SOFT TECHNOLOGY AND TECHNOLOGY TRANSFER: LESSONS FROM BRITISH MISSILE DEVELOPMENT

by Benjamin Cole

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The leakage and export of ballistic missile technology from states like Russia, Ukraine, and China in recent years have heightened concerns about the proliferation of ballistic missiles. Yet, the precise impact of technology transfers on the indigenous programs of proliferators is difficult to determine. However, useful observations can be discerned from the British attempt to develop the Blue Streak ballistic missile system. This program, initiated in the mid-1950s, sought to provide Britain with its own ballistic missile, a medium-range system.[1] Although Britain made considerable progress, it canceled the program in 1960, for reasons described below.

Britain received substantial U.S. technological assistance in this program, and thus it represents a well-documented case study of a state attempting to integrate foreign technologies into an indigenous development program. Because of Britain's advanced technological level and the enormous benefits of its strong links to the United States, this also represents one of the best possible cases for successful technology transfer. Therefore, any limits on such efforts identified in this case study should apply even more strongly in the case of current proliferators, since these countries are generally less advanced technologically and do not enjoy special relationships with their suppliers.

This case study focuses in particular on the role and importance of what Aaron Karp calls the "soft technology" of missile development. Soft technology refers to the range of managerial and technical skills necessary to master new hardware. According to Karp, "Although it is easily overshadowed by the more concrete aspects of missile hardware, the soft technology is unquestionably more important. Without sound policy choices, good organization, skilled personnel and adequate financing, no amount of even the very best equipment can be sufficient to create long-range ballistic missiles."[2]

This article will test Karp's thesis about soft technology, which suggests that so long as a state possesses good soft technology, it should be able to master all of the technological problems of long-range missile development. Consequently, if Karp is right, control of relevant technologies through the Missile Technology Control Regime (MTCR) may not be able to prevent proliferation. To the extent that states can develop the kind of knowledge and financing emphasized by Karp, and these remain uncontrolled by the MTCR, his thesis predicts that efforts to limit missile proliferation will not succeed in the long term.

This article examines three questions in order to test the validity of Karp's thesis. First, I examine whether soft technology helps to explain the technological problems Britain encountered in its attempted assimilation of American technology transfers. If the thesis is valid, the effect of specific transfers of hard technology will depend upon the quality of the proliferator's soft technology, and a proliferator's progress will be primarily contingent upon improvements in its soft technology. Second, I investigate whether weaknesses in specific areas of British soft technology account for the main technological bottlenecks in the Blue Streak development program. Karp's thesis suggests that technological choke points will vary for each proliferator depending upon the particular weaknesses in its soft technology. Third, I examine whether technology transfers instead compensated for the weaknesses in British soft technology. On this point, Karp suggests that specific technology transfers cannot wholly compensate for weaknesses in a proliferator's soft technology.

I conclude that the Blue Streak case supports Karp's thesis to a large extent but not entirely. The case confirms the importance of soft technology, but it also suggests that in some circumstances hard technology can compensate for weaknesses in soft technology. This has two implications. On the one hand, it highlights the limits of hard technology transfers. Without adequate soft technology, technology transfers do not necessarily result in missile proliferation. On the other hand, the case study also suggests that transfers of hard technology can have a significant impact on missile programs when a state's overall soft technology is good, even if gaps exist in that state's abilities.

This article first outlines the history of the Blue Streak project, discussing the reasons behind its initiation and cancellation. It then provides a detailed analysis of the strengths and weaknesses of each of the four components of soft technology identified by Karp. It starts with British policy choices, specifically the design of the Blue Streak system and the development strategy underpinning the British ballistic missile program. The next three sections then cover the management, personnel, and finances of the project, respectively. The article then outlines an element of British hard technology that also proved relevant: the development infrastructure (i.e., tools and test facilities) within the firms contracted to develop Blue Streak. Finally, it analyzes how the strengths and weaknesses of British soft technology and development infrastructure affected the development of Blue Streak, especially the assimilation of technology transferred from the United States. The conclusion then draws larger policy lessons from the case. It finds the implications for technology control regimes might not be as dire as Karp's thesis suggests. However, it also points to the need to develop new policy instruments to deal with the full range of materials and knowledge that go into missile proliferation.

THE HISTORY OF BLUE STREAK

In the 1950s, the British government planned for the country's nuclear deterrent to be based solely on a fleet of strategic V-bombers. These were subsonic jet aircraft specifically designed to carry the large, first-generation British nuclear weapons. However, intelligence reports from the early 1950s indicated that future developments in defensive guided-weapon systems would render the V-bombers increasingly vulnerable to Soviet air defenses in the 1960s. These reports prompted British planners to examine the possibility of procuring a ballistic missile system to eventually assume the role of the primary deterrent.[3]

Yet, it was not until 1953-54 that the government's scientific advisers considered it feasible to develop an indigenous ballistic missile system capable of targeting the majority of population centers in the Soviet Union. In 1954, British Minister of Supply Duncan Sandys secured an agreement with the U.S. Secretary of Defense Charles Wilson for U.S. technical assistance to a British ballistic missile program. The Sandys-Wilson agreement was critical to Britain's decisionmaking process because it addressed Britain's lack of ballistic missile development experience and its need for the system within a short timeframe.[4] In August 1955, the operational requirements for the Blue Streak system were issued; the development program aimed to produce an initial deployment in 1963, with full deployment in 1965. Thereafter, it would fulfill the primary deterrent role until 1970. During the course of its development, the project suffered from missed deadlines, increasing costs, and technological obsolescence.[5] These problems prompted some decisionmakers to advocate canceling the project in favor of either collaborating with the United States on a more advanced system or procuring a complete system from the United States. These calls were initially rejected, but intelligence reports about the Soviet deployment of SS-3 and SS-4 intermediate-range ballistic missiles (IRBMs) in the wake of the Soviet launch of Sputnik in October 1957 raised concerns about the vulnerability of Blue Streak to preemption. These concerns led the Royal Navy to advocate procuring the Polaris missile from the United States. The uncertainty over Blue Streak's survivability, coupled with increasing divisions among decisionmakers, led to the creation of the British Nuclear Deterrent Study Group to examine the long-term options for the British deterrent. The group recommended that Blue Streak be canceled because it would be vulnerable to preemption.[6] The government accepted this recommendation and, in early 1960, secured an agreement to procure Skybolt air-launched ballistic missiles from the United States. The cancellation of Blue Streak was confirmed in April 1960, and ever since, Britain has relied on the United States to supply it with strategic nuclear delivery systems (although these did not include Skybolt, which the United States ultimately canceled because it had its own technical problems). I now turn to a step-by-step analysis of the various components of soft technology, in order to assess how they affected the outcome of technology transfer in the case.

