The Fleet Ballistic Missile Strategic Weapon System: APL's Efforts for the U.S. Navy's Strategic Deterrent System and the Relevance to Systems Engineering

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This article summarizes how APL has adapted and applied systems engineering practices and principles to a complex weapon system. APL has made significant contributions to the development of the initial and successive generations of the nation's largest nuclear deterrent system, the Fleet Ballistic Missile Strategic Weapon System. APL also has made contributions to the development of technologies that improved the performance of the system and its operation. The ability to contribute meaningfully to the success of this system-of-systems relies on a fundamental understanding of systems engineering activities relevant to each phase of the system life cycle. Representations of this life cycle imply that the results of work performed during prior phases identify the needs and dictate the nature and scope of effort for the ensuing phases. This article principally describes the value of a rigorous testing and evaluation program in identifying needs and defining the nature and scope of future work. Testing efforts produce observations and data and are followed by analyses of those observations and data. Next come assessments of system performance and decisions about how gains in operational performance or capabilities will be achieved. Ways of improving performance range from incorporating relatively simple modifications into operational procedures to developing new technologies or subsystems. This article thus contends that systems engineering activities and ancillary testing and evaluation programs are useful and valuable throughout the entire life cycle of a complex, critical system.

INTRODUCTION

In late 1955, a new U.S. Navy organization, the Special Projects Office (SPO), faced the challenge of developing and fielding an innovative and revolutionary weapon system—a ballistic missile fired from a submerged submarine—within a decade. APL's technical contributions to the Navy's Fleet Ballistic Missile (FBM)

Strategic Weapons System (SWS) commenced soon afterward, in early 1957. APL's contributions continue through the present day, more than 50 years later. The Laboratory's support of the newly formed FBM SWS program was predicated on APL's history of achievements for the Navy's surface fleet. These achievements included the development, testing, and evaluation of guided missile systems that were being fielded in the early and mid-1950s.[1]

The original schedule to deploy this innovative weapon system by the mid-1960s was quickly shortened by several years, with a new deadline of 1960, when Soviet advances in strategic ballistic missiles (also known as nuclear armed ballistic missiles) necessitated that the Navy obtain an operational capability earlier than originally planned. The compressed schedule required that all aspects of this new weapon system be developed and simultaneously tested in such a way that confidence would be established in the system's ability to meet its objectives in the harsh and continually changing environment in which it was intended to operate. The Navy SPO wanted APL to peek into the future, so to speak, by using an orderly testing and evaluation approach to accelerate design and development.[1]

In 1960, less than 5 years after the start of the program, the USS *George Washington* became the first submarine to test-launch a ballistic missile. It was capable of carrying 16 missiles, each armed with a single warhead. In mid-1962, the USS *Ethan Allen* launched a ballistic missile armed with a nuclear warhead that was detonated at the end of flight. To date, this remains the only complete or end-to-end test of the FBM SWS. Today's *Ohio*-class submarines have the ability to carry and deliver 24 missiles, each equipped with multiple independently targeted warheads.[1]

Since the onset of the program, the sole mission of submarines that launch the FBMs (also known as SSBNs and Boomers and referred to hereafter as SSBNs) has been strategic deterrence: in other words, their mission is to dissuade an adversary from using or threatening to use a nuclear weapon. This system, which is truly a system-of-systems, has accomplished its mission since its first deployment. It is stealthy, powerful, accurate, and reliable and, thus, credible enough to inflict damage on potential adversaries to the extent that they see no benefit from using or threatening to use nuclear weapons against the United States.

Figure 1 illustrates the successive generations of the SWS by depicting its evolution relative to the generational advances of its two largest and most prominent subsystems, the missile and the submarine. The first version of the first missile, the Polaris A1, was in service from 1960 to 1965 aboard five submarines. The next version, A2, was deployed in late 1961 and was removed from service in 1974. The A3 version was the first Polaris to have multiple reentry vehicles and was in service from 1964 to 1981. The Poseidon missile was in service from 1971 to 1992 aboard 30 *Lafayette*- and *Benjamin Franklin*-class submarines. The Trident I (C4) was deployed in 1979 and was phased out in the early 2000s. Trident II (D5) has been deployed since 1990 and has been designed for an ~30-year life, or until 2027.

The following section describes APL's efforts to develop and continually improve a testing and evaluation program that is useful to and concurrent with Navy initiatives focused on developing and improving the complex sea-based nuclear deterrent system

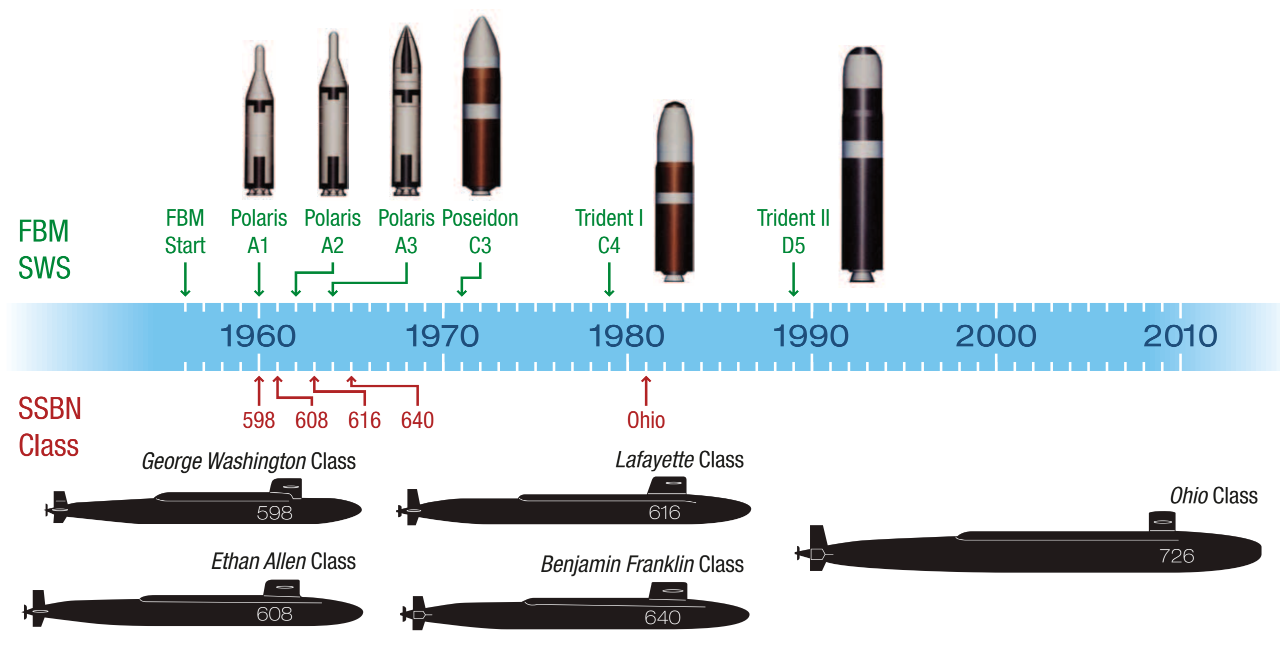


Figure 1. Chronology of introduction of successive generations of missiles and submarines.

known as the FBM SWS. Included is a discussion of the attributes of APL's efforts, how these efforts influenced several generations of FBM SWSs, and how they may have influenced the discipline known as systems engineering.

