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LEARNING FROM EXPERIENCE

VOLUME III

Lessons from the United Kingdom's *Astute* Submarine Program

Prepared for the United Kingdom's Ministry of Defence

Approved for public release; distribution unlimited

RAND NATIONAL DEFENSE RESEARCH INSTITUTE

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Preface

Large, complex design and construction programs demand personnel with unique skills and capabilities supplemented with practical experiences in their areas of expertise. This is especially true in designing and constructing nuclear-powered submarines. These vessels require that unique engineer and designer skills be nurtured and sustained and that program managers at all levels be trained and educated so as to create the pool of knowledge and experience to conduct a successful program.[1] In the past, key technical and management personnel in the submarine community were nurtured and sustained by numerous sequential design and acquisition programs. By participating in one or more programs, personnel gained experience to be the leaders in future programs.

But as the operational lives of submarines have lengthened and as defense budgets in most nations have been constrained, new submarine programs are occurring less frequently. Today, there are substantial gaps between new program starts, resulting in fewer opportunities for personnel to gain the experience they need to manage complex processes and make informed decisions than in the past. Future managers of new programs may not have the benefit of learning from the challenges faced and issues solved in past programs.

Recognizing the importance of past experiences for successful program management, the Director Submarines of the United Kingdom's (UK's) Defence Equipment and Support organization asked the RAND Corporation to develop a set of lessons learned from previous

1 See Schank et al., 2005a; Schank et al., 2007.

submarine programs that could help inform future program managers. This volume describes the important lessons from the *Astute* program. The other volumes in the series provide a summary of lessons from the submarine programs of the United States and Australia and of lessons across the three countries:

- MG-1128/1-NAVY, *Learning from Experience, Volume I: Lessons from the Submarine Programs of the United States, United Kingdom, and Australia*
- MG-1128/2-NAVY, *Learning from Experience, Volume II: Lessons from the U.S. Navy's* Ohio, Seawolf, *and* Virginia *Programs*
- MG-1128/4-NAVY, *Learning from Experience, Volume IV: Lessons from Australia's* Collins *Submarine Program.*

This research was conducted within the Acquisition and Technology Policy Center of the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community.

For more information the Acquisition and Technology Policy Center, see http://www.rand.org/nsrd/ndri/centers/atp.html or contact the director (contact information is provided on the web page).

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Summary

To design and construct conventional or nuclear-powered submarines, modern navies and shipbuilders need personnel and organizations that possess unique and specialized skills and expertise. These vessels are among the most complex systems that countries produce, and the technical personnel, designers, construction tradesmen, and program managers who work on them represent pools of knowledge that take years to collect and that cannot be replicated or replaced easily or quickly.

In years past, the pace of construction of replacement submarines was quick enough in most countries that key technical and management personnel in submarine programs were able both to work on a stream of successive submarines and to pass their knowledge on to personnel who followed in their footsteps. Individuals who participated in one program gained experience to be leaders or intellectual resources in following programs.

But two events have coalesced in recent years to complicate such transfers of knowledge: Defense budgets have become constrained, and the operational lives of submarines have lengthened as the vessels' production and maintenance procedures have benefited from continuous process improvements and as navies have changed how they operate the vessels. The result is that the pace at which submarines will be replaced is likely to slow, creating significant time gaps between successive programs and far fewer opportunities for veteran personnel to pass on their knowledge to succeeding generations of submarine workers and program managers.

Recognizing the importance of documenting and imparting experiences from past submarine programs, the Director Submarines of

the United Kingdom's Defence Equipment and Support organization asked the RAND Corporation to develop a set of lessons learned from previous submarine programs that could help inform future program managers. The RAND project team focused on the *Astute* program of the United Kingdom. The team derived lessons from previous reports on the *Astute* program[1] and from numerous interviews that the team conducted with past submarine program managers and submarine personnel at BAE Systems Submarine Solution's Barrow yard, which is the shipyard that builds UK nuclear submarines.

RAND's search for lessons also involved reviewing the history of UK nuclear submarines from HMS *Dreadnought* through the start of the *Astute* program; investigating how operational requirements were set for the *Astute* class; exploring the acquisition, contracting, design, and build processes that the *Astute* program employed; and assessing the plans and activities surrounding integrated logistics support for the submarine class.

The lessons that RAND identified are managerial in nature. The project team looked for instructive aspects of how the *Astute* program was managed, issues that affected management decisions, and the outcomes of those decisions. At times, it was difficult for the team to judge the "success" or "failure" of program decisions. Views change during the conduct of a program and are based on the perspective of individuals. The important point is that the decisions were not necessarily "good" or "bad." Rather, they were or were not fully informed by knowledge of the risks and consequences.

In some cases, the RAND team identified lessons that have not really been learned. In other cases, the team identified lessons that have been learned but forgotten (or ignored). Since cost is typically the metric for judging program success, the majority of the lessons focus on controlling program costs.

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1 For example, see Schank et al., 2005a; Scott, 2002; Willett, 2004; Kincaid, 2002.

The End of the Cold War and Reduced Government Spending

Two events mark the majority of the lessons that the RAND team identified: the end of the Cold War and Whitehall's subsequent decision to reduce both military spending and the government's professional workforce. These resulted in substantial time gaps between the design and build of the *Astute* and its predecessor nuclear submarines—gaps whose ultimate impact on program cost and schedule risk were greatly underestimated by the private sector and the Ministry of Defence (MOD). Both parties also underestimated the impact of the MOD shifting responsibilities to the private sector, which was ill prepared to assume them.

Given these circumstances, the MOD and the private sector made decisions on the *Astute* program without fully understanding their effect. The MOD assumed, for example, that using three-dimensional computer-aided design (3D CAD) software would reduce the labor hours and costs for designing and building the submarine. That assumption proved to be ill founded.

At the same time, it is important to judge the decisions that the government and the private sector made in connection with the *Astute* program in the context of the time they were made. What in hindsight may seem like an ill-advised decision may have actually been appropriate at the time. For example, the significant time gap between the end of the *Vanguard* program and the start of the *Astute* program noted above had adverse impacts on the *Astute* program. The message is not necessarily to avoid gaps but to understand the potential impact of a gap and to incorporate that understanding into the decisionmaking process.

Top-Level Strategic Lessons

Top-level strategic lessons are global in nature and span all programs that design and build new platforms or support the Royal Navy submarine flotilla. They are appropriate for senior management in the

MOD and the Royal Navy, including the Director Submarines. They include the following:

- *Be an intelligent customer who understands the implications of various decisions and an informed customer who knows the status of programs.* Ensure that new processes and new systems are fully analyzed and are not just theoretical ideas.
- *Delineate the roles and responsibilities of the MOD, prime contractor, and subcontractors.*[2] If major responsibilities are shifted from the government to the private sector, ensure that industry is qualified to accept those new responsibilities.
- *Develop knowledgeable and experienced managerial, oversight, and technical support personnel.* Growing future program managers and technical personnel within the MOD and the Royal Navy requires planning and implementation far in advance of any one specific program.
- *Take a long-term, strategic view of the submarine force and the industrial base.*[3] Understand how a specific program impacts the long-term strategic plan for the submarine force and the whole naval flotilla.

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[2] At a minimum, the MOD should assume the following responsibilities: Set operational requirements for the new submarine by working with industry, the Royal Navy, and other stakeholders; assess safety and technical issues in accordance with the MOD's policy that safety risks should be as low as reasonably practicable; oversee and monitor the design process to ensure requirements and standards are met and, when necessary, provide concessions to those requirements; oversee and monitor the build process to ensure that the submarines are delivered on schedule and at projected cost; ensure submarine construction quality and acceptability by developing a testing, commissioning, and acceptance process that ensures that the submarines have been delivered to design intent; and ensure through-life submarine safety and maintenance and post-delivery control of design intent.

[3] A big contributor to the problems faced by the *Astute* program was the substantial time gap between the design and build of the *Vanguard* class and the start of the *Astute* program. This led to a situation in which submarine design and build skills atrophied in the United Kingdom, resulting in a costlier and lengthier *Astute* procurement effort. The issue is not that the gap should have been avoided, but that the MOD neither anticipated the impact of the gap nor factored into the cost and schedule estimates the need to rebuild industrial base capability.

Setting Operational Requirements

Decisions made very early regarding the desired operational performance of the new submarine influence the technology risk for the program and its likelihood of success. The operational requirements for the platform are translated to performance specifications that lead to technology choices to achieve the desired performance. The operational requirements, especially the desired operational availability, also affect integrated logistics support (ILS) planning. Important lessons here include the following:

- *Clearly state operational requirements as a mix of key performance requirements and technical standards*. Have the discipline to avoid changing requirements unless there is a clear need for the change, and ensure that there is a sound understanding of the impact on cost and schedule of requirements changes.
- *Involve all appropriate organizations when setting operational requirements.* Engineers, designers, operators, maintainers, and technical experts in various areas should all be involved early and throughout a new program.
- *Understand the current state of technology as it applies to the program and how the platform's operational requirements impact technology risks and costs*. Understand the relationship among operational requirements, available technologies, potential new technologies, costs, and risks.
- *Understand that operational requirements also must specify how to test for the achievement of that requirement.* Although it is often difficult to plan tests early in a program, it is necessary to ensure all parties agree on the processes to measure how the performance of the platform meets operational capability objectives. Incremental testing of equipment before it becomes part of a system and before that system is inserted into the hull should be encouraged.

Establishing an Acquisition and Contracting Environment

Establishing an open and fair acquisition and contract environment is another important aspect of any program. Good decisions here—what organizations will be involved in designing and building the new submarine, the type of contract, the specifics within the contract (including incentives), the decisionmaking process to employ when issues arise, and the payment schedule—will resonate throughout the life of the program. The *Astute* program originally felt that competition was possible. But when the industry consolidated and competition was no longer possible, it may have been warranted to consider revising the original request for proposals. Key lessons for establishing an effective acquisition and contracting environment include the following:

- *Consider a single design/build contract for the first-of-class.* Having a single qualified firm complete the detailed design and build a submarine helps to integrate the two processes and reduces confusion and misinterpretations.[4]
- *Use a contract structure with provisions to handle program risks.* While the government can try to place all risk on a contractor through use of a fixed-price contract, the government ultimately holds all program risk. It is far better to structure a contract that holds the contractor responsible for risks under its control (labor rates, productivity, materiel costs, etc.) and holds the government responsible for risks beyond the contractor's control (inflation, changing requirements, changes in law, etc.).
- *Develop realistic cost and schedule estimates.* Costs must be realistic and based on the best knowledge and information available. The aim of all parties should be to establish as much as possible a realistic cost estimate and not to drive for cost reduction where it cannot be justified.
- *Make informed decisions on which equipment will be furnished by the government and which by contractors.* These decisions are based

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[4] The *Astute* program probably made the right decision in having a single prime contractor; the problem during its early stages stemmed from the inexperience of the prime contractor and the lack of integration between the design and build teams.

on many factors; one of the most important is which party, the MOD or the prime contractor, is better positioned to manage the subcontractors and the integration of that equipment into the submarine.[5]

- *Develop a timely decisionmaking process to minimize and manage changes.* Changes invariably occur during any program. They may crop up in the desired performance of the platform; in the systems and equipment used to achieve performance; in the schedule; or in the responsibilities of the organizations involved in designing, building, and testing the platform. Changes may affect cost, schedule, or capability. Management structures must be in place to deal with any of the contract changes that are proposed during the program.
- *Establish an agreed-upon tracking mechanism and payment schedule.*[6] Ensure that the tracking system is properly designed and used to produce outputs that are helpful in managing the program.
- *Include an adequate contingency pool.* Whereas a complex project would normally have a contingency fund on the order of 10 to 15 percent or more, the *Astute* contract's contingency fund was approximately 5 percent.

Designing and Building the Submarine

It is important to get all the right organizations—designers, builders, operators, maintainers, and the technical community—involved

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5 The assignment of Rolls-Royce as subcontractor to the prime contractor rather than its typical role as prime contractor to the MOD caused some friction during the initial stages of the *Astute* program. Rolls-Royce has numerous contracts with the MOD to support submarines already in service, and the MOD is Rolls-Royce's most predominant customer. Rolls-Royce has longer-term contracts and more revenues from these other sources than it receives by providing the nuclear steam-raising plant (NSRP) to BAE Systems for the *Astute* class.

6 During its first several years, the *Astute* program had no effective mechanisms to track progress on the submarine's design and build. This made it impossible for the MOD and prime contractor to recognize problems that were growing in the program. At the same time, the program's payment clauses were tied to production metrics such as length of installed pipe or electrical cable that proved to be counterproductive: the shipyard installed pipe and cable before the design was complete that it subsequently had to rip out and re-install.

throughout a program, to understand how operational requirements impact design and construction, and to plan for the appropriate testing of the systems and platform to ensure that requirements are met. To some degree, lessons for the design and build process overlap the lessons that emerged from the earlier stages of the submarine program. These design and build lessons include the following:

- *Involve builders, maintainers, operators, and the technical community in the design process*. Design/build should go further than merely involving builders in the design process. It is important to think of the design team as a collaboration of submarine designers and engineers with inputs from those who must build to the design, operate the submarine, and maintain it. This collaboration should extend throughout the duration of the design program. However, throughout the design/build process, it is important to keep in mind that the cost-effectiveness of the submarine's post-delivery or ILS period is the true design and construction target.
- *Specify and manage adequate design margins.* Without adequate margins, it may not be possible to modernize and upgrade equipment.
- *Design for removal and replacement of equipment.* Adequate access paths and removal hatches should be included in the design, so as to facilitate removing and replacing damaged or obsolete equipment. For command, control, communications, computing, and intelligence (C4I) equipment, modularity and interoperability should be incorporated into the design.
- *Complete the majority of the design drawings before the start of construction.* It is far better to delay construction to ensure that the design is largely complete than risk the costly rework and changes typically resulting from an immature design. A good rule of thumb is to have 3D CAD electronic product models approximately 80 percent or more complete when construction begins.
- *Develop an integrated master plan for design and build.* A program should have an overall integrated schedule detailing the tasks, milestones, and products produced during the design and build

of the submarine. This integrated master plan shows the order of tasks and events and the interrelationships between them.

- *Track progress during the design and build process.* A properly designed and utilized project tracking system will help to predict program cost and schedule status.
- *Ensure sufficient oversight at the design and build organization.* The program should have a strong presence at the shipyard to provide on-site construction oversight for deviations from design, ensure compliance to quality and testing procedures, and keep the MOD aware of the challenges that the program faces.[7] MOD representatives on-site should be experienced in both technical and managerial aspects of delivering a submarine program and also have some decisionmaking capability in order to facilitate concessions and deviations that have only a minor impact on cost, schedule, or performance.
- *Conduct a thorough and adequate test program.* Develop the test program during system design and update it during the conduct of the program.

Establishing an Integrated Logistics Support Plan

Operating and supporting new submarines after they enter service account for the vast majority of their total ownership costs. Therefore, it is imperative to establish an ILS plan for the new submarines. Important lessons here include the following:

- *Establish a strategic plan for ILS during the design phase.* Such a plan must be put in place early in the program. Personnel from

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7 At the beginning of the *Astute* program, MOD oversight at the Barrow shipyard was greatly reduced as part of the movement to control Government spending. This lack of on-site presence blinded the MOD to the design and construction problems that were emerging during the early years of the program. The MOD has since increased its presence at Barrow to approximately 30 people (from a low of two naval officers and two civilians) in order to have more visibility and inputs into the build program.

organizations responsible for maintaining the submarine should be involved in the design process. Additionally, the submarine's concept of operations must take account of the fact that the vessel will require time for preventive and corrective maintenance and for equipment modernizations.

- *Maintain adequate funding to develop and execute the ILS plan.* Resist reducing ILS planning funds when problems arise in other portions of the program.

Acknowledgments

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Of course, any errors of omission or commission in the document are the sole responsibility of the authors.