BRITAIN'S SOFT TECHNOLOGY: AN ASSESSMENT

Design And Development Strategy

Since Blue Streak was intended to fulfill the role of the primary deterrent, it needed to be capable of carrying a one-ton warhead to a range of 2,000 to 2,500 nautical miles (nmi), with a circular error probable (CEP) of 8,000 feet, and it was required to have 95 percent overall reliability.[7] Britain had extensive experience developing and operating small sounding rockets, such as the Skylark, which were used for conducting research in the upper atmosphere. However, it had never produced a ballistic missile system, and these were exacting technical requirements to meet in one's first effort.

Karp argues that the development strategy adopted by a state is a critical determinant in the success or failure of a project. The most successful development strategy for ballistic missiles is an incremental one, which starts with short-range systems and gradually builds systems with successively longer ranges. Successful producers such as the United States, Russia, France, and China adopted this approach. However, British requirements forced it to dive into the field at the medium-range ballistic missile (MRBM) level. Significantly, all of the states that have adopted this approach have failed to develop their systems.[8]

The British approach raises questions about the soundness of its development strategy. British engineers felt that they did not need to pursue the same incremental strategies as the other nuclear weapon states. Robert Cockburn, the controller of guided weapons and electronics in the Ministry of Supply,[9] argued that Britain was following an alternative form of incremental development strategy. This overlapping development strategy started with the V-bombers armed with stand-off missiles, progressed to low-level supersonic bombers armed with stand-off missiles in conjunction with land-based "flat flying missiles" (i.e., cruise missiles), followed by an MRBM, and then by intercontinental ballistic missiles (ICBMs).[10] This progression implies that the experience gained from developing strategic bombers and cruise missiles could effectively substitute for (and is therefore equivalent to) the experience that would have accrued from successfully developing shorter range ballistic missile systems. However, some key elements of ballistic missile design, such as re-entry vehicles and rocket engines, are fundamentally different from airplane and cruise missile design. These differences raise questions about whether Cockburn's development strategy is indeed viable, a point I will return to once I have identified the major problems Britain encountered.

In choosing a design and development strategy, Britain had the major advantage of virtually unrestricted and ongoing access to U.S. technology and experience.[11] In particular, it sought continued discussion and information on the development of U.S. ballistic missile projects and the supply of sample components. Initially, Britain sought specific information in six areas: the results of wind tunnel tests and the effects of high rates of heating; the results of re-entry test vehicle work; the progress of motor development; the experience of the use of the Azusa radar; structural test results from the Atlas ICBM and Viking sounding rocket programs; and the results of tests on inertial navigation components.[12] The single most significant technology transfer in this case, however, was the blueprints for the North American Aviation (NAA) S-3 engine. Similar to the Atlas boosters, this engine was used in Thor and Jupiter, the first generation of American MRBMs.

The objective of having the Blue Streak missile ready for initial deployment in 1963 affected the design goals. The chief goals were simplicity; a minimum of risks (where innovative technology was incorporated, it was paralleled by the development of a simpler version that provided a higher assurance of success); considerable flexibility in performance goals to accommodate possible changes in warhead size, weight, shielding requirements, and counter-measures;[13] and a low price.[14]

One S-3 engine would provide a range of only 1,300 to 1,700 nmi, which left British designers with three options: to increase the power of the S-3 by 20 percent; to use twin motors; or to develop a system with staged motors.[15] The designers finally decided to use a single-stage system incorporating two S-3s, which would make possible ranges up to 2,500 nmi. They chose this route because such a system could be adapted to incorporate more motor units if required.

This choice had both positive and negative repercussions. While it removed the requirement to master the complexities of missile staging, the use of a twin-engine configuration would increase the development time, subject the missile to a higher "g" force, and increase the all-up-weight of the missile (i.e., the weight of the missile when fueled and ready for launch).[16] This decision also made the project contingent upon the successful development of a strong, lightweight structure. The designers recognized that if unforeseen difficulties prevented the achievement of low structure weight ratios,[17] switching to a two-stage system might prove necessary. Thus, the initial design was critical, because any changes would involve very long time cycles and could introduce new sources of unreliability.[18]

Given the boldness of the choice to start development with an MRBM, it would have been hard to do much better on the design element of soft technology. Design choices inevitably involve a series of trade-offs. In this case, the design of Blue Streak made the task of developing the booster relatively easier, but it made the tasks of developing the structure and the guidance system relatively more difficult. Since it was not possible to minimize the development problems of all elements of the missile, the British designers made decisions that should not have caused excessive problems for the missile development effort.

Management

Several analysts have observed that success in missile development depends substantially on effective management of a project.[19] Although no British firms had ever developed a ballistic missile, Britain had a large and sophisticated aerospace industry that rivaled the best in the world. It had plenty of experience developing large aerospace projects, such as the V-bombers, and had been conducting research and development (R&D) on the Blue Moon and Red Rapier cruise missile projects.[20] These were air-launched systems that would have carried warheads weighing up to one ton with ranges of 100 and 400 miles, respectively. They were also significantly larger than the compact and lightweight cruise missile systems of the 1990s.

In the 1950s, no single British firm had the necessary expertise or spare capacity to develop all elements of ballistic missile technology. One alternative was to create an entirely new organization along the lines of the Manhattan Project that would oversee design, development, and production of the system. Most of today's proliferators would probably choose this route. However, the British believed that this would remove resources from other projects, take longer to establish, and be more costly.[21] Instead, the Ministry of Supply contracted with a number of different firms to produce Blue Streak.

The DeHavilland Propeller Company received the main contract to develop Blue Streak. Three other companies were assigned to build the main subcomponents. The DeHavilland Aircraft Company (which was another part of the same firm as the Propeller Company) was contracted to produce the missile structure; Rolls Royce was contracted to produce the engines; and the Sperry Gyroscope Company was contracted to produce the inertial guidance system. Other firms were awarded more minor contracts. Finally, one government agency, the Royal Aircraft Establishment at Farnborough (the RAE), conducted research and development on re-entry. Both the Ministry of Supply and the RAE exercised government control. The RAE acted as a design initiator and approver, monitored how the firms were proceeding, and gave requirements to the firms, but it did no detailed design work.[22] Despite its lack of missile experience, Britain had honed its management skills since the end of World War II in the development of a number of large-scale projects, such as the V-bombers and other guided-weapons projects. Consequently, the firms applied clearly established methods of management and control to the Blue Streak project. A complex committee structure oversaw development of the project: A coordinating committee met every six months, and under its direction, a set of eight committees were responsible for more regular and specific coordination of different elements of the system. Supplementing this committee was a U.S.-U.K. Advisory Committee on MRBMs that also discussed operational and developmental problems. Though complex, the structure matched established practice for guided-weapons projects.