THE EARLY YEARS

Based on APL's history in supporting the development and testing of missiles defending the Navy's fleet at that time (Talos, Terrier, and Tartar), the Laboratory was requested to provide a group of individuals dedicated to achieving the mission of the SPO.[1] The initial tasking, in addition to providing research and analyses of individual technical issues, was to "assess Fleet Ballistic Missile Weapon System designs, tests and evaluations, devise performance specifications and requirements, test plans and programs, and evaluate and review results of subsystems, components and weapon system tests."[2] The tasking letter continued as follows:

> The primary objective of this work is to provide fundamental understanding of factors and techniques which control or relate to the performance, stability, or utilization of the FBM Weapon System, and to ensure the adequacy and compatibility of design and achievement of necessary performance and evaluation objectives, as well as to insure adequate test and evaluation programs.[2]

This directive established the foundation of APL's systems engineering and testing and evaluation activities for the FBM program. From this initial tasking, APL developed a comprehensive systems evaluation approach that has been applied to six generations of increasingly capable missile systems, from Polaris (A1, A2, and A3) to Poseidon (C3), to Trident I (C4) and Trident II (D5), and to the five generations of submarines that have patrolled the oceans since 1960. Figures 2 and 3 contain technical data and illustrations comparing the different generations of missiles and submarines.

On the basis of SPO's tasking, APL began to develop a comprehensive systems engineering and testing and evaluation program that would provide the Navy sponsors not only assurance of the performance of the weapon system as planned at initial operational deployment but also assurance of the system's performance throughout its operational life.

Because this issue of the *Johns Hopkins APL Technical Digest* focuses on systems engineering, it seems appropriate to look at the state of the art of systems engineering and views of the utility of testing and evaluation during the early days of the FBM SWS program. Fortunately, leaders of the Laboratory at that time published their thoughts on the topic. They left the impression that, although the discipline of systems engineering was considered nascent, it probably greatly contributed to the success of the development, integration, and testing activities of the FBM SWS program.

The director of APL in 1960, Dr. Ralph Gibson, wrote:

> Systems engineering is already being recognized as a branch of the art with problems, methods, and objectives peculiar to itself. It is becoming recognized in the academic world as an association of disciplines, modes of thought and operation, which is worthwhile presenting systematically to the student as preparation for intellectual leadership.[3]

Dr. Richard Kershner, the first head of APL's Polaris Division in 1958 and the first head of the Space Department in 1960, adds "the systems engineer must make use of an empirical approach" (p. 154 in Ref. 4). In his writings, Kershner used missiles and warheads as examples of rapidly developing systems that were complex, integrated assemblies of a large number of diverse

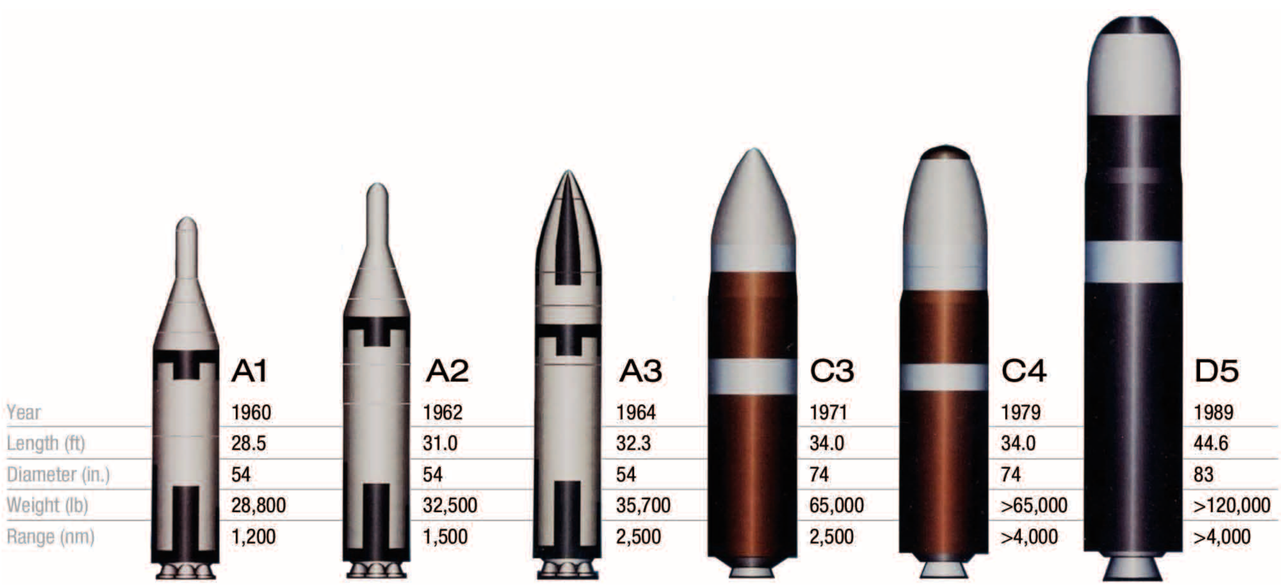
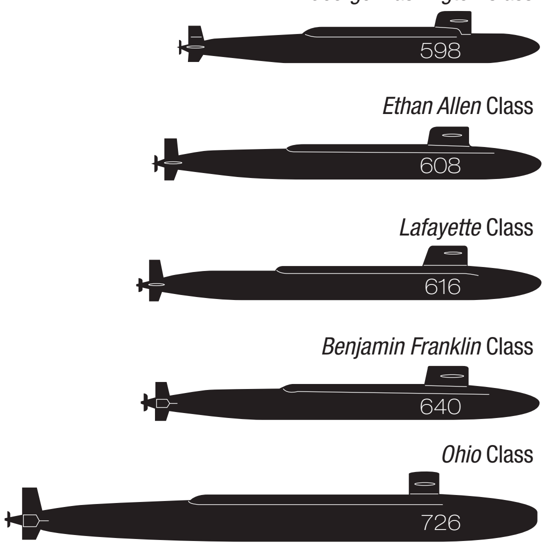


Figure 2. Characteristics of missiles.



	Length (ft)	Beam (ft)	Submerged Displacement (tons)	Propulsion
George Washington Class	382	33	6,700	Steam turbine—water-cooled nuclear reactors
Ethan Allen Class	410	33	7,900	Steam turbine—water-cooled nuclear reactors
Lafayette Class	425	33	8,260	Steam turbine—water-cooled nuclear reactors
Benjamin Franklin Class	425	33	8,250	Steam turbine—water-cooled nuclear reactors
Ohio Class	560	42	18,700	Steam turbine—water-cooled nuclear reactors

Figure 3. Characteristics of submarines.

components. He observed that the speed of development of components usually exceeded that of the larger system. He added that the interaction of the components and performance of the system could not be adequately estimated by equations printed in textbooks, which, by the time they are printed, are historical rather than contemporary or possibly relevant treatises. The validity of equations in textbooks, notes Kershner, is "transitory" (p. 155 in Ref. 4) and, presumably, insufficient for fully understanding or accurately predicting performance of complex assemblages of new technologies.