Abbreviations

3D	three-dimensional
B2TC	Batch 2 *Trafalgar* Class
BCWP	budgeted cost of work performed
BCWS	budgeted cost of work scheduled
CAD	computer-aided design
CFE	contractor-furnished equipment
CNNRP	Chairman Naval Nuclear Regulatory Panel
CSMA	Captain Submarine Acceptance
C4I	command, control, communications, computing, and intelligence
DEC	Director of Equipment Capability
DGSM	Director General Submarines
DPA	Defence Procurement Agency
EVM	earned value management
GFE	government-furnished equipment
HSE	Health and Safety Executive
ILS	integrated logistics support
IPT	integrated project team

MOD	Ministry of Defence
NII	Nuclear Installations Inspectorate
NSRP	nuclear steam-raising plant
PNO	Principal Naval Overseer
RCNC	Royal Corps of Naval Constructors
SEPP	Submarine Enterprise Performance Programme
SS	diesel-electric submarine
SSBN	nuclear ballistic missile submarine
SSN	nuclear attack submarine
S&T	science and technology
UK	United Kingdom
VSEL	Vickers Shipbuilding & Engineering Limited

CHAPTER ONE
Introduction

Lessons from past experiences are an important tool for preparing managers to successfully lead future programs. This is especially true in managing complex military programs governed by various rules, regulations, procedures, and relationships not typically found in commercial projects. In the past, the frequent start of new programs afforded junior-level managers the opportunity to gain experience and prepare for more senior management roles in future programs. However, as operational lives of current naval platforms have lengthened and as defense budgets have been constrained, the gaps between the starts of new programs also have lengthened. The managers of new programs often do not have the benefits of experience gained on previous programs. In this environment, it is important that lessons, both good and bad, from previous programs be captured and provided to future program managers, senior naval decisionmakers, and technical resource managers.

Recognizing the need to document lessons from past programs to provide insights for future program managers and decisionmakers, the submarine organizations of the United States, the United Kingdom (UK), and Australia asked the RAND Corporation to codify teachings from past submarine design and acquisition programs. This volume provides the lessons from the UK's *Astute* submarine program.

The monograph lays out a number of lessons identified both in previous reports on the *Astute* program[1] and in numerous interviews

[1] For example, see Schank et al., 2005a; Scott, 2002; Willett, 2004; Kincaid, 2002.

that RAND conducted with past submarine program managers and submarine personnel at the shipyard that builds UK nuclear submarines—BAE Systems Submarine Solution's Barrow yard. We were particularly interested in

- how political, budget, and operational environments influenced decisions made during the program
- how operational requirements guided the design and related to the technologies available at the time
- what contracting and acquisition processes were used during the program
- how the private-sector industrial base that designs, builds, and maintains submarines and their systems changed over the long history of UK nuclear submarines
- how the UK Ministry of Defence (MOD) and the shipbuilding industrial base interacted
- how integrated logistics support (ILS) plans were developed during the design and construction of the submarines to the new submarines when they entered service
- how other issues, both internal to the program and external, influenced decisions and outcomes.

The lessons we strive to identify are managerial in nature, not technical. We do not focus, for example, on why a specific valve or pump was chosen, but rather on how the program was managed, the issues that impacted management decisions, and the outcome of those decisions.

It is often very difficult to judge the success of a specific program; success can be measured in performance, cost, or schedule terms. One person's view of how successful a program was can differ greatly from the views of others. It is even more difficult to identify specific actions or decisions that contributed to success or non-success; many factors interplay throughout the conduct of a new program. We had to keep this in mind as we sorted through the lessons of the *Astute* program.

Organization of the Monograph

Chapter Two provides a brief background of UK nuclear submarines from HMS *Dreadnought* to the start of the *Astute* program. Chapter Three describes how operational requirements were set for the *Astute* class, and Chapter Four describes the acquisition and contracting process used for the *Astute* program. Chapter Five explores the design and build of the *Astute* submarines. Chapter Six addresses integrated logistics support plans and actions. Chapter Seven provides the lessons from the *Astute* program.

CHAPTER TWO

History of British Submarine Programs

The United Kingdom has a long history in submarine design and production dating back to the construction of the *Nordenfelt* by the Barrow Ship Building Company in 1886.[1] From then through the end of World War II, the UK developed numerous classes of new diesel-powered submarines and built almost 500 submarines. Many of the classes were very small: Technical problems in one class of submarines, coupled with new technologies, would rapidly lead to a new class. During peak production at the start of World War II, an average of more than two boats per month was produced. Several shipyards supported submarine construction, including Vickers-Armstrong at Barrow, Cammell Laird, Scotts, and the Royal Dockyard at Chatham.

Two new classes of diesel-powered submarines were developed after World War II—the *Porpoise* and the *Oberon* classes. These classes followed the incremental technology strategy used in the development of previous classes, which resulted in designs that were evolutionary rather than revolutionary. Improvements were made in battery capacity, submerged performance, and radiated noise. The *Oberon*-class submarines proved especially effective, and several were built in the UK for service in other navies, including the Royal Australian Navy. However, with the advent of nuclear power for submarines, the design and build of diesel-powered submarines in the UK ended for approximately 20 years until the 1980s and early 1990s, when the *Upholder* class was

[1] Appendix A of Schank et al., 2005a, contains a more detailed history of UK submarines.

designed and built. *Upholder* boats currently serve in the Royal Canadian Navy.

Advent of Nuclear Submarines in the UK

Submarine propulsion technology underwent a revolutionary change when the United States commissioned the first nuclear-powered submarine, the USS *Nautilus*, in 1954. Shortly thereafter, the United Kingdom started developing its own nuclear propulsion program, which had a target date of 1961 to launch the first nuclear-powered submarine in the Royal Navy, HMS *Dreadnought*. As the UK nuclear program was beginning, the United States agreed to provide a proven *Skipjack*-class reactor plant for use in the *Dreadnought*. Relationships were established between Rolls-Royce and Associates,[2] the UK single point of contact, and the Westinghouse Corporation, the U.S. provider of nuclear equipment. Vickers-Armstrong laid the keel of the *Dreadnought* in 1959 and the Royal Navy commissioned the ship in 1963.

After completing the *Dreadnought*, the UK embarked on its first entirely British nuclear submarine design and development program. The resulting *Valiant* class of nuclear attack submarines (SSNs) was quickly followed by the nuclear ballistic missile submarines (SSBNs) of the *Resolution* class and then the SSNs of the *Swiftsure* class. As the build of the six submarines in the *Swiftsure* class was ending, the build of the *Trafalgar* class started; the seventh and last *Trafalgar* boat was delivered in late 1991. The *Trafalgar*-class submarines are the SSNs currently operated by the Royal Navy.

In 1980, the United Kingdom decided to modernize its strategic nuclear deterrent and purchased the Trident missile system from the United States. The four-boat *Vanguard* class was developed to deploy the Trident missiles. The first *Vanguard*-class boat was laid down in 1986 and the last boat in the class was delivered in 1999.

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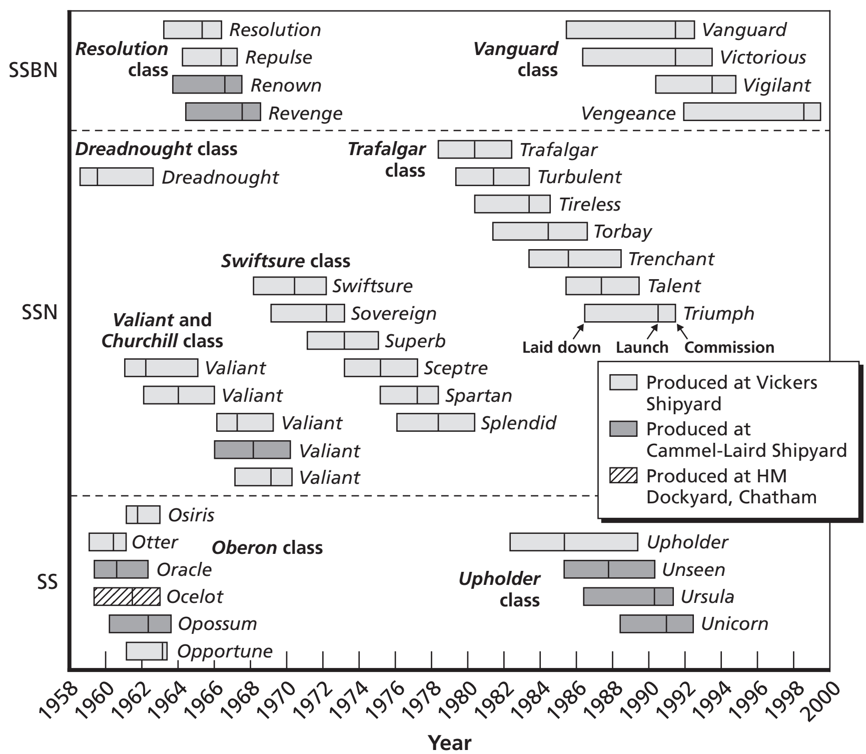
[2] Rolls-Royce and Associates was formed from selected staff from various organizations including Rolls-Royce, Vickers Shipbuilding & Engineering, Foster Wheeler, and Babcock.

Figure 2.1 shows the various classes of UK submarines, both nuclear and conventional-powered, from 1958 to 2000.

The Evolving Submarine Industrial Base

Although several shipyards built diesel-powered submarines, the vast majority of nuclear-powered submarines were built at the Vickers shipyard in Barrow (see Figure 2.1). With nationalization and then denationalization of the British shipyards in the 1980s and a series of mergers and acquisitions, the Barrow shipyard went through multiple

Figure 2.1
Production and Commissioning History of British Submarines (1958 to 2000)



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owners before 1995.[3] When British shipbuilding was privatized again in 1986, Vickers Shipbuilding & Engineering Limited (VSEL) became a subsidiary of British Shipbuilders and changed its name to VSEL PLC. The shipyard was purchased in 1995 by GEC Marconi, the shipyard's owner when the last two *Vanguard*-class submarines were delivered. Ownership again changed in 1999 when BAE Systems, created by the merger of British Aerospace and GEC Marconi, bought the Barrow shipyard.

Rolls-Royce became the sole provider of all nuclear steam-raising plants (NSRPs) for British submarines, a role in which it serves to this day. It oversees a range of nuclear component suppliers, many of them sole source. Likewise, both the shipyard and the government oversaw a large number of vendors providing components and systems, either as contractor-furnished equipment (CFE) or as government-furnished equipment (GFE).

Strong Role of Government

One important aspect of all UK nuclear submarine programs up to and including the *Vanguard* class was the large role played by the MOD and the Royal Navy. The Naval Staff at Whitehall set the requirements for a new class of submarines based on the prospective mission needs and concept of operations. The requirements process started with the development of the staff target document, which defined the defense need in detail and the likely capabilities that would meet it. The Directorate of Operational Requirements, assisted by submarine experts in other directorates, was responsible for developing the staff target.[4]

For each class, the staff target was given to the Director General Submarines (DGSM) for further study and development.[5] The Pro-

3 The ownership changed at least eight times, all in association with Vickers.

4 In many ways, the staff target was a predecessor to today's User Requirement Document.

5 The DGSM included a number of smaller directorates, each responsible for a specific area of underwater warfare. These smaller directorates included nuclear propulsion, combat systems, sonar, naval architecture, and torpedoes and weapons among others.

curement Executive, established in 1971 as the single procurement agency for the MOD,[6] triggered various studies by in-house engineers and naval architects that examined the desired capabilities and how to provide them. The comparative operational analyses and cost-benefit trade-off studies helped update and refine the staff target. The operating flotilla and the intelligence community also provided inputs to the staff requirement.

A project team within DGSM then started to develop the layout of the new submarine and define its major systems and equipment. This team took responsibility for the overall design and system performance and set the standards for design and construction. Concept studies provided broad technical alternative solutions to operational needs and contributed to the further refinement of the staff target. The MOD, with support from the industrial base, then conducted feasibility studies on the most promising alternatives. The feasibility studies led to a decision to proceed with a specific design. Information from previous classes of submarines, coupled with feedback from the flotilla on problems with existing classes, factored into the development of the new submarine's specifications.

A Class Policy Document was then created to document the overall design and its philosophy. It also dealt with integrating into the design any changes to requirements over the 10- to 15-year period from the start of concept studies to the delivery of the first submarine in each class. Such changes might result from new missions, technology advances, or the desire to decrease costs. This document, started at the same time as the initial staff requirements, typically led to a number of additional requirements to improve individual aspects of the submarine. Several hundred change notices incorporated into the lead ship of the class could be described in the Class Policy Document.

The completion of the contract specifications led to a contract with the shipbuilder to start the detailed design of the new class. The Procurement Executive also initiated contracts with multiple vendors to provide systems and equipment to the shipbuilder. Overall, the MOD

[6] The DGSM was part of the Procurement Executive. The Procurement Executive became the Defence Procurement Agency (DPA) in 1999.

acted as design authority[7] and prime contractor, providing a range of systems, including the NSRP, to the shipbuilder as GFE.

The shipbuilder had very little input into the decisionmaking process at this stage. Although the MOD looked to the shipbuilder for expertise in naval architecture and platform systems and structures, the MOD and the Royal Navy had hundreds of engineers and designers involved in developing the initial systems and arrangement drawings that formed the basis of the detailed design and build contract. There was significant technical expertise, with a great depth and breadth of experience. The Royal Corps of Naval Constructors (RCNC)[8] and the engineering officers of the Royal Navy supplemented the technical resources at the MOD. Organizations were located at Bath (platform requirements), Portland (combat systems), and Portsdown (also combat systems). Other supporting organizations, such as the Yarrow-Admiralty Research Department, assisted in developing the design specifications for predominantly the secondary propulsion plant.

The shipbuilder performed detailed design and construction but with a good deal of oversight from the MOD. The project team, along with various equipment-related teams and specialist sections within the MOD, provided inputs to the detailed design and approved technical decisions. The Principal Naval Overseer (PNO),[9] supported by organizations that oversaw the manufacture of critical items, had a staff of approximately 50 people stationed at the shipyard to oversee product assurance and construction, test, and commissioning activities. Through the PNO, the MOD had a mechanism to independently ensure that the nuclear submarine was designed to contract specifica-

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[7] Joint Service Publication 430 defines *design authority* as "An organization with the professional competence and authority to specify design requirements, undertake design tasks, apply configuration management to designs and associated documentation, whilst continuously monitoring the effectiveness of those activities for a given material state" (UK Ministry of Defence, 2004).

[8] The RCNC had the competence that allowed the MOD to assume the role of design authority. It had a substantial training and professional development program that grew knowledgeable people through tours at the various dockyards and shipyards.

[9] The Principal Naval Overseer roles during design and construction at the shipyard were very similar to those of the U.S. Navy's Supervisor of Shipbuilding at the U.S. shipyards.

tions, built as designed, and ready for final acceptance. The PNO could approve small changes and provided deep insight into schedule and cost performance.

Testing of the submarine's systems, components, and subsystems was performed by the shipyard's Dockside Test Organisation composed of members from the shipyard, the ship crew, and the MOD. They prepared the test agenda and acceptance criteria, executed the tests, and documented the results. As the submarine neared completion and drew closer to delivery, the Captain Submarine Acceptance (CSMA) carried out intermediate inspections. CSMA also performed the final inspection, ensuring that overall quality was sufficient to enable the ship to go to sea. The process included acceptance by the DGSM that the details of the contract had been met and by the CSMA that the submarine was fit for service. The process was characterized by visibility to all interested parties, whether within the government or the shipbuilder.

The MOD played a very strong role throughout the design and build process. It took full responsibility for the major aspects of performance and provided the majority of the systems and equipment to the shipbuilder. It carried all the risks and managed those risks in a very hands-on way. A cost team at the shipyard gathered design and build data and used those data to help inform the cost status of ongoing programs as well as help estimate the costs for future submarines.

Moving Toward the *Astute* Program

In the three decades after the delivery of HMS *Dreadnought*, the UK developed five classes of nuclear submarines and built a total of 26 boats, all but three at the Vickers shipyard in Barrow. Employment at Barrow topped 13,000 during these years. The Royal Navy and the Ministry of Defence had significant design and technical resources and played a major role as initial designer, system integrator, and design authority. The Cold War pitted the UK and its allies against a strong and technically advanced adversary, and defense budgets reflected the heightened tensions of the time. With the retirement of the *Swiftsure*-class submarines on the horizon, the UK started a new submarine design program in this fertile environment. The beginning of the *Astute* program, however, would see radical changes in the government and in the industry.