Considering the large number of firms involved and the complexity of the project, it is not surprising that problems arose with managing and coordinating the various elements of the project. In particular, the firms differed in development philosophies concerning the project. Rolls Royce saw the project in terms of developing the engineering needed to demonstrate that a satisfactory propulsion system could be provided. In contrast, DeHavilland and the Ministry of Aviation (which took over the functions of the Ministry of Supply in 1959) put the emphasis on the delivery of engines to meet an arbitrarily planned program. Although there was some overlap between the two perceptions, the conflict of emphasis was marked. Val Cleaver, the head of the rocket motor department at Rolls Royce, considered the dispute to be of increasing importance as the project progressed.[23]

Work at the Sperry Gyroscope Company was also hampered by poor management and coordination. In 1958, the RAE learned that Sperry had not designed the inertial navigation system to be capable of accommodating all of the different components that were under development at other firms, but for Sperry to re-design the platform at that time would have entailed significant problems. There were also coordination problems between DeHavilland and Rolls Royce. The latter company appeared to be ignoring vibrational forces that were too small to be of importance for motor design considerations, but that might be of importance in the overall missile vibration problem.[24] This difficulty resulted from the lack of a chance to conduct tests, in part because of pressure to keep to the schedule.

By 1958, delays in the schedule prompted the Ministry of Supply to overhaul the management structure. In particular, the Ministry identified Sperry as requiring additional control and technical support from the RAE and the Ministry. In addition, the top-level coordinating committee would meet every three months; and a new appointment, the director general (ballistic missiles), would make all decisions. Also, more of the lower panels would be chaired by the Ministry.[25] Finally, a new progress committee to meet quarterly was also proposed. Despite the problems, the RAE believed that the management structure overall worked well. Cockburn's form of incremental development strategy took advantage of the fact that the firms and the Ministry of Supply had previous experience successfully managing large aerospace development projects.

Judging from Britain's experience, a Manhattan Project-style of management is not necessarily superior. Proliferator states appear to choose this approach only because they lack the existing industrial capacity and experience that made Cockburn's incremental approach possible in the United Kingdom. Rather than the development strategy or management style, the most significant problems in Blue Streak arose from inadequate funding. As subsequent sections will show, finance limitations restricted the rate at which the firms could develop their infrastructure and build new capital facilities, and this was the main source of difficulties. Before discussing finance and infrastructure, though, it is necessary to consider the third aspect of soft technology identified by Karp, the availability of skilled personnel.

Personnel

The initial task of the Blue Streak project firms was to assemble their engineering teams, but Britain possessed very few engineers who had previously worked on ballistic missile projects. Karp argues that large numbers of skilled engineers are required to design a system, and a skilled workforce is required to build it. He argues that, while shorter range systems can be built using skills acquired in existing enterprises,

> building larger rockets, however, requires infrastructure and talents previously unheard of elsewhere in other civilian or military industries. A labor force proficient in the skills of fuel mixing, chemical milling, beryllium fabrication and the thousands of other exotic skills of missile making cannot be cobbled together merely by raiding existing companies.[26]

Yet, this is precisely what Britain was forced to do, as it quickly attempted to assemble the necessary teams to get the project started.

Rolls Royce, the engine contractor, had extensive experience developing airplane engines, including the Avon, used to power the Vickers Valiant V-bomber, but it had never previously produced a rocket motor. Nonetheless, it rapidly assembled a team of engineers from both inside and outside of the firm. Some had previous rocket experience, but most had only worked on aircraft engines.[27] An exception was Val Cleaver, the head of the rocket department, who had worked on the Sprite, Super-Sprite, and Spectre rocket engines at DeHavilland until 1955.[28] However, these engines were small, with thrusts between 5,000 and 8,000 pounds. The engines that would propel Blue Streak would have a thrust of 135,000 pounds, so the jump in capability was enormous.

Despite never having previously produced a ballistic missile engine, Rolls Royce adapted to the task with ease. The team discovered that aerospace technique is almost directly transferable from aircraft to missile engines. Some of the equations used had to be slightly modified, but they were essentially similar.[29] The level of expertise within the team was such that, at the outset of the project, some believed that their experience in turbine development might enable them to improve the design of components, which could then be incorporated into the U.S. design.[30] The clearest example of convertibility from aircraft to missiles was the design—based on some existing Rolls Royce gas turbine engines—of the new turbopump for the modified versions of the S-3 engine developed in Britain, which were designated the RZ series.[31] At that time in the United States, NAA was having problems with the turbine development for the S-3 because it lacked the facilities for a complete testing program.[32] In contrast, Rolls Royce already possessed the necessary facilities and proceeded to re-design the turbine. Some design changes, including the re-designed turbine, were fed back to NAA, but by that time, the United States was engaged in developing the next generation of propulsion technology, particularly solid propellants. Therefore, only some of the design changes were of any use to NAA.[33]

However, the team probably adapted their skills so easily because Rolls Royce was already working at the leading edge of airplane engine development, unlike many of today's proliferators. Current proliferators have encountered difficulties in adapting their skills and knowledge. For example, when India procured the Vikas liquid-fueled engine from France, it had to send 50 engineers to France on a long-term assignment in order to master it.[34] In contrast, British engineers made only short visits to their counterparts in the United States.

DeHavilland, which was in charge of the missile structure, had different prior experience from the other British firms. It had neither produced any of the V-bombers, nor worked on the superstructure of Blue Moon or Red Rapier. Instead, it had produced the Comet, the first jet-powered airliner. DeHavilland gained experience engineering large aerospace structures from the Comet, and also developed a number of surface-to-air missiles. By 1958, DeHavilland was still suffering from a shortage of skilled engineers, but this resulted from a lack of spare capacity within the firm rather than a skill shortage within British industry.

The DeHavilland team was aided by the large degree of similarity of technique between ballistic missile and aircraft structures. Although ballistic missiles differ because they rely on pressurization for structural integrity, the techniques in riveting and welding are very similar, despite requiring modification in some instances.[35] Therefore, DeHavilland managed the switch to ballistic missile development with relative ease. Its lack of experience with electronics proved to be a problem, but this was resolved through a cooperation agreement with General Electric Company (GEC). DeHavilland mastered the design and development problems to such an extent that some believed that the structural design was not only superior to comparable U.S. systems, but also lighter.[36]

In contrast to Rolls Royce and DeHavilland, building engineering teams proved to be particularly difficult at Sperry, the contractor for the guidance system. One of the principal concerns at the initiation of the project was whether Britain could develop an inertial guidance system within the project's timetable. Sperry had the hardest job of all the firms involved in the project because a ballistic missile guidance system was a great advance over its previous work; Rolls Royce and DeHavilland already had vast experience in their respective fields.[37] Sperry's experience in developing inertial guidance systems for aircraft formed the basis for its work on Blue Streak, but its problem was that, although components of the right level of accuracy existed for aircraft use, they were not developed for missiles.[38] Therefore, Sperry faced the task of adapting and developing known techniques and technology to this new field.

