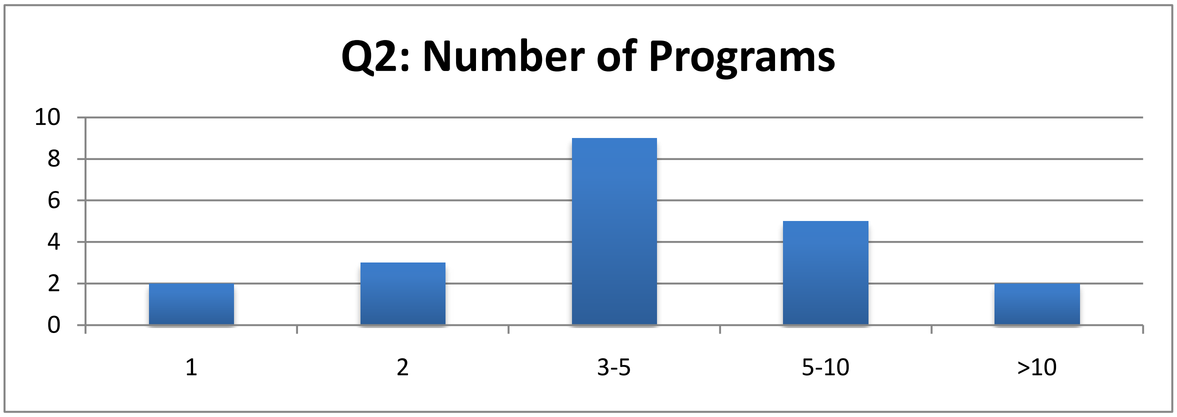
D. General Survey Questions

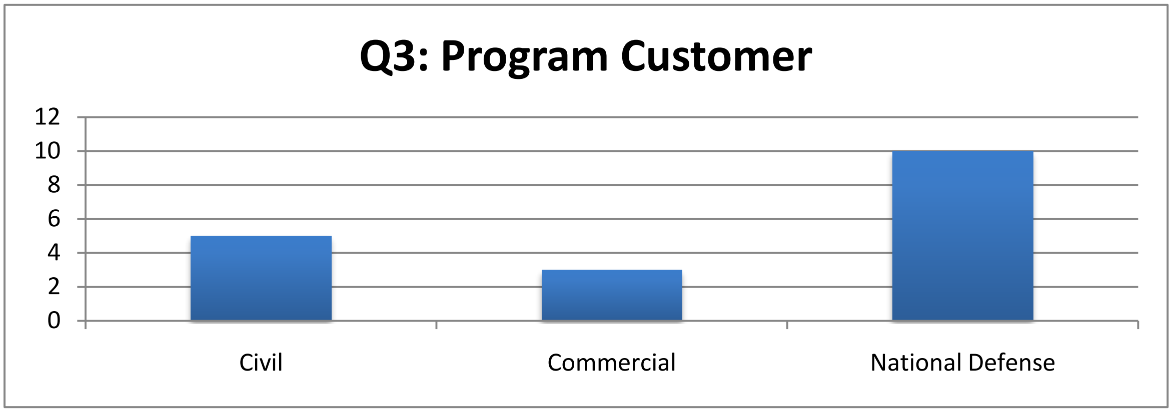
26. The definitions and categories of testbeds and simulators (from question 5) vary greatly from company to company; do you agree with the given definitions or would you propose changes?

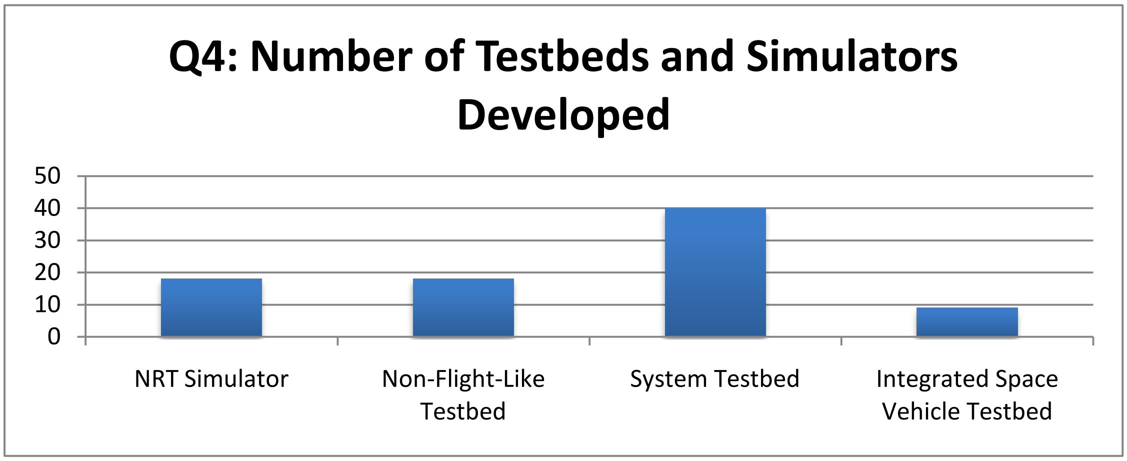
27. Do you have any lessons learned or other comments on how to improve mission assurance for testbeds and simulators?

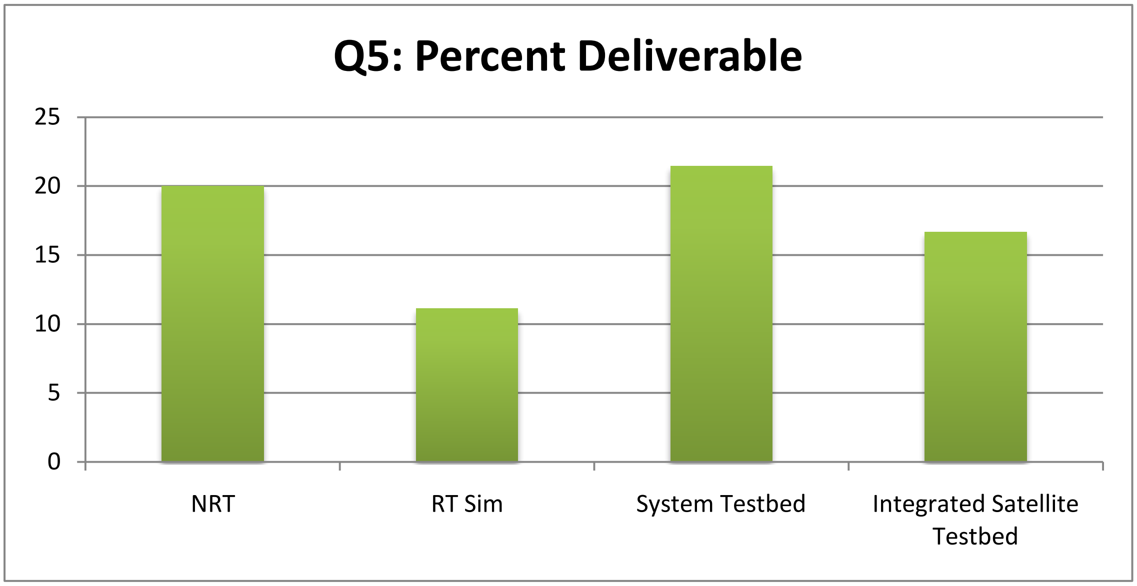
Appendix B1.2: Survey Results for Tb&S Developers