The Beginnings of the *Astute* Program

In the 1980s, the MOD conducted a number of studies to determine the replacement for the *Swiftsure* and *Trafalgar* classes of attack submarines. Whereas *Trafalgar* was a close derivative of the *Swiftsure*, the goal for the SSN20 (the original name for the new project) was a new submarine with a major upgrade in capability. The Russian threat during the Cold War was significant and the UK, much like the United States with the *Seawolf* design, was seeking to counter Soviet advances in anti-submarine warfare and in ballistic missile submarine capabilities.

The SSN20 was to include an improved nuclear propulsion plant, a large increase in firepower, an integrated sonar suite, new combat systems, a larger pressure hull with new steel, increased stealth characteristics, and control surfaces modified for enhanced agility.[10] Cost was not a large constraint at this point.

The original cost estimates for the new submarine were significantly higher than those for the previous classes, reflecting the desire for a revolutionary design rather than an evolutionary design with enhanced capabilities. But as the initial feasibility studies drew to a close, the Berlin Wall fell and the Cold War ended, prompting some policymakers to question whether the enhanced and costly capabilities of the SSN20 were necessary. As a result, a new set of studies was conducted with cost control as the main objective.

The new studies generated concepts for a "Batch 2 *Trafalgar* Class" (B2TC) which would build on the successful *Trafalgar* class, updated with a new tactical weapon system under development for the *Swiftsure* and *Trafalgar* boats and the NSRP of the *Vanguard* class. Further changes would be introduced only to meet modern safety requirements and eliminate obsolescence. The program was assumed to have low technical risk: The new class would use systems and modules from then current classes, as shown in Figure 2.2. The back end of the *Trafal-*

[10] Schank et al., 2005a.

gar class, the NSRP of the *Vanguard* class, the *Swiftsure* and *Trafalgar* upgrade, and some parts of the front end of the *Upholder* class would all be used in the new class of submarines.

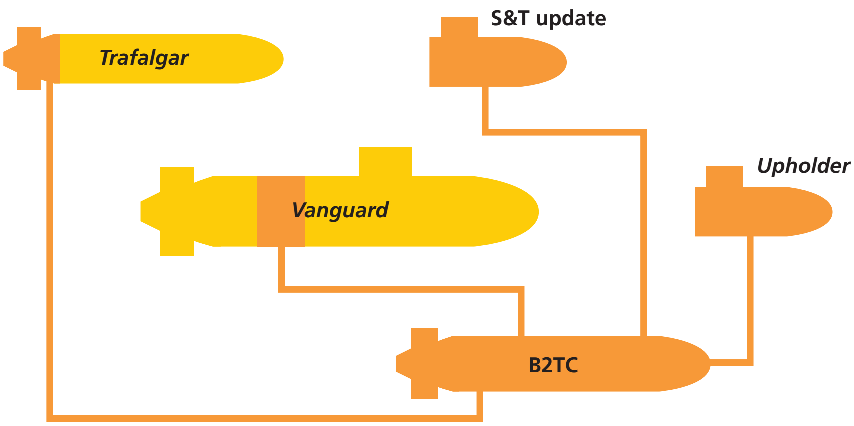
The studies phase for the new class began in the early 1990s. At the same time, the perceived roles of the government and those of private industry were undergoing a radical change.

The Changing Role of Government

Up through *Vanguard*, the UK had employed a large administrative infrastructure and in-house technical staff to manage new submarine acquisition. This prompted some observers to question whether the government overhead costs exceeded the value that they added. These questions were being asked just as a broader cultural change was leading to a shift in the government's interactions with the private industries that provided the weapon systems. This shift was epitomized by the election of Prime Minister Margaret Thatcher, who promised to decrease the size of government and shift many MOD responsibilities to private industry.

Within the submarine community, this policy shift eliminated entire organizations, including the PNO and the CSMA, which had provided necessary oversight for the design and build of all previous classes of complex nuclear submarines. Also, the Royal Corps of Naval

Figure 2.2
Original Design Concept for the *Astute* Class



RAND *MG1128/3-2.2*

Constructors, a key oversight organization, stopped recruiting new members. The belief at the time was that private industry could replace these legacy naval organizations and that competitive pressure would lead to lower costs. Given the issues surrounding nuclear submarines, however, the government had to retain the key responsibilities for safety in operations and have the expertise to provide oversight and guidance.

Although the *Vanguard*-class submarines were built within approved budgets, the MOD felt the shipbuilder was making excessive profits on the build of the boats for the risks it was taking. The MOD had served as prime contractor through the *Vanguard*, providing the preliminary designs and much of the equipment to the shipbuilder. But with the shift in policy, government leaders came to believe that a strong prime contractor from industry could manage the shipyard and the major vendors much better than the MOD, and at a lower cost. Additionally, the MOD believed that competition for the role of prime contractor would help lead to innovation and cost reduction.[11]

Low cost and the transfer of risks to industry were the mantras of the day. The seemingly low technical risk of the B2TC concept and the potential benefits of an industry prime contractor further motivated a new procurement strategy that would hold down costs. The management of the majority of the risks in a new nuclear submarine program would be handled by industry and government infrastructure could be reduced to further realize cost savings. The MOD would transition from a "hands on" to an "eyes on, hands off" approach with the new program. Furthermore, a maximum-price contract would further protect the MOD from cost growth in the program.

Competition for Prime Contractor

As explained in greater detail in Chapter Four, the MOD in 1992 awarded studies contracts to a number of potential B2TC prime con-

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[11] In addition, three-dimensional computer-aided design (3D CAD) tools appeared to offer further cost reductions during the design and build of a new submarine and the MOD felt that 3D CAD advances could be better exploited by the private sector.

tractors: VSEL, the shipyard that had built the vast majority of the UK's nuclear submarines; GEC Marconi; Rolls-Royce and Associates; and British Aerospace. All the companies indicated that they could produce a submarine that met the B2TC staff requirement. A draft invitation to tender was distributed in October 1993, and a final version was provided in July 1994.

As an incentive to bid for the new program, now called *Astute*, the contract was to design the submarine, build the first three boats, and support those first three boats for eight boat years—all under a fixed, maximum-price contract. Furthermore, the prime contractor would have design authority and would procure all equipment, including the NSRP.[12] The design was very closely specified and involved some 13,000 system technical requirements.

GEC Marconi, partnered with BMT Group (which would produce the submarine design), and VSEL, partnered with Rolls-Royce and Associates, submitted proposals for the new program in June 1995. Following this competition, a contract was awarded to GEC in March 1997.

Advent of Smart Acquisition

Shortly after the *Astute* contract award, a Labour government was elected, replacing the Conservatives. Prime Minister Tony Blair campaigned on an agenda of change and the modernization of government roles and interactions with the private sector. The government turned to the recommendations of consultant McKinsey & Co. McKinsey had examined the MOD acquisition system and found it to be ineffective and underfunded in its early stages, to have placed too much reliance on technical specifications and competitive tendering, and to possess weak project management, with key people spending too little

[12] Clause 72N of the contract mandated that Rolls-Royce and Associates would be the subcontractor for the NSRP. The MOD would provide as GFE only a few pieces of specialized security and cryptography equipment.

time in post and having low accountability and poor supervision.[13] The new government revised defense system procurement under the term Smart Procurement (later changed to Smart Acquisition) and a new acquisition cycle termed CADMID[14] replaced the Downey cycle.[15] A Director General of Smart Acquisition was established to oversee the new process and further refine the concept.

The original contract for *Astute* was signed slightly before the advent of Smart Acquisition. Although not directly affecting the contract, Smart Acquisition did impact how the program was managed. An integrated project team (IPT) was established at Abbey Wood to manage not only the *Astute* program but also the *Swiftsure* and *Trafalgar* upgrade program. The Director General organizations were replaced by executive directors in the newly formed Defence Procurement Agency. Separately, the operational requirements staffs were replaced by the Directors of Equipment Capability (DECs). The DECs would determine requirements and oversee funding issues. Technical staff was reduced under the assumption that the private sector would assume much of the technical responsibilities. The large MOD on-site groups at the shipyard to oversee design and construction were eliminated. The MOD policy of retaining the minimum capabilities to be an informed customer was now firmly in place. Unfortunately, as time would tell, the cuts went too deep and some risks could not be transferred to industry.

The *Astute* Program Today

The *Astute* was launched in June 2007 and left the shipyard to start her operational trials in November 2009. HMS *Astute* was commissioned

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[13] Kincaid, 2002.

[14] The phases of CADMID are Concept, Assessment, Demonstration, Manufacture, In-service, and Disposal. See UK Ministry of Defence, 2004.

[15] The Downey cycle predated Smart Acquisition. Introduced in 1962, the Downey cycle included the following phases in defense equipment acquisition: Staff Target Development, Feasibility Studies, Project Definition, Full Development, Production, and Operational Service. The Downey cycle was viewed as sequential and inflexible.

into the Royal Navy on August 27, 2010. The second boat in the class, HMS *Ambush*, was launched in June 2011. Boats 3 and 4 are under construction and the procurement of long-lead equipment, including the reactor cores, has been authorized for boats 5 and 6. Current plans are for an *Astute* class of seven submarines.

A summary of significant milestones in the *Astute* program is provided in Table 2.1. With this brief overview of the program, we now turn to more detailed discussions of specific aspects of the program.

Table 2.1
***Astute* Milestones, 1980–2010**

Date	Milestone
1980s	Original studies conducted for follow-on to the *Trafalgar* class. This replacement submarine, originally called the SSN20, was to be a major change to the *Trafalgar*. The end of the Cold War changed the requirements, and thus a new set of requirements was dubbed the Batch 2 *Trafalgar* Class
June 1991	Feasibility studies begun on B2TC
1993	UK announces that it plans to reduce its submarine force to an all-nuclear-powered fleet of 16
February 1993	Keel laid down on HMS *Vengeance*, the last *Vanguard*-class ship
October 1993	Draft invitations to tender for B2TC sent
July 1994	Final invitations to tender for design and build the first three of the class with an option for two more
July 1994 to June 1995	Competition held between GEC Marconi and VSEL to build *Astute* class
May 1995	GEC Marconi reorganized by dissolving Naval Systems and Marconi Radar and Control. The company creates a new division: GEC-Marconi Major Prime Contracts
June 1995	GEC acquires VSEL and operates it as GEC Marine
December 1995	GEC Marconi identified as the MOD’s preferred bidder
March 1997	Contract to build first three boats awarded to GEC

Table 2.1—Continued

Date	Milestone
1998	Strategic Defence Review announces a reduction to 14 submarines by 2006 (10 SSNs and 4 SSBNs)
September 1998	*Vengeance* launched at Barrow shipyard
November 1999	*Vengeance* commissioned
November 1999	British Aerospace and Marconi Electronic Systems merge to become BAE Systems
January 2001	Keel laid down for *Astute*
2003	Defence White Paper reduces number of SSNs to 8
February 2003	MOD and BAE Systems reach new contract agreement
October 2003	Keel laid down for *Ambush*
December 2003	MOD and BAE Systems sign re-baselined contract amendment
March 2005	Keel laid down for *Artful*
May 2007	UK MOD awards contract to BAE Systems to start to build the fourth boat, HMS *Audacious*
June 2007	*Astute* launched
October 2007	*Astute* makes first dive
November 2009	*Astute* leaves Barrow for its operational base in Faslane after successfully completing its first phase of sea trials
March 2010	MOD gives BAE Systems the go-ahead to start building the fifth submarine and to procure long lead items for the sixth

CHAPTER THREE

Setting the Requirements

This chapter describes how the requirements were set for the new submarine program that became the *Astute* class. It outlines the early beginnings of the SSN20 program and how the initial requirements changed in light of the end of the Cold War and the pressures on the UK defense budget. It also shows how the new view of the role of the government in major defense system acquisition programs resulted in a complex mix of high-level performance requirements and thousands of lower-level technical specifications for the *Astute* program. The chapter then describes how the nuclear regulatory procedures changed and their impact on the program. Finally, it discusses how the management of the requirements changed when the original contract was modified in December 2003.

The Beginnings of the New Submarine Program

Specifying the requirements for a new class of submarines to replace the *Trafalgar* and *Swiftsure* classes began during the height of the Cold War. The goal for the new submarine, initially named SSN20, was to counter the increasing capabilities of Soviet ballistic missile submarines. Initial requirements for the SSN20 included an increase in speed, diving depth, firepower, and the ability to detect and avoid Soviet submarines. The SSN20 would also have a new, improved nuclear reactor, an integrated sonar system, and a more capable combat system. It would also be built with a new type of steel.[1] Rather than the evolutionary improvements in prior classes of UK submarines, the desired capabilities for the SSN20 would likely require a revolutionary step in UK submarine designs.

The Changing Threat and Budget Environments

As studies progressed on SSN20 requirements and conceptual designs, initial cost estimates suggested the desired capabilities would lead to a significantly more expensive submarine compared with prior classes. During a time when there was significant pressure on the government's budget, these costs were viewed as prohibitive.

As the SSN20 requirements were being examined, the Cold War came to an end. No longer was there a significant threat from Soviet submarines, and the need for the enhanced capabilities of the SSN20 was further questioned. Reacting to the new threat environment and the call for a peace dividend, the naval staff reset the requirements for the new submarine and renamed the program Batch 2 *Trafalgar* Class.

The goal for B2TC was a submarine with similar capabilities to the *Trafalgar* class but with only slightly greater acquisition and support costs. To control costs, the B2TC would incorporate the best of what was available or planned for in-service submarines. The B2TC would use the PWR2 nuclear reactor of the *Vanguard* class and the planned combat system upgrade for the *Swiftsure* and *Trafalgar* classes. It would also incorporate modules and systems of the *Trafalgar* and *Upholder* classes (see Figure 2.2).

The B2TC would have some new requirements compared with the *Trafalgar* class. The size of the reactor compartment for the PWR2 resulted in a larger diameter hull than the *Trafalgar*, providing increased volume. The new design included a 50 percent increase in weapons storage. Originally, the goal was for six torpedo tubes. Cost constraints

[1] The requirements for the U.S. *Seawolf*-class were developed during the same time frame and had similar aspirations. See Schank et al., 2011b, for a description of the U.S. *Seawolf* program.

led to an initial design with five tubes. However, shortly after the contract was signed, the first major change order was to add back the sixth tube. Another change notice after the contract was signed was the need to accommodate a large lock-in, lock-out chamber to support diver ingress and egress. These new and changing requirements, along with the larger hull diameter, would greatly influence the design efforts for the B2TC.

The early goal of a new design, that it would be a modest step from the *Trafalgar* design, proved to be overly optimistic. The initial requirements suggested a much larger submarine than the *Trafalgar*—in excess of 7,000 displacement tons compared to the 5,200 tons of the *Trafalgar* class. Also, the initial estimate that only four of the 13 major systems would require a new design greatly underestimated the impact of the B2TC requirements while overestimating the availability and suitability of the existing systems. Ultimately, ten of the 13 systems would be new or extensively modified.

Impact on Requirements of the Changing Role of Government

The development of the requirements for the B2TC, now named *Astute*, was also greatly influenced by the evolving role of government in the acquisition of new weapons systems. Up through the *Vanguard* class, the Royal Navy and the MOD would develop the design for a new nuclear submarine and clearly specify the standards and requirements for its build. The shipbuilder would then develop the detailed functional (Stage 1 engineering) and spatial (Stage 2 engineering) design drawings and equipment procurement specifications to enable the trade workforce to build the submarine based on those requirements and specifications. Throughout this process, the MOD maintained what is today considered the design and technical authority.[2]

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[2] Joint Service Publication 430 defines the *design authority* as "An organisation with the professional competence and authority to specify design requirements, undertake design tasks, apply configuration management to designs and such areas as the submarine hull, mechanical and electrical engineering, submarine safety, and ship design and engineering."

The new government reforms were founded on the belief that the private sector could perform certain roles more efficiently than the public sector. This put pressure on the MOD to greatly reduce its design resources and to transfer much of the design responsibility to the private sector. Now, the MOD would treat the design and build of the *Astute* with an "eyes on, hands off" policy.