In 1955, Sperry had only 10 engineers working on Blue Streak, but it tried to argue that "numbers are not necessarily a criterion of progress. At this stage of a new project we believe that quality of thinking is perhaps rather more important than quantity."[39] By November 1956, the team had been increased to 32, but 50 was still seen as the ideal.[40] Unlike at DeHavilland, this shortage of personnel seems to have derived from a general skill shortage within British industry.

Finally, the Royal Aircraft Establishment had relevant experience for its oversight functions, but had less background for its R&D work on re-entry. The RAE had overseen the development of the V-bombers. Through the Rocket Propulsion Establishment (RPE), it had also undertaken considerable development work on the Raven motor used in Skylark, the Gamma motor that was eventually used in the Blue Steel air-launched cruise missile (which had begun development in 1955), and the Black Knight sounding rocket, which was built to conduct re-entry tests for the Blue Streak project.[41] Therefore, the RAE had some expertise in most aspects of ballistic missile development except re-entry and guidance. However, because of a lack of spare capacity within the organization, it had difficulty building a large enough team to work on Blue Streak. Personnel were largely gathered from other departments and other guided-weapons or aircraft projects.[42]

Apart from the actual warhead, the major technological problem concerning the re-entry head was the heat shield, an entirely new area for British engineers. DeHavilland designed the re-entry head, while the RAE investigated the principles of re-entry and tested the materials. Kinetic heating on re-entry was initially considered to be the other major problem facing the project. In the 1950s, Britain had only limited knowledge of heat transfer at supersonic speeds and no knowledge about its effects at hypersonic speeds. Yet, despite the fact that this was an almost entirely new field for British engineers, the re-entry problem had been solved by the time of Blue Streak's cancellation, again indicating the ease with which British engineers adapted to the technology.[43]

Overall, Cockburn's development strategy proved to be adequate for providing suitably qualified personnel on all facets of ballistic missile technology, except perhaps with respect to guidance systems. However, just because relevant expertise existed somewhere in Britain did not always mean it existed within a given Blue Streak contractor. In practice, at different stages of the strategy, specific firms lacked the necessary expertise in key areas. In particular, DeHavilland had not produced a V-bomber, while Sperry had not worked on the guidance system for the Red Rapier or Blue Moon cruise missiles. In fact, some firms with relevant experience were not brought into the project. These included Hawker Siddeley, which had worked on rocket propulsion, and the Bristol Aeroplane Company and Vickers, which were developing Red Rapier.

Thus, Britain did not attempt to nurture long-term teams within industry by applying Cockburn's strategy in an ongoing way to the same core set of firms. The British Blue Streak experience proves that it is possible to cobble teams together from other sections of industry, without the need to establish a single, focused, government program. However, the Blue Streak case suggests the success of such an approach will be determined by the quality of a state's industrial infrastructure, particularly its aerospace sector. In contrast to the British experience, current proliferators may have problems cobbling teams together because their industrial infrastructures are often weak and their aerospace sectors are limited. Therefore, they are forced to nurture long-term teams through Manhattan Project-style programs. By bringing their limited number of skilled engineers together, this should enable proliferators to maximize the limited resources that they have at their disposal, assuming that their programs are managed efficiently.

Finance

Of the four aspects of soft technology under consideration, the budgetary aspect caused the greatest problems in this case. The cost of Blue Streak increased dramatically during its development. When the initial contracts were issued, the estimated cost of development and deployment was £150 million. By November 1958, this figure had risen to £480 million,[44] and the final estimated cost was £600 million.[45] The records show that the project always suffered from underfunding, which seriously affected the pace of progress. Due to the economic circumstances prevailing in Britain at the time, the whole project suffered from extreme financial limitations. Money-saving measures were implemented each year, even to the point of jeopardizing the future of the project. The main example of this was the canceling of parallel sub-system development efforts intended as insurance measures, such as the English Electric Company's inertial guidance program.

In late 1957, a Ministry of Supply official assessed the effect of the government's unwillingness to commit additional resources to the project. His report stated:

> The Blue Streak program is hindered by the apprehension in the minds of the project coordinating firm and the member firms that the money necessary to carry on the program will not be forthcoming. The most telling symptom is unwillingness to build teams. No good chief engineer is going to take high class men from secure jobs at the risk of having to sack them within the year. Section leaders know that with weak teams serious problems will remain overlooked till too late if design or construction has gone too far. Therefore their actions lack positive drive and the project gathers only feeble momentum.[46]

As a consequence, only the technical approaches most likely to work were developed, and riskier proposals that might have proven to be better solutions in the long term were not developed in parallel.[47] To accelerate the pace of the project, the government could have accorded it some form of exceptional priority. This status would have enabled more money to be devoted to the program than previously.[48] However, the Ministry of Supply believed that the financing should not be tied too closely to the rate of progress, because this would lead to variations in the annual rate of expenditure. These annual variations were likely to be so large that such an approach would have drawn resources away from other areas of the defense research and development program. This problem could have been avoided if the project were simply removed from the defense budget, but the Ministry knew its financial control enabled it to maintain technological control over the project. The Ministry also thought that the removal of financial restrictions would lead to the dispersion of scientific effort. This dispersion might lead to the development of a better weapon but could extend the development time.[49]

Since the British Treasury was always opposed to Blue Streak on the grounds that it was too expensive, it was always slow in approving new rounds of expenditure. From 1958, when the project's likely vulnerability to Soviet IRBMs put its future in even more doubt, the prime minister wanted the project continued on the minimum basis necessary for success. Thereafter, the Treasury became even more reluctant to approve additional expenditures. However, there is some doubt about whether the commitment of additional resources in the latter stages of the project would have had much impact. The Ministry of Supply considered it unlikely that more money would have brought the completion date forward.[50] However, Rolls Royce argued that limited finances curtailed production opportunities and slowed the buildup of staff, leading to poor morale. It asserted that the removal of financial restrictions could bring the completion date nearer, and would be better value for the money.[51] Although there is some difference of opinion about the degree of impact, it is clear that financing was a serious constraint. Of the four aspects of soft technology assessed here, this was the greatest problem area for Blue Streak.

DEVELOPMENT INFRASTRUCTURE: AN OVERLOOKED FACTOR

However, precisely because British soft technology was in general fairly strong, soft technology did not impose the greatest obstacles in the Blue Streak case. Instead, certain aspects of hard technology turned out to be a greater weakness in Britain. Specifically, as the project progressed, the weak infrastructure of the firms and RAE proved to be the primary factor slowing the pace of the project. Despite the high quality of its aerospace industry, Britain did not possess all of the specialized infrastructure required for ballistic missile development. It lacked some machine tools, some testing facilities (including a vehicle to conduct trials of re-entry vehicle designs), and all of the major capital facilities (i.e., facilities for static- and flight-testing). Soon after the initiation of the project, work began on a static-testing facility, a flight-testing facility in

Australia, and the Black Knight sounding rocket for the re-entry tests. Although work on the test facilities always lagged behind what the firms sought, Black Knight was successfully completed in time for the series of re-entry tests in 1959.