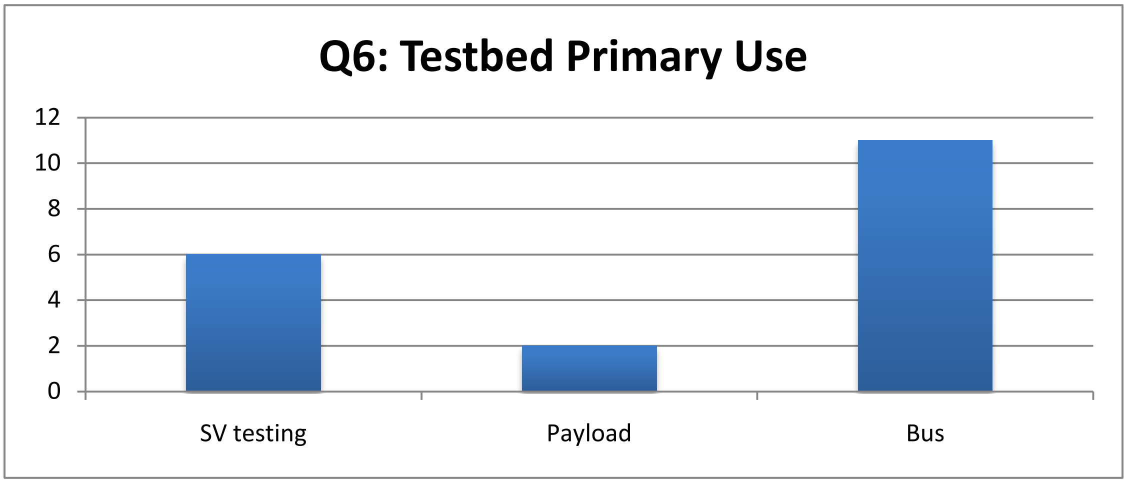


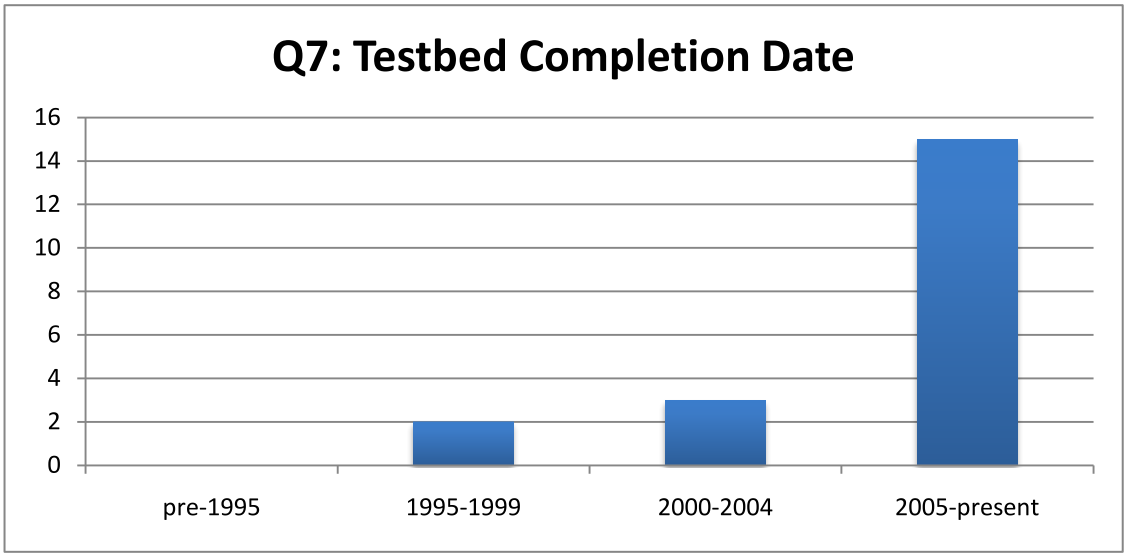


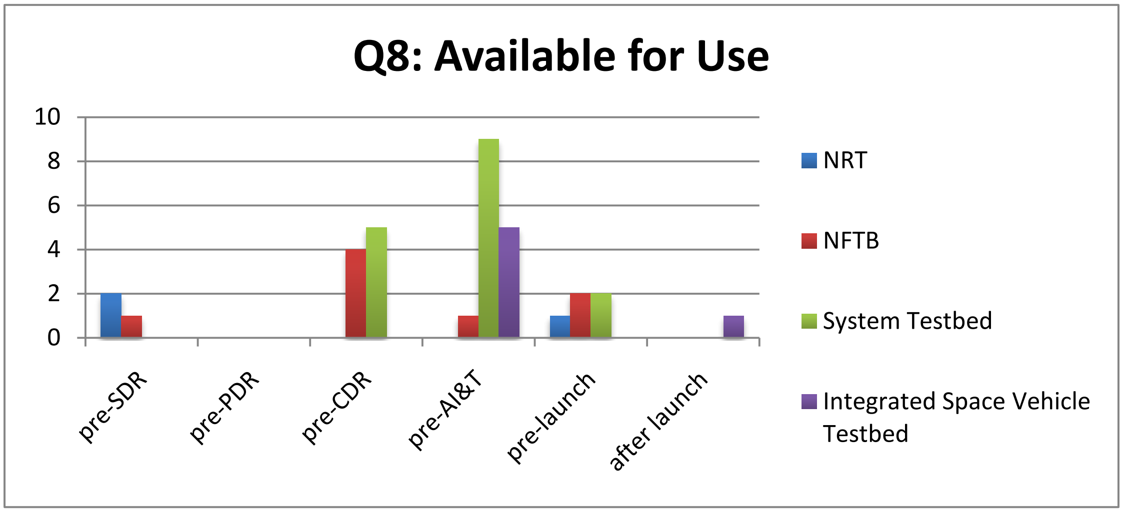


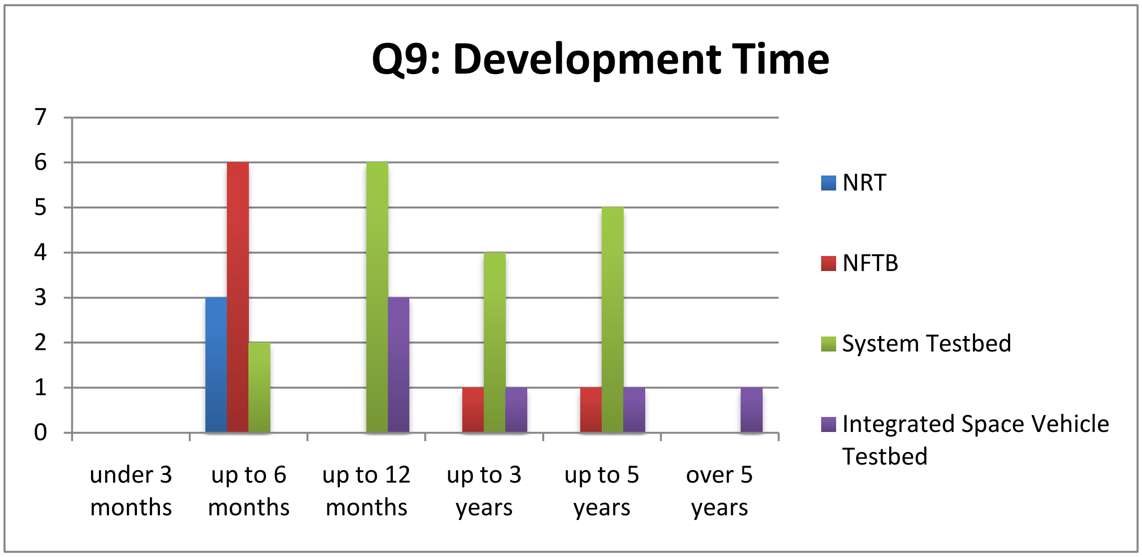

Q4: Number of Testbeds and Simulators Developed
50
40
30
20
10
0
NRT Simulator
Non-Flight-Like Testbed
System Testbed
Integrated Space Vehicle Testbed

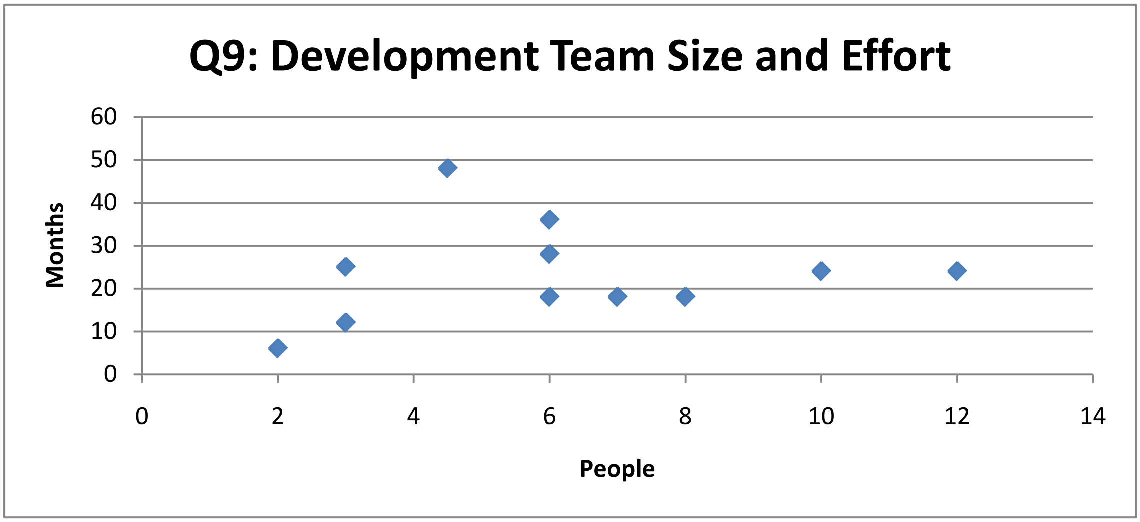

Q5: Percent Deliverable
25
20
15
10
5
0
NRT
RT Sim
System Testbed
Integrated Satellite Testbed

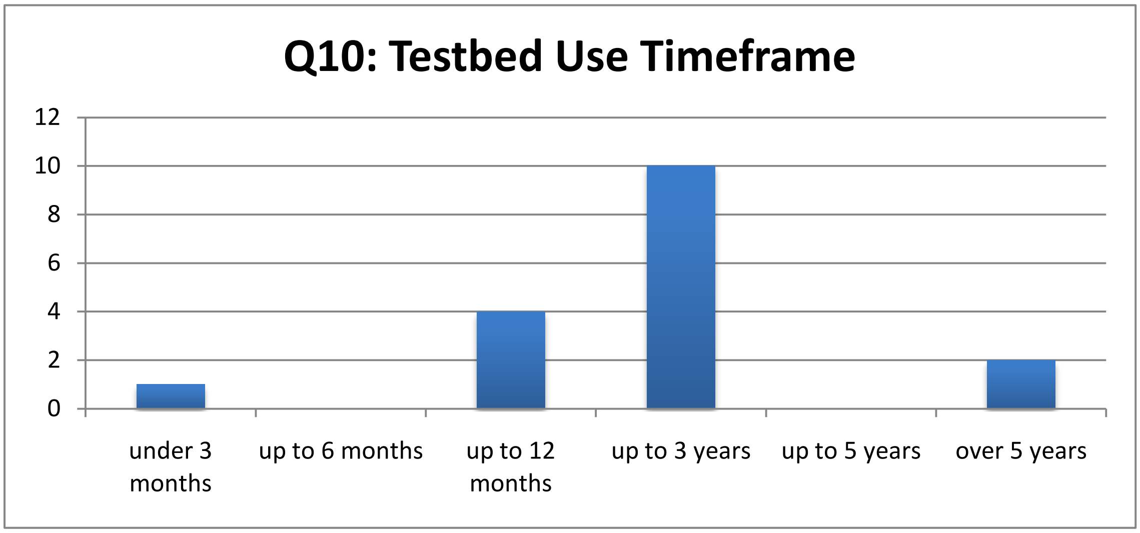

Q6: Testbed Primary Use
12
10
8
6
4
2
0
SV testing
Payload
Bus

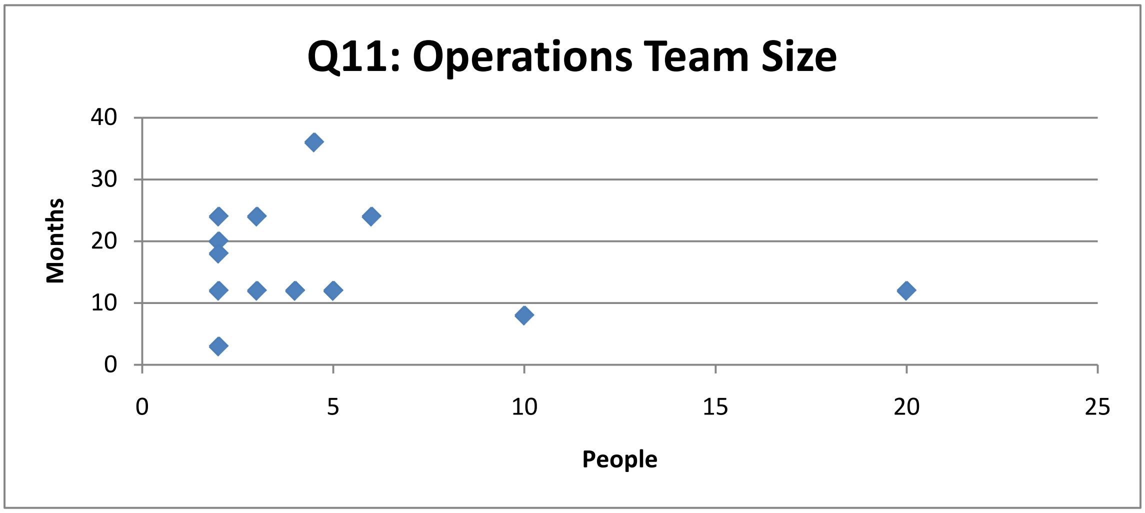

Q7: Testbed Completion Date
16
14
12
10
8
6
4
2
0
pre-1995
1995-1999
2000-2004
2005-present

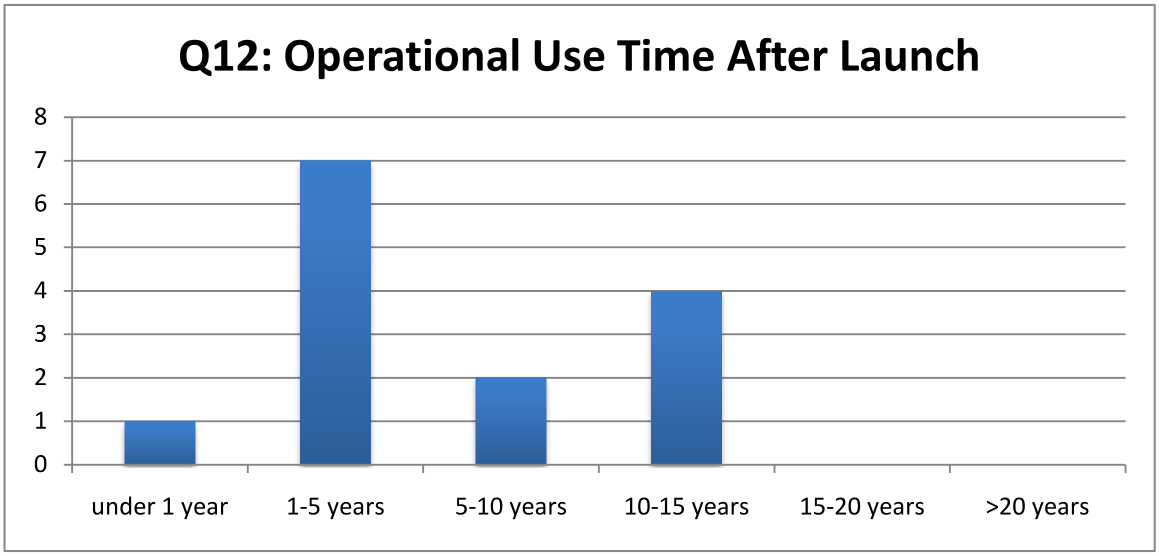

Q8: Available for Use
10
8
6
4
2
0
pre-SDR
pre-PDR
pre-CDR
pre-AI&T
pre-launch
after launch
NRT
NFTB
System Testbed
Integrated Space Vehicle Testbed

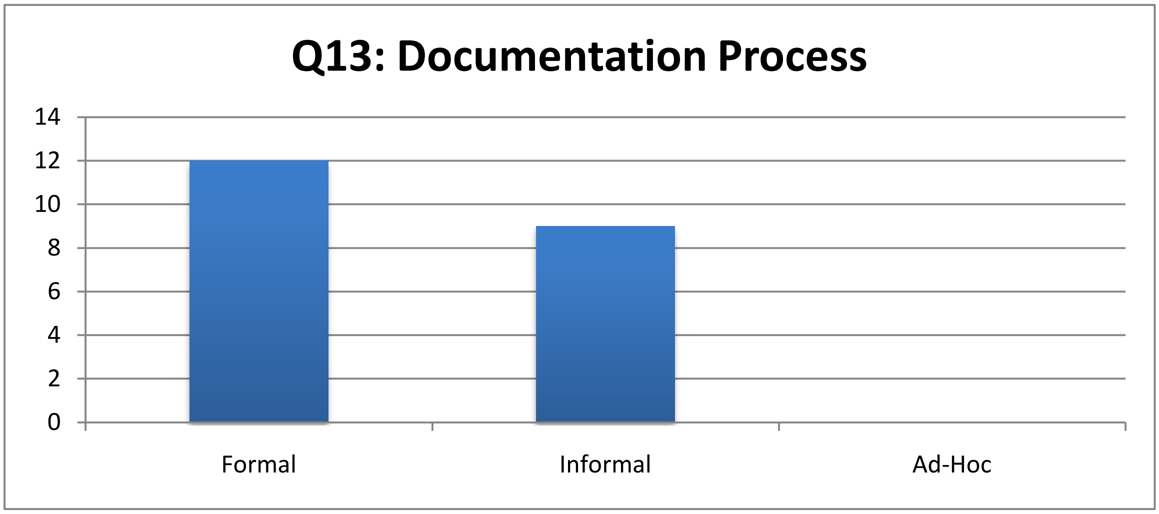

Q9: Development Time
7
6
5
4
3
2
1
0
under 3 months
up to 6 months
up to 12 months
up to 3 years
up to 5 years
over 5 years
NRT
NFTB
System Testbed
Integrated Space Vehicle Testbed