This environment was new to the MOD. Whereas the MOD and Royal Navy technical experts had previously played an important role in setting requirements and drafting specifications for a detailed design of a new submarine, the conceptual design for *Astute* would now be developed by the prime contractor. The MOD had to craft operational requirements and specifications in a way that would not bias the competition between an experienced submarine design organization (VSEL) and other potential competitors with far less submarine design and build expertise but would also ensure that the resulting submarine would be fit for its purpose. This leveling of the playing field resulted in an overly detailed requirement definition that caused difficulties and confusion.

As a result, the contract requirements for *Astute* specified a mixture of performance and technical outcomes—including 15 high-level requirements in such areas as speed, the performance of the integrated combat system, and signatures, with some 13,000 technical requirements that went down to a very detailed level, some even requiring specific fasteners or equipment. This myriad of requirements proved difficult for the prime contractor to decipher and in some ways restricted the innovation desired in the new design by specifying certain systems and equipment.

In this new environment, the submarine designer/builder had to demonstrate not only that the thousands of contract requirements were met but also that the submarine was safe to operate. The Naval Authorities engaged with the small MOD team and the prime contrac-

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The technical authority is responsible for establishing technical standards in each area and evaluating the risk associated with any design non-conformance with technical standards that might occur during the design and construction processes. To be effective, the design and technical authority roles required skilled and experienced staff with predominantly technical and engineering skill sets.

tor to receive assurance that the submarine was safe when constructed against eight key hazard areas. It was left to the MOD team to manage the acceptance against the 13,000 individual requirements. Ultimately, due to the difficulty in processing thousands of requirements and reconciling conflicts, the 13,000 technical requirements for the first three *Astute*-class submarines were reduced to approximately 3,000. Still, the contract requirements require a good deal of documentation for acceptance. Because of the problems that developed from how the original requirements were set, the contracts for boats 4 through 7 are based on the design specification that had been established during the development of the first three vessels rather than on a collection of requirements. The design specification gives the MOD a defined design baseline for a build contract, under its reclaimed role of design authority for boats 4–7.

Nuclear Regulatory Requirements[3]

In addition to the high-level performance requirements and the thousands of low-level technical specifications, the *Astute* program was conducted during a time when the nuclear regulatory requirements were facing a greater insistence by the regulatory authorities that safety principles, criteria, and guidelines should be applied with the same level of rigor in the defense arena as was being applied in the civil sector.

Under the Nuclear Installations Act of 1965, no site may be used to install or operate any nuclear facility unless the Health and Safety Executive (HSE) has granted it a license. The shipyard in Barrow is licensed and regulated by the Nuclear Installations Inspectorate (NII), which resides within the HSE. The shipyard is also authorized by the MOD's nuclear regulator and is, therefore, subject to joint regulation.

The 1965 act contains an exemption for a "nuclear reactor comprised in a means of transport" (i.e., a submarine reactor plant). However, the Secretary of State for Defence has a policy that, although the MOD is exempt from regulation, it will, so far as is reasonably practi-

[3] The majority of this section is from Raman et al., 2005, pp. 43–47.

cable, have policies at least as good as the NII regulations. In this vein, the MOD appointed the Chairman Naval Nuclear Regulatory Panel (CNNRP)[4] as its regulator with responsibility for establishing and maintaining standards and arrangements for the Naval Nuclear Propulsion Programme. CNNRP's main area of concern is the submarine, whereas NII's main area of concern is safety of operations within the licensed site.[5] As a result, there is some dual regulation when nuclear propulsion plant work is performed at a privately owned site.

Both regulators operate in a nonprescriptive regime, which places reliance on self-regulation by the licensee.[6] In this approach, neither regulator prescribes the safety standards a licensee is expected to follow. Instead, both organizations use similar principles (NII, Safety Assessment Principles; CNNRP, Safety Principles and Safety Criteria) to assess the arrangements put in place by the licensees in response to the license and authorization conditions. Specifically, Condition 14 requires licensees and authorized entities to "make and implement adequate arrangements for the production and assessment of safety cases consisting of documentation to justify safety during the design, construction, manufacture, commissioning, operation and decommissioning phases of the installation."

Starting in 1996 (just prior to the award of the initial contract), the NII and MOD agreed to change their approach to dual regulation. The MOD agreed to provide the HSE licensee with data on the design of the submarine nuclear reactor. The intent was not for NII to look into the reactor design but instead for NII to gain understanding of the reactor's safety-related matters and how they interacted with shore-based facilities.[7] For *Astute*, NII and CNNRP regulate nuclear submarines jointly. They described their respective roles and responsibilities in a 2003 letter of understanding in which they agreed (1) to share infor-

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4 The CNNRP has been replaced by the Defence Nuclear Safety Regulator.

5 See NAO, 2002, p. 13.

6 NAO, 2002, p. 13. In this paragraph we use the term "licensee" to refer to an entity licensed by NII or authorized by CNNRP (or both).

7 NAO, 2002, p. 13.

mation and (2) to jointly determine and agree on any action and take all reasonable steps in deciding which organization should take action.[8]

The change to joint regulation and NII access to reactor plant design data made licensees address all hazards in their safety cases, including the interrelationships of site and reactor plant hazards. Addressing these interrelationships added complexity—with corresponding effort and cost—to the preparation and implementation of post-1996 safety cases, even though the principles by which the two regulators assess safety cases had not changed.

Although NII's principles were last revised in 1992 and CNNRP issued its principles in 1994, BAE Systems has asserted that regulatory pressures in the 1990s greatly increased the cost of developing the safety cases. BAE Systems asserted that nuclear regulatory costs increased due to the adoption and implementation of the safety management arrangements needed to produce and comply with the post-1996 safety documentation. BAE Systems describes the current safety cases as the first on the Barrow site for which a comprehensive Site Safety Justification has been required for all operations carried out to build, commission, and test nuclear-powered submarines.

Additionally, the nuclear regulatory cost for the *Astute* contract increased because of the new requirement for CNNRP authorization of the Barrow site. That authorization was provided in November 2004.

Revised Contract Brought Changes to the Management of Requirements

As we will discuss in more detail in the next chapter, schedule delays and cost overruns resulted in a revised contract in December 2003. One key aspect of the contract revision was a change in the "eyes on, hands off" role played by MOD in managing the requirements of the *Astute* program. The new contract resulted in the MOD again assuming much of the risk, especially the financial risk, with the program. With

8 NII and CNNRP Letter of Understanding, 2003.

that change in role, the MOD adopted a more "hands on" approach to management of the program from 2003 onward.

As mentioned above, the approximately 13,000 technical specifications in the original contract were reduced to about 3,000 technical requirements. With the revised contract, the MOD took a much stronger role in managing those requirements. Now, when the submarine design requires a change to any requirement, a deviation requiring MOD approval must be processed. The deviation process is managed by the Integrated Project Team (IPT), which can address the matter itself or seek outside technical advice.

The prime contractor requests a concession when any aspect of the detailed design or as-built condition does not meet the intent of the contract specifications. This allows the prime contractor design authority to determine if the as-built condition still meets the contracted requirement. If the as-built condition still meets the requirement, BAE Systems as the design authority can approve the concession; if not, corrective action or MOD approval of a concession is needed. The concession process is handled by the prime contractor, although the MOD is kept apprised on the whole process. The MOD can challenge any part of the process if it deems that attention by the higher-level contractor or the MOD is required.

The IPT is structured with "requirement owners" who have the tasks of requirements fulfillment and compliance assigned to them. The requirement owners work closely with the prime contractor, onsite IPT members, MOD technical experts, and others to ensure that the system requirements will be met in the detailed design and build. Although the requirement owners have access to the MOD's technical experts and to outside experts in organizations, such as QinetiQ, there is no formal requirement to use them. However, there is an informal, yet compelling, reason for the IPT requirements owners to seek advice and concurrence from the technical experts concerning safety issues. In sum, the IPT is the technical decisionmaker for the MOD and continuously ensures that the design and build process meets contract requirements.

The delegations of authority, along with multiple organizations providing independent oversight of prime contractor and IPT technical decisions, appear to provide the MOD with appropriate tools to manage the government's interests on the *Astute* design and build program.

CHAPTER FOUR

Acquisition and Contracting Strategy

This chapter provides an overview of the contracting strategy used by the MOD for the acquisition of the *Astute*-class submarines. It first describes how a level of discontent with the *Vanguard*-class contracts and a change in the role of government in weapon system acquisition led to a very different contracting environment for the *Astute*. It then describes how the competition and negotiations resulted in an initial contract to design the *Astute,* produce the first three submarines in the class, and provide several years of in-service support for the submarines. The competition and contract negotiations were so drawn out that it took more than three years from the original invitation to tender until the initial contract with GEC was signed. The chapter concludes with a description of the problems that arose during the design and build of the *Astute* and how those problems resulted in the need to renegotiate the original contract.

The Mindset at the Time

Several factors led to a change in the acquisition and contracting strategy of the MOD for the new class of submarines. Although the *Vanguard* program was generally viewed as a success that resulted in a highly capable class of ballistic missile submarines, the MOD felt that VSEL, the owners of the Barrow shipyard, had made excessive profits on the *Vanguard* contracts. The sentiment throughout the MOD was that competition would help lower acquisition costs and that weapon system contracts should be fixed-price to protect the interest of the government.

The high overhead costs of government were also being challenged. The belief at the time was that private industry could perform many of the roles that were the responsibility of the MOD much more efficiently and effectively. Costs could be further reduced if government were downsized and risks and responsibilities were transferred to industry. Key among the movement to downsize MOD for the new submarine program was the transfer of design authority to the submarine design contractor, a role previously held by the MOD.

One problem with the concept of competition for the new class of submarines was that only one company, VSEL, had developed detailed designs for all UK nuclear submarines and owned the only shipyard that had built the vast majority of those submarines. To entice additional organizations to bid for the design and build of the *Astute* class, the MOD packaged the design of the submarine with the build of the first three boats in the class as well as several years of contractor support of the submarines once they entered service. It hoped that this substantial package of work, and the resulting value, would lead to a stronger competition among various private-sector companies.

The Competition

A draft invitation to tender for the *Astute* contract was announced in October 1993, and a final invitation to tender was provided in July 1994. Four potential contractors had taken part in the studies phase of the B2TC, and these four companies formed themselves into two teams to bid for the contract. GEC Marconi teamed with BMT to submit one bid in June 1995; VSEL teamed with Rolls-Royce and Associates to submit a bid at the same time. VSEL and Rolls-Royce had extensive experience in the detailed design and build of UK nuclear submarines and in the nuclear steam-raising plant (NSRP). GEC Marconi and BMT had little or no experience with UK submarines.

The MOD then started detailed assessments of the two bids. Each bid was graded on the compliance with each requirement, the level of compliance, and the confidence that this level of compliance would be maintained based on the understanding and design evidence offered by the two bidding teams. Cost was a key consideration in the assessment process.

The MOD viewed the GEC Marconi bid as innovative and offering a lower cost. The proposed build strategy relied on a modular build in which large assemblies were put together off the boat and then slid into the submarine rings during construction. This approach had been used in Sweden and was starting to gain foothold in the United States at Electric Boat. GEC Marconi proposed to build sections of the submarine in various shipyards in the north of England where large-scale unemployment could result in new jobs and lower wages. The sections would be shipped to the Devonport dockyard, where nearly all UK submarines were refueled and maintained, for final assembly and fueling of the nuclear reactor. The modular build philosophy and the use of three dimensional computer-aided design (3D CAD) tools would lead to reduced costs compared with the design and build practices used up to that time.

The MOD viewed the VSEL tender less favorably, and it had a higher proposed cost. It was considered conservative with regard to cost risks. The submarine would be built at the Barrow shipyard and included some expected cost growth in the supplier base since the vendors had not designed and built submarine equipment for many years. One interview conducted during this research characterized the VSEL proposal as "an expensive and dull design." The VSEL design met the requirements and, as time would tell, its tender had more cost realism than that of its competitor.

The competition took a different turn in June 1995, when GEC Marconi bought the Barrow shipyard from VSEL. This move added strength to the GEC Marconi bid since the company now had a shipyard with extensive experience in building nuclear submarines. In order to maintain the competition, GEC Marconi agreed to isolate the VSEL bidding team from its team. Based on the innovation and cost of the proposed design, the MOD advised GEC Marconi in December 1995 that it had won the competition and had been selected as preferred bidder.

Contract Negotiations

GEC Marconi's bid price, although lower than the bid price of VSEL, was viewed by the MOD as still too high. It worked with GEC Marconi on the acquisition cost following the "no acceptable price, no contract" approach of the time. This policy required that the government agree to a price within affordability constraints prior to placing a contract.

The MOD developed a large cost element spreadsheet that it populated with return data from the *Vanguard* class and inputs from the subject matter experts within the MOD. However, the modular build approach and the use of 3D CAD software for the design and build of the submarines presented a problem when estimating the cost of the contract. These aspects were new in UK submarine design and build, and no one understood how costs might be affected. The MOD assumed, and the prime contractor agreed in principle, that both approaches would significantly reduce design and build costs. This assumption later proved to be a gross overestimate, especially with respect to savings associated with 3D CAD software. Because the goal was to using existing systems and equipment from the *Vanguard*, *Trafalgar*, and *Swiftsure* classes, the MOD also assumed that only four of the 13 major systems on the submarine would be new.

Despite concerns about the completeness of the *Vanguard* data, the impact of the modular build approach, and the use of 3D CAD software, the cost negotiations led to an agreement on a reduction in cost. GEC Marconi submitted a new bid price in November 1996. Although the new price was several hundred million pounds lower than the original bid, the MOD still believed it was too high. Negotiations on cost continued. With elections coming up, the fear that a new government might cancel the submarine program led to a push to have the contract signed. Although very little of the design for the new submarine was complete, GEC Marconi signed the contract with the MOD on March 14, 1997. The £2.4 billion contract price was significantly less than the original GEC Marconi bid and even less than the cost estimate that the MOD had developed. Our interviews suggest that there should have been a recognition that the agreed-to price was "too good to be true"; ultimately, this proved to be the case.

The contract was structured on a fixed maximum-price basis, with a target cost and incentives for the contractor to reduce costs. Any cost increases over the maximum contract price would be assumed by the contractor. Following the desire for less government involvement and oversight, GEC Marconi received more authority, including formal design authority. To help control costs, the contractor agreed to deliver the first three submarines with the same configuration rather than individually incorporating successive changes, as had been the practice with previous classes. The contract also included eight boat years of contractor logistics support based on the assumption the contractor would reduce in-service costs through design trade-offs.[1] GEC Marconi could make these design trade-offs as long as the result met the requirements in the contract. One casualty of the price negotiations was a lower risk contingency in the target price to pay for unanticipated problems that arose during the design and build of the submarines: The contract had a contingency of only £133 million, down from £451 million in the original GEC Marconi proposal.

The maximum-price contract and the assignment of the prime contractor as design authority greatly limited the ability of the MOD to influence the design of the submarine. The MOD had little authority to mandate certain design details or to argue for changes in the design of the submarine. Any such changes to the design would result in increased risks and contract change costs to the MOD, an outcome that was to be avoided. Therefore, the maximum-price contract basically restricted the ability of the MOD to influence the ultimate design and build of the *Astute*.

The payment clauses in the contract were keyed to such production milestones as volume of installed pipe, electrical cabling, and vent work. This would prove counterproductive: The shipyard would install pipes, cables, or vents before the design was complete in order to receive a milestone payment. This outfitting of the submarine modules before the completion of the design ultimately resulted in the need to rip out

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[1] The in-service support included logistics support for the first several years of the first boat's service life and a smaller number of years for the second and third boats totaling eight years of support.

what had been installed and led to significant additional, unplanned hours for rework.

Although VSEL and GEC Marconi had joined together during the competition, the original opposing bid teams were separated by a firewall until the contract was awarded. When GEC Marconi won, the shipyard at Barrow was able to see the details of the GEC Marconi bid and the contract. At that point, the shipyard realized that the GEC Marconi team did not fully understand the magnitude of the problem it faced and that the terms of the contract it had signed would prove difficult to fulfill.