At the outset of the project, engineers from Rolls Royce visited NAA and reported that they found no unusual manufacturing processes being used in production of the S-3.[52] As the project developed, most of the components for the engine could be made from existing machines at the firm.[53] However, Rolls Royce lacked the machines for producing the tubes that made up the walls of the thrust chamber. These machines had to be procured from the United States, although the rigs for forming and brazing the tubes into thrust chambers were constructed by Rolls Royce itself. Rolls Royce also did not have enough testing facilities to be able to stay on schedule. Initially, it proved impossible to test all of the individual components, and consequently, the first motors were built without direct testing of some of the parts,[54] while the fuel injector heads were sent for testing to the United States.[55]

Finally, provision of capital facilities was also inadequate to keep development on schedule. Rolls Royce anticipated it could develop an engine 18 months before the static-test facilities for a full engine test would even become available.[56] Comparison with the United States shows the paucity of capital facilities. While in 1959-60 Britain had one and one-half missile test stands available for static firing, NAA had six for development of the S-3.[57]

Sperry was similarly hampered by its limited machine tools and testing facilities. In 1955, the Ministry of Supply estimated that it would require 18 months to establish the necessary workshops and machinery. Specifically, Sperry lacked the facilities for testing and calibrating the accelerometers to the necessary accuracy;[58] thus comparative assessments of the accelerometer were not available until 1958. Similarly, in 1956, the Ministry identified the lack of facilities for testing gyros at RAE as a major bottleneck. RAE also had to request a new centrifuge for testing accelerometers.[59] As the project continued, progress on Sperry's Type-B gyro was hampered by its inability to make, assemble, and satisfactorily test the prototypes. By March 1958, Sperry was being forced to consider limited-scale production of some components before their technological evaluation could be completed (thereby incurring the risk of having to make later modifications).

It was much the same story at DeHavilland, which lacked the necessary welding equipment to manufacture the missile structure. It was forced to seek assistance from the U.S. firm Convair on its tank-welding rig, and to procure four welding machines from the National Electric Welding Company in the United States.[60] Lack of testing facilities also meant that DeHavilland was unable to do all of the necessary individual tests before the first full structure test.[61] Nevertheless, DeHavilland was ready for the first test of the complete structure in 1958, and the first full test of the structure with two engines running took place in 1959.[62] Because of the lack of component testing, if serious problems had emerged at that time, they would have seriously affected the overall timetable of the project.

This history shows that Cockburn's development strategy had not fully equipped British industry to engage in ballistic missile development. Still, the necessary infrastructure was successfully built during the course of the program. The rate of buildup was inadequate to keep the project on schedule, but this was a direct consequence of the government's unwillingness to provide adequate funding. Also, in order to build the complete infrastructure, Britain needed help from the United States. Thus, successful technology transfer of missile components required not only good soft technology in the recipient, but also complementary provision of relevant facilities and equipment.

Reports indicate that current proliferators are facing similar problems in gaining access to the necessary machine tools and testing facilities. Proliferators have had to expend considerable effort to procure such items. North Korea, for example, has procured spectrum analyzers from Japan for assessing the accuracy of digital guidance systems;[63] Iran, meanwhile, gained access to Russian wind tunnel facilities to conduct some testing of the Shahab-3 system.[64] The experience with Blue Streak suggests that the scarcity of such facilities will significantly inhibit the pace of proliferators' missile programs.

ASSESSING THE IMPACT OF TECHNOLOGY TRANSFER

The development of Blue Streak illustrates both the limits and the value of technology transfer. With respect to limits, it turned out that no major item of technology or assistance that Britain received from the United States was directly usable or applicable to Blue Streak. This necessitated varying degrees of re-design and development on virtually everything to integrate those technologies and components into a completely new system. Despite these difficulties, however, the program still benefited from technology transfer. This section will first outline some of the more significant development problems encountered by each of the major contractors in turn in assimilating U.S. technology. It will then evaluate the degree to which the overall program was accelerated nonetheless.

To begin with the most significant technology transfer, the S-3 engine, it is clear that assimilating this technology was not easy, but Britain managed it relatively successfully. From the outset, the S-3 required significant re-design and development in order to meet British requirements because it was not a fully tested, reliable, or flyable motor.[65] Moreover, the range specifications for Blue Streak would require 180 seconds of powered flight while the S-3 was only designed for 150 seconds. This longer flight time also necessitated extensive R&D to solve problems such as propellant utilization and cut-off times.[66]

The engine design was restricted by the missile structure as well. The U.S. Atlas only experienced seven and one-half "g" forces during flight, but due to the acceleration that could be achieved by the twin-engined configuration, Blue Streak was likely to experience 18 g during flight. Because 18 g would have imposed major design and development problems on the other elements of the missile, it was decided to develop a thrust control system for the engines that would reduce the problem to 12 g. Stressing the missile to cope with 12 g would have been relatively easy. But if the missile had to be designed to experience 18 g, it would have required a complete re-stress and probably a great deal of re-design.[67] However, because there was no indication of when Rolls Royce could solve the thrust control problem, it was decided in the end to stress the whole missile to withstand 18 g anyway.[68]

A considerable amount of development work had to be undertaken by Rolls Royce to improve the S-3, convert the design to British manufacturing processes and materials, and then adapt it to meet the requirements for Blue Streak. Despite this, however, the work at Rolls Royce ultimately proceeded successfully. Using the S-3 as a model, it developed a family of five engines: the RZ-1 was a direct copy of the S-3; RZ-2 was an anglicized version of the S-3, modified to fit onto Blue Streak; RZ-3 was a simplification of the RZ-2, but incorporating additional control systems for throttling and propellant utilization; RZ-12 was a pair of RZ-2s; and RZ-13 was a pair of RZ-3s. The first RZ-12 testing took place in March 1960, and the first motor was ready by December 1960. The first RZ-3 would have been ready for DeHavilland by October 1961.[69]

Turning from the engines to the guidance system, it was evident from the outset that Sperry would face considerable technological problems, and concerns were expressed about its approach. Nearly all of Sperry's engineers were employed initially on component design, and very little effort was devoted to thinking about the general system.[70] As an insurance measure, a number of different components were developed in parallel. Hence, Sperry attempted to re-design its Type-B gyro, which was originally designed for use in fighter aircraft, while it also designed an entirely new spherical gyro. Sperry also had access to the American Kearfott T2502 gyro. Finally, Ferranti was also contracted to develop an integrated gyro-accelerometer.

For the accelerometer, it was decided to rely entirely on the development of a British component. Options included a single axis accelerometer, which was a re-design of the one being developed for Blue Steel, as well as a three axis model and a string accelerometer that were designed specifically for Blue Streak. As a consequence, Sperry had to design the stable platform to be capable of accommodating any of these components.