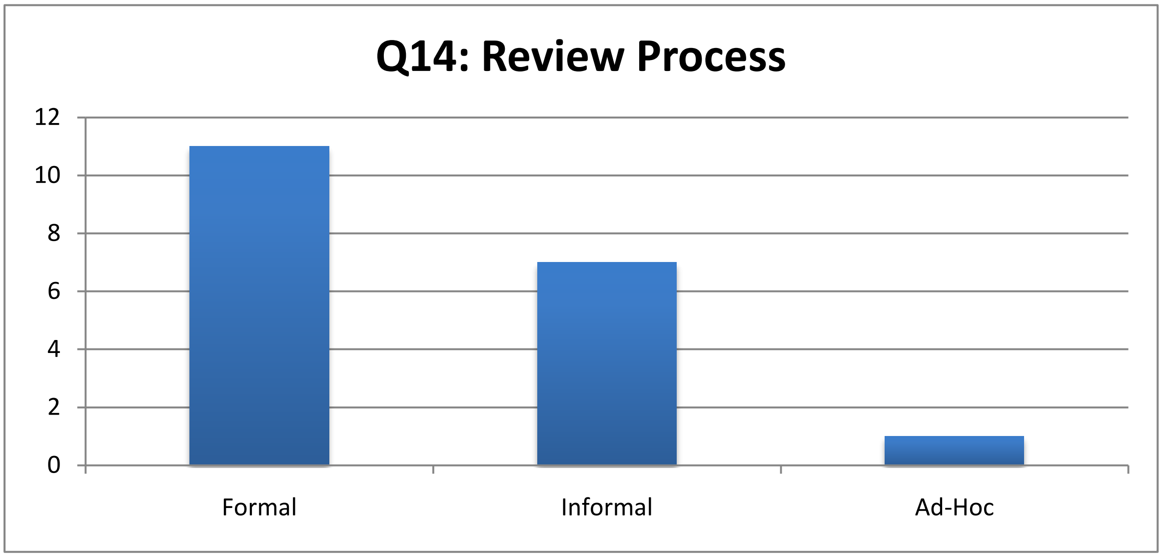

Q9: Development Team Size and Effort
Months
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
People

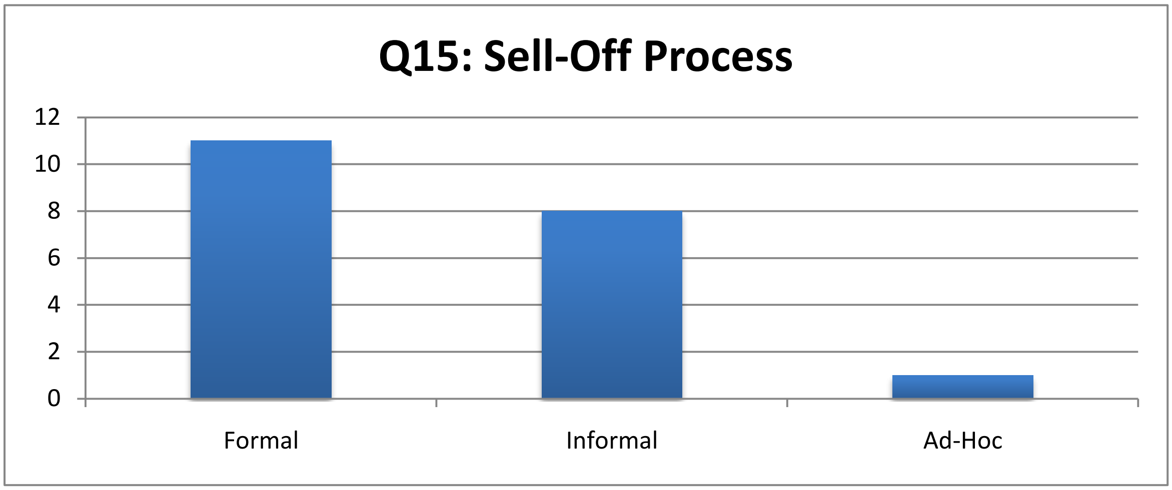

Q10: Testbed Use Timeframe
12
10
8
6
4
2
0
under 3 months
up to 6 months
up to 12 months
up to 3 years
up to 5 years
over 5 years

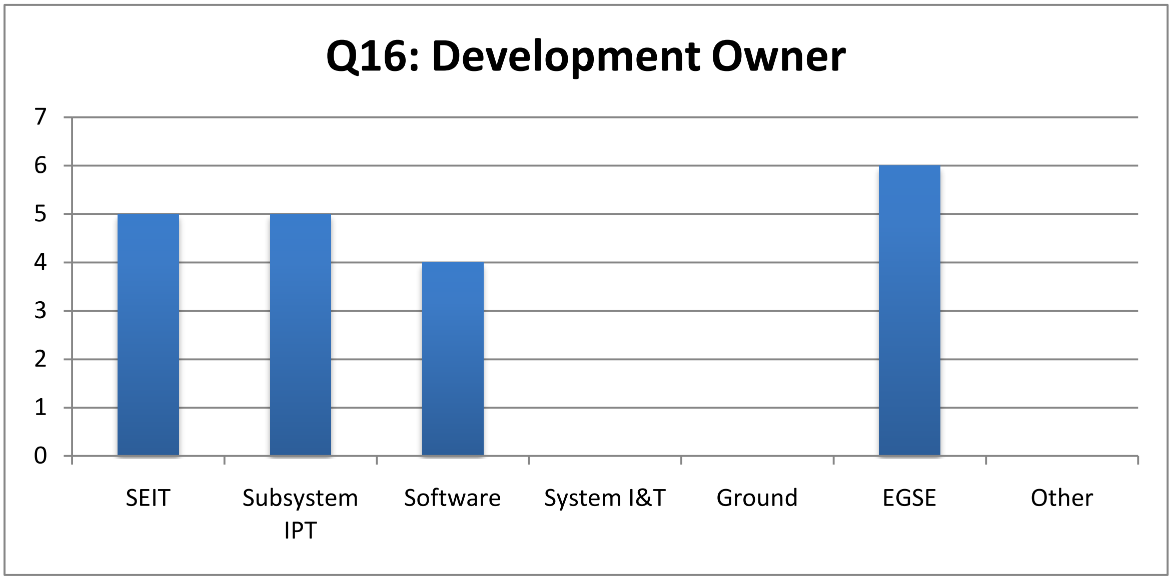

Q11: Operations Team Size
Months
40
30
20
10
0
0
5
10
15
20
25
People

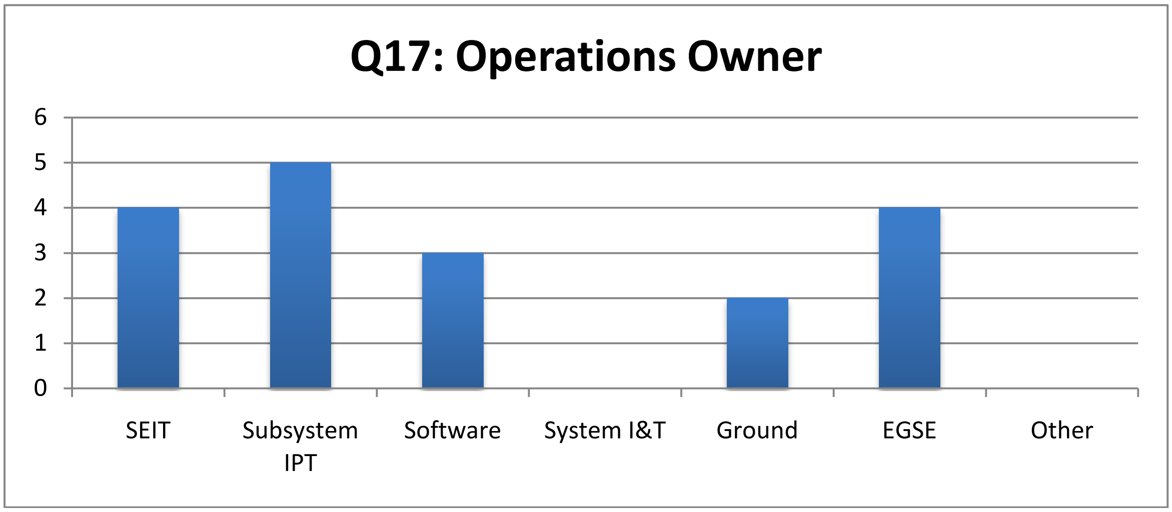

Q12: Operational Use Time After Launch
8
7
6
5
4
3
2
1
0
under 1 year
1-5 years
5-10 years
10-15 years
15-20 years
>20 years