Changed View on Government Oversight and Furnished Equipment

Astute was the first contract in which the MOD transferred the management of the majority of risks to the prime contractor. This was viewed as allowing the MOD to reduce oversight of the design and build process, leading to lower government overhead costs. Given the trend toward less government involvement in the acquisition process, the MOD believed that GEC Marconi, the prime contractor, could better control the shipbuilder. Ultimately, to reduce build costs, the prime contractor could even hold competitions among various shipbuilders for specific hull work packages. Therefore, the contract required separation between the prime contractor, GEC Marconi-Major Prime Contracts, located in Farnborough outside of London; and the shipbuilder, GEC Marine in Barrow, during the competition. As we discuss further in the next chapter, this separation led to coordination problems during the design and build of the *Astute*.

Prior to *Astute*, the MOD had provided submarine equipment, including the NSRP and reactor core, to shipbuilders as GFE. The new contract eliminated GFE except for a few pieces of classified equipment. This was done under the belief that the prime contractor could reduce costs through competition for the various systems, equipment, and parts. The prime contractor was also pushing for more control over the conduct of the project. One major impact of this change was to assign Rolls-Royce, the design authority and builder of the NSRP, as a subcontractor to GEC Marconi. Interviews suggested that Rolls-Royce did not totally agree with this contractor-subcontractor relationship, leading to friction between GEC Marconi and Rolls-Royce.

In addition to providing the NSRP for new submarines, Rolls-Royce had contracts to support submarines already in service, including those going through midlife refueling. In these contracts, Rolls-Royce was the prime contractor and was viewed as a Tier 1 supplier. Its relegation to a Tier 2 supplier for the *Astute* without a direct connection to the MOD was viewed by Rolls-Royce as a downgrade in authority and status. The issue of how to contract with Rolls-Royce—as a prime contractor for the NSRP or as a subcontractor to the shipbuilder—remains open to this day.

Although many of the risks in managing the program were transferred to the prime contractor, the MOD recognized that it had to retain certain risks. Because the prime contractor had no prior experience in the design or procurement of an NSRP, the contract (Clause 72N) established the MOD as the authority ultimately responsible for nuclear safety. The contract also indemnified the prime contractor with respect to the fissile material used as the energy source for the submarine (Clause 71). Furthermore, the MOD basically insures the boats against loss, damage, or liability (Clause 16) and will pay for the costs of safety upgrades mandated by regulatory authorities (Clause 61).

The First Few Years

For a number of reasons, the design of the *Astute* did not progress smoothly after the contract was signed. These reasons, which we discuss in greater detail in the next chapter, included the following:

- There was no planning for the transfer of responsibilities from the MOD to the prime contractor.
- Numerous skilled submarine design and build personnel were reaching retirement age and were leaving both the MOD and the private sector.

- Management of the prime contractor changed when British Aerospace bought GEC Marconi in November 1999 and created BAE Systems.
- The physical separation and cultural differences between the prime contract office and the shipyard led to a lack of cooperation and coordination.
- Personnel exiting the submarine community and the change in management of the prime contractor led to numerous changes in leadership at the prime contractor and at the shipyard.
- The problems associated with using a complex software environment to design a submarine for the first time was underestimated.
- The philosophy of the MOD to let industry assume the design authority role led to an "eyes on, hands off" policy that deliberately isolated the MOD from the problems faced by the prime contractor.
- Both the MOD and the prime contractor underestimated the impact of the long gap between the design of the *Vanguard* and the start of the *Astute*.

Several other factors, which were beyond the control of the MOD or BAE Systems, also contributed to the cost growth. The inflation rates assumed with the original contract proved to underestimate the growth of inflation that occurred during the early years of the contract. Furthermore, BAE Systems overestimated the volume of surface ship work that would take place in the shipyard, causing an increase in the overhead rates applied to the *Astute* contract. Finally, both the MOD and BAE Systems underestimated the level of cost and schedule risk inherent in the design and build of *Astute* (mostly due to factors mentioned above) and did not provision properly for addressing those risks.

All of these problems led to a significant slowdown in the design of the *Astute*. Because the prime contractor wanted to meet contract schedules, construction of the lead ship started when very little of the design was complete. The problems surfaced in August 2002 when it was determined that the program was more than three years late and several hundred million pounds over budget.

The Contract Is Renegotiated

A program review of the problems led to the recognition that both the MOD and industry had underestimated the difficulties of transferring design authority to an inexperienced contractor, especially with so much churn in the MOD and in industry. The MOD realized that it had to take back some of the risks it had transferred to the prime contractor and change its level of oversight and involvement in the program. It worked closely with BAE Systems to reset the contract price and schedule and to establish a new acquisition environment.

A contract modification was signed in December 2003 that removed the cost ceiling from the prime contract and specified a maximum level of cost liability for the prime contractor. The first boat, *Astute*, would continue on a target cost-plus-incentive-fee arrangement, while boats 2 and 3 would be priced in the future on an actual cost basis. Incentives were added to encourage the contractor to reduce costs. The MOD added approximately £430 million to the contract and BAE Systems agreed to assume approximately £250 million of the cost overrun.

The contract price was again increased by £580 million in 2007 due to increased inflationary costs and some unfulfilled schedule assumptions at the Barrow shipyard. There was also an agreement on a target cost-plus-incentive fee, with a maximum price for both boats 2 and 3. The procurement of boat 4 was approved in May 2007, and subsequent funding for long-lead items was approved for boat 5. In March 2010, the MOD gave BAE Systems approval to build boat 5 and purchase long-lead items for boat 6.

Present Situation

The contract specifics were adjusted significantly when the contract was renegotiated in 2003. Other changes have been subsequently made to the relationships between the MOD and the prime contractor. A design management arrangement recognizes that the technical design is done by the prime contractor but that design authority for the first three boats in the class will transfer to the MOD once they enter service. Also, design authority for subsequent boats in the class will now reside with the MOD during build. With these changes, the MOD has again retained the responsibility for making decisions on the design and build of the submarines that affect cost or performance.

The interim cost plus arrangements for the second and third boats in the class were converted to a firm-price, target cost-plus-incentive-fee contract in 2007. The following boats will be contracted separately through an approvals and contract arrangement unique to each submarine. These follow-on boats (boat 4 through boat 7) will be contracted on the basis of a design specification as opposed to the requirements-based specification used for the first three boats. In many ways, this is a return to how contracts were established prior to *Astute*.

HMS *Astute* was launched in June 2007; she left the Barrow shipyard for trials in November 2009. The submarine was commissioned into the Royal Navy on August 27, 2010, and, as of this writing, is undergoing its full testing and trials.

The UK National Audit Office Major Projects Report for 2009 showed that the currently estimated cost for the *Astute* contract was £1.35 billion (or 53 percent) above the original contract price and that the delivery of the first boat was 57 months late.[2] Currently, the MOD estimates that the total costs for a seven-boat *Astute* class will be on the order of £9 billion, with approximately £4.5 billion spent to date.

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2 NAO, 2009.

CHAPTER FIVE

Designing and Building the *Astute*

This chapter describes the design and build of the *Astute*. It focuses on factors and decisions that impacted the overall management of the program, not on technical decisions made during the design and build process. The chapter first looks at the various factors that led to problems at the start of the *Astute* design and build effort. It concludes with a discussion of the difficulties that arose during the build of the submarines and their testing and commissioning.

Stumbling at the Start

The design effort for *Astute* began in earnest with the signing of the contract in March 1997. Earlier feasibility and trade-off studies provided some concept of what the *Astute* would look like. With its roots in the B2TC program, the design effort was originally guided by the integration of systems used on current classes of submarines or planned for future introduction into the flotilla. What at first was believed to be a modest upgrade to the *Trafalgar* design proved to be more extensive. The reactor from the *Vanguard* class required a wider and longer hull than the *Trafalgar*. At the same time, the requirement for lower radiated signatures than that of the *Trafalgar* led to a more complex design. Both the prime contractor and the MOD greatly underestimated the complexity associated with the integration effort. Also, a number of unanticipated factors or overly optimistic assumptions led to problems early in the design phase.

Although the prime contractor was to assume the risks previously managed by the MOD, the transfer of these responsibilities was not well thought out or planned. The general assumption was that the downsizing of government and the increased responsibilities of the private sector would lead to skilled personnel migrating from the public to the private sector. This did not happen because many experienced people had already retired or changed career fields.

At the prime contractor, many people who participated in the contract proposal and negotiations moved on to other projects. GEC Marconi, having never designed a submarine, had few technical resources on which to build the new project team. Another key factor that slowed the design effort was the physical separation of the prime contractor design team in Farnborough from designers and engineers at the shipyard in Barrow. This separation, coupled with the tensions between management at GEC and the shipyard over the new ownership, meant that skilled shipyard designers who had worked on the *Vanguard* class were not integrated into the prime contractor design team.[1]

There was an additional churn in the management of the prime contractor and of the shipyard when British Aerospace bought GEC Marconi in November 1999 and formed BAE Systems. Ownership of the shipyard had changed three times in less than five years, resulting in numerous shipyard managers over a short period of time. Many skilled project managers at the shipyard left during these transitions.

Downsizing at MOD led to a loss in experience and technical knowledge. The philosophy of "eyes on, hands off" was based on the prime contractor being responsible for itself and being able to deliver a submarine designed and built to the requirements and specifications. The MOD on-site presence at the shipyard was reduced to four people from the staff of 50 present during the *Vanguard* program. Furthermore, there was very little involvement from the experienced operators and maintainers of the Royal Navy. Overall, the MOD was rapidly losing its ability to be an informed and intelligent customer.

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[1] When the contract was renegotiated, one of the stipulations was that the design team be moved to Barrow and co-located with the shipyard designers and engineers.

Both industry and the MOD underestimated the impact of the gap on designing and building nuclear submarines in the UK. It had been almost 20 years since the *Vanguard* was designed and several years since the last submarine in the *Vanguard* class was delivered. Whereas the United States chose to proceed with the *Seawolf* class design and build, the UK decided to change from an ambitious Cold War platform to a more affordable upgrade of existing submarine classes. This decision further delayed the requirements and contracting processes for the new submarine and in effect added an additional decade to the start of a new submarine design.

Employment at the shipyard dropped from more than 13,000 to approximately 3,000. Although most of the workers who departed were craftsmen skilled in building submarines, many designers and engineers had also retired or moved to other careers. The shipyard filled the submarine design and construction void by designing and building surface ships. When the *Astute* contract was awarded, the shipyard had projects for a new oiler and new amphibious ships. Although these projects sustained some of the workforce, designing and building surface ships, especially relatively simple surface ships, was very different from designing and building nuclear submarines. Also, the design resources that remained at Barrow were split among three different projects—the oiler, the amphibious ships, and the *Astute*. The diversion to the surface ship work reduced even further the number of designers and engineers available to support the *Astute* program.

As the MOD was losing its ability to be an intelligent customer, the submarine industrial base was also losing its ability to be an intelligent provider. Skills and expertise were lost throughout the submarine enterprise, including the vendor base that provided parts and equipment. The gap between *Vanguard* and *Astute* had a large effect on the suppliers. It had been assumed that many of the parts from the *Vanguard* and *Trafalgar* classes would be used for the new class. However, most of this legacy equipment was no longer available. Many approved vendors had left the industry when orders stopped, and reestablishing suitable vendors took time and caused further delays in the design of the *Astute*.

The loss of expertise and the changing management at the prime contractor and the MOD led to other oversights that greatly affected the subsequent design and build program. The design process proceeded with almost no involvement from the builders at the shipyard, the operational planners in the Royal Navy, or the maintainers at the dockyards. The interactions among operators, builders, maintainers, and designers that had existed in prior submarine programs were entirely missing during the early design stages of the *Astute*.

Furthermore, an integrated master plan to design and build the submarine was never fully developed, and there was no process in place to track progress. The lack of a master plan caused disconnects in the design process and led to a decision to start building the submarine before the design was fully mature. The lack of a system to track progress meant that no one really understood what had been accomplished and how far behind schedule the program was.

How changes to the contract were managed also delayed the design process. As mentioned, the contract included a mix of high-level requirements and detailed specifications. At times, the 13,000 or so technical requirements were confusing or conflicting. Numerous issues arose concerning changes or concessions to the contract requirements. The MOD, having granted design authority to the prime contractor, was reluctant, or ill equipped to make timely decisions on proposed changes and concessions. Furthermore, the MOD did not want any changes that would lead to increased contract costs. The prime contractor, with few experienced technical personnel, was also not prepared to make decisions. As a result, many design decisions did not get made or were not timely. This also caused delays in completing the design.

As problems mounted during the early years of the program, the MOD had little or no insight to the resulting impact on the cost and schedule of the project. The "eyes on, hands off" approach of the MOD and the lack of an integrated master plan against which to track progress, buoyed by the belief there was a maximum-price contract, led to almost no oversight at the shipyard and little interactions with the design team. It is not clear what the MOD could have done if it had been aware of the problems faced by the prime contractor. Transferring design authority left the MOD with no authority or mechanism to challenge the steps taken, or not taken, by the submarine designer and builder.

Design Software Problems

One large factor that contributed to delays in the design schedule and increases in contract costs was the use of 3D CAD software. During contract negotiations, the MOD had assumed that using modern design software would significantly reduce man-hours. However, this proved unfounded. The software actually increased costs rather than lowered them.

Previous submarine designs relied on two-dimensional design tools with detailed drawings produced by hundreds of draftsmen (now referred to as designers). Wooden mock-ups also played a key role in understanding the layout of the submarine and the access routes for pipes and cables.[2] These mock-ups, which were not developed for the *Astute* design, also allowed the shipbuilder to understand physical integration and human factor issues.

The Barrow shipyard had started to use 3D CAD tools for the design of the auxiliary oiler and the amphibious ships. However, the ship-based design tool used for these relatively simple designs did not come close to the design tool needed for a complex, densely packed nuclear submarine.

The assumption by the MOD and the prime contractor was that the software could be removed from the box, installed on the computers, and used without delay for designing *Astute*. As General Dynamics Electric Boat learned when it started using a 3D CAD tool for submarine design, extensive modifications are needed to fit a generic design tool to a specific program and shipyard. Compounding the problem was the shortage of knowledgeable designers in the UK with experience in using 3D CAD tools. The growing pains associated with the 3D CAD design environment resulted in having few drawings complete when the decision was made to start the construction of the *Astute*.

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2 A one-fifth scale plastic model was also built for the *Vanguard* class.

The extent of the problems and their effect on program cost and schedule began to emerge in mid-2002. Estimating that the program was at least three years late and several hundred million pounds over budget, the MOD recognized the need for significant changes. The contract was renegotiated, and the MOD began to take on a larger oversight and decisionmaking role. Also, the Programme Management Team turned to the United States for help in producing the detail design drawings for the vessel.

Electric Boat Provides Assistance

In 2003, the MOD solicited the help of General Dynamics Electric Boat through a foreign military sales agreement with the United States. Approximately 100 experienced Electric Boat designers and managers—about a dozen of them on-site at the Barrow shipyard and the rest back in the United States—began to interact with BAE Systems and help with the design effort. The Electric Boat designers helped set up the design tool and processes at the prime contractor and started to develop the detailed drawings necessary for construction through a secure data link between Barrow and Groton.

Electric Boat also began to transfer production knowledge to the shipyard. It passed along modular construction techniques that it had developed for the *Ohio* and *Virginia* classes, including the advanced outfitting of the submarine rings using a vertical method rather than the traditional horizontal process. It helped develop an integrated master plan through a separate contract with the MOD's integrated project team, which further developed the earned value management system being used to track program progress. Eventually, an Electric Boat employee was assigned as the *Astute* Project Director with BAE Systems at the Barrow shipyard responsible for all aspects of delivery.

Through the interactions with Electric Boat, the growing expertise of the prime contractor, and the increased involvement of MOD, the design portion of the *Astute* program started to make progress.

Building the Boats

As a result of the gap in nuclear submarine production, the Barrow shipyard lacked expertise in its nuclear submarine-builder workforce. Shipyard personnel did not possess a thorough knowledge of the detailed build processes that enable efficient submarine construction. Knowledge about managing the complex build process and ensuring quality construction had evaporated. During the gap, production practices had not advanced as they had in the United States and other countries, and the processes at Barrow still resulted in little advanced outfitting of the major modules that would form the submarine. For example, the "old" practice was that no pipe was longer than two meters, the length a worker could carry down into the submarine during build. This practice resulted in numerous welds.