Perhaps the most significant design problem facing Sperry was stressing the guidance system to withstand 18 "g" forces. High accelerations would lead to large reductions in the accuracy of the guidance components,[71] but re-designing the components to cope with such accelerations meant increasing their complexity, volume, and weight. By February 1956, the Type-B gyro had only been stressed to eight g.[72]

Sperry had mixed success in developing these components. It successfully completed development of the three axis accelerometer by the time of Blue Streak's cancellation. However, the Type-B gyro was being pushed to its limits to meet the accuracy requirements. By 1958, the Type-B gyro could not meet the same specifications as the American T2502 and was not reliable enough to test satisfactorily. The RAE determined that there would not be any dramatic improvement in the behavior of the Type-B within the Blue Streak timetable, so it decided to use the T2502 in the guidance system.[73] Subsequently, the first models of the Blue Streak guidance system used the T2502 and the three axis accelerometer.

Thus, Cockburn's strategy seems to have failed to produce a pool of skilled engineers who could cope with the demands of developing MRBM guidance systems. Nevertheless, it must be acknowledged that the overall design of Blue Streak imposed some exacting requirements for a team attempting to develop its first missile guidance system. The accuracy being demanded, together with the requirement to stress the components to 18 g, greatly complicated a task that would have pushed Sperry to the limits of its ability in any case. Yet, even despite this, it was likely that the Type-B would have been able to meet a relaxed accuracy requirement of three nmi CEP. Also, it appeared that further development would have enabled it to meet all the specifications, although not within the Blue Streak timetable.[74] If Blue Streak had been subject to only seven and one-half "g" forces (like U.S. missiles), or if lesser accuracy had been acceptable, the engineers at Sperry would have had a relatively easier task.

As for the missile structure, the work at DeHavilland initially relied heavily on access to U.S. expertise,[75] yet this did not meet all of DeHavilland's requirements. The Blue Streak structure had to be both lighter and stronger than Atlas to cope with the heavier propulsion unit and the higher "g" forces that it would experience.[76] However, designing a structure to cope with high "g" forces invariably increases its weight. While DeHavilland had access to U.S. designs, techniques, and data, it could not use U.S. structural test results because the thrust of Blue Streak and its duration differed from those of U.S. systems.[77] This left DeHavilland with significant design and development problems to resolve.

By 1958, it became evident that DeHavilland was not sufficiently proficient in electronics and systems engineering; thus, the Ministry of Supply forced it to work with the electronics firm GEC. This development indicates that firms with experience engineering large airplane components do not necessarily have *all* of the necessary skills to build a ballistic missile. Nevertheless, the fact that several British electronics firms were capable of providing the necessary expertise demonstrates that most of the relevant experience was readily available. By the time of cancellation, DeHavilland had manufactured the first structures for the planned test-flight program in Australia.

The RAE also used U.S. data in its work on re-entry. However, some of the Ministry of Supply's technical consultants in the academic community argued that this data should not be used as the sole basis for the British program because it arrived in small quantities and was of doubtful accuracy. They saw a danger in accepting U.S. reports when detailed support was not made available for study and evaluation. Britain might be misled by U.S. theories because it was ignorant of the underlying assumptions and details. Therefore, Britain conducted its own theoretical studies, which were complemented by U.S. data.[78] Initial work in Britain focused on heat sinks, the easiest type of heat shield to develop. This type of shield dissipates some of the heat generated by re-entry, and absorbs much of the rest. The RAE initially studied the properties of copper, iron, and various steels. However, it quickly became evident that an ablative design would have to be used. Ablative heat shields dissipate the heat generated on re-entry through a thin outer layer of the shield that burns very slowly, so that very little heat spreads to the inside of the re-entry vehicle. The RAE had previously conducted very little theoretical work on ablation. But it quickly began investigating a range of materials such as carbon, quartz, silicon carbide, silicon nitride, and durestos, as well as a design involving transpiring water.[79] Full-scale ground tests of the re-entry shield were impossible because of the magnitude of the heat required, although the shield's aerodynamic properties were tested in plasma jets and shock tubes.[80] New manufacturing techniques also had to be developed to weld and form the materials being used into re-entry heads. By 1959, these techniques appear to have been worked out,[81] and preliminary designs were tested on Black Knight.[82] Blue Streak was canceled before the full program of flight tests had been completed, but both the heat sink and ablative head would have been ready for their initial flight tests in mid-1961.[83]

In the end, despite the various difficulties that have been outlined, Britain was able to incorporate much of the technology transfer from the United States and these transfers did benefit the program. At the time of cancellation, Blue Streak was on course for initial deployment in 1965, meaning the program would have involved a 10-year development period. Experts believe that U.S. assistance pared five years off the development time for Blue Streak;[84] if the United States had not been involved, it would have been a 15-year development program. However, if the British government had made additional resources available to overcome some of the major bottlenecks, the project might have been completed a few years sooner.

CONCLUSION

This analysis confirms Karp's thesis about the importance of soft technology, but it also indicates the critical impact that hard technology transfers can have on proliferation. The Blue Streak case clarifies that more than just soft technology is required; the transfer of U.S. technology also helps explain the relative success of this project. But the limits of hard technology transfer are also evident. The date of completion for the project thus really resulted from a combination of the excellent quality of British soft technology and the provision of U.S. assistance. Consistent with Karp's emphasis on soft technology, this case study makes it clear that U.S. assistance took five years off the schedule only because Britain was capable of assimilating it so effectively. If British soft technology had been weaker, Britain would have faced greater difficulties in assimilating U.S. assistance. The result was that all elements of the Blue Streak missile, except for the guidance system, were on course for successful development at the time of cancellation.

British soft technology was weakest in respect to guidance. Consistent with Karp's thesis, this did prove to be the principal technological choke point in the program. British engineers were able to bypass this problem, however, through the use of an American gyro. This shows, as Karp indeed acknowledges, that soft technology is not the sole determinant of outcomes, as specific technology transfers can sometimes compensate for weaknesses in soft technology. However, although hard technology transfers provided the project with an immense head start and the ability to overcome some technological choke points, they could not be used to resolve all of the problems that British engineers encountered.

Consequently, the quality of a state's soft technology is one of the principal factors that determines the range bracket within which it can seriously consider initiating an indigenous ballistic missile project. Because the soft technology of the current set of likely proliferators is poor relative to the British level in this case, these states cannot adopt the British development strategy with any reasonable assurance of success. Instead, these states have had to start their programs with the Scud-B and other similar short-range systems, before moving on to medium-range systems. However, as Karp acknowledges, hard technology transfers can be a critical factor in the progress of some projects. Technology transfers can enable proliferators to overcome specific technological bottlenecks caused by deficiencies in their soft technology or even skip some stages in their development strategies. North Korea, in particular, is perceived as requiring transfers of engine and guidance technology in order to complete the Taepo-dong-2 program.[85] However, the limits of technology transfers documented in the Blue Streak case indicate that such transfers are not a solution to all of the technological problems that proliferators face. Proliferators must still be able to assimilate these transfers into their indigenous programs.