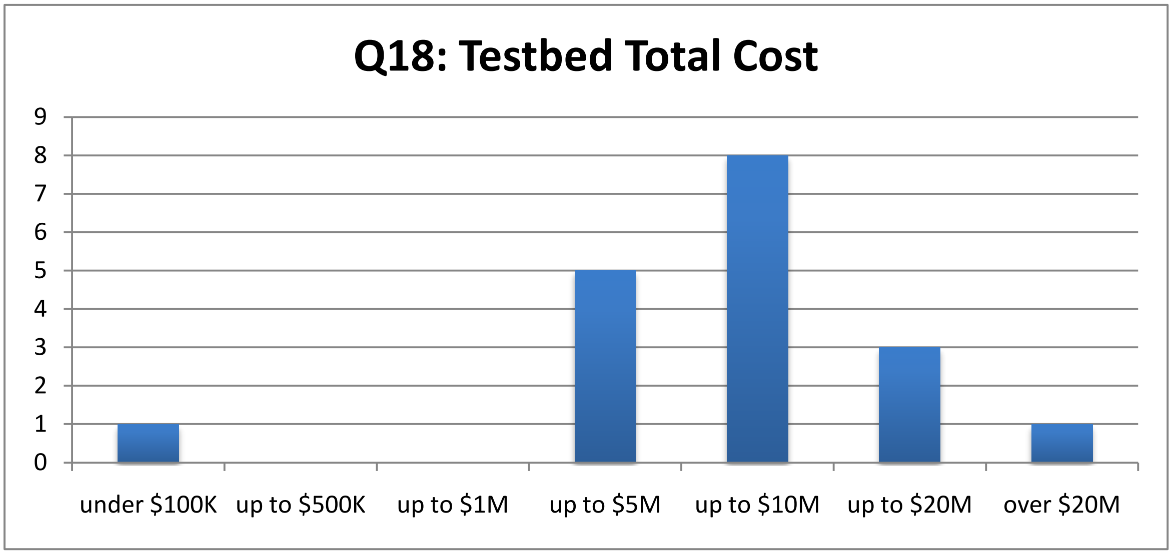

Q13: Documentation Process
14
12
10
8
6
4
2
0
Formal
Informal
Ad-Hoc

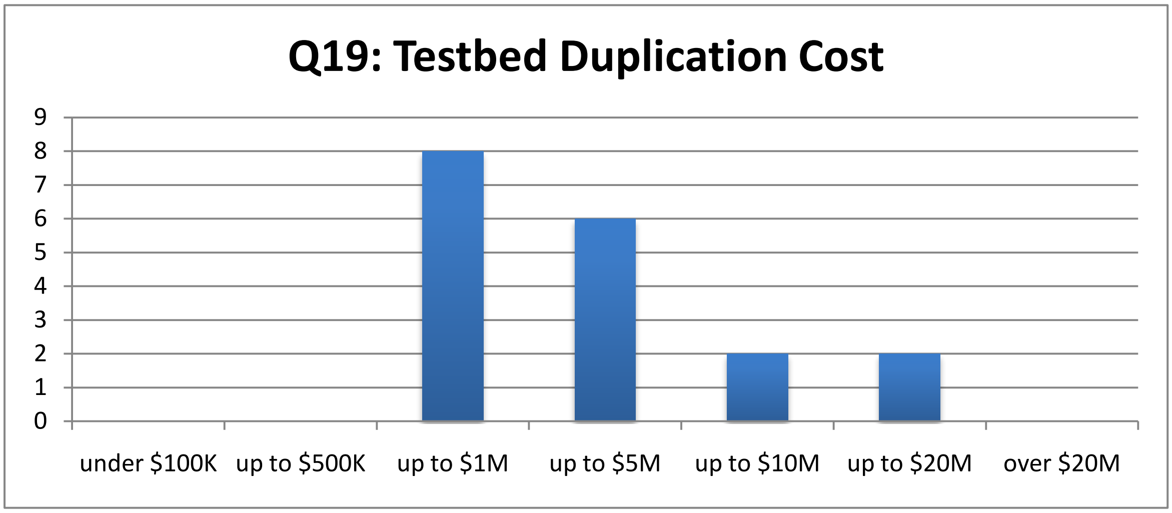

Q14: Review Process
12
10
8
6
4
2
0
Formal
Informal
Ad-Hoc

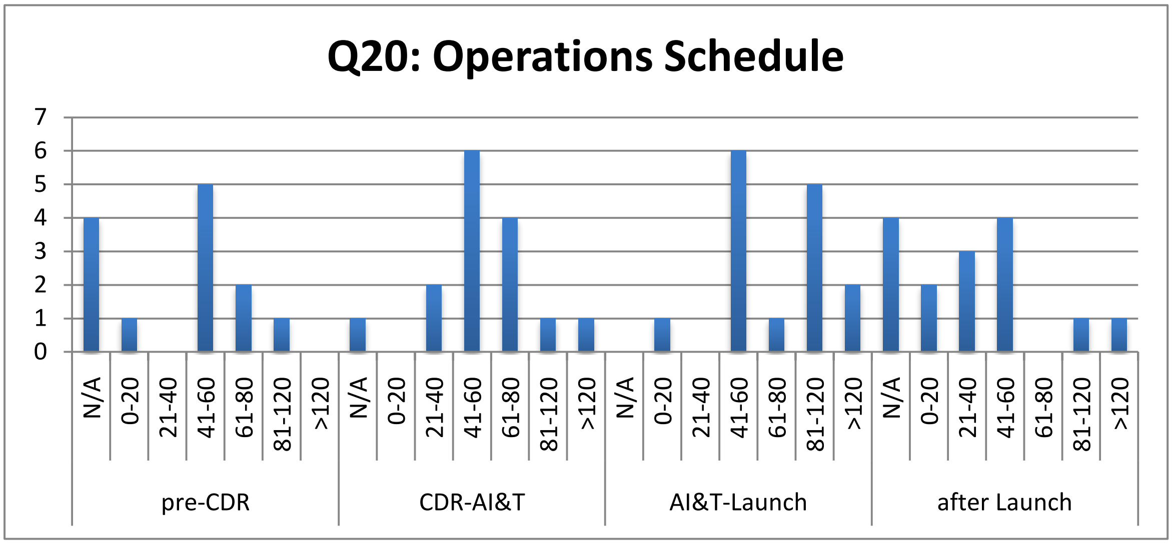

Q15: Sell-Off Process
12
10
8
6
4
2
0
Formal
Informal
Ad-Hoc

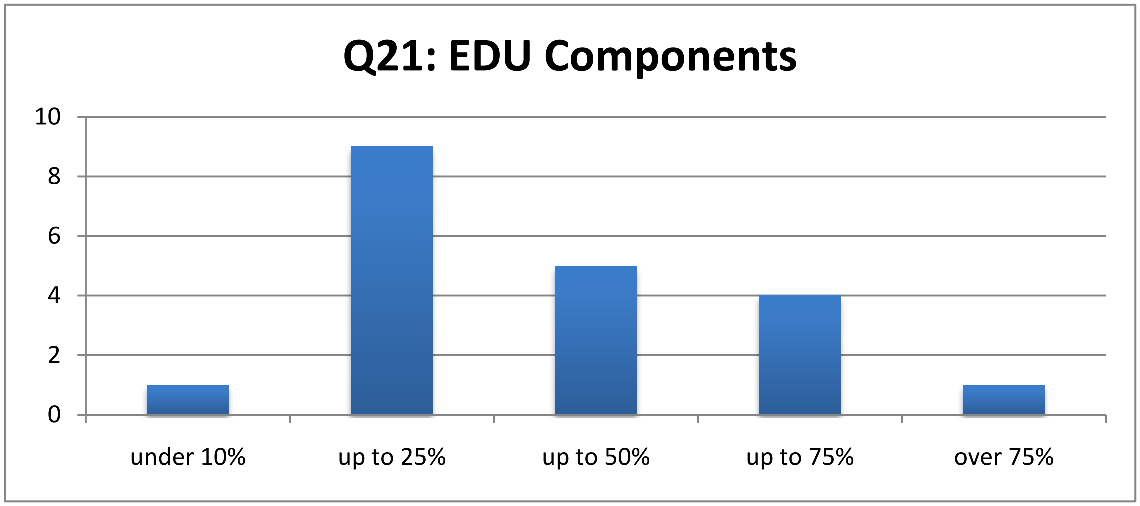

Q16: Development Owner
7
6
5
4
3
2
1
0
SEIT
Subsystem IPT
Software
System I&T
Ground
EGSE
Other

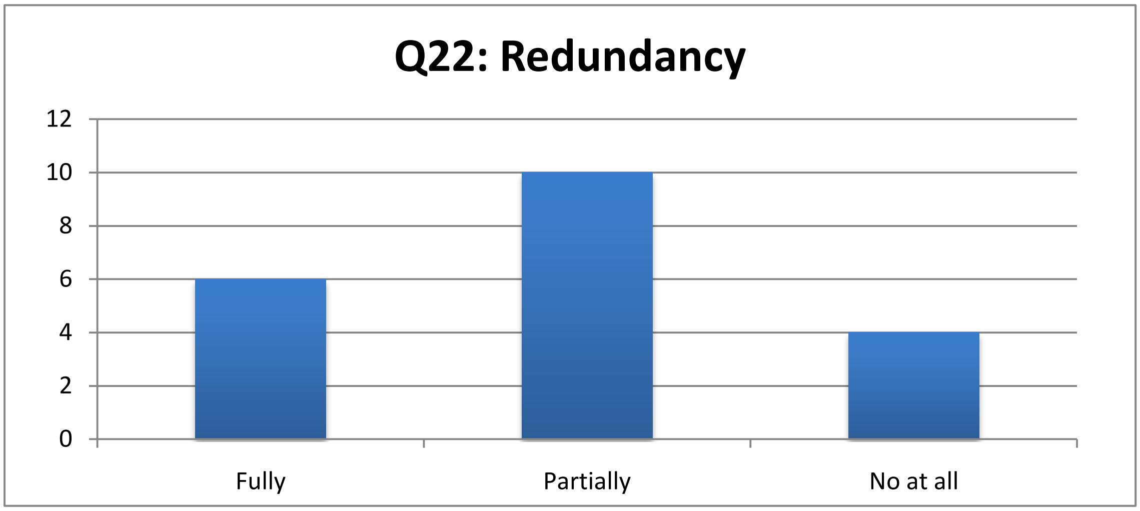

Q17: Operations Owner
6
5
4
3
2
1
0
SEIT
Subsystem IPT
Software
System I&T
Ground
EGSE
Other

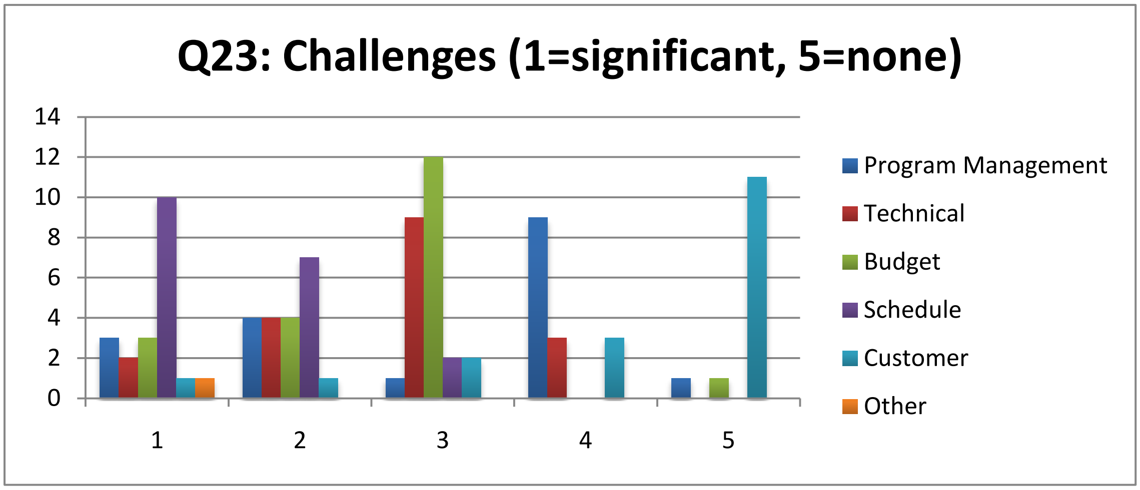

Q18: Testbed Total Cost
9
8
7
6
5
4
3
2
1
0
under $100K
up to $500K
up to $1M
up to $5M
up to $10M
up to $20M
over $20M

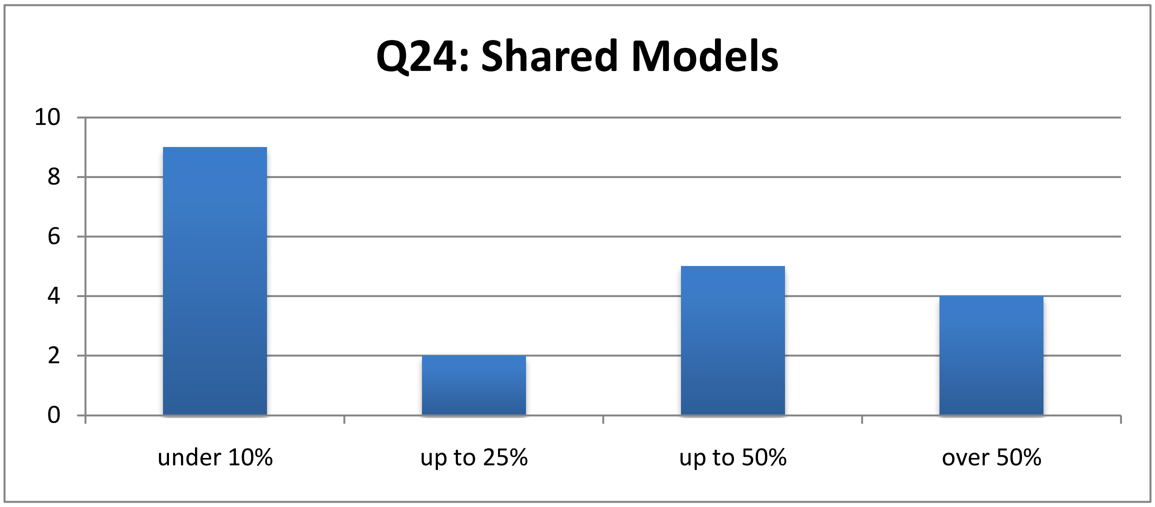

Q19: Testbed Duplication Cost
9
8
7
6
5
4
3
2
1
0
under $100K
up to $500K
up to $1M
up to $5M
up to $10M
up to $20M
over $20M


Q20: Operations Schedule
7
6
5
4
3
2
1
0
N/A
0-20
21-40
41-60
61-80
81-120
>120
pre-CDR
CDR-AI&T
AI&T-Launch
after Launch


Q21: EDU Components
10
8
6
4
2
0
under 10%
up to 25%
up to 50%
up to 75%
over 75%


Q22: Redundancy
12
10
8
6
4
2
0
Fully
Partially
No at all


Q23: Challenges (1=significant, 5=none)
14
12
10
8
6
4
2
0
1
2
3
4
5
Program Management
Technical
Budget
Schedule
Customer
Other


Q24: Shared Models
10
8
6
4
2
0
under 10%
up to 25%
up to 50%
over 50%

Appendix B2.1: Survey Questionnaire for Tb&S Product Users

The following is the survey developed to solicit feedback from industry program users of Testbeds and Simulators.

A. Background Information

1. Please indicate your years of experience as follows:

	Year in Aerospace	Years working on Tb&S
F. <5	______	______
G. 6-10	______	______
H. 11-15	______	______
I. 16-20	______	______
J. >20	______	______

2. Number of programs that you have worked on performing operations of Testbeds and Simulators?
   F. _____ 1
   G. _____ 2
   H. _____ 3-5
   I. _____ 5-10
   J. _____ > 10

B. Program Questions

3. Who was the program customer?
   D. _____ Civil
   E. _____ Commercial
   F. _____ National Defense

The MAIW Tb&S Team has categorized program testbeds and simulators into four generalized categories as follows:

Non-Real-time Simulators (NRT): This simulator is a purely software simulation, hosted on a workstation, and includes no flight or EM hardware in the loop. The simulator includes the flight software (FSW) - ported and running on the host environment - in a closed-loop simulation with spacecraft hardware, dynamics and environment models and/or payload simulation models. The implementation includes a command and telemetry interface to the simulation software.

FSW RT Simulator: This simulator is almost a purely software simulation, hosted on a workstation, but includes non-flightlike processors to host FSW in the loop. These simulators are often run without orbital and attitude dynamics in the loop. This implementation requires a Realtime Operating System. The implementation also includes a command and telemetry interface to the simulation software.

System Testbed: This testbed provides a Hardware-in-the-Loop test environment that includes a combination of Engineering Models (EMs) and/or flight units for some of the vehicle boxes, coupled with a Real-Time Simulator that simulates other flight subsystems as well as the orbital and attitude dynamics and the environment. The implementation includes all the supporting ground support equipment including a ground console to provide a command and telemetry interface. The System Testbed category includes:

- FlatSats (most boxes and harnessing represented in flightlike hardware)
- Software Testbeds (for testing FSW in EM processors)
- Vehicle Simulators (for payload interface testing)
- Payload Simulators (for spacecraft bus interface testing).