The 3D CAD environment would ultimately produce very detailed drawings on how to build the submarine modules. These drawings included information on steps and processes to use during the build and outfitting of the modules. This level of detail was new to the craftsmen at Barrow, who previously had worked with drawings that contained little detail and used their years of submarine building experience to decide how to actually build what was represented in the drawings. This conflict between the detail in the drawings and the previous practices of the Barrow workers led to further confusion and delays in the build program while the production workforce learned to follow the increased drawing detail and the drawings were tailored to meet production workforce requirements.

The build proceeded in a somewhat uncoordinated fashion while the systems required to plan and monitor progress across the complex program were developed. These systems were greatly improved through application of U.S. knowledge and experience, which saw the development of the integrated master schedule. Because the build started in an uncoordinated fashion before the detailed design drawings were complete, the initial *Astute* modules would later require significant rework, adding to increased cost and schedule delays.

Testing and Commissioning

As with the design and build, the testing and commissioning of the *Astute* was not without problems and delays. Again, the impact of the gap was felt. Barrow had not tested and commissioned a nuclear submarine in approximately ten years, and it had been almost 17 years since the testing and commissioning of a first-of-class. The shipyard did not anticipate the challenges it would face with the *Astute*.

An effective testing and commissioning program had not been established when the design requirements for the platform were set. There was no link between a stated requirement and how it would be tested. This disconnect was in part due to the changing roles and responsibilities of the MOD. Prior to *Astute*, the MOD and the Royal Navy had been responsible for testing and commissioning the boat. With *Astute*, this role was transferred to the prime contractor, which was ill prepared to accept it. Furthermore, although the concept of progressively testing parts, equipment, and systems was in place, it required improvement to provide an effective overall submarine testing program.

With hindsight, some of these problems could have been overcome if the organizations that provided in-service dockyard support to the UK submarine flotilla had been involved. Devonport Management Limited, later bought by Babcock, ran the dockyard at Plymouth, where refueling and major repairs on all UK nuclear submarines was performed. Unfortunately, the experienced dockyard personnel at Plymouth were not integrated with the BAE Systems testing and commissioning activities.[3] This problem is now being addressed through the Submarine Enterprise Performance Programme (SEPP), which is developing better cooperation between key submarine suppliers (BAE Systems, Babcock, and Rolls Royce) and the MOD.

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3 With the privatization of the majority of the Devonport dockyard and the establishment of Devonport Management Limited, these experienced personnel were now in a different private company, which was not considered by many to be in competition with BAE Systems for submarine work.

The loss of knowledge and the lack of a structured test program resulted in delays and mishaps after the submarine was launched in June 2007.[4]

Current Status

The build of the *Astute*-class submarines has been improved through various management initiatives implemented by the MOD and BAE Systems. For example, the shipyard has started a program called Construction Vision, which aims to reduce the down-time associated with getting parts and tools to the modules in the Devonshire Dock Hall. There are now yellow towers next to each submarine that contain workshops, the foreman's office, and the tools and equipment needed during the build. Production workers are recognized as the key to reducing man-hours to build a submarine. Thus, if there is a question about a drawing, a draftsman will go to a production worker rather than a worker going to a draftsman.

Recognizing that it could not transfer many of the risks to the prime contractor and that it would have to assume a more "hands-on" approach, the MOD in 2003 increased its oversight presence at Barrow. There are now more than 30 MOD personnel at Barrow on the *Astute* program who interact with the shipyard designers and builders, help make decisions on changes to the contract requirements, and provide feedback to the MOD on the status of the program. Relationships between the MOD and the prime contractor have also improved greatly. The MOD is now fully integrated with the prime contractor team and is playing a decisionmaking role when issues arise during design and build.

Management of the supply chain has also been greatly improved. The Key Supplier Forum was created in January 2006 with quarterly

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[4] In September 2007, an oil pump failed on two turbine generators, causing them to run "metal-on-metal" and resulting in damage to the bearings. Although it was originally believed that a hole would have to be cut in the pressure hull to replace the equipment, a process was developed to repair the damage without removing the equipment. This solution saved time and money, but the oil pump mishap further delayed the delivery of the *Astute*.

meetings to assess the health of the key suppliers (ten vendors provide 70 percent of the material value of the submarines). The MOD and the prime contractor work with these suppliers to provide an overview of future programs and the challenges they all face. The suppliers also share best practices and work together to reduce the cost of the equipment and material provided for the build of the *Astute* class.

The MOD and BAE Systems also worked jointly on reducing the costs for boats 4 through 7. This effort took advantage of lessons learned during the U.S. *Virginia* program to reduce the build costs by several million dollars per boat by focusing on the combat system and by reducing the number of parts and the complexity of several other systems on *Astute*.

Although it had a few unresolved issues and had not yet completed all its tests and trials, HMS *Astute* was commissioned into the Royal Navy on August 27, 2010.[5] HMS *Ambush*, the second boat in the *Astute* class, was launched in January 2011 and will enter service approximately two years later. Boats 3 to 5 are currently under construction with long-lead orders placed for boat 6.

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5 While the *Astute*-class submarine build has improved since the start of the program, many individuals we interviewed suggested that there are still issues to be resolved and that lessons from building the first boat are not being incorporated in subsequent boats. One concern is that changes made on the first boat, so that it would be acceptable to the MOD after issues were identified during testing and commissioning, have not yet been fully incorporated into the production of subsequent boats. These change requests should have been resolved and the needed changes made for future boats in the class.

CHAPTER SIX

Integrated Logistics Support

Up through the *Vanguard* class, the Royal Navy's submarines were maintained in service at either the Faslane operating base or the dockyards in Rosyth or Plymouth. Faslane could accomplish moderate levels of submarine maintenance; the dockyards performed all refuelings and major maintenance.[1] During this time, the management and eventual ownership of the dockyards transitioned from the government to the private sector. Regardless of ownership, the various organizations involved with in-service support developed knowledge and expertise on submarine upkeep, and the MOD was a major partner in the submarine upkeep process. The shipbuilder at Barrow provided little or no in-service support.

The *Astute* contract sought to change that traditional approach by including several boat years of contractor support for the first three boats in the class. This initial support period would hopefully lead to a longer contract to support the *Astute* class. The assumption behind this change was that the contractor would design the submarine to reduce in-service costs. The prime contractor would demonstrate the reliability of the various systems and describe the maintenance plan and the resulting in-service support costs. The focus on total ownership costs, from design to decommissioning, was important because in-service costs for a submarine typically greatly exceed the original acquisition cost.

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[1] Nuclear submarine refueling and major maintenance is now performed only at the Devonport Dockyard in Plymouth.

During the conceptual design phase, the contractor considered design changes that could reduce in-service support costs. For example, it proposed that a larger hull diameter (at least partially due to the size of the NSRP) would facilitate equipment removal and repair. Unfortunately, because of schedule delays and cost increases in the submarine's design and build, in-service support took somewhat of a backseat to the emerging program problems. As with many new programs, the focus was on controlling near-term acquisition costs; in-service support costs would occur several years in the future. Also, the prime contractor lacked the expertise to fully understand in-service support requirements, risks, and costs. As a result, when the build contract was placed in 1997, it was agreed that the elements of cost associated with ILS would be established at a later date. When the original contract was renegotiated in 2003, the clause that included several years of in-service support was removed because the prime contractor was still unable (or unwilling) to quantify the risk and offer a price. Therefore, the MOD had to revert to the traditional approach to in-service support.

The result was that the prime contractor focused on a submarine that could be produced at the lowest possible cost rather than on one that could be supported at a reduced cost, an original contract requirement. Many design choices will likely make support of the submarine more difficult and lead to increased in-service costs. For example, removal routes for major equipment were not always properly planned before cable or pipe was installed in the submarine, potentially making it necessary to either remove other equipment or make cuts in pipe work before major components can be removed for repair. The pressure to reduce further schedule delays and cost overruns led to construction decisions before in-service support risks could be identified and managed properly. Furthermore, BAE Systems had little interaction with the submarine maintainers (i.e., Babcock and Rolls-Royce) during the design of the *Astute* and therefore did not take advantage of their knowledge and expertise concerning what goes into a supportable submarine design.

Although in-service support was not adequately addressed during the design phase, several individuals we interviewed suggested that the *Astute* will have a better maintenance package than previous UK submarines. BAE Systems has analyzed each system on the submarine down to the component level and is using the MOD policy of condition-based maintenance philosophy to monitor those components. It is breaking each phase of the maintenance plan into a set of tasks, all maintained in a large database. Also, the support goal is for more maintenance to be accomplished while the submarine is in the water, reducing the need to dock the submarine for maintenance and upkeep.

The in-service support of all UK in-service submarines should be enhanced by SEPP, a proposed partnership among the MOD, Babcock, BAE Systems, and Rolls-Royce. SEPP defines the roles and responsibilities of the partners and develops a common commercial construct through the life of a submarine. The partnership aims to improve affordability and availability of submarine support. SEPP is an integral part of the *Successor* program, the follow-on to the *Vanguard* class of ballistic missile submarines, in which a level of collaboration and partnering, not seen during the *Astute* program, is viewed as key to program success.

Although it has reverted to the support approach in place before the *Astute* program, the MOD still faces challenges in the planning for the upkeep and maintenance of the submarines. There must be an effective exchange of the necessary data from BAE Systems to the support organizations so that maintenance planning can proceed. Of course, time will tell how the costs for supporting the *Astute*-class submarines will compare to the costs of supporting the *Trafalgar* and *Vanguard* submarines, once they enter service. One positive fact is the extended life of the nuclear reactor core, which will preclude an extensive and expensive midlife refueling.

CHAPTER SEVEN

Lessons Identified from the *Astute* Program

The various reports and documents that have attempted to understand the source of the problems faced by the *Astute* program list numerous "lessons."[1] The majority of these lessons can be attributed to two key events: the end of the Cold War and the decision to reduce government spending. These events led to a substantial gap in designing and building nuclear submarines in the UK, with both the private sector and the MOD greatly underestimating the ultimate impact on program cost and schedule risk. Both parties also underestimated the impact of the MOD shifting responsibilities to a private sector that was ill prepared to assume them.

In this environment, both the MOD and the private sector made decisions without fully understanding their impact. For example, the MOD assumed, and the private sector agreed in principle, that the use of 3D CAD software would lead to a significant reduction in the man-hours, and therefore the costs, needed to design and build the submarine. Also, the MOD assumed that a maximum-price contract to design the submarine, build the first three boats in the class, and provide several years of in-service contractor support would incentivize the prime contractor and protect against cost overruns. Both assumptions proved ill founded.

The important lessons from the *Astute* program are not that bad decisions were made. Decisions must be judged in the context of the time they were made. What may seem in hindsight like a bad decision

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1 Several of the people we interviewed provided us with their official or unofficial list of lessons from the *Astute*.

may actually have been appropriate at the time. For example, the gap between submarine programs certainly had an adverse impact on *Astute* outcomes. But the lesson is not necessarily to avoid gaps but to understand the potential impact of a gap and incorporate that understanding into the decisionmaking process. The costs of eliminating gaps in submarine design and construction must be weighed against the cost and schedule implications of starting a new program after a gap. A similar observation can be made about the use of 3D CAD software. Using modern design tools can certainly have a positive impact on program design and construction, and moving to a modern 3D CAD tool was probably the right decision. Nevertheless, there are cost and schedule implications of moving to a new design tool. Underestimating the difficulty of conversion was the real problem.

It appears that both the MOD and the prime contractor have learned from their previous actions and decisions. The MOD has taken back certain responsibilities and has established a partnership with the prime contractor. Although there are challenges ahead, the program appears to be moving in the right directions. It is important, however, that the lessons from the *Astute* program, both good and bad, be recorded for future submarine program managers. That is the objective of this chapter.

Lessons are appropriate at two levels—the relatively short-term and narrow focus of a specific program and the long-term, future strategic visions of the MOD for the submarine force and the industrial base. To be useful, lessons should be categorized along different dimensions, although many can fall into multiple categorizations.

In this chapter, we first describe lessons learned at the strategic level. We go on to list the lessons at the program level in terms of setting a new submarine's operational requirements, putting contracts in place and establishing contractual relationships, designing and building the vessel, and planning for ILS.

Top-Level Strategic Lessons

The top-level strategic lessons are global in nature and span all programs that design and build new platforms or support the Royal Navy submarine flotilla. They are appropriate for senior management in the MOD and the Royal Navy, including the Director Submarines. The lessons discuss the need to be an intelligent and informed customer, the assignment of roles and responsibilities to the government and to the private sector, the growth of informed and experienced future program managers, and the management of the nuclear submarine industrial base, including the design organizations, shipyards, and vendors that provide nuclear submarine design, construction, and support.

The MOD must be an intelligent and informed customer. If the program is to be successful, the MOD must be both an intelligent customer who understands the implications of various decisions and an informed customer who knows the status of programs and where corrections are needed. The MOD should not be influenced by briefing slides that promise great advantages of new processes or systems without the expertise to fully evaluate those new processes or systems. At the start of the *Astute* program, the MOD was beginning to lose both of these attributes. Under pressure to reduce government spending, submarine-related organizations were disbanded or greatly reduced in capability. Realizing that it could not take a hands-off approach, the MOD has now begun rebuilding lost technical and managerial knowledge and oversight. It is important for future programs that the MOD's technical and managerial knowledge and oversight continue to allow it to be an informed and intelligent customer for nuclear submarines. Maintaining these capabilities will be challenging because defense budgets will continue to face pressures and gaps may exist in the start of new submarine programs. These challenges can best be met through learning the next three lessons.

Roles and responsibilities must be delineated between the MOD, the prime contractor, and subcontractors. The start of the *Astute* program saw the movement to the private sector of many roles and responsibilities previously held by the MOD. This also resulted in attempts to transfer the risks associated with those responsibilities.[2] As an example, the role of design authority,[3] which had been filled by the MOD in previous programs, was assigned to the prime contractor for the *Astute* program. When the problems began to surface in 2002, the MOD realized that it had to hold the responsibility for certain risks and, with the restructuring of the contract, took back some of the responsibilities and risks that it passed to the prime contractor.

Certain risks remain the sole responsibility of the MOD. These include obtaining the desired military performance from the new submarine and ensuring safety of operations. The government should also strive to deliver the overall program on time and within budget. It shares this risk with the prime contractor and must use all available tools to monitor contract performance, interact with the contractor, and optimally incentivize the builder to meet schedule and cost milestones.[4]

It is, therefore, important that the MOD establish the proper roles, responsibilities and risks that it can assume or assign to the prime contractor and the major subcontractors. At a minimum, the MOD should assume the following responsibilities:

- Set the operational requirements for the new submarine by working with industry, the Royal Navy, and other stakeholders.
- Assess safety and technical issues in accordance with the MOD's policy that safety risks should be as low as reasonably practicable.

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[2] The maximum-price contract also tied the hands of the MOD. It was reluctant to impose conditions or mandate changes to the design of the submarine for fear they would lead to cost increases.

[3] With the transfer of design authority to the prime contractor, the MOD moved the responsibility for managing technical and financial risks to industry. In practice, when these risks materialized, the MOD realized that the consequences of these risks (program lateness and the need to renegotiate program costs) would still need to be borne by the MOD.

[4] The prime contractor also faces risks if it does not efficiently deliver a cost-effective submarine; however, while the prime contractor may go out of business, the MOD is still responsible for the defense of the nation. Also, there are risks to the prime contractor if the submarine is unsafe, but the MOD has always been ultimately responsible for the health and well being of the sailors. For *Astute* and prior submarines, the MOD has acted as duty holder with final approval authority for all product safety cases.

- Oversee and monitor the design process to ensure requirements and standards are met and, when necessary, provide concessions to those requirements.[5]
- Oversee and monitor the build process to ensure that the submarines are delivered on schedule and at projected cost.
- Assure submarine construction quality and acceptability by developing a testing, commissioning, and acceptance process that ensures the submarines have been delivered to design intent.
- Ensure through-life submarine safety and maintenance and post-delivery control of design intent.