Kershner's emphasis on an empirical approach was likely influenced by APL's experience with the Talos, Terrier, and Tartar systems and probably was partially driven by an appreciation for the need to incorporate new technologies as late as the production phase of a system. It seems reasonable to assume that those experiences set the stage from which Kershner "conceived the rigorous continuous test protocols of the Fleet Ballistic Missile Programs that are still adhered to today."[5] In addition, Kershner stressed the importance of efforts known as modeling and simulation to systems engineers today by saying: "the simulation technique is, of course, particularly important in the development of those systems which (like atomic bombs or guided missiles) are expended or destroyed in actual operation so that repeated final tests are extremely expensive" (p. 161 in Ref. 4). There was no mention of other factors that constrain or prevent use of an empirical approach. For example, constraints can include safety or environmental hazards that typically accompany demonstrations and tests of such systems while they are completing their missions, bans on atmospheric testing that prohibited detonation of nuclear warheads after 1962, or costs.

Gibson, Kershner, and Dr. Alexander Kossiakoff, then APL's Assistant Director for Technical Operations and eventually the first Chair of The Johns Hopkins University's Systems Engineering Program, seemed convinced that systems engineering was a valuable way of solving problems typically encountered during the evolutionary phases of a new complex system. Yet, none of the three defined exactly when the work of the systems engineer should stop (or, alternately, the point in the life of a system at which systems engineers no longer make significant contributions). One may reason, however, that Kershner and Kossiakoff expected the work of a systems engineer to cease before the deployment phase.

Kossiakoff wrote:

> In systems where the components interact strongly, and particularly where there are environmental factors which cannot be fully assessed prior to the construction and test of the full-scale models, the system engineer must remain in control of the technical program until the final stages of the prototype development or even final production design (p. 88 in Ref. 6).

Kershner reinforced this notion by saying "it is fair to say that the development program is complete when the actual flights and the simulations agree in performance" (p. 161 in Ref. 4). Kossiakoff noted that "the solution to this problem is to make explicit provisions for incorporating engineering changes or modifications or new technology after the start of production. In this way the equipment can be kept modern in an orderly manner without risks" (p. 114 in Ref. 4).

However, we must consider that, in 1960, there were few, if any, 50-year-old weapons or systems. New system development programs quickly emerged from innovative and promising concepts or technologies. For example, Kershner followed his work on Talos with concepts for an advanced guidance and control system. The system performed so well that the Navy immediately placed it into production, naming it Terrier. Problems with mass production of Terrier led Kershner and Kossiakoff to propose and develop a new concept for missile construction. It revolved around compartmentalizing a missile into standalone subsystems that could be tested before integration. The system that followed was the Tartar missile system.[5]

Although there is consensus that the discipline of systems engineering is useful during the design, development, and production phases of new complex systems, there does not appear to be accord on when it is no longer useful. It seems plausible that Gibson, Kershner, and Kossiakoff were so busy generating novel concepts and starting new developments that they did not have time to ponder when systems engineers could no longer make meaningful contributions. Thus, the continuing FBM SWS testing and evaluation program may be an appropriate paradigm for describing the nature and value of the work performed by systems engineers throughout the life of a system, particularly those with a deployment longevity of 30–50 years. Today there are aircraft such as the B-52 and the U-2 that are more than 50 years old and *Ohio*-class submarines that are nearing 30 years old. The Boeing B-52 Stratofortress is a long-range, subsonic, jet-powered strategic bomber that has been operated by the U.S. Air Force since 1955. The Lockheed U-2 is a single-engine, very-high-altitude reconnaissance aircraft operated by the Air Force and previously used by the Central Intelligence Agency. Its first flight was in August 1955. The U-2 is used today for electronic sensor research, satellite calibration, and data-validation missions, all of which are outside its original purview. These systems proved amenable to improvements or adaptable to new missions presumably because of effective systems engineering programs that included comprehensive testing and evaluation activities.

APL'S APPROACH TO EVALUATION AND TESTING OF FBM SWS

Figure 4 depicts the basic approach to evaluation and testing of the FBM system; APL developed and implemented this approach starting with the USS *George Washington* and the Polaris A1. Each of its major elements was established and implemented in the initial testing and evaluation program for the Polaris FBM weapon system that was developed by APL and known as the "Technical and Operational Test Program." It is delineated in APL Report POR-1A,[7] published in February 1959. Figure 4 has commonly been referred to as the "circle diagram." Although neither revolutionary nor circular, it establishes a very logical approach to ensuring that the important elements in any evaluation and testing effort address fundamental elements

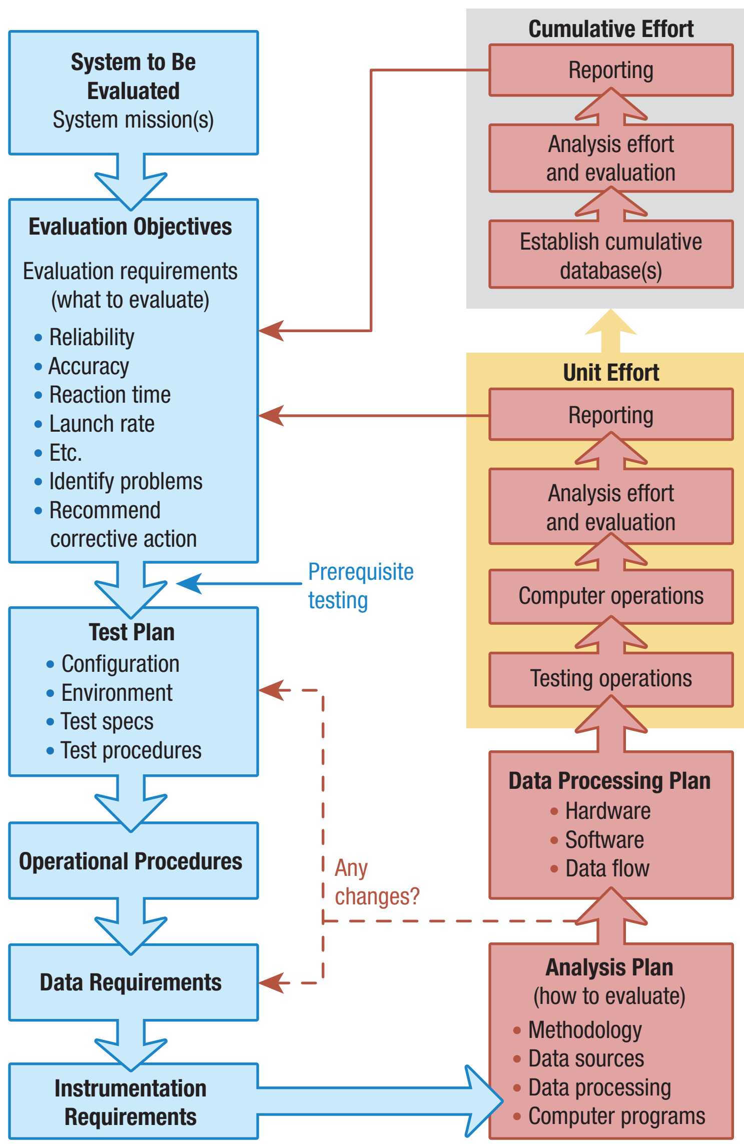


Figure 4. System evaluation diagram.

in a methodical manner and that any shortcomings are resolved and improvements are implemented into the activity. In the following sections, we discuss the attributes depicted in Fig. 4.