The Blue Streak case also suggests that relevant hard technology comprises more than just missile systems or their components. It shows that machine tools, testing facilities, and the ability to identify, acquire, and use the right materials are other elements of hard technology that can hamper the effectiveness of even good quality soft technology. For example, British engineers were able to develop the re-entry heat shield only because they had access to the necessary materials and development facilities. Overall, though, development infrastructure proved to be one of the major choke points in the British program. Since most would-be proliferators lack an advanced industrial infrastructure, they have had to acquire the necessary machine tools and other facilities from other states. This lack of industrial infrastructure also means that proliferators will probably not produce all of the necessary materials indigenously. Consequently, while soft technology is the most important factor in successful ballistic missile development, it is not enough to guarantee success. Instead, hard technology transfers are also necessary, in conjunction with the presence of good soft technology, for proliferators to make progress with their programs.

While the third world states most often identified as likely missile proliferators mostly do not possess soft technology equivalent to that of Britain in the 1950s, some have overcome their deficiencies through the employment of foreign engineers. Russian technology transfers to Iran in the late 1990s proved to be highly successful because they were supported by large numbers of North Korean, Chinese, and Russian technicians.[86] Nonetheless, shortages of skilled engineers still limit Iran's ability to assimilate foreign technology.[87] Most proliferators are gradually developing dedicated ballistic missile research and development infrastructures. In turn, these facilities increase and improve the skill levels of their engineers. The indications are, however, that most proliferators are still suffering from a skills shortage.

To conclude with some policy implications, the Blue Streak case suggests that even if a proliferator possesses good soft technology, its progress can still be constrained by control of hard technology. Therefore, one should not conclude that just because soft technology is crucially important, controls exercised by the MTCR will eventually become irrelevant. Instead, this case suggests only that control efforts must be careful not to place too much emphasis on finished components and sub-components. Among elements of hard technology, the control of materials and development facilities is just as significant. Likewise, international control efforts also need to be broadened to include soft technology. However, the fact that proliferators can acquire the skills and competencies required for ballistic missile development from basic aerospace technique suggests that efforts to prevent the necessary skills and competencies from spreading to proliferators will be difficult. Karp argues that efforts to control soft technology transfers through government-to-government cooperation should be broadened to deal more directly with individual ministries and enterprises.[88] Such measures have already proved to be effective, halting the Russia-India cryogenic engine deal in 1993 and denying India access to Russian propulsion engineers.[89] However, the fact that individual firms, particularly in Russia and China, are passing on such expertise without government sanction indicates how difficult this will be to achieve in regular practice. Having a better understanding of where the main barriers to successful proliferation really arise should help the international community better target its efforts.

[1] By the current conventions of many organizations, Blue Streak would even be considered an intermediate-range ballistic missile. However, at the time of its development, it was referred to as a medium-range system, so to avoid confusion that label is used throughout.

[2] Aaron Karp, *Ballistic Missile Proliferation: The Politics and the Technics* (Oxford: Oxford University Press, 1996), p. 97.

[3] Andrew Brooks, *V-Force: The History of Britain's Airborne Deterrent* (London: Jane's, 1982), pp. 83-88, 97.

[4] Peter Malone, *The British Nuclear Deterrent* (London: Croom Helm, 1984), p. 65.

[5] Humphrey Wyn, *RAF Nuclear Deterrent Forces* (London: Her Majesty's Stationery Office, 1994), pp. 373-393.

[6] DEFE 7/1328, BND(SG)(59)19(Final), "British Controlled Contribution to the Nuclear Deterrent," 31/12/59 (This and all subsequent documentary sources cited come from British government records held at the Public Records Office, Kew, London. The abbreviations and dates used are those by which the items are listed at the Public Records Office).

[7] AIR 2/14975, Air Staff Requirement, Operational Requirements OR/1139, April 1955.

[8] Karp, *Ballistic Missile Proliferation*, pp. 66-72.

[9] The Ministry of Supply was one of the principal ministries in defense decisionmaking. It was responsible for procurement and oversaw domestic defense research, development, and production.

[10] Timothy Raison, "Science, Defence and the Time Factor," *New Scientist*, February 27, 1958, p. 102.

[11] For further details, see Benjamin Cole, "The Development of Blue Streak: An Analysis of the Role of Ideas in British Nuclear Weapon Procurement Policy," Ph.D. thesis, Southampton University, June 1996.

[12] AIR 2/13211, Technical Memo, No.GW243, March 1955.

[13] AVIA 65/1427, "A Technical Reappraisal of the UK Ballistic Missile Programme Assuming the Availability of a 600lb Warhead," undated.

[14] Author's interview with former Blue Streak engineer (name withheld by request), June 27, 1994.

[15] AIR 2/13211, Technical Memo GW243, "A Survey of the Present Position on the Evaluation of the Blue Streak Project," by the Staff of the RAE, undated.

[16] *Ibid.*

[17] Structure weight ratios refer to the ratio between the weight of the unfuelled missile and its weight when fueled and ready for launch.

[18] AVIA 54/2141, Notes of First Meeting of A1 Panel, 1/2/56.

[19] Stephen Twigge, *The Early Development of Guided Weapons in the UK* (Reading: Harwood, 1993), p. 125; Karp, *Ballistic Missile Proliferation*, pp. 77-78.

[20] Red Rapier was superseded by the Blue Steel air-launched cruise missile program in 1955, while the Blue Moon requirement was superseded by Blue Streak.

[21] AIR 8/2057, Note by DCAS Pike, Blue Streak and DeHavilland, 13/1/56, sent to PUS, 26/1/56.

[22] Author's nterview with former Blue Streak engineer (name withheld by request), June 27, 1994.

[23] AVIA 65/597, Cleaver to Philips, 3/12/59.

[24] AVIA 54/2130, 6/6/58.

[25] AVIA 65/1581, Meeting to Discuss Improving the Management, 8/4/59.

[26] Karp, *Ballistic Missile Proliferation*, p. 82.

[27] Author's interview with Mr. S. L. Bragg (formerly head of Performance Section at Rolls Royce), March 1995.

[28] Ian E. Smith, "Arthur Valentine Cleaver, 1917-1977," *Journal of the British Interplanetary Society* 45 (1992), p. 306.

[29] Author's interview with Mr. S.L. Bragg, March 1995.

[30] AVIA 54/2132, Upshall to US/LGW, 1/6/56.

[31] Arthur V. Cleaver, "The Blue Streak Propulsion System," paper for the European Symposium on Space Technology, London, June 1961.

[32] AVIA 54/2132, Pinkerton to BJSM, 1/6/56.