Integrated Space Vehicle Testbed: This testbed type is a mating of an integrated flight spacecraft with a Hardware-in-the-Loop (HITL) Simulator providing orbital and attitude dynamics models. The integrated Space Vehicle testbed also requires other components of the AI&T environment, typically a suite of power STE components and a command and telemetry interface to the spacecraft.

4. Which type of testbeds and simulators did you use for this program?
   E. _____ NRT Simulator(s)
   F. _____ FSW RT Sim(s)
   G. _____ System Testbed(s)
   H. _____ Integrated Space Vehicle Testbed(s)

5. What was your primary use of the system testbed(s) identified in Question #4?
   D. _____ SV testing
   E. _____ Payload testing
   F. _____ Bus testing

6. What type of user were you for this program?
   A. _____ FSW Developer/Integrator
   B. _____ FSW Tester
   C. _____ Ground Systems
   D. _____ AI&T
   E. _____ Subsystem Engineer (type): ___________
   F. _____ System Engineer
   G. _____ Mission Engineer
   H. _____ Other: _______________

C. System Testbed Questions

Answer the following questions for your user team for the system testbed you used the most:

7. What was the start date of use of the system testbed for this program?
   E. _____ Prior to 1995
   F. _____ 1995-1999
   G. _____ 2000-2004
   H. _____ 2005 to present

8. How many hours per week were you scheduled to use the testbed for each of the program phases?

	Pre-CDR	CDR to AI&T Start	AI&T to Launch	Operations
H. N/A	________	________	________	________
I. 0-20 Hours/wk	________	________	________	________
J. 21-40 Hours/wk	________	________	________	________

K. 41-60 Hours/wk	_______	_______	_______	_______
L. 61-80 Hours/wk	_______	_______	_______	_______
M. 81-120 Hours/wk	_______	_______	_______	_______
N. > 120 Hours/wk	_______	_______	_______	_______

9. Was your scheduled time for using the testbed sufficient to meet your needs (assuming that your team was large enough to use all allocated time)?
   A. ______ Yes
   B. ______ No, needed additional 0-20 hours/week
   C. ______ No, needed additional 21-40 hours/week
   D. ______ No, needed additional 41-60 hours/week
   E. ______ No, needed additional 61-80 hours/week
   F. ______ No, needed additional 81-120 hours/week
   G. ______ No, needed additional >120 hours/week

10. Was the testbed ready in time to meet your needs?
   A. ______ Yes
   B. ______ No, needed <3 months earlier
   C. ______ No, needed 3-6 months earlier
   D. ______ No, needed 7-12 months earlier
   E. ______ No, needed 1-3 years earlier
   F. ______ No, needed more than 3 years earlier

11. If the testbed had been ready for use earlier than when it was, could you have made use of it for your needs?
   A. ______ No (earlier would not have been useful)
   B. ______ Yes, could have used up to 3 months earlier
   C. ______ Yes, could have used up to 6 months earlier
   D. ______ Yes, could have used up to 1 year earlier
   E. ______ Yes, could have used up to 3 years earlier
   F. ______ Yes, could have used more than 3 years earlier

12. Was the testbed schedule able to accommodate specific short-term tasks requiring more than your usual scheduled time (e.g., high-priority anomaly resolution)?
   A. ______ Always
   B. ______ Usually
   C. ______ Sometimes
   D. ______ Never

13. How do you communicate your testbed requirements to the testbed manager?
   A. ______ Formal (review process, controlled document)
   B. ______ Informal Requirements (not officially released)
   C. ______ Ad-Hoc (sparse documentation or verbal requests)

14. What testbed hardware fidelity is required for your use? Check all that apply.
   A. ______ EM Components
   B. ______ Cross-Strapping
   C. ______ Full Redundancy
   D. ______ Flight-like Harnesses

E. ______ Flight Components
F. ______ Other: ___________________

15. What kind of problems were found in I&T that you feel should have been caught by testing on the testbed prior to I&T? Check all that apply.
A. ______ FSW defects
B. ______ EGSE defects
C. ______ HW defects
D. ______ Cable and harness defects
E. ______ Database defects
F. ______ Operational Sequence issues
G. ______ Other: ___________________

16. Did you encounter any of the following types of testbed defects during your use of the testbed? Check all that apply.
A. ______ Incorrect Interface Emulator
B. ______ Simulator Defects
C. ______ Wrong FSW Version in use
D. ______ Inadequate Fidelity of Components
E. ______ Incorrect Database
F. ______ Harness Problem (not flight-like)
G. ______ Other: ___________________

17. How many of your uses could have been performed on an NRT or RT FSW Simulator instead of the System Testbed if they were available in time?

	NRT	RT FSW Simulator
A. Almost All (90%-100%)	______	______
B. Many (>50%)	______	______
C. Some (<50%)	______	______
D. None	______	______

18. How well were your needs of the testbed satisfied during the following periods (0=N/A, 1=Failed to Meet Expectations => 5=Strong Satisfaction)?

	Pre-CDR	CDR-AI&T	AI&T-Launch	Ops
A. Requirements Verification	______	______	______	______
B. FSW Development and Integration	______	______	______	______
C. Anomaly Resolution	______	______	______	______
D. Fault Management/ Off-nominal Testing	______	______	______	______
E. AI&T Test Procedure/ Script Development	______	______	______	______
F. Engineering Test (subsystem, e.g., ADCS, EPS, etc.)	______	______	______	______
G. Ops training/Rehearsals	______	______	______	______
H. Risk reduction	______	______	______	______
I. HW interface compatibility	______	______	______	______
J. Ground Components	______	______	______	______

Interface Tests

K. Other: ________________ ______ ______ ______ ______

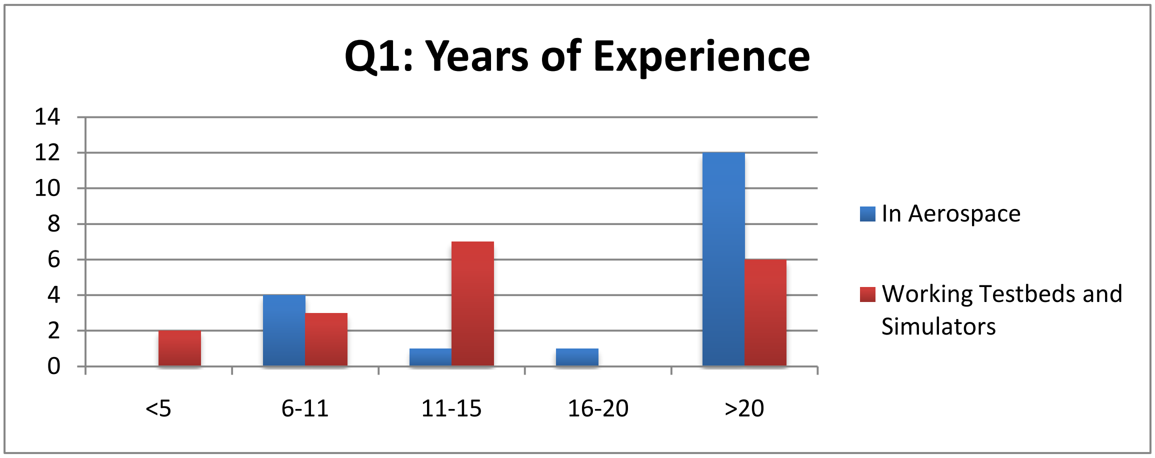
19. What visibility did the testbed have in your program?
    A. _____ High Visibility
    B. _____ Medium Visibility
    C. _____ Low Visibility
    D. _____ Don’t know

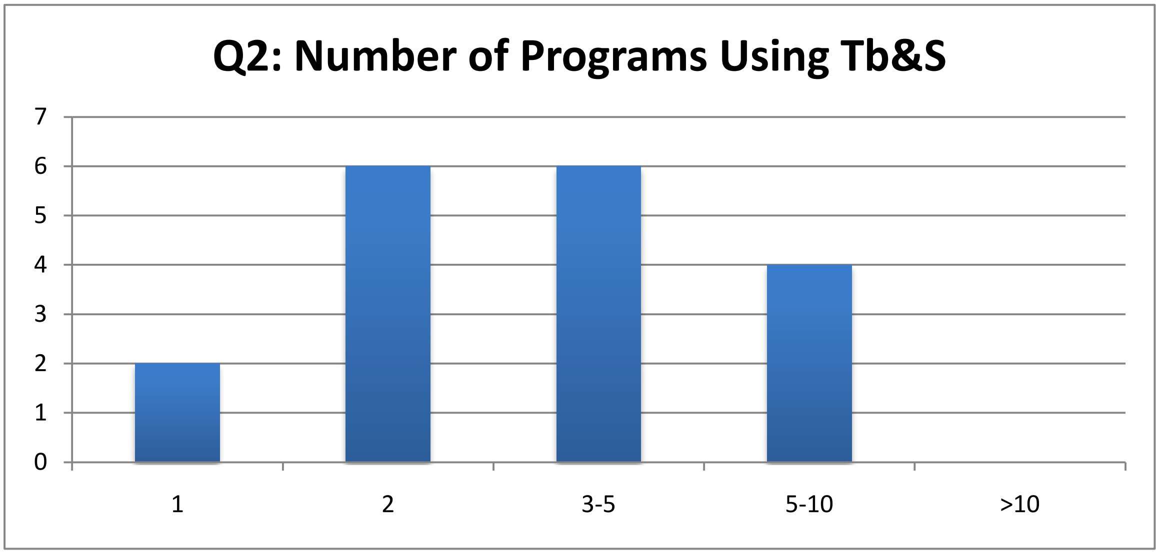
20. Are there specific tools or capabilities that you wish were added to the testbed?

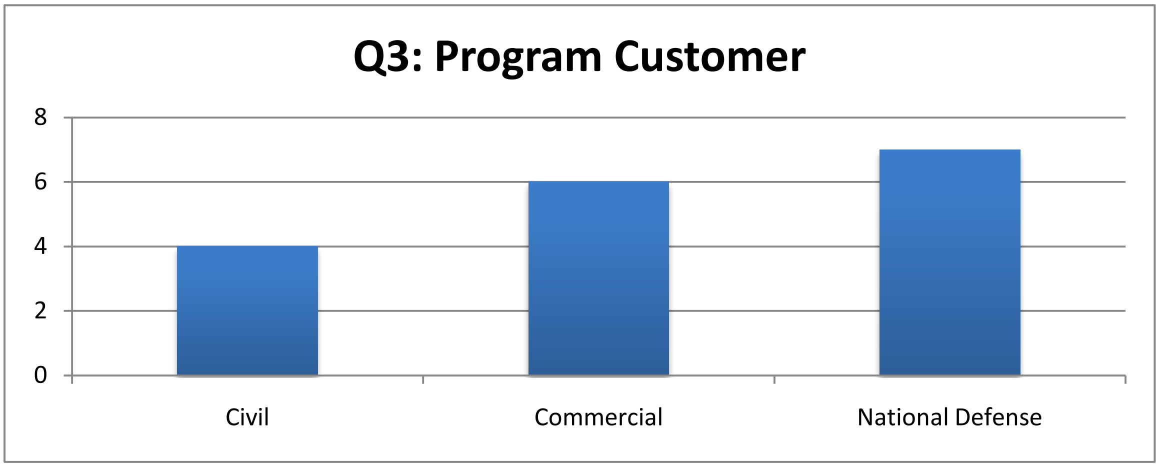
D. General Survey Questions

21. Do you have any lessons learned or comments on how to improve mission assurance for testbeds and simulators?

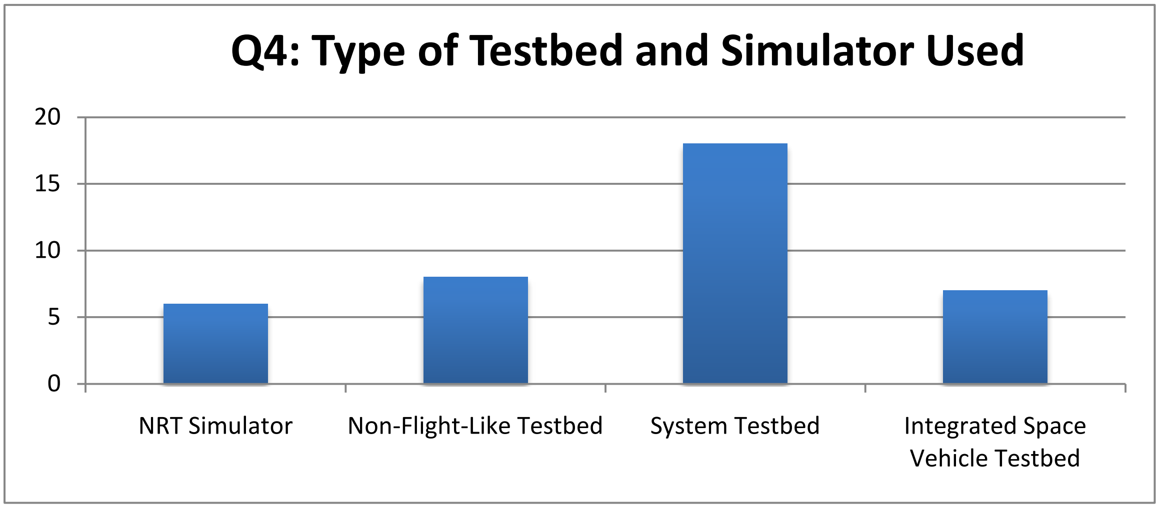
Appendix B2.2: Survey Raw Results for Tb&S Users