Defining what system and missions will be evaluated is primary to developing an appropriate evaluation and testing effort. After substantiating these definitions, the evaluation objectives need to be clearly established, and evaluation requirements—what to evaluate—need to be clearly stated. After identification of these fundamental attributes, testing plans and analysis plans need to be developed. These activities identify the needed data and the means to obtain the data, thereby identifying and implementing needed instrumentation or data collection efforts. These activities could even lead to the development and implementation of tests to gather the needed information. The actual evaluations of discrete events, such as a missile launch, and the cumulative evaluation of several tests provide the information required to determine whether the evaluation objectives are being met. Important to the ongoing success of this approach are the feedback paths (dotted lines) shown in Fig. 4.

This system evaluation diagram has served as the basis for APL's system testing and evaluation approach for every generation of the FBM weapon system. It has helped identify new tests for the weapon systems as new capabilities or requirements have been incorporated into next-generation weapon systems. For example, the introduction of navigation accuracy tests for the Trident II weapon system was identified and developed as a new test with the introduction of a new subsystem to the navigation system, the navigation sonar system. Tests that would provide an operationally representative environment were not achievable with the tests that existed for the FBM system when the highly accurate Trident II weapons system was introduced. APL devised a test, to be conducted during an operational patrol, that would gather the necessary information. APL staff's familiarity with the operational environment enabled them to develop a test that would meet with approval of the operational Navy staff and would obtain the information that APL and the Navy's Strategic Systems Programs (SSP) needed to properly assess system performance.

Many attributes of this diagram can be mapped into the more general, and often used, systems engineering activity cycle (or "loop"), depicted in Fig. 5. The various phases shown in Fig. 5, in their application to APL's FBM system efforts, have been predominantly directed at testing and evaluation and not at design and development. The similarity of the activities depicted in Figs. 4 and 5, as they apply to evaluation efforts for the FBM system, reinforces the validity of the original testing and evaluation regime that APL established for the FBM program in 1959.

APL'S CONTINUING SYSTEM EVALUATION OF THE FBM SWS

One of the most critical elements of the FBM SWS evaluation is the testing and evaluation activity that

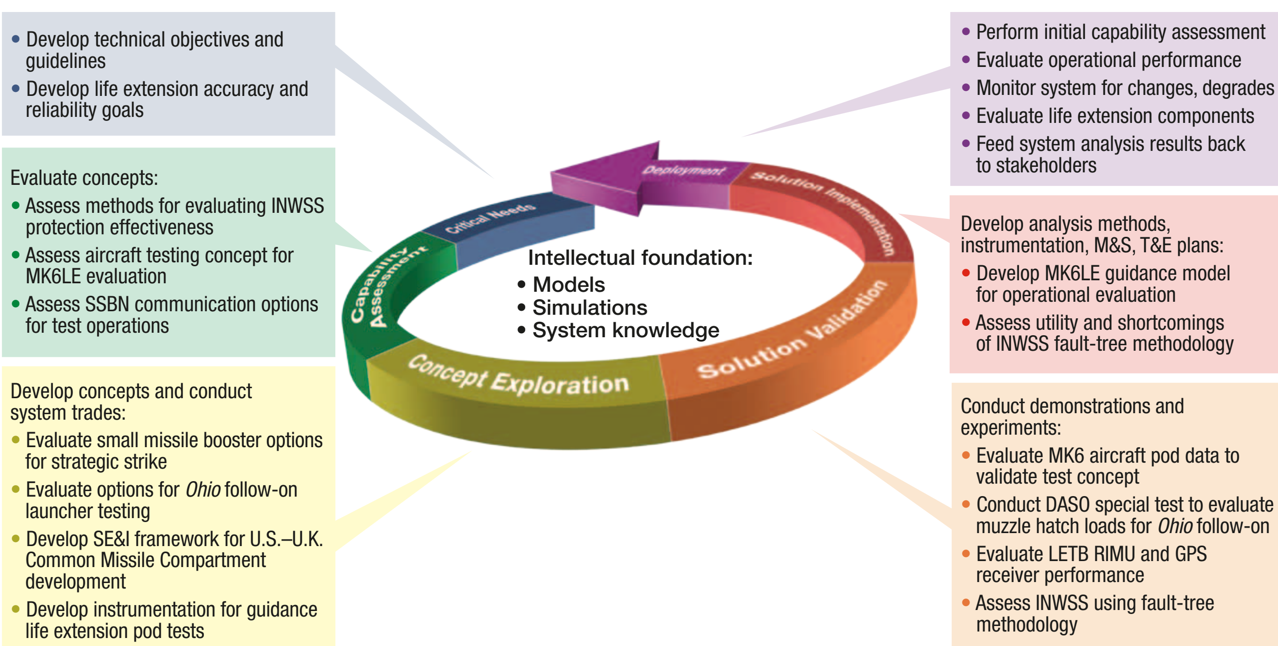


Figure 5. FBM systems engineering cycle of activity. INWSS, integrated nuclear weapons security system; LETB RIMU, life extension test bed reentry inertial measurement unit; MK6LE, MK6 life extension; M&S, modeling and simulation; SE&I, system engineering and integration; T&E, testing and integration.

continues throughout the weapon system's deployed life. The system continues to be assessed beyond the traditional initial and follow-on operational testing and evaluation efforts that are the purview of the service operational test authority ending shortly after deployment of the system. This continuing assessment is mandated by the DoD for all strategic nuclear weapon systems. Traditional operational testing and evaluation is focused on operational requirements, mission effectiveness, and user suitability. The subject being examined during operational testing and evaluation is usually a preproduction version of the system.[8] These continuing assessments use a methodology that provides confidence bounds on the performance estimates specified, which gives assurance to SSP, the operational Navy, and strategic planners at U.S. Strategic Command (USSTRATCOM) that the FBM weapon system is performing as reported.

Summarized in Fig. 6 are the major elements of weapon system testing and evaluation that APL has conducted for every generation of FBM systems. This testing and evaluation activity is primarily associated with the deployment, or final, phase of the systems engineering cycle. The attributes of these tests are conceived and developed during earlier phases of the cycle but are implemented during the deployment phase. The cumulative effect of the work through the various phases of the cycle, from the beginning to today, is the knowledge acquired during system development and operations in a sea-based environment, as noted in the center of Fig. 5. This knowledge is the primary contributor to the attributes of the continuing testing elements depicted in Fig. 6. A significant amount of that knowledge has been captured and validated in models and simulations, enabling not only a better understanding of the performance of the FBM SWS but also a way to describe operations and performance in engineering terms, to specify requirements for the future, and to develop appropriate evaluation tests.

In the following bullets, we describe each of the elements of the evaluation and testing approach (depicted in Fig. 6), some of the attributes of each, and how each element complements the overall continuing testing regime.

- **Demonstration and Shakedown Operation.** This first element in the testing and evaluation approach is a series of tests referred to as a Demonstration and Shakedown Operation (DASO). These tests are conducted by the crew and use operational procedures in a manner that duplicates deployed operations, but the tests are monitored by contractors, SSP naval staff, and APL staff. These tests assess the readiness of the unit for operational deployment.