[33] Author's interview with Mr. David Wright, Oral Historian, British Rocketry Oral History Project,

April 24, 1998.

[34] Karp, *Ballistic Missile Proliferation*, p. 80.

[35] Author's interview with former Blue Streak engineer (name withheld by request), June 27, 1994.

[36] Author's interview with Sir James Lighthill (former head of RAE), October 1993.

[37] Author's interview with former Blue Streak engineer (name withheld by request), June 27, 1994.

[38] AIR 2/13206, Notes of Meeting to Discuss the Requirements for a Medium Range Ballistic Missile, 16/3/55.

[39] AVIA 54/2135, Broadbent to MOS, 21/12/55.

[40] AVIA 54/2127, Record of MOS Visit to Sperry, 9/12/55.

[41] Dennis J. Lyons, "Ballistic Research Rockets With Particular Reference to Black Knight," *Journal of the Royal Aeronautical Society* 65 (March 1961), p. 175.

[42] Author's interview with former Blue Streak engineer (name withheld by request), June 27, 1994.

[43] AVIA 54/2145, Minutes of Fourth Meeting of A7 Panel, 23/10/57.

[44] CAB 131/20, D(58)63, Ballistic Rockets, 14/11/58.

[45] DEFE 7/1328, BND(SG)(59)19 (Final), "British Controlled Contribution to the Nuclear Deterrent," 31/12/59.

[46] DEFE 13/193, "Observations on the Blue Streak Programme," W.H. Wheeler, November 1957.

[47] *Ibid.*

[48] DEFE 13/193, Letter, Jones to Sandys, 3/1/58.

[49] AVIA 65/1427, "Main Events in the Blue Streak Programme 1955-58," 2/4/58.

[50] PRO, AVIA 65/1427, Letters, Rolls Royce to Cockburn, 17/1/58; and PS/Minister to US(LGW), 14/1/58.

[51] PRO, AVIA 65/1427, Rolls Royce to Cockburn, 17/1/58.

[52] AVIA 54/2132, NAA Liaison Group, Progress Meeting, 11/8/55.

[53] Author's interview with Mr. S.L. Bragg, March 1995.

[54] AVIA 54/2127, Pearce to Bullock, 3/12/57.

[55] AVIA 54/2133, 6/2/58.

[56] AVIA 54/2142, Notes of First Meeting of A1 Panel, 1/2/56.

[57] AVIA 54/2134, 1/5/58.

[58] AVIA 54/2143, Minutes of A3 Panel, 19/9/56.

[59] AVIA 54/2142, Notes of Second Meeting of A1 Panel, 10/10/56.

[60] AVIA 54/2130, Povey to Bonser, 27/2/57.

[61] AVIA 54/2130, "Blue Streak Structural Test Programme," Notes of Meeting in Structures Department, RAE, 22/11/57.

[62] AVIA 54/2130, Wilkins to Serby, 4/1/57.

[63] "CIA Confirms Missile Developments," *Jane's Defence Weekly*, March 26, 1994, p. 3.

[64] "Secret Israeli Data Reveals Iran Can Make Missile In Year," *Defense News*, October 6-12, 1997, p. 4.

[65] AVIA 54/2132, Upshall to US/LGW, 1/6/56. In particular, initial analyses of the design and operation of the turbopumps and the fuel injector head highlighted a number of unsatisfactory features which could be amended in future designs (see AVIA 54/2132, Report on Progress, at 31/2/56).

[66] U.S. analysis of cut-off times could not be used because it did not use the same bonker system as Blue Streak (bonkers are small rocket motors in the re-entry vehicle which are used after the missile's main engines have been shut down and the re-entry vehicle has separated, in order to nudge the re-entry vehicle towards the correct velocity and position in space, prior to re-entry). See AVIA 54/2142, Minutes of Sixth Meeting of A3 Panel, 27/2/57.

[67] AVIA 54/2132, Pearce to Serby, 9/1/56.

[68] AVIA 54/2132, CGWL to DGGW, 23/8/55.

[69] AVIA 65/597, Notes of Meeting in DG(BM)'s Office, 12/1/60.

[70] AVIA 54/2127, Record of MOS Visit to Sperry, 9/12/55.

[71] AVIA 54/2128, Report, "Effect of High Acceleration on Equipment for Project 3000," 21/6/56. It was estimated that if the gyro was stressed to withstand 12 g, its performance would deteriorate by a factor of four if it was actually subjected to 18 g (AVIA 54/2135, Minute by Bostock, 14/2/56).

[72] AVIA 54/2141, First Meeting of A1 Panel, 1/2/56.

[73] AVIA 54/2136, "Choice of Gyroscope," W.H. Stephens, 16/6/58.

[74] AVIA 54/2136, Bullard to DG/GW, 6/12/57.

[75] AVIA 54/2130, Letter from MOS to BJSM, 3/5/56, and letter from Goodwin to Bonser, 26/4/56.

[76] AVIA 54/2132, MOS to BJSM, 17/2/56.

[77] AVIA 54/2130, 6/6/58.

[78] AVIA 54/2146, Howarth to Leslie, 26/3/56.

[79] AVIA 54/2145, Notes of First Meeting of A1 Panel, 17/10/56.

[80] G.V.E. Thompson, "The Re-entry Problem," *New Scientist*, February 13, 1958, p. 120.

[81] See AVIA 54/2044, correspondence with Hudswell Clarke and Co. Ltd., 1958.

[82] For details, see Andrew Morton, *Fire Across the Desert* (Canberra: Australian Government Printing Service, 1989), p. 424.

[83] AVIA 54/2145, Minutes of Fourth Meeting of A7 Panel, 23/10/57.

[84] Author's interview with the Rt. Hon. Aubrey Jones, former Minister of Supply, April 15, 1993; C. J. Bartlett, *The Long Retreat* (London: MacMillan, 1972), p. 109.

[85] "North Korea Grasps At Stage Beyond NoDong-1," *Jane's Defence Weekly*, March 19, 1994, p. 18.

[86] "China Lends Hand With Iran Missiles," *Sunday Telegraph*, November 23, 1997, p. 31; "Russia Is Assisting Iran's Missile Drive," *Jane's Defence Weekly*, October 1, 1997, p. 3; "Secret Israeli Data Reveals Iran Can Make Missile In Year," *Defense News*, October 6-12, 1997, p. 4.

[87] Aaron Karp, "Lessons of Iranian Missile Programs for U.S. Nonproliferation Policy," *The Nonproliferation Review* 5 (Spring-Summer 1998), p. 22.

[88] *Ibid.*, p. 24.

[89] Alexander A. Pikayev, Leonard S. Spector, Elina V. Kirichenko, and Ryan Gibson, "Russia, the US and the Missile Technology Control Regime," *Adelphi Paper* 317 (London: International Institute of Strategic Studies, March 1998), pp. 63-64.