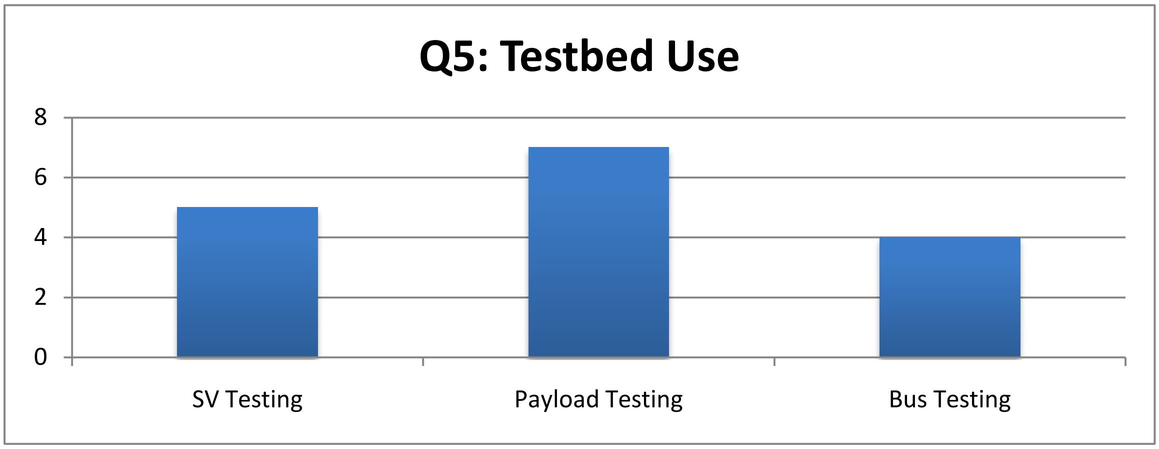




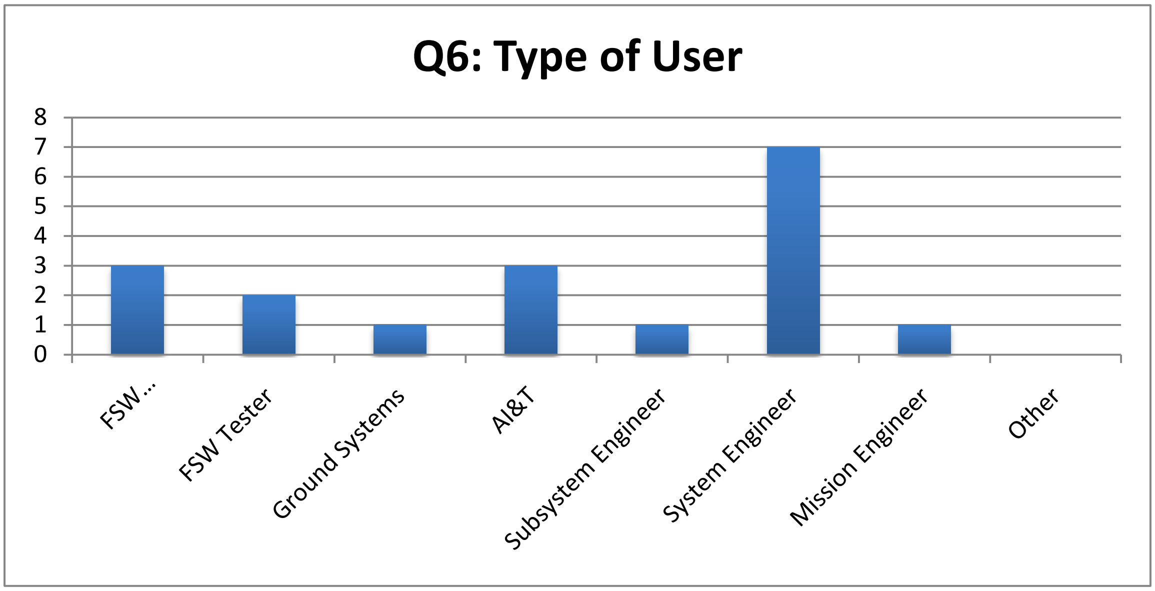
Q3: Program Customer
8
6
4
2
0
Civil
Commercial
National Defense

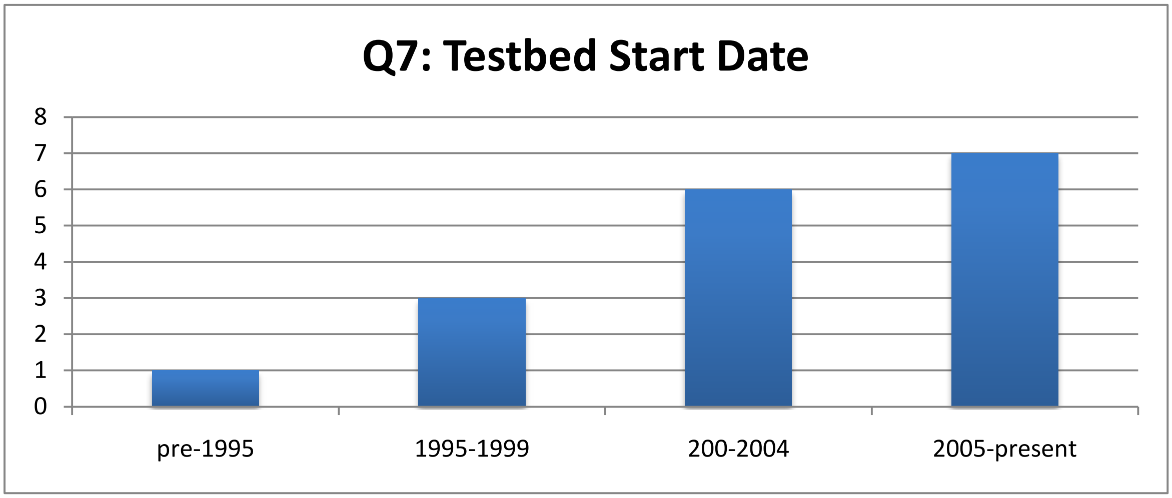


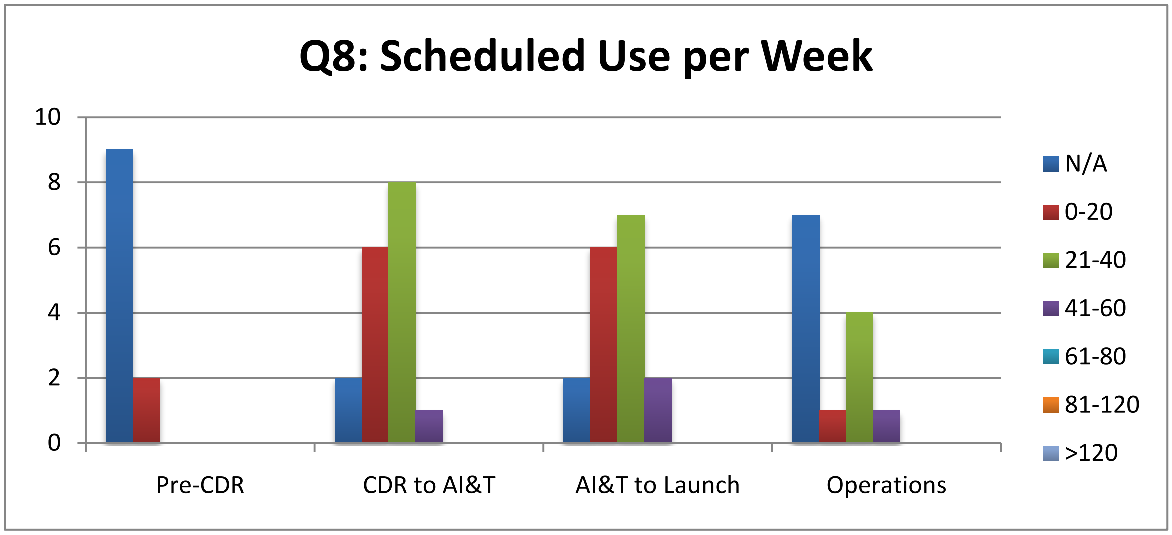
Q4: Type of Testbed and Simulator Used
20
15
10
5
0
NRT Simulator
Non-Flight-Like Testbed
System Testbed
Integrated Space Vehicle Testbed

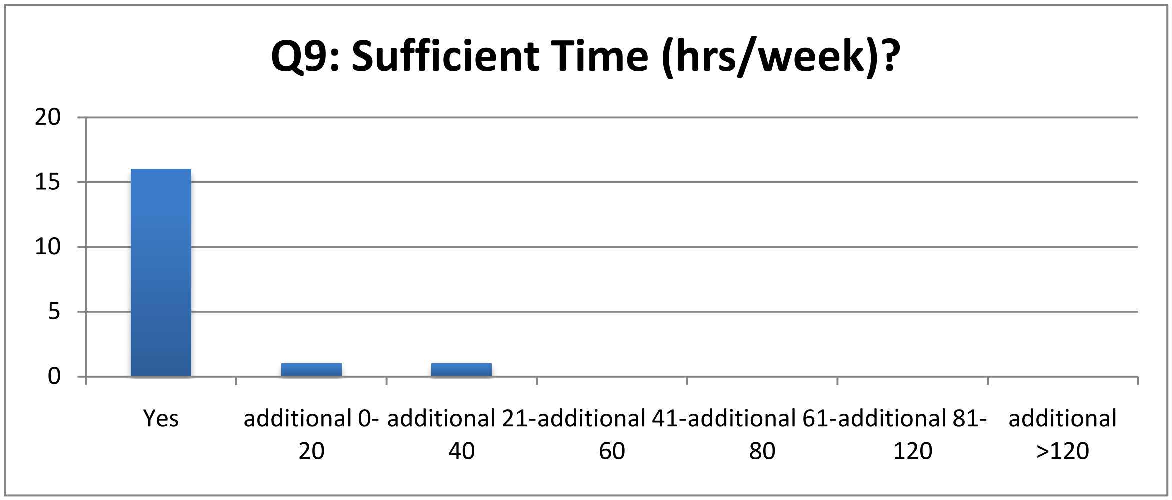


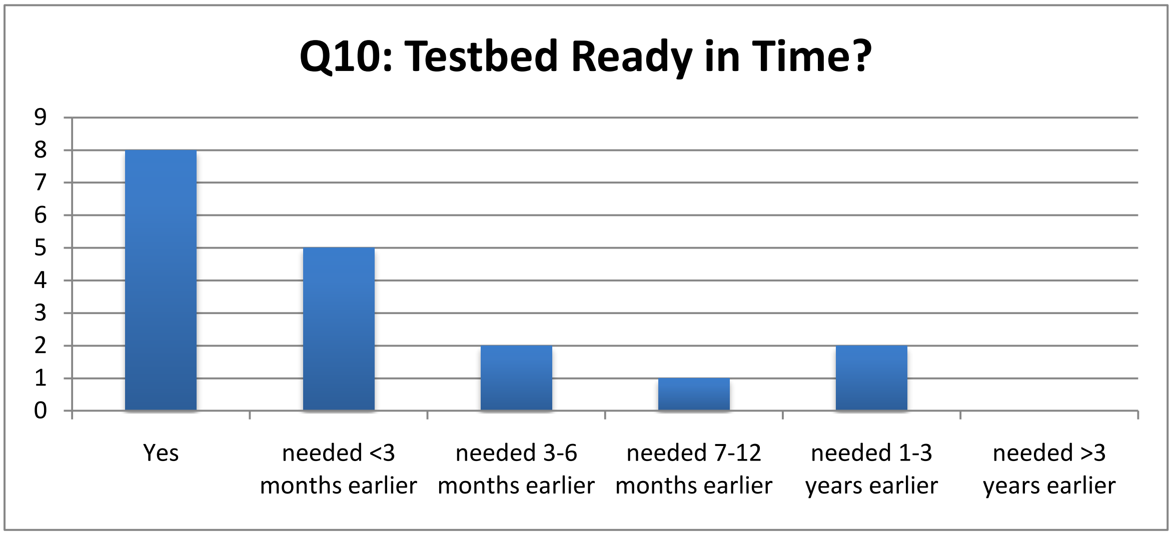
Q5: Testbed Use
8
6
4
2
0
SV Testing
Payload Testing
Bus Testing