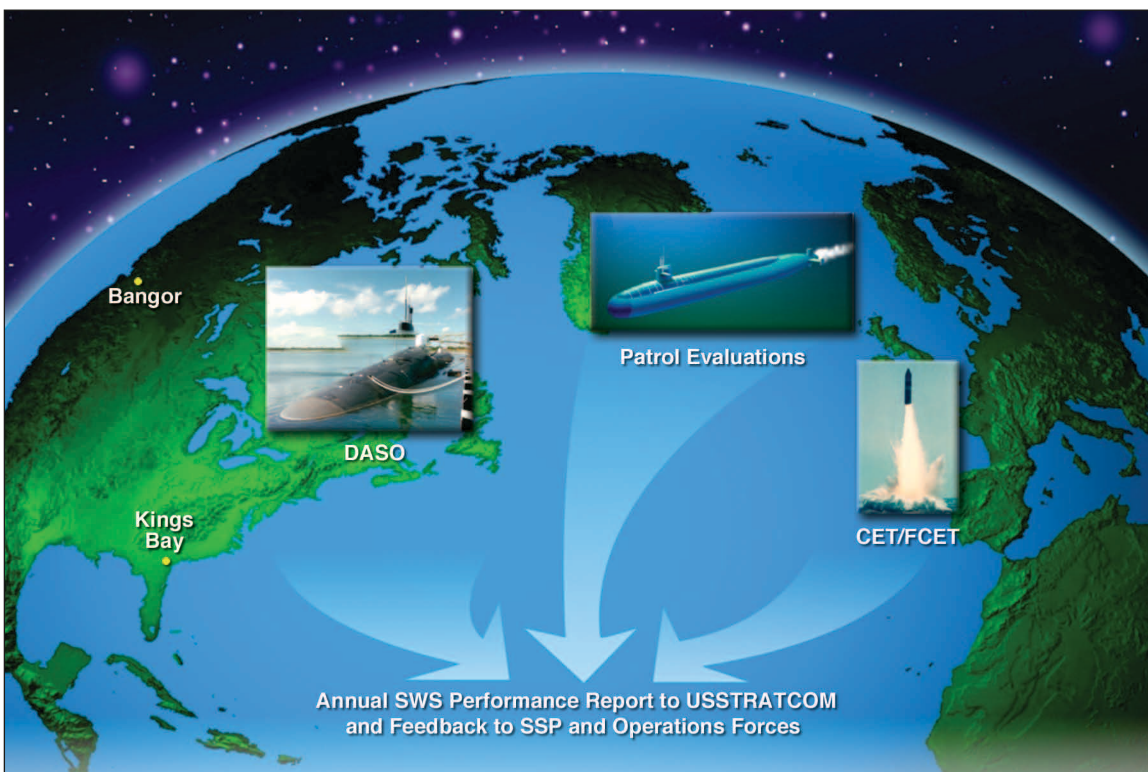


Figure 6. Testing elements of FBM continuing evaluation and testing program. FCET, Follow-on Commander-in-Chief Evaluation Test.

- **Patrol Evaluation.** This second element of the testing activity involves a series of instrumented weapon system and subsystem tests that are conducted on all operational deterrent patrols of every SSBN as part of the day-to-day operations of the weapon system. These testing activities provide the information for a continuing assessment of the performance of the weapon system on each SSBN in its operational environment.

- **Operational Tests.** Finally, the third element is the series of system evaluation tests known as operational tests [now called Commander's Evaluation Tests (CETs) to distinguish them from the operational tests identified as part of initial and follow-on operational testing and evaluation]. These tests are conducted annually throughout the life of the FBM weapon system and provide the most realistic end-to-end test of the operational performance of the system. They generally involve two or three SSBNs annually. An SSBN on patrol is selected, unbeknownst to the crew, before commencement of the tests. Missiles from that SSBN's complement of missiles are then randomly chosen for flight testing and are configured with instrumentation. The subject SSBN resumes a patrol posture in a designated launch area. At a random time, a launch message is sent via tactical systems and procedures, and the crew follows tactical procedures and launches the designated missiles.

This complement of test evolutions, developed by APL at the outset of the Navy's FBM program in the 1960s, has provided the basis for the successful system evaluation and testing effort that APL has conducted for the FBM program for more than 50 years.

Central to the success of APL's system evaluation and testing activity for the FBM program and SSP has been the access to and interactions among all organizations responsible for the performance of the FBM systems: SSP, APL, the weapon system contractors, the operational Navy, and strategic planners. Figure 7 depicts APL's relationships with these organizations; as can be seen, APL system evaluation results go to SSP technical staff and their associated contractors; patrol evaluations are provided to the operational Navy, staffs, and crews [Commander, U.S. Fleet Submarine Force (COMSUBFOR)/Commander, Submarine Force, U.S. Pacific Fleet (COMSUBPAC)]. Finally, estimates of weapon system performance are provided by APL annually, independent of SSP concurrence, to the SSBN operational naval staff and, through them, to USSTRATCOM. Table 1 identifies the focus areas of and metrics available to the various cognizant organizations.

Each of the organizations with which APL interacts in its systems testing and evaluation activities is responsible for unique contributions to the overall FBM system operations, contributing to system success, as follows:

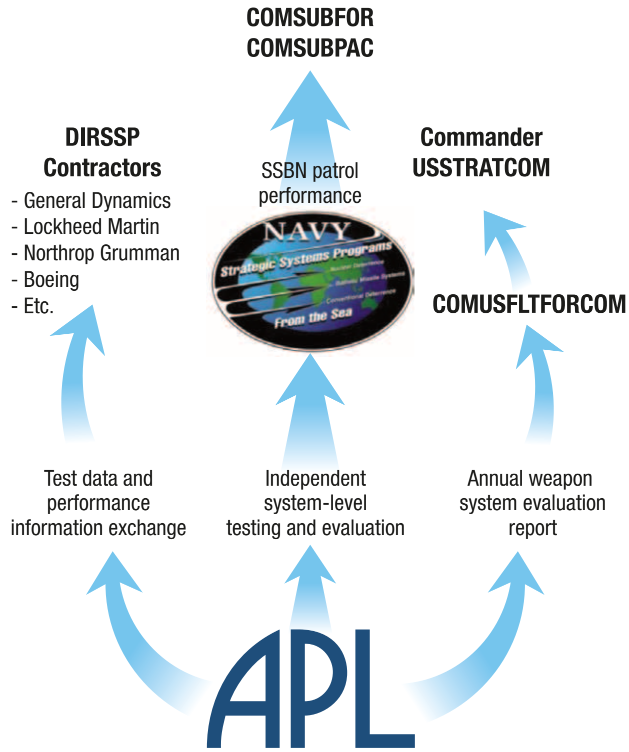


Figure 7. Submarine-launched ballistic missile SWS evaluation organizational relationships. DIRSSP, Director, SSP.

- COMSUBFOR manages the human and materiel resources that enable submarines to patrol the Atlantic, Arctic, Eastern Pacific, and Indian oceans and the Mediterranean Sea. The principal responsibility of the Commander, Submarine Force, U.S. Atlantic Fleet (COMSUBLANT) is to operate, maintain, and equip submarines in support of fleet and national tasking, reporting directly to the Commander, U.S. Fleet Forces Command (COMUSFLTFORCOM).

- COMSUBLANT operates and maintains six FBM submarines, which are based in Kings Bay, Georgia.

- COMSUBPAC reports to the Commander, U.S. Pacific Fleet. COMSUBPAC operates and maintains eight FBM submarines, which are based in Bangor, Washington.

