SEQUENCE.

Cover ....DELETED
Inside cover ....DELETED
Prof John Simpson. ....DONE
Ridley, Soviet ABM Challenge ....DONE
Panton, Politics and Strategic Background. ....DONE
Moore. Why Chevaline? ....DONE
Ridley, Requirement & early R&D prog ....DONE
Polaris missile cutway Upgraded illustration not in the original publication.
Tilt-out cutway A3T Upgraded illustration not in the original publication.
Tilt-out cutway A3TK Chevaline Additional illustration not in the original publication.
A3T ReB proportions Additional illustration not in the original publication.
SC Metcalf & Dommett, Intro to Chevaline ....DONE
Polaris missile cutway again Upgraded illustration not in the original publication.
Front end cutway Upgraded illustration not in the original publication.
Tilt out sequence drg Upgraded illustration not in the original publication.
Tilt-out cutway A3TK Chevaline Additional illustration not in the original publication.
Threat deployment sequence Upgraded illustration not in the original publication.
Flight trials sequence at Woomera ....DELETED
Org & Management ....DELETED
Kate Pyne, AWRE contribution ....DONE
Mike Rance, RAE contribution. ....DONE
Table 1. RAE expertise ....DONE
Table 2. Principal companies ....DONE
Table 3. Falstaff outcomes ....DONE
Falstaff pic. .... To do
Mike Rance, Industry contribution ....DONE
Tables ....DONE
BAE contribution ....DELETED
Abbreviations List ....DELETED
Glossary of Terms. ....DONE

Royal Aeronautical Society Symposium.

"The History of the UK Strategic Deterrent: The Chevaline Programme."

28 October 2004.

KEYNOTE ADDRESS: Professor John Simpson OBE.

About thirty-five years ago I started my academic career by writing a study on the procurement of the UK Polaris missile force. I was therefore honoured some time ago to be asked to introduce today's discussions on a programme that I and most of the country knew nothing about it when my study was published: the Chevaline upgrade programme for Polaris. It is therefore with great regret that my recent accident means that I will not be able to be with you in person today and benefit immediately from its presentations and discussions. Not the least of the reasons for this is the recent award to the Mountbatten Centre at the University of Southampton by the UK Arts and Humanities Research Board of a three-year research grant to enable a small research team to chronicle the history of UK nuclear weapon activities from 1953-72, in which some of the issues underlying the Chevaline programme will play a central role. The start of work on this project has now had to be delayed to early 2005.

One of the motivations for returning to my interests in UK nuclear history for the third time in my academic career was the stimulus generated by the symposium the Royal Aeronautical Society held in 1999 on the early history of the UK strategic deterrent. One paper presented at this meeting stands out in my mind: the account by Peter Jones of how the defensive capabilities of the then USSR had acted as a major technical driver for the UK strategic offensive nuclear forces. Five years ago it did not seem possible for any detailed discussion of this issue to occur beyond the impact of the development of USSR air defences and its offensive ballistic nuclear missiles upon the operations and future of the V-bomber force. Today, the operation of the 30 year rule for the opening of archived material means that a more detailed public analysis is now possible of the uniquely UK concerns over the technical and physical vulnerability of its small nuclear deterrent force from the early 1950s onwards.

Some of these concerns involved the vulnerability of nuclear warheads to disablement: others involved the vulnerability to destruction by Soviet interceptor missiles of the planned ballistic missile successors to the air-breathing deterrent vehicles of the period 1956-1969. Indeed it is now clear that one major factor in the procurement decisions on Blue Streak, Skybolt and Polaris was their respective throw-weight, and thus their capability to deploy both the warheads of larger yield needed for the UK national strategic role and the increasingly necessary missile defence countermeasure equipment. This in turn lead to difficult issues of the range penalties this would generate; the enhanced vulnerabilities of their delivery platforms; and the recognition almost from the start of the Polaris acquisition process that that one of the initial triplet warheads might have to be sacrificed to such countermeasures equipment in any mid-life upgrade. The result was Chevaline.

The detailed technical story of the improved front end for Polaris, which was in service for nearly 13 years of the 28 years of UK Polaris patrols has so far been little chronicled. What is known about Chevaline has tended to focus on the beliefs that the project was mismanaged and over budget that originated from the 1982 Public Accounts Committee report, which some would argue was inherently flawed. The technical challenges confronting those involved have yet to be sketched out in public, nor the reasons why many of them resulted from the very different threat the USSR missile defence capabilities posed to the UK deterrent force in contrast to the much more numerous capabilities of the US.

Yet the Chevaline story is not one of technical challenges alone. It is one of the complex interactions between the political, technical and military aspects of the US-UK nuclear weapon and delivery system relationship. It is a period when a succession of UK governments, parliaments and their advisors remained unclear of the continued political and security value to the UK of its nuclear deterrent capabilities. Also involved were differing judgements by the Royal Navy as the operating arm on the one hand, and those responsible for the technical credibility nuclear deterrent in Aldermaston and the MoD on the other, over several key issues ranging from the need for an upgrade in the first place; the alternatives to Chevaline that might be available; and safety and reliability issues. It also involved intelligence and technical estimates of what future Soviet offensive and defensive capabilities were likely to be, and thus what was the nature of the enhanced offensive threat and countermeasures capabilities the UK should seek to acquire.

Today therefore provides a very welcome opportunity for some of the key individuals who were involved with the Chevaline project to speak in public for the first time about these broad range of issues. We will hear from Bob Ridley about the problems which faced UK Polaris, particularly the way that the decision to procure Polaris, taken by the US President and UK Prime Minister at Nassau in December 1962, was challenged almost immediately by the development of Soviet ABM defences whose capabilities were open to a wide range of possible interpretations. This problem had to be addressed by the succession of British cabinets and their advisors that followed. Frank Panton will take you through what must have been a tortuous and difficult time for all concerned, with not all of those involved having a strong belief and enthusiasm for a UK deterrent force, or a wish for the UK to continue to provide an independent contribution to NATO's 'common defense'.

Once embarked on, the Chevaline programme presented considerable technical challenges and uncertainties. You will learn from Bob Ridley, Kate Pyne and Steve Metcalf about specific technical aspects of the programme, and how the challenges they posed were overcome. In that context, Kate and Mike Rance will describe the roles of Aldermaston and Farnborough, while Dave Reade and Mike will cover some of the industrial contributions. You will then hear from Steve Metcalf about the problems caused by the introduction of the improved front end into the Royal Navy's four Polaris submarines, and also how confidence in the system was established through the programme of flight trials.

The organisational challenges inherent in managing the complexity of the programme were also considerable, given the deadline for deployment. They involved the integration of activities taking place in the many establishments and organisations that at that time formed part of the UK and US governmental structures, as well as industrial groupings and companies in both countries. Very few of their names exist today, and to track down all their changes in status and ownership would almost require a symposium in itself. Stan Orman will therefore conclude the presentations by offering a personal perspective on Chevaline in the wider context of these and other project management issues, while Philip Pugh will attempt to elucidate the politically sensitive issue of how much it all cost in both contemporary and comparative terms.

Wearing my academic nuclear non-proliferation hat, perhaps this is an appropriate point for me to make it clear that, as with other aspects of nuclear history, not all of the challenges presented by Chevaline, and