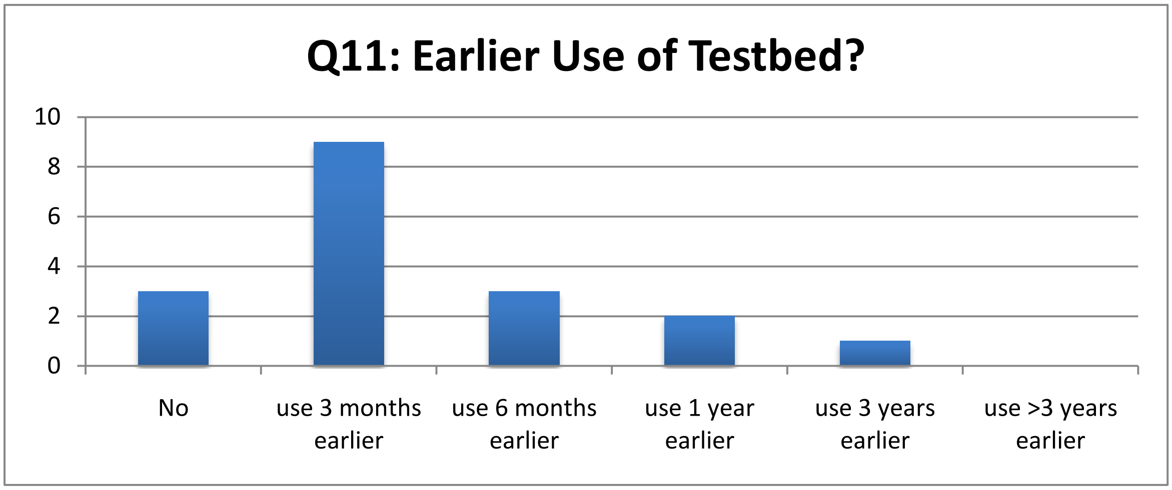

Q6: Type of User
8
7
6
5
4
3
2
1
0
FSW…
FSW Tester
Ground Systems
AI&T
Subsystem Engineer
System Engineer
Mission Engineer
Other

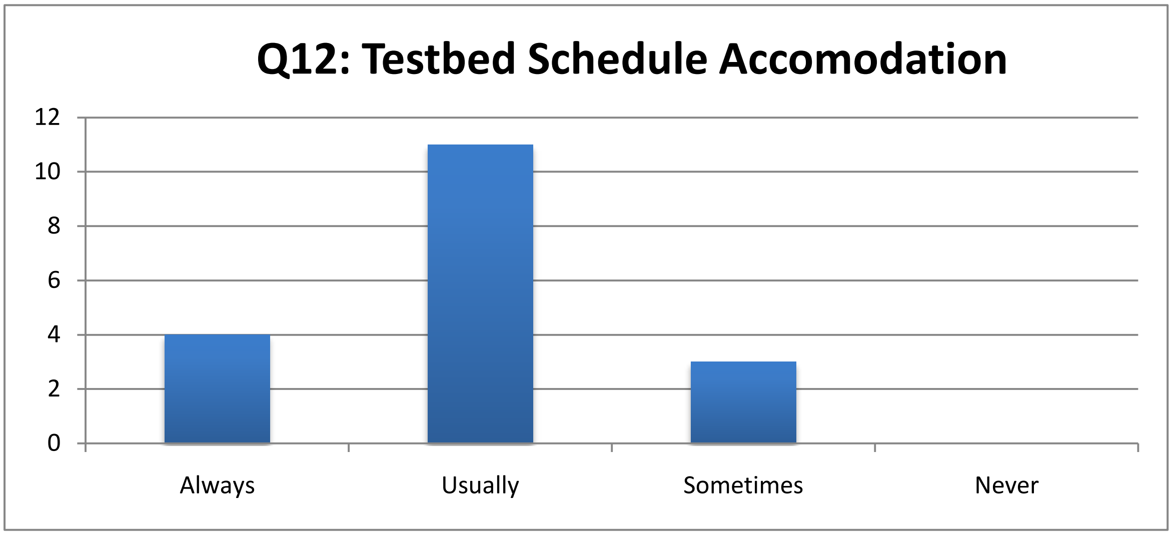

Q7: Testbed Start Date
8
7
6
5
4
3
2
1
0
pre-1995
1995-1999
200-2004
2005-present

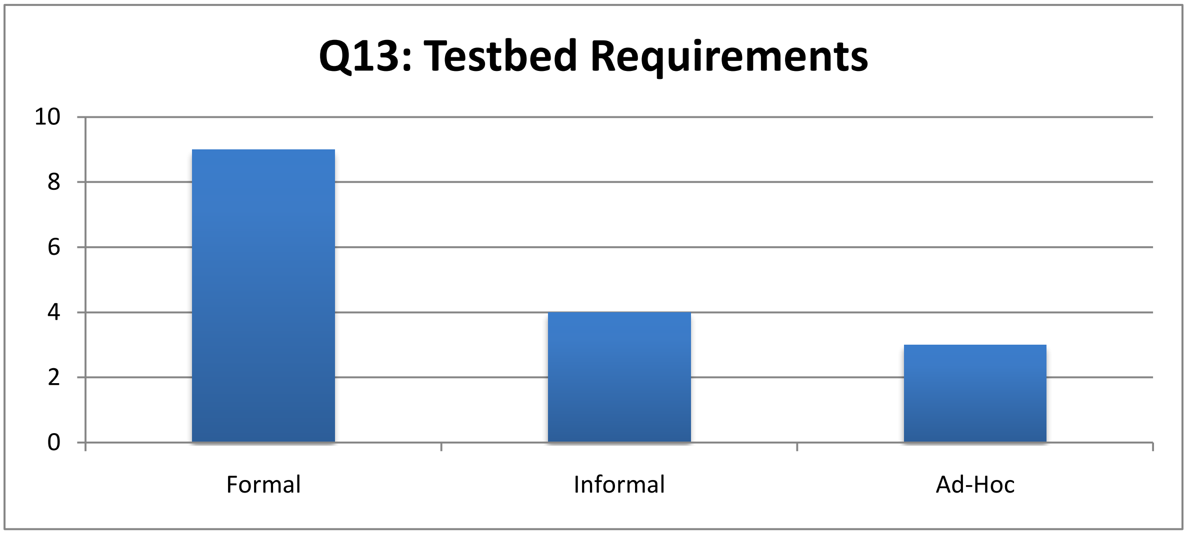

Q8: Scheduled Use per Week
10
8
6
4
2
0
Pre-CDR
CDR to AI&T
AI&T to Launch
Operations
N/A
0-20
21-40
41-60
61-80
81-120
>120

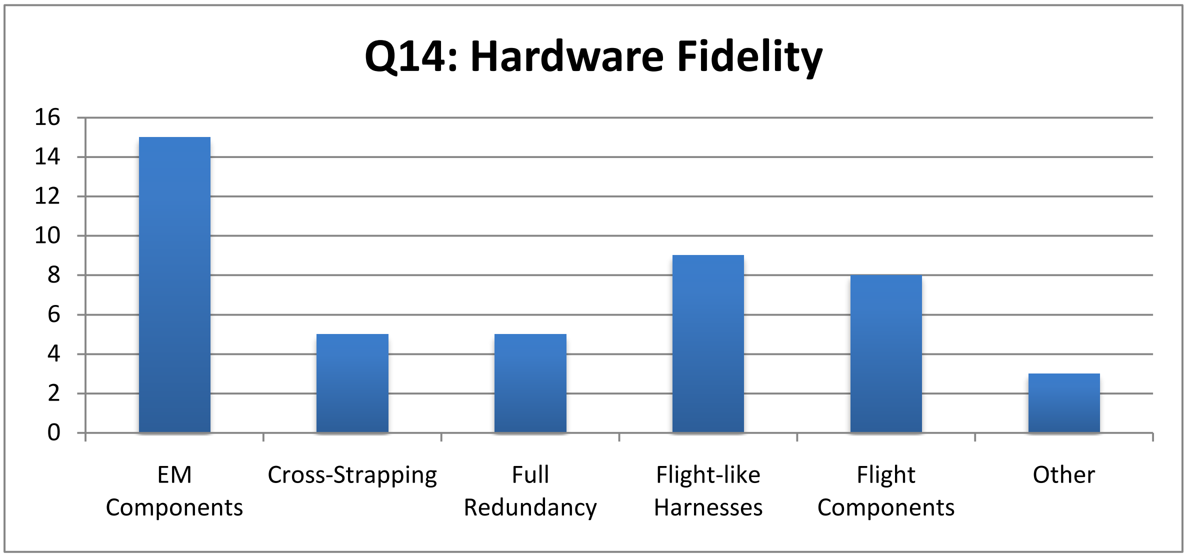

Q9: Sufficient Time (hrs/week)?
20
15
10
5
0
Yes
additional 0-20
additional 21-40
additional 41-60
additional 61-80
additional 81-120
additional >120

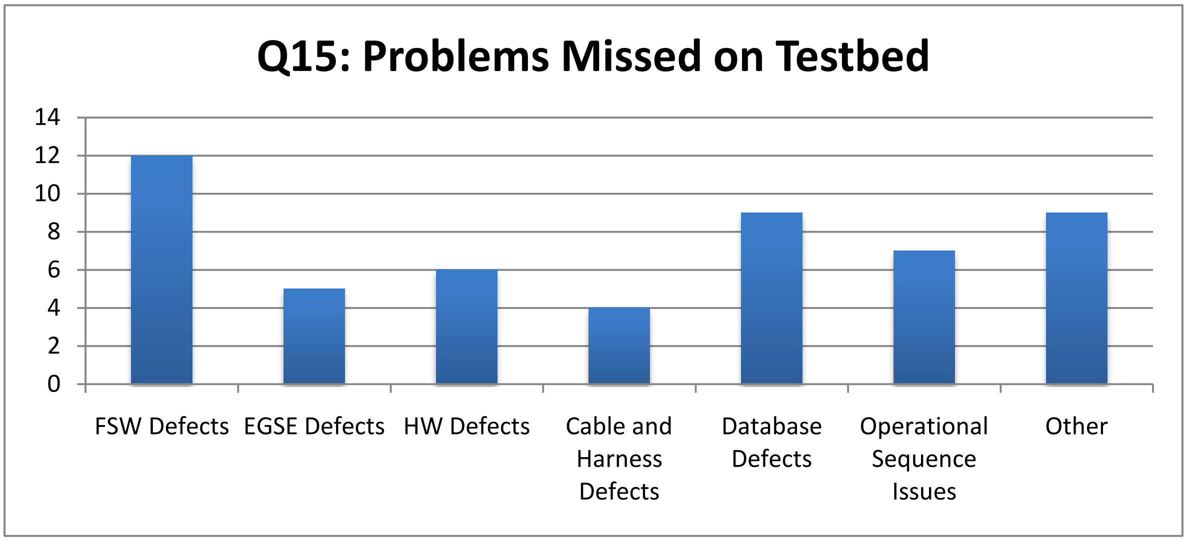

Q10: Testbed Ready in Time?
9
8
7
6
5
4
3
2
1
0
Yes
needed <3 months earlier
needed 3-6 months earlier
needed 7-12 months earlier
needed 1-3 years earlier
needed >3 years earlier

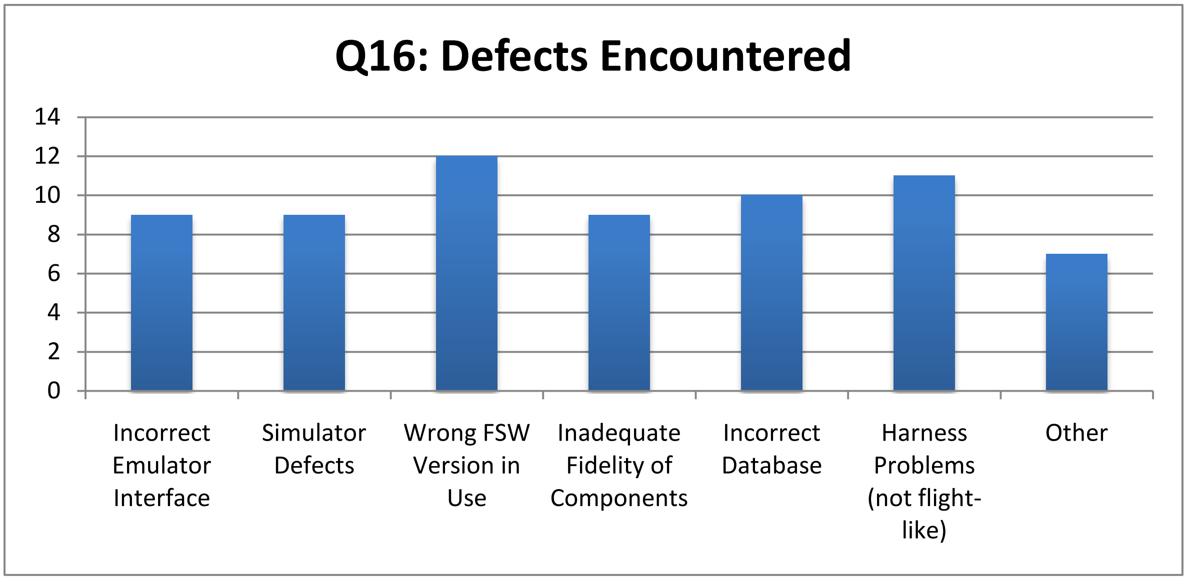

Q11: Earlier Use of Testbed?
10
8
6
4
2
0
No
use 3 months earlier
use 6 months earlier
use 1 year earlier
use 3 years earlier
use >3 years earlier