- COMSUBFOR and COMSUBPAC provide the training, logistical plans, and in-service engineering development necessary to assure the readiness of the submarine forces to respond to both peacetime and wartime demands.

- There are three major contractors for the FBM SWS. General Dynamics Electric Boat Division is the builder of the 560-ft-long SSBN. General Dynamics

Table 1. Weapon system performance data provided annually by APL: communities of interest, areas of interest, and metrics.

Audience	Interest/Focus Areas	Metrics
Acquisition community (SSP, contractors)	Contract requirements, incentives	Technical objectives and guidelines specifications, ship installation testing program, test results, readiness
Operational commanders (SSP, COMSUBFOR)	Operability, maintainability, repairability, proficiency/training	Failure rates, mean time between failures, mean time to repair, readiness
Force planners (COMSUBFOR, USSTRATCOM)	Weapon effectiveness, availability, responsiveness	Reliability, accuracy, timeliness, survivability

is also the contractor for the fire-control system. Lockheed Martin Corporation is the contractor for the Trident II (D5) ballistic missile, a three-stage solid-propellant rocket weighing 130,000 lb with a range of more than 4000 nautical miles. Northrop Grumman Corporation is the contractor for the missile launcher. These three major contractors, under the direction of the SSP technical staff, also are responsible for engineering tasks such as configuration management, subsystem qualification, interface design and control, and other engineering management processes critical to fielding and maintaining the missile, launcher, and fire-control subsystems.

- Since its creation in 1992, USSTRATCOM has been the DoD's combatant command for the nation's strategic nuclear forces, independent of political boundaries. Commander, Task Force 144, COMSUBFOR, and Commander, Task Force 134, COMSUBPAC, are operational commanders to USSTRATCOM for strategic deterrent submarine operations. In the years since its creation, USSTRATCOM has been assigned additional missions. Its tasks expanded from its core responsibility for the strategic nuclear missions to responsibilities that now include seven additional missions: space operations; global strike; global intelligence, surveillance, and reconnaissance; missile defense; information operations; global network operations; and combating weapons of mass destruction.[9]

VALUE OF APL'S SYSTEM TESTING AND EVALUATION WORK

At this point, a reasonable question may be the following: how effective, or how valuable to the operational Navy and USSSTRATCOM, has APL's work been? Figure 8 illustrates the major events and the sequence in which they occur after the decision to launch a Trident II (D5) missile. The effectiveness of the Navy's strategic command, control, and communications system in delivering emergency action messages to an SSBN is the purview of two additional testing and evaluation programs executed by APL: the Strategic Communications Assessment Program (SCAP) and FBM Continuing Communications Evaluation Program (CEP). SCAP and CEP are complementary to the FBM SWS testing and evaluation, which is directed toward assessing the area in the figure labeled "Weapon System Reliability."

Although it does not specifically cite the FBM SWS continuing testing and evaluation program, the *Report of the Secretary of Defense Task Force on DoD Nuclear Weapons Management*[9] offers an answer to the question posed in the previous paragraph.

The report affirms the worth of several APL programs "essential to the credibility of the sea-based nuclear deterrence": CEP, SCAP, and the SSBN Security Technology Program.[9] CEP and SCAP are managed by APL's Applied Information Sciences Department, and the SSBN Security Technology Program is managed by the National Security Technology Department. The Global Engagement Department (GED) manages the FBM SWS continuing testing and evaluation program. Clearly, APL's contributions via testing and evaluation of several facets of the FBM SWS remain a significant factor in maintaining its high level of readiness and exceptional performance. While discussing the report during a news conference, the chair of the task force, the Honorable James Schlesinger, stated with respect to its nuclear deterrence mission: "We were quite pleased, generally, with the Navy's performance." In addition, Schlesinger noted the "high morale" of the Navy crews.[10]

UTILITY OF APL'S TESTING AND EVALUATION APPROACH TO THE SYSTEMS ENGINEERING DISCIPLINE

The specific impact collectively of APL's continuing testing and evaluation programs during the deployment phase assure that the FBM SWS remains an effective

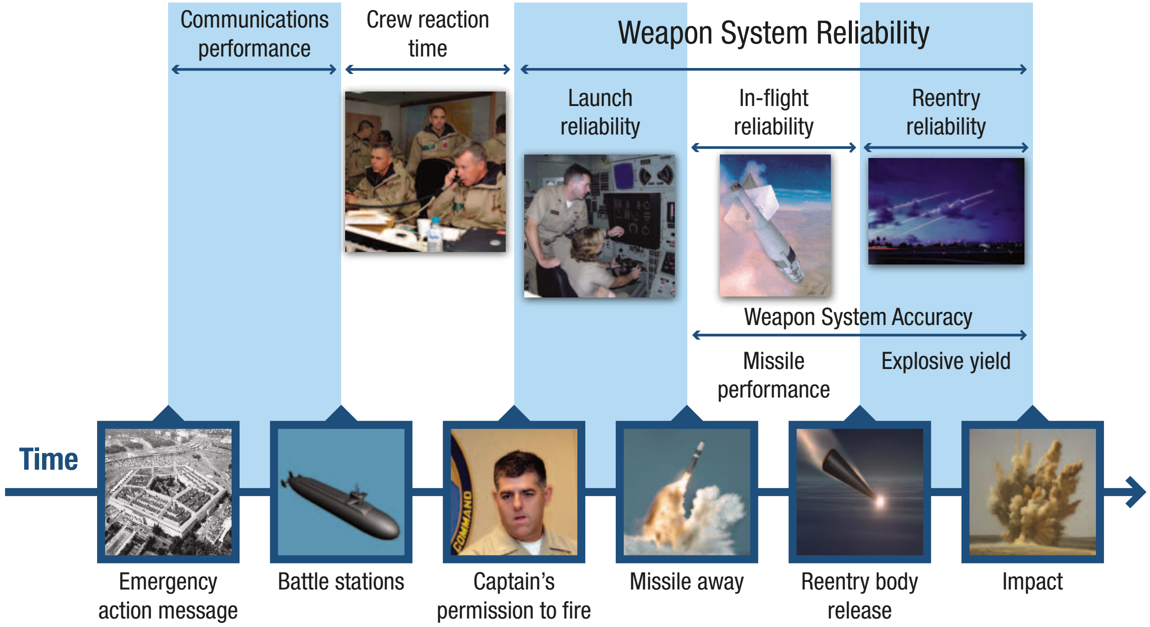


Figure 8. Factors relevant to annual performance evaluation and planning, programming, and budgeting.

deterrent. Each program generally conforms to a similar methodology, one that is also used by another discipline known as value engineering: Usage data are collected and analyzed to determine the root cause of any problems encountered. After a risk assessment of alternative solutions is conducted, corrective actions are formulated.

The methodology is broadly applicable. It applies to just about any project needing data, although the ways of collecting and analyzing data can vary. Success is measured by the extent to which the data and the results of the analyses are useful to achieving the specific objectives of the assessment project. APL's continuing testing and evaluation programs collect data primarily by using instruments during planned tests, and then by using sophisticated models and simulations to analyze the data.