The design authority responsibility should have remained with the MOD for the *Astute* program. Although this responsibility was assigned initially to the prime contractor during the design and build of the first three *Astute*-class submarines, it will revert to the MOD once those submarines enter service and will remain with the MOD for the subsequent boats in the class. Although the MOD and the prime contractor attempted to formulate a process to accommodate this transfer of risk, ultimately the acceptance of the ship as safe for operations is the responsibility of the MOD. The MOD must therefore assume the risks associated with the design authority process from the start of a new program.

Overall, the MOD and the prime contractor must establish a collegial and interactive partnership in which information and issues flow freely. Effective interactions will help the MOD better understand the product it will receive and help the prime contractor develop a product that better fits the MOD's needs. In some cases, the MOD must assume risks; in other cases, the prime contractor should assume risks. Finally, where necessary, risks should be shared between the MOD and the prime contractor.

Knowledgeable and experienced personnel must be available to fill management, oversight, and technical support positions. Successful programs have experienced and knowledgeable people in key management,

[5] Standards must be regularly reviewed and updated as needed. The MOD and prime contractor should agree on the standards at the start of the program.

oversight, and technical positions. Growing future program managers and technical personnel within the MOD and the Royal Navy requires planning and implementation far in advance of any one specific program. Promising officers and civilian personnel must be identified early in their careers and provided suitable education and assignments to ongoing programs at a junior management level. Assigning people who have "earned their stripes" on the *Astute* program is critical to the success of the *Successor* program.

Just as knowledgeable and experienced people are needed in the MOD and the Royal Navy, experience and knowledge is also needed at the prime contractor and major subcontractors. The rapid change in ownership of the company that had designed and built the vast majority of the Royal Navy's nuclear submarines, coupled with the movement of key people from the submarine sector to retirement or other career fields, resulted in a lack of experienced managers and technicians at the prime contractor. The prime contractor also has the responsibility to grow and maintain experienced managers and technical leaders.

Another important aspect is continuity in leadership and in team composition. Managers, leaders, and team members in the MOD, the Royal Navy, and the industrial base should stay within a program for a sufficient amount of time to gain knowledge of the program and maintain goals.[6] Changing leadership, which occurred frequently within the prime contractor for the *Astute* program, can introduce managers with different goals and strategies that could be detrimental to the success of a program. Experienced leaders should be replaced with other personnel knowledgeable of and experienced in nuclear submarine programs.

The MOD and the Royal Navy must take a long-term, strategic view of the submarine force and the industrial base. A specific program is only one step in developing a successful military capability and in sustaining the industrial base capacity that is needed to provide and support that capability. Taking a long-term view means understanding how a specific program nurtures and feeds the overall strategic plan for the submarine force.

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6 Smart Acquisition suggested that personnel be assigned to a program for a minimum of four years.

One big contributor to the problems faced by the *Astute* program was the substantial gap between design and build of the *Vanguard* class and the start of the *Astute* program. This led to a situation in which submarine design and build skills atrophied in the United Kingdom, resulting in a costlier and lengthier *Astute* procurement effort. The issue is not that the gap should have been avoided, but that the MOD neither anticipated the impact of the gap nor factored into the cost and schedule estimates the need to rebuild industrial base capability.

There are likely to be similar gaps in the future due to constrained defense budgets and the long operational lives of submarines. The MOD must address whether to sustain sufficient resources during such gaps or to allow them to atrophy again and be reconstituted when needed. There are costs and benefits to each approach.[7] In addressing these options, the MOD must be prepared to estimate the implications of a gap on future programs as well as the cost of sustaining key resources, skills, and experiences during a gap.

Nurturing design and build skills goes beyond the prime contractor and the shipyard. Skills and expertise also must be sustained at MOD technical organizations that support both new and in-service submarines. A new submarine does not remain static once it is delivered to the force. Technologies change, new capabilities are needed, new threats emerge and evolve, all of which require maintaining a technology/capability edge and updating platforms with new technologies and new capabilities. Sustaining submarine design, build, and technical support resources will be a challenge in the future, but it is a challenge the MOD must face.

Setting Operational Requirements

One important aspect of a new program involves the decisions made very early regarding the desired operational performance of the new submarine. These early decisions influence the technology risk for the program and the likelihood that the program will succeed. The oper-

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7 See Schank et al., 2005a, 2005b, 2007.

ational requirements for the platform are translated to performance specifications that lead to technology choices to achieve the desired performance. The operational requirements, especially the desired operational availability, also impact ILS planning.

At a high level, the *Astute* program[8] had the operational goal of performing better than *Trafalgar* with only a slight increase in cost. Its performance goals relied on next-generation evolutions from existing systems and technologies.[9] Major systems, such as the PWR2 nuclear reactor and an upgraded combat system,[10] were either specified or strongly encouraged. Although the performance goals were only a modest step beyond the performance of submarines in service, the goal of lower cost proved to be more revolutionary in nature.

The MOD may have been able to achieve lower cost in a stable environment supported by clearly defined roles and a robust industrial base. However, the gap in design and build and the shifting of responsibilities and risks led to increasing rather than decreasing costs. The problems faced by the *Astute* program had little to do with setting the operational requirements. There are, however, still some important lessons for future program managers.

Operational requirements must be clearly stated and be an appropriate mix of key performance requirements and technical standards. The contract requirements for *Astute* were a mix of high-level performance attributes (e.g., speeds, signatures) and thousands of detailed requirements, technical specifications, and standards. The myriad of requirements, specifications, and standards were at times conflicting and difficult to interpret. The MOD has recognized the complexity of the initial contract requirements and is using performance-based specifications for the first three boats in the class. For the fourth and following boats, a product build and test specification forms the basis of the contract.

8 Then known as B2TC.

9 Interviews suggest that electrical versus mechanical actuation was really the only area where new technology was needed.

10 Upgraded from *Swiftsure* and *Trafalgar*.

The operational requirements must be clearly stated as the desired performance of the submarine in various key areas. Key areas include speed, payload, and signatures, as well as other key characteristics such as crew size and operational availability. These performance requirements must be backed with some level of technical specifications, especially in the area of safety. Changing requirements as a program progresses can lead to cost overruns and schedule delays. It is important to set the requirements early and avoid changing those requirements unless there is a clear and compelling need. When requirements are changed, the program office must understand the cost and schedule implications of the change.

Requirements specification is a difficult balance of staying within known and approved standards and allowing innovation in the design, especially to reduce costs. The operational requirements should be supported by standards that relate to different functional systems. The program should allow the prime contractor to challenge standards and specifications if it can prove that the change will reduce cost or improve performance with the same or less risk. The MOD must have knowledgeable and experienced personnel to objectively evaluate contractor's change proposals.

Involve all appropriate organizations in setting operational requirements. One shortfall of the *Astute* program was that it failed to appropriately involve all knowledgeable organizations in setting requirements. In some cases, the technical experts in the laboratories and test centers, including those that had responsibility for various standards, did play an active role in the requirements setting process. In these areas it can be said that the technical community had too large a role in setting requirements, which partially contributed to the large number of standard specifications included in the original contract. However in other areas, operators, maintainers, and builders had little input during the requirements setting process.

The program manager must be supported by adequate technical, operational, and management expertise. This is especially important when setting requirements early in the program. Technical experts in laboratories and test centers can keep the program manager informed on existing and new technologies. The Royal Navy can provide insights into current submarine missions and capabilities, and the organizations that maintain submarines can provide information on how designs and operational requirements influence support costs. Experienced designers and builders can shed light on the difficulties and costs of achieving certain operational objectives. Moreover, these experienced designers and builders can help MOD engineers and acquisition experts draft contract specifications that balance these demands. Additionally, they can offer advice to achieve a coherent requirement set that specifies desired performance and safety outcomes in a manner clearly understood by all parties.

The important issue is that the program manager and other decisionmakers understand the trade-offs between the cost, performance, and risks of technical choices when setting requirements. The technical organizations and the operators, builders, and maintainers must be able to effectively show the implications of different operational requirements to allow the program manager to make design and operational trade-offs in a structured and coherent manner.

Involving various organizations is important throughout the life of the program. The program manager should have decisionmaking authority and must draw on various technical and operational resources to make those decisions. Also, involving all appropriate organizations helps develop future knowledgeable, experienced program managers.

Program managers must understand the current state of technology in those areas that apply to their programs and how a platform's operational requirements impact technology risks and costs. This lesson is really an elaboration of the previous one. It stresses the point that understanding and managing technology and technical risks is very important during the conduct of a program. Desired operational performance drives a new platform's characteristics and technologies. Program managers must be supported by a technical community that completely understands technologies that are important to the program, where needed technologies exist, and where they must be significantly advanced. Although it is necessary in some instances, relying too heavily on significant advances in technology can raise the risk of achieving desired operational capabilities and of meeting cost and schedule goals.

It is important for program managers not only to know the current state of various technologies but also to understand how changes to operational requirements relate to the technologies that are available. That is, if certain operational goals are beyond the state of current technology, what operations can existing technologies support? This relates to trade-offs between operational requirements and technological risks (and costs). Again, this area is where both operators and the technical community are important during the early stages of a program. The program managers must understand technical boundaries and the risks inherent in an evolutionary versus a revolutionary strategy. Existing systems can be scaled to some degree. However, scaling an existing system too far leads to difficulties and ultimately results in entirely new systems or significant problems. Also, integrating existing systems may be more challenging than anticipated. For *Astute*, the MOD and the prime contractor greatly underestimated the effort involved in integrating various systems and equipment from previous classes of submarines.

Even when the operational requirements for a new class are similar to those of the previous class, program managers need to be kept informed of the continued ability to deliver the level of technology needed. With the long operational life of modern submarines, equipment and system obsolescence is a major driver of change and risk. Obsolescence risk is often compounded by change in safety or legislation that makes legacy systems and equipment noncompliant.

Program managers must also be knowledgeable about technical advances in processes that control the design and build of the submarine. They must be able to exploit those process advances while being fully aware of the risks that they introduce.

Program managers must understand that when they specify an operational requirement they must also specify how to test for the achievement of that requirement. The "hands-off" approach taken by the MOD during the initial stages of the *Astute* program led to (or resulted from) the deactivation or downsizing of the Royal Navy and MOD technical organizations that had overseen the testing and commissioning of all prior UK nuclear submarines. Without this knowledge and expertise, testing was largely ignored during the contract negotiations and early stages of the program. Planning for testing and commissioning did not begin until approximately five years after the contract was signed. With the first of class, both parties struggled to identify and approve procedures to test whether the vessel's performance met its requirements and to completely understand the time required for testing for the new capabilities and design.

Stating an operational requirement is the first step in setting program goals. But that first step must be complemented by a plan to understand if the platform meets the requirement. This typically involves test procedures—who will test, how the test will be conducted, and how success or failure will be measured. Although it is often difficult to plan tests early in a program, doing so is necessary to ensure all parties agree on the processes to measure how the performance of the platform meets operational capability objectives. Incremental testing of equipment before it becomes part of a system and before that system is inserted into the hull should be encouraged.

Establishing a Contracting Environment

Establishing an open and fair acquisition and contract environment is another important aspect of any program. Bad decisions here will resonate throughout the life of the program. Issues include choosing the organizations involved in designing and building the new submarine, the type of contract, the specifics within the contract (including incentives), the decisionmaking process to employ when issues arise, and the payment schedule. A number of lessons in this area are important for future programs. Although they often overlap, they aim for a fair, collegiate partnership among the program office, prime contractor, and subcontractors.

Consider a single integrated detail design/lead ship construction contract with an experienced prime contractor. Having a single firm complete the detailed design (based on the concept and feasibility studies led by the MOD) and build a submarine helps to integrate the two processes and reduces confusion and misinterpretations. The *Astute* program probably made the right decision in having a single prime contractor; the problem during its early stages stemmed from the inexperience of its prime contractor and from the lack of integration between the design and build teams. GEC Marconi had never designed a submarine, and the distance—both in miles and relationships—between the prime contractor design office in Farnborough and the shipyard in Barrow contributed to many of the early problems.

The original contract went beyond just the lead ship and included building the first three boats. When there is uncertainty in the design and the cost, it is preferable to complete the submarine design and at least start the build of the first of class before contracts are negotiated for subsequent boats in the class. This may result in a two- to three-year gap between the start of build for the first build and the start of the second in class. At that point, however, the detailed design should be largely fixed, and build costs should be better understood.

Use a contract structure with appropriate provisions to handle the technical risks in the program. In an attempt to reduce the risks of cost growth, the MOD sought and the prime contractor agreed to a maximum-price contract. Unfortunately, both the MOD and the prime contractor underestimated the substantial risks in having such a lengthy period of time between the *Astute* and its predecessor submarine program and in transferring responsibilities to the prime contractor. The two parties also overestimated the cost savings and efficiencies from using 3D CAD software and the modular build process. The result was a program that was unachievable for the original contract price.

The maximum-price contract led to an environment in which (1) BAE Systems had no motivation to provide more than what it interpreted were its obligations in a contract with ill-defined specifications and (2) the MOD was afraid to enforce ill-defined specifications for fear of being liable for contract changes that it could not pay for.

Fixed maximum-price contracts are appropriate when there is little risk and uncertainty (e.g., when technologies are mature and when specifications are well defined) and when few changes to an established design or build are anticipated. While the government can try to place all risk on a contractor through use of a fixed-price contract, the government ultimately holds all program risk. It is far better to structure a contract that holds the contractor responsible for risks under its control (labor rates, productivity, materiel costs, etc.) and holds the government responsible for risks beyond the contractor's control (inflation, changing requirements, changes in law, etc.). Otherwise, contractors will greatly increase their bid prices to accommodate risks that they cannot control. Appropriate cost-sharing provisions can be drafted to handle risks that neither party controls or that both parties have equal influence over (technology changes, overhead rates, acts of God, energy shortages, etc.).

Any contract, whether fixed-price or cost-plus, must have adequate incentives for the contractor to "do better." The *Astute* contract had such incentives but they did not lead to the desired reduction in cost (possibly due to the numerous other challenges facing the program and the restart of the industrial base). Technical risks must be identified early, and much thought must be given to deciding, with industry, the appropriate form of the contract and the incentive and risk-sharing clauses built into it that provide effective incentives to take proactive risk mitigation actions early in the program. Getting this wrong, as happened with the original *Astute* contract, can almost guarantee problems with the conduct of the program and the relationships between the MOD and the contractor.

The contract should specify desired performance requirements and procedures to test them. But the contract should avoid specifying how those performance requirements should be achieved. The prime contractor should have the ability to decide how best to meet performance requirements. Understanding and specifying adequate test procedures is an area where the involvement of the technical community is especially important.

Develop realistic cost estimates to design the new submarine and to build the new design. In hindsight, the mantra "it's too good to be true" certainly applied to the *Astute* contract price. The prime contractor, using overly optimistic cost assumptions and eying the possibility that a new UK government might no longer support the program, agreed to a price that was substantially below the original bid price (which itself was an underestimation of the difficulty of delivering a nuclear submarine program).

In future contracts, costs must be realistic and based on the best knowledge and information available. The aim of all parties should be to establish as much as possible a realistic cost estimate and not drive for cost reduction where it cannot be justified. Thorough and sound estimates of cost should be developed by both the prime contractor and the MOD, and any discrepancies in cost estimates should be understood and discussed by the two parties. The MOD should be supported by an independent cost-estimating organization that utilizes all available data and information and understands the risks that are involved in the program. Such a cost-estimating capability should be strengthened in the MOD.

Make informed decisions on which equipment is government-furnished versus contractor-furnished. One important decision when establishing the acquisition strategy is which equipment will be bought and managed by the MOD and supplied to the builder as GFE or government-furnished information and which equipment will be bought and managed by the contractor (as CFE). These decisions are based on many factors; one of the most important is which party, the MOD or the prime contractor, is better positioned to manage the subcontractors and the integration of that equipment into the submarine.

The assignment of Rolls-Royce as subcontractor to the prime contractor, rather than its typical role as prime contractor to the MOD, caused some friction during the initial stages of the *Astute* program. Rolls-Royce has numerous contracts with the MOD to support the in-service submarines, and the MOD is Rolls-Royce's most predominant customer, with longer-term contracts and more revenues than it receives by providing the NSRP to BAE Systems for the *Astute* class. The MOD will gain by contracting directly with Rolls-Royce for all NSRP supply and support. Such an integrated relationship could yield benefits from economies of scale and coordinated planning of all Rolls-Royce activities to support both construction and in-service support. The team in the MOD must be adequately staffed to manage the contract with Rolls-Royce for support to submarine procurement alongside other MOD contract deliverables and must recognize that delays in providing NSRP components to the construction process can lead to schedule delays and cost increases.