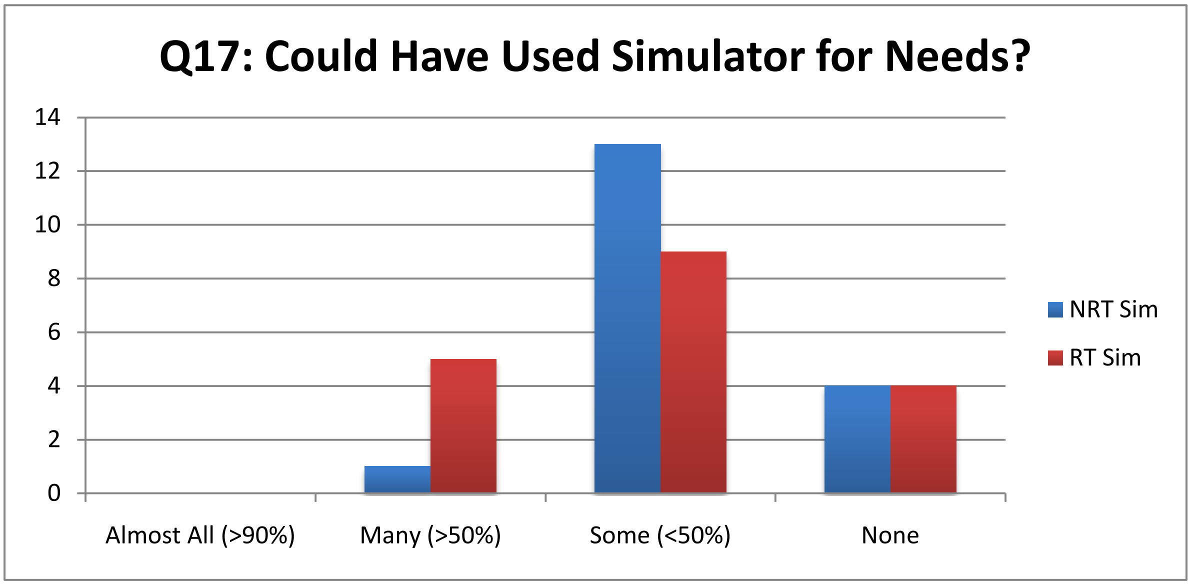

Q12: Testbed Schedule Accomodation
12
10
8
6
4
2
0
Always
Usually
Sometimes
Never

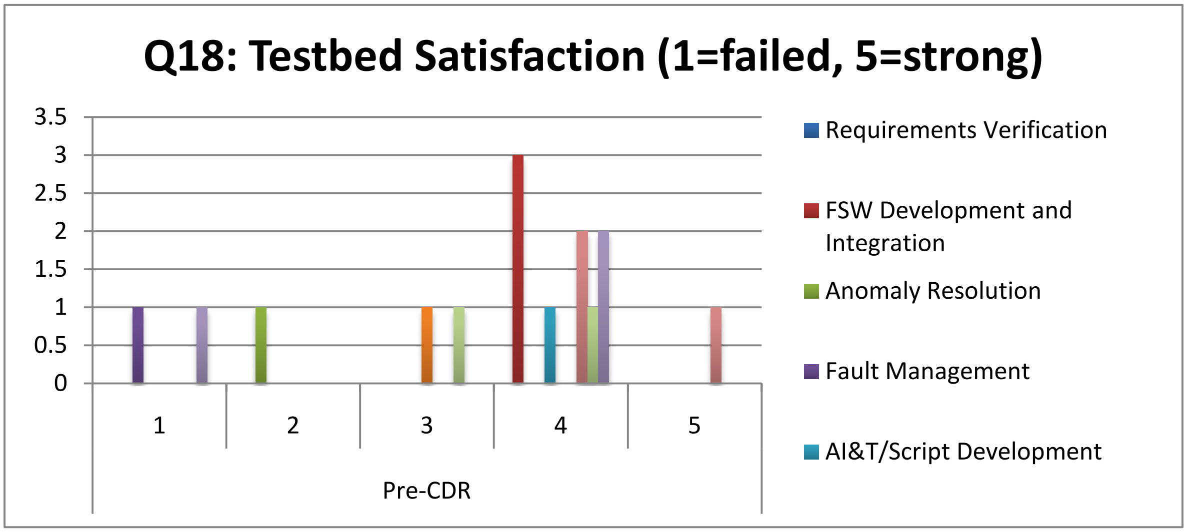

Q13: Testbed Requirements
10
8
6
4
2
0
Formal
Informal
Ad-Hoc

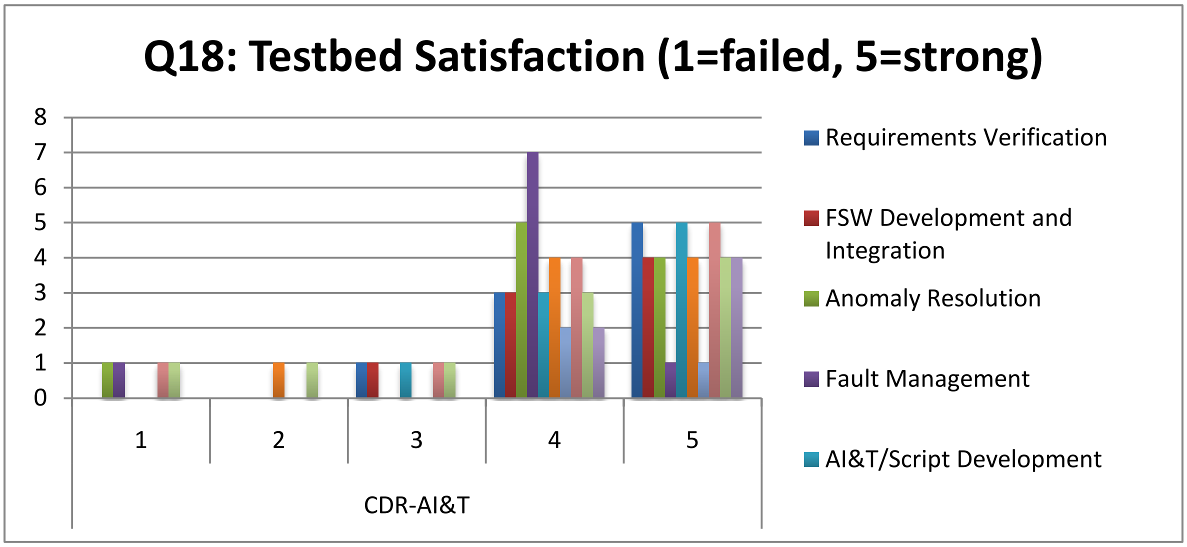

Q14: Hardware Fidelity
16
14
12
10
8
6
4
2
0
EM Components
Cross-Strapping
Full Redundancy
Flight-like Harnesses
Flight Components
Other

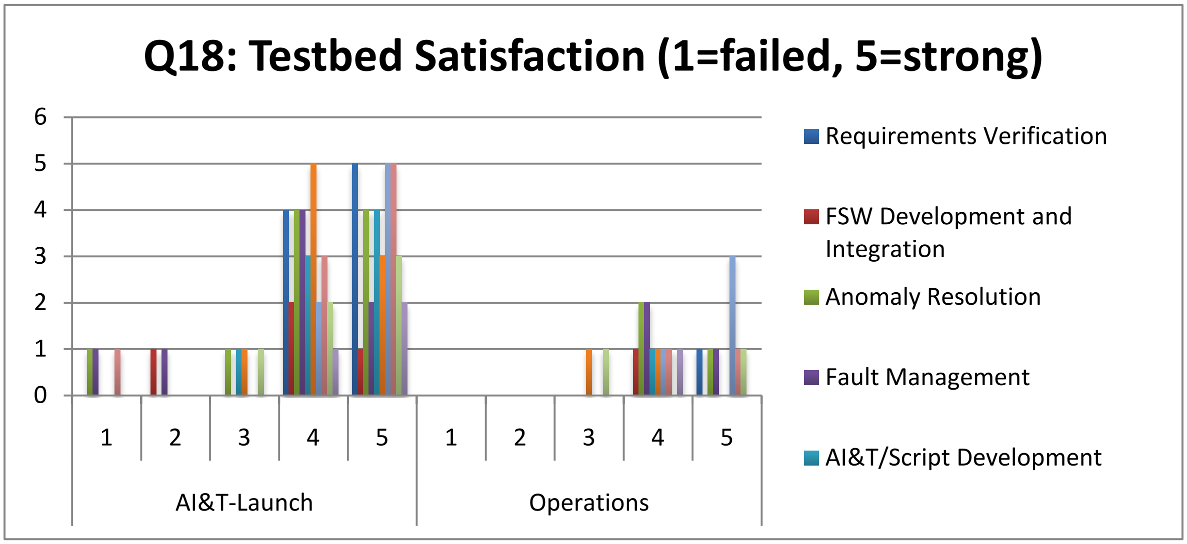

Q15: Problems Missed on Testbed
14
12
10
8
6
4
2
0
FSW Defects
EGSE Defects
HW Defects
Cable and Harness Defects
Database Defects
Operational Sequence Issues
Other

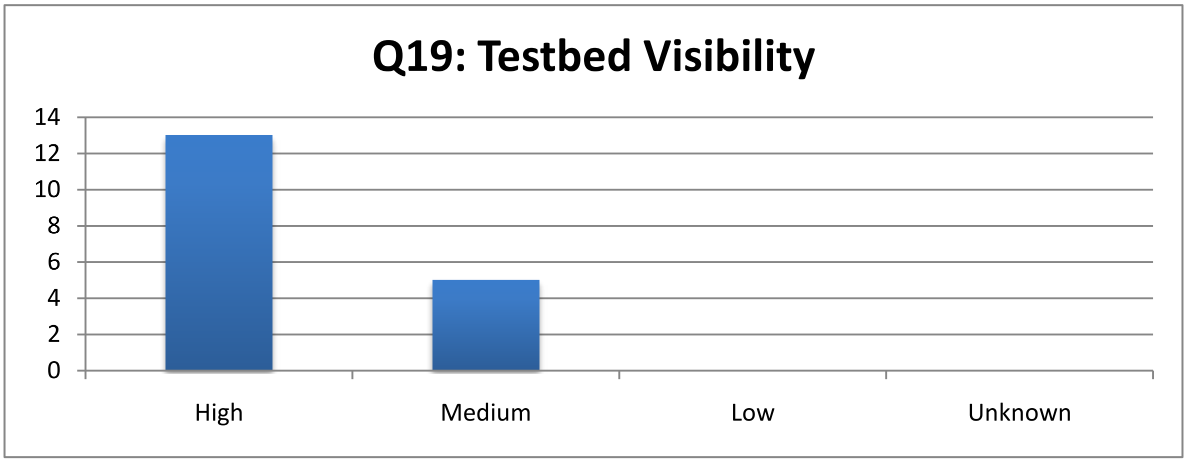

Q16: Defects Encountered
14
12
10
8
6
4
2
0
Incorrect Emulator Interface
Simulator Defects
Wrong FSW Version in Use
Inadequate Fidelity of Components
Incorrect Database
Harness Problems (not flight-like)
Other


Q17: Could Have Used Simulator for Needs?
14
12
10
8
6
4
2
0
Almost All (>90%)
Many (>50%)
Some (<50%)
None
NRT Sim
RT Sim


Q18: Testbed Satisfaction (1=failed, 5=strong)
3.5
3
2.5
2
1.5
1
0.5
0
1
2
3
4
5
Pre-CDR
Requirements Verification
FSW Development and Integration
Anomaly Resolution
Fault Management
AI&T/Script Development


Q18: Testbed Satisfaction (1=failed, 5=strong)
8
7
6
5
4
3
2
1
0
1
2
3
4
5
CDR-AI&T
Requirements Verification
FSW Development and Integration
Anomaly Resolution
Fault Management
AI&T/Script Development


Q18: Testbed Satisfaction (1=failed, 5=strong)
6
5
4
3
2
1
0
1
2
3
4
5
1
2
3
4
5
AI&T-Launch
Operations
Requirements Verification
FSW Development and Integration
Anomaly Resolution
Fault Management
AI&T/Script Development


Q19: Testbed Visibility
14
12
10
8
6
4
2
0
High
Medium
Low
Unknown