The methodology is useful for the following reasons:

> In [the deployment] phase, systems engineering processes support in-service reviews; trade studies; and decisions made about modifications, upgrades, and future increments of the system. Interoperability or technology improvements, parts or manufacturing obsolescence, aging issues, premature failures, changes in fuel or lubricants, joint or service commonality, and so on, may all indicate the need for system upgrade. . . . After a system or item is fielded, changes are often expensive to implement. However, large potential savings to operations, maintenance, and other logistics functions might justify an investment. The development, evaluation, and implementation of such changes lie within the overall systems engineering process.[11]

Value engineering is an organized and systematic approach directed at analyzing the function of systems, services, and supplies for the purpose of achieving their essential functions at the lowest life-cycle cost consistent with required performance, reliability, quality, and safety.[11]

There is a relationship between value engineering and systems engineering.[11] The DoD recognizes value engineering as a systems engineering tool that is useful for making decisions about greater economy in developing, acquiring, operating, and supporting the products necessary to achieve its mission.[11] A systems engineer manages a set of requirements and perhaps engineering architectures and designs for the value engineer to reference while conducting risk assessments and trades among system performance, risk, cost, and schedule. With this, we can now infer that system engineers can make significant contributions in all phases of a program.

We have thus far presented examples of how data acquired via tests and analyzed during all phases lead to improvements in performance and operations and also lead to defining the critical needs for the next generation of system or subsystem capabilities. Next, we will provide examples of how the continuing testing and evaluation program transitioned to systems engineering activities that produced new systems.

SYSTEM TESTING AND EVALUATION: A SEGUE INTO DESIGN, DEVELOPMENT, AND INTEGRATION ACTIVITIES

APL activities in testing and evaluating the SWS are broad in terms of the type of work and the objective. Beyond those activities already mentioned, add the following to the list: assessing range safety issues; identifying data and instrumentation requirements; developing instrumentation; defining and refining analysis methodologies; improving the information technology infrastructure critical to data acquisition, protection, analysis, and dissemination; scripting test procedures; and designing and improving physics-based models critical to test data analysis.[12]

At the inception of the FBM program, APL conducted many specific studies and engineering investigations for SPO (now SSP). These involved reviews of the Polaris guidance electronics packaging approach, staging and warhead separation concepts, submarine vulnerability, missile shipboard safety, and conceptual design of a launch tube quenching system. However, the studies, the engineering investigations, and even the very comprehensive and decades-spanning continuing testing and evaluation program are considered mere ingredients, albeit critical ingredients, of the systems engineering process rather than systems engineering per se. Referencing the systems engineering diagram shown in Fig. 5, one can see where these FBM activities fit into different phases, and in some cases multiple phases, of the systems engineering process.

For example, each activity relies on one or more activities recognized as necessary in the systems engineering process but does not always deliver a system per se. A system or engineered product typically is viewed as the result of a progression of work that includes design, development, integration, and developmental and sometimes operational testing and evaluation activities—that is, the full spectrum of work commonly associated with the systems engineering process (p. 11 in Ref. 8).

Nevertheless, APL's work has generated engineered products containing diverse components and advanced technologies that could rightfully be considered systems, or maybe more accurately stated, advanced prototypes of systems. For each of those products, APL's scope of work fit the commonly accepted notion of systems engineering for the early and intermediate stages of development—critical needs through solution validation as identified in the APL representation of the process. The final stages of the systems engineering process, production (also known as solution implementation in the APL circle) and deployment, were typically completed by contractors of the government. In the case of the FBM weapon systems, the deployment phase is now where APL is and has been most heavily involved, by executing a continuing system testing and evaluation program that identifies possible performance issues and solutions for resolution by the government and its contractors.

The FBM systems testing and evaluation program has been a catalyst for the following FBM-related systems engineering initiatives by APL:

- Development of a prototype Polaris A1 reentry system nose-fairing eject mechanism that was later adopted by Lockheed Martin Corporation[12]
- The concept of satellite navigation, which then led to the Transit satellite navigation system[12]
- Invention of a novel thrust vector control, maximizing the range capability of the Polaris A1 and A2 missiles[12]
- Theoretical and experimental research to explain the mechanism of unstable burning of solid rocket propellants, which led to the development of engineering tools needed to design and build solid-propellant rocket motors[12]
- The conceptual exploration and solution validation of the SATRACK system, which enabled the accuracy error measurements for the FBM SWS[13]
- Development of the mathematical approach to the evaluation and development of the instrumentation to acquire the needed data for accuracy evaluation of the Trident II D5 SWS. The instrumentation was a device known as a Global Positioning System (GPS) translator; later derivatives of this translator were designed and built to support reentry body (RB) evaluations as the need to define the accuracy contributors to reentry flight became more critical. Translators to support these tests were much smaller, because they had to fit into the small space on an RB.[14,15]
- Development of a multimedia simulation-based training tool with which students can practice driving a virtual submarine while responding to problem scenarios. It has improved the effectiveness, timeliness, and scope of training while reducing the cost.[16]
- Range safety requirements mandate that a reentry impact area instrumentation ship, the Navy Mobile Instrumentation System (NMIS), be stationed at a point over the horizon from the RB impact location. This requirement means that the NMIS cannot collect telemetry and GPS translator data at impact. APL designed, developed, and tested a prototype recording system mounted in a buoy that successfully collected data from the RB upon impact and transmitted the data to the NMIS.[17]

FUTURE SCOPE OF WORK FOR THE FBM SWS PROGRAM

APL's systems engineering and testing and evaluation activities for the FBM program have primarily occurred near the deployment phase and after deployment with continuing system evaluations. For the FBM programs, APL has had limited involvement in the predeployment systems engineering and evaluation activities depicted in Fig. 5. Principally, APL involvement in predeployment activities has been to define testing instrumentation and tests needed to assess defined weapon system performance requirements. In some cases this has required the development of new instrumentation and data collection capabilities. In all cases, APL strove to make the instrumentation as unobtrusive as possible.

The other activities depicted in Fig. 5 have not been a principal effort for the FBM weapon systems to date. However, in recent years, as the experience level for system development has receded within SSP's group of long-term contractors working on FBM, and with the long interval from the development and deployment of Trident II (circa 1990) to the next development (late 2010s), SSP has requested that APL become more involved in the earlier phases of the systems engineering process. Because of APL's continuing evaluation of the operational FBM system, its staff provides a unique perspective to any future weapon system developments. As the Navy and SSP commence planning for the follow-on Sea-Based Strategic Deterrent and its submarine platform, APL staff are actively engaged in several concept and development activities to a much greater degree than with previous FBM systems. These activities are built on the basic intellectual foundation of APL's system knowledge that is derived from the continuing system evaluation described in earlier paragraphs.

In general, the systems engineering challenges facing APL can be derived from the SSP mission statement: provide credible and affordable strategic solutions to the warfighter. This statement, which is a combination of objectives for value engineering and systems engineering initiatives, is augmented by the following:

- Provide technology; design, development, production, and operational support; and retirement services to the fleet
- Be credible to the extent of meeting requirements for missions and warfighting effectiveness and assuring reliable and supportable operations for long terms
- Be affordable with respect to cost effectiveness across the entire life cycle
- Be strategic, which now means ensuring timely and accurate delivery of conventional as well as nuclear warheads
- Find solutions for several problems ranging from articulating novel concepts through producing weapons systems
- Support the warfighter, meaning the sailor, resource sponsor, combatant command, and Navy Program Manager[18]

The entire FBM SWS, as well as each subsystem, is undeniably large and complex. The definition and management of the interactions of the subsystems with each another and with the operating environment are a vital function of systems engineering.[6] Hence, APL, with its intellectual foundation consisting of knowledge of both systems engineering practices and principles and FBM SWS design and operational details, can significantly contribute to the process of defining and managing future interactions and interfaces.