One important issue surrounding GFE and CFE is the need to sustain a viable vendor base. One impact of the gap between *Vanguard* and *Astute* was the atrophy of the supplier base resulting in the need to identify, and certify, many new suppliers. Both the MOD and the prime contractor should continually monitor the supplier base to identify any potential problems and to look for potential savings through either long-term partnering arrangements or competition at the vendor level. This important role is currently performed by BAE Systems, which regularly monitors the supply chain to identify vendors facing problems as well as new sources for material and equipment.

Develop a process to minimize and manage changes. The MOD strove to minimize changes during the *Astute* program due to the desire to control costs. However, changes in requirements did occur, even late in the program—such as when a new captain of the *Astute* requested a change to improve navigation and safety after the submarine was in the water. Also, the transfer of design authority to the prime contractor and the hands-off approach of the MOD presented a difficult environment for making decisions on minimizing and managing changes. Despite the challenges, the *Astute* program did have a change management process that identified essential changes, but that process typically could not implement the needed changes in a timely fashion.

Changes invariably occur during any program. They may crop up in the desired performance of the platform, in the systems and equipment used to achieve performance, in the schedule of the project, or in the responsibilities of the organizations involved in designing, building, and testing the platform. Changes may affect cost, schedule, or capability. Management structures must be in place to deal with any of the contract changes that are proposed during the program. It is important that those in the program office understand the full impact of proposed changes and have a procedure in place to approve or reject them. And change decisions must be implemented in a timely manner. Returning design authority to the MOD may help establish a more effective process to manage change if it is accompanied by the availability of sufficient experienced and informed MOD staff.

Understanding the effect of proposed changes requires that technical experts, cost estimators, and contractors all be involved. When funding is limited and schedules are tight, changes that increase costs or add schedule delays must be scrupulously examined.

Establish agreed-upon tracking mechanisms and payment schedules and develop a timely and thorough decisionmaking process. During the first years of the *Astute* program, there were no effective mechanisms in place to track progress on the design and build of the submarine. This made it impossible for the MOD, and even the prime contractor, to recognize the growing program problems. One important change at Barrow, started by both the prime contractor and the MOD and assisted by Electric Boat, is the installation and use of an earned value management system. While it is important to have such a system in place, it must be properly designed and used to produce outputs that are helpful in managing the program. We discuss effective progress tracking systems in more detail in the next section.

The payment schedule in the contract should be tied to either a clearly defined and meaningful milestone plan or a well defined physical progression system. Adequate funds to handle difficulties that occur later in the program need to be reserved. The payment clauses in the *Astute* contract were tied to production metrics, such as length of installed pipe or electrical cables. These milestones proved counterproductive because the shipyard would install pipe or cable before the design was complete, requiring subsequent rip-out and rework. In establishing payment schedules for future vessels, care must be taken to incentivize real progress and not to introduce wrong behaviors.

Issues will arise during the conduct of a program, and most will require timely decisions. It is important that a program have a decisionmaking process with appropriate checks and balances that involves all applicable organizations—the MOD, the Royal Navy, the technical community, the program office, and the prime contractor. This process must thoroughly address all the appropriate issues and their effect on cost, schedule, and performance. It also must be timely so as not to delay the program or add cost.

Include an adequate contingency pool in the contract. The *Astute* effort lacked adequate contingency funds to manage risks and program changes. Where normally a complex project would have a contingency fund on the order of 10 to 15 percent or more, the *Astute* contract's contingency fund was approximately 5 percent. Not having an adequate contingency fund with agreed processes for disbursement adversely impacted relations between the customer and the supplier, limiting what the program office or the contractor could do when problems arose. The size of the contingency fund is related to the technical risks in the project: More risks require larger contingencies.

Designing and Building the Submarine

Many lessons from the *Astute* program described above also apply to the design and construction phases of a new program. It is important to get all the right organizations—designers, builders, operators, maintainers, and the technical community—involved throughout a program, to understand how operational requirements affect design and construction and plan for the appropriate testing of the systems and platform to ensure that requirements are met. Therefore, several lessons described below repeat those described previously.

Involve builders, maintainers, operators, and the technical community in the design process. An important lesson from the United States' *Virginia* program was to use a design/build process during the design of a new submarine. This process involves having the builders actively involved in the design process to ensure that what is designed can be built in an efficient manner. Design/build should go further than merely involving builders in the design process. The design should also be informed by operators, key suppliers, maintainers, and the technical community. Therefore, it is important to think of the design team as a collaboration of submarine designers and engineers with inputs from those who must build to the design, operate the submarine, and maintain it. This collaboration should extend throughout the duration of the design program. However, it is important to keep in mind throughout the design/build process that the cost-effectiveness of the submarine's post-delivery or ILS period is the true design and construction target. While maintenance ease is a desired trait, it must be considered in the context of the overall life-cycle costs, so that the design does not become unaffordable.

It is important not only to have the technical community involved in the design process but to listen and react to the concerns they may raise. The degree to which existing technology is "pushed" in a new design will affect the risks to cost, schedule, and performance of the end platform. The technical community should understand the state of the technology and the degree to which a new design extends that technology. It is also important to have clearly defined and effective technical leadership to avoid indecision and delays. In the *Astute* program, it was often unclear who had responsibility for technical decisions.

Specify adequate design margins and manage them during the design and build of the submarines. A general lesson throughout UK submarine programs is that a new submarine design must include adequate weight, stability, power, cooling, and bandwidth margins and these margins must be closely managed during the design, build, and operation of the submarines. New ships and submarines typically start with what are believed to be adequate design margins, but they are often consumed during the design and build process or early in the platform's life. Without adequate margins, it may not be possible to modernize and upgrade equipment. New power and cooling plants may be needed, but they may exceed available weight margins. Existing systems may be downgraded or ship operations may be constrained if adequate margins are not available. As with past programs, there were no difficulties managing margins in the *Astute* program. Even though done well with *Astute*, managing margins is an important overall lesson for future programs.

Include in the design the capability to remove and replace equipment that may become damaged or obsolete during the life cycle of the new submarine. The operational life of a submarine is typically greater than the life of some of the technologies incorporated in its design. This is especially true for command, control, communications, computing, and intelligence (C4I) equipment. Adequate access paths and removal hatches should be included in the design to facilitate removing and replacing damaged or obsolete equipment. For C4I equipment, modularity and interoperability should be incorporated into the design.[11]

[11] See Schank et al., 2009, for a discussion of controlling the C4I upgrade costs on ships.

Data and information architectures should be developed that allow the installation of electronic equipment as late in the build process as possible to take advantage of rapid changes in information technology. Open architectures should prove useful to equipment integration and future modernization efforts.

The development of the Ashvale facility and the Warspite facility at the Barrow shipyard is a positive lesson from the *Astute* program. These facilities provided for early testing of the *Astute* combat system before it was installed on the submarine. This helped to optimize the production process and to reduce the risks of combat system operations and integration.

Complete the majority of the design drawings before construction begins. One very important lesson is to ensure that the majority of the 3D CAD product model are complete before construction begins. There is often a rush to remain on schedule or to show progress to the government or the public. It is far better to delay construction to ensure that the design is largely complete rather than risk the costly rework and changes typically resulting from an immature design. Using three-dimensional product models facilitates the design/build process, but these models must be completed early to assist manufacturers in ordering material and in downloading manufacturing data to numeric-controlled machinery. Completing the three-dimensional product model early ensures that all pieces fit and minimizes expensive rework. A good rule of thumb is to have the electronic product model approximately 80 percent or more complete when construction begins.

Develop an integrated master plan to sequence design and construction events. One aspect that blinded the MOD to the *Astute* program's schedule problems was the lack of an accurate integrated master plan. A program should have an overall integrated schedule detailing the tasks, milestones, and products produced during the design and build of the submarine. This integrated master plan shows the order of tasks and events and the interrelationships between them. It can indicate the critical path for achieving the program schedule and the impact on the schedule of delays in any tasks.

Development of a master plan should start with a listing of the primary milestones in the design and build process, possibly starting with the commissioning of the first-of-class (i.e., working backwards). Milestones would include such things as the completion of test and trials, the launch of the submarine, cutting the first steel, and design drawing completion. Next, the master plan should list the multiple tasks that feed into each milestone. There will be several milestones, and many subsequent tasks, during the design and build of the first-of-class. The master plan must consider the tasks and milestones for the prime contractor as well as for the major systems and equipment subcontractors. For example, the delivery of the NSRP to the shipbuilder is a key milestone whose delay could impact the build schedule for the submarine. A path through the master plan should track the milestones and events that comprise the delivery of the NSRP, including any contracting periods and design products.

Each task should have a time and resource requirement. For example, building the NSRP may require a certain number of months and man-hours. Milestones will have desired dates. For example, the NSRP may be needed at the shipyard by a certain date. There will be levels of risk and uncertainty in many of the task time and milestone date estimates. Typically, task durations, resource requirements, and completion dates are expressed with qualifiers, such as desired, expected, earliest start/finish, latest start/finish. Modern scheduling software can readily show expected completion dates, resource levels, and other important statistics using either a deterministic or stochastic process.

A key decision in establishing the integrated master plan is the level of detail. Although more detail can provide greater insights, it increases the effort to create and manage the integrated master plan. The important point is to capture the relationships between various tasks and milestones that will indicate potential schedule and cost challenges.

Another important aspect of an integrated master plan is continually keeping it updated. Real-world events will occur that could affect the timing of future tasks and milestones. Master plans may be adequate and useful when first developed, but they will quickly lose their value identifying cost and schedule issues if they are not updated as changes occur or new information becomes available. The development and management of the master plan requires resources and funding. Changes to resource and funding levels may have an impact on the master schedule and must be considered.

An integrated master plan is the first step in understanding the status of a program. The development of a system to monitor progress, the subject of the next lesson, is the necessary second step.

Develop a management system to track progress during the design and build process.[12] During the first several years of the *Astute* program, there was no effective system to monitor the progress of the design and build. Ultimately, the earned value management (EVM) system was put in place. However, the use of the system represents a cultural change for the shipyard, and workers still find it difficult at times to allocate the proper data to the right project or task. An accurate cost accounting system is a necessary prerequisite for a meaningful EVM system.

Earned value metrics compare the budgeted cost of work performed (BCWP) with the budgeted cost of work scheduled (BCWS) at a given point in time. When a BCWP value is less than that of the BCWS, the project is considered behind schedule. If the BCWP value exceeds the BSWS value, the project is considered ahead of schedule. The schedule performance index is equal to BCWP divided by BSWS. The cost performance index is the BCWP divided by the actual cost of work performed. An index number less than 1 indicates the project is behind schedule and over budget.

There are a number of assumptions underlying EVM, and EVM has a number of limitations. It provides few, or even incorrect, insights if the proper data are not collected and reported correctly. EVM also lacks flow and value-generation concepts. *Flow* refers to how resources and activities are sequentially related. *Value-generation work* is work performed in one time period that will allow future work to begin. Because building to sequence is so critical in submarine programs, EVM must be used with care to avoid introducing poor behaviors.

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[12] See Arena et al., 2005, for a discussion of various methods used to monitor the progress of shipbuilding programs, including a specific description of EVM.

Whether EVM or another progress monitoring metric is used, it is important to have an effective system to track progress and predict cost and schedule status.

Ensure that sufficient MOD oversight exists at the shipyard during the design and build periods. At the beginning of the *Astute* program, the MOD oversight at the Barrow shipyard was greatly reduced as part of the movement to control government spending. This lack of on-site presence blinded the MOD to the design and construction problems that were emerging during the early years of the program. The MOD has since increased its presence at Barrow to approximately 30 people (from a low of two naval officers and two civilians) in order to have more visibility and inputs into the build program. The program should have a strong presence at the shipyard to provide on-site construction oversight for deviations from design, assure compliance to quality and testing procedures, and keep the MOD aware of the challenges that the program faces. The on-site MOD representatives should be experienced in both the technical and managerial aspects of delivering a submarine program and also have some decisionmaking capability in order to facilitate concessions and deviations that have only a minor impact on cost, schedule, or performance.

Develop a thorough and adequate testing program. We mentioned previously that a new program must specify not only the desired operational requirements but also test procedures to ensure those requirements have been met. The testing procedures should be developed during the design portion of the program. Testing should involve the design and build organization(s) as well as the technical community and the Royal Navy.

Planning for Integrated Logistics Support

Although logistics support occurs over a decade from the initial design of the submarine, early planning for ILS must inform the design and construction of the submarines and the establishment of the facilities, contracts, and procedures to ensure the desired level of operational availability. Typically, in-service operating and support costs over the life of the submarine are much larger than the initial acquisition cost of the boat. Yet, the focus of a design and build program is often on reducing the unit procurement cost, not the whole-life cost of the platform. It is difficult to convince senior decisionmakers to spend more money in the short term to save greater amounts in the long term. Therefore, persuasive arguments are necessary to ensure that the costs of integrated logistics support are considered during the design and build process.

Establish and support a strategic plan for ILS during the design phase of a new program. A strategic plan for ILS must be put in place early in the program, preferably during the design phase. As mentioned in the design and build lessons, personnel from the organizations responsible for maintaining the submarine should be involved in the design process to ensure that the ultimate platform can be supported efficiently and effectively. Funding should be established to develop the ILS plans and should be protected during program execution.

A strategic ILS plan is predicated on the following tenets:

- Maximize equipment commonality during submarine design through part standardization.
- Support the operational availability target through equipment reliability testing.
- Ensure that maintenance ease and accessibility requirements take long-term costs into consideration.
- Take fully into account the need to be consistent with strategic through-life plans for technology and capability development both within the MOD and within the overall submarine enterprise.

A concept for operating and maintaining the submarine should support the development of the ILS plan. The concept of operations must recognize that the submarine will require time for preventive and corrective maintenance and for equipment modernization. The end result should be a periodic cycle of training, operations, and maintenance that holds throughout the life of the submarine. The development of the concept of operations and maintenance must involve the operators as well as the maintainers.

To develop a maintenance plan, several things must be well understood, including equipment reliability and maintainability and hull corrosion control. This involves frequent interactions between the design authorities and the original equipment manufacturers to obtain data. It also involves a thorough understanding, informed by a robust database, of the reliability and maintainability of any existing equipment used in the new platform. Data should be underwritten by reliability testing of new equipment through the full mission profile of the new submarine. Program managers should carefully consider the downstream impact of equipment failure. Maximizing the use of standard or common systems, equipment, and parts whenever possible in the design can provide valuable insights into reliability and maintenance.

The strategic plan for ILS should indicate specific periods when maintenance, modernization, and training will be performed; where the activities will take place; and which organizations will perform them. There should be clear guidance on how these maintenance activities will be accomplished. Equipment reliability and the need to control corrosion will factor into when maintenance should be performed. Some maintenance will be the responsibility of the crew at the operating base; higher-level maintenance and modernization will be the responsibility of government or private-sector organizations and will be accomplished either at the operating base or at a shipyard. As discussed above, the end result should be a thorough plan for maintenance and modernization throughout the life of the submarine.

Finally, the ILS plan must include provisions for equipment modernization during the operational life of the submarine. It is inevitable that some equipment, especially electronic equipment, will require updates. It is important that modernizations be part of the strategic ILS plan. Modernizations may involve the higher-level maintenance organization but will more likely involve the original equipment manufacturers. Electronic equipment may require time-phased upgrades involving both hardware and software. Setting periodic hardware and software upgrades will establish a drumbeat of modernizations throughout the program.

Provide and maintain adequate funding to develop the ILS plan. Most important, there must be sufficient funds to develop the strategic ILS plan, funds that are "protected" during the design and build of the platforms.

Summary

In this chapter, we have listed numerous lessons from the *Astute* program. Many of these lessons have a central theme: Involve knowledgeable people from various technical and operational organizations in an open and interactive environment. Designing and building a submarine is one of the most complex undertakings for a new program. It requires careful management and oversight and a delegation of roles and responsibilities that recognizes which party—the shipbuilder or the government—is best positioned to manage risks.

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