The major systems in this system-of-systems are changing again. For example, Lockheed Martin Corporation began work in 2007 to extend the life expectancy of the Trident II (D5) missiles from 30 to 45 years. The effort, known as the D5 Life Extension Program, includes upgrading the missile's guidance, missile electronics, and reentry systems.

The first *Ohio*-class SSBNs are expected to begin retiring in 2029. This means that replacements must be ready by 2029. Those modified must support the Trident II (D5) missile until at least 2042. The Navy is investigating two replacement options. The first is a variant of the *Virginia*-class nuclear attack submarine (SSN). The second is an SSBN that either has a different hull or is a derivative of the *Ohio* class.

The tasks of designing and developing valid solutions and integrating and evaluating components, new or modified, is always complex and difficult and requires the best efforts of expert technical teams operating under systems engineering leadership.[6] Test planning should start as new concepts are formulated. Testing plans should become more detailed as the design of the concept matures. Systems engineering has the responsibility for defining testing requirements and evaluation criteria and shares the responsibility for test planning and test engineering with the developer of the new or modified component.[6] The nature of APL's work will likely change in one of three ways: (*i*) the Laboratory will modify the continuing testing and evaluation program, (*ii*) it will become the Navy's most objective systems engineer for the solution validation and solution implementation phases, and/or (*iii*) it will become more involved in development testing and traditional operational testing and evaluation.

BEYOND THE FBM SWS: AMERICA'S NEW GLOBAL STRIKE CAPABILITIES

Events of the past 20 years have presented contemporary technical challenges to APL. Some of those challenges have already surfaced and are being confronted, some are emerging and approaches for addressing them are being devised, and some are yet unknown. Just about all of them have roots in one or more of the following:

- The Cold War competition with the former Soviet Union is over, and with it the need (perceived or otherwise) to match or exceed the quantity and quality of Soviet weaponry no longer exists.

- The rise of transnational terrorism has introduced new dangers, diminishing the usefulness of nuclear weapons to deter terrorist attacks or effectively retaliate after they occur.
- Advances in technology, especially in satellite-aided guidance, make it possible to target conventional weapons with greater accuracy, making use of nuclear weapons less attractive politically and economically.
- The number of nations with nuclear weapons is increasing.

The implementation of a comprehensive testing and evaluation approach for the several generations of the operational FBM SWS has resulted in providing high-confidence performance estimates for the operational forces. This has enabled the Navy and strategic nuclear leadership to use the FBM SWS confidently, because they know how the system will perform, with defined confidence levels, under expected operational conditions. The Navy's confidence in this approach, particularly the confidence of the operational Navy, led to the development and implementation of a similar operational evaluation for the SSGN Attack Weapon System. The principles and approaches established for the FBM weapon systems have been applied to the SSGN Attack Weapon System; activities have included initial system testing and evaluation of a predeployment activity similar to the FBM-type DASO, followed by evaluations of the operational deployments of the SSGN. The types of testing and the data collected have been tailored to the evaluation requirements, in accordance with the system evaluation diagram shown in Fig. 4.

The SSGN gives the Navy an unprecedented capability to accomplish tactical strike and Special Operations Forces missions from a stealthy platform in America's global war on terrorism (now known as Overseas Contingency Operations). There are four SSGNs. Each is capable of carrying up to 154 Tomahawk or Tactical Tomahawk land-attack cruise missiles, each has communications capabilities appropriate for its missions, and each can carry up to 66 Special Operations Forces personnel and their equipment. APL's selection for operational evaluation of the SSGN was the result of its long-term experience with testing and evaluation of the FBM weapons systems as well as with decades of systems engineering experience with the Tomahawk missile system.

The National Research Council's Committee on Conventional Prompt Global Strike (CPGS) Capability developed a set of scenarios with which to assess the feasibility and merits of CPGS. The scenarios, for example, included the need to disable a ballistic missile launcher poised to send a nuclear weapon to the United States or an ally, an opportunity to strike a gathering of terrorists leaders or a shipment of weapons of mass destruction during a brief period of vulnerability (i.e., minutes or hours), and the ability to disrupt an adversary's command and control capability as an *a priori* condition of a broader combat operation.[19] The committee concluded that a high-confidence CPGS capability would be useful and that assessments of concepts and development should begin immediately.

APL's GED is currently engaged in early systems engineering activities evaluating CPGS concepts, including a hypersonic cruise missile and a mission planning system. APL staff has been engaged in early trade-off and concept evaluations of interest to the DoD, the Defense Advanced Research Projects Agency, the U.S. Air Force, and USSTRATCOM. The experience gained from the comprehensive evaluations of the FBM systems and the methods that have made them successful are being applied to the CPGS. The experience and methods are particularly useful in identifying topics in need of investigation, as well as data and instrumentation requirements for observations and tests, as development progresses—that is, an empirical approach. As efforts to mature concepts advance through development phases to operational deployment, APL staff members are likely to be called upon to provide concurrent evaluations to assess progress and readiness for deployment.

CONCLUSIONS

Testing and evaluation is an integral part of systems engineering activities, regardless of the phase of development or the maturity of a system; this is particularly true for a system large enough and complex enough to be considered a system-of-systems. Thoughtfully designed testing efforts enable observations and produce data that, when analyzed, facilitate decisions on how best to improve performance or capability. A comprehensive testing and evaluation program contributes significantly to the decision-making process as well as to subsequent system engineering activities. It can define solutions to problems and enable engineering changes or modifications during and after the start of production and throughout deployment. In this way, to restate the words of Dr. Kossiakoff, the system can be kept modern in an orderly manner.

Strategic systems testing and evaluation is one of the eight core competencies of APL and served as a critical resource to the Navy as it developed several generations of the FBM SWS. Today, the GED has a strategic relationship with the Navy because it possesses the characteristics associated with an independent and objective testing and evaluation organization as well as, more generally, those traits associated with a university-affiliated research center:

- Comprehensive knowledge of FBM SWS requirements and problems
- Current operational experience
- Independence and objectivity
- Freedom from real or perceived conflicts of interest

Opportunities exist for the GED to expand its system-level testing and evaluation programs for its current strategic partner, SSP, as well as for new sponsors. As with past accomplishments, the current systems engineering challenge is to discover opportunities to design and develop totally new systems through the prototype stage as opposed to testing and evaluating and then integrating systems engineered by other organizations. Regardless, the principal focus is assuring the success of a deterrent or strike system in accomplishing its operational mission and in meeting its requirements and development objectives throughout a long operating life.

The utility of a continuing testing and evaluation program lies in improving performance of existing systems and identifying needs and requirements for entirely new systems, new components, or new technologies. Such a program has enabled APL to look beyond the obvious to truly understand the problems and the conditions that influence the problems. In this regard, there is sufficient evidence to contend that in any phase of the life cycle of a system, a systems engineer can make contributions that either improve performance or lay the foundation for a next-generation system.

Critical to the effectiveness and productivity of the next-generation systems engineering activities is the capability of a testing and evaluation program to collect and analyze meaningful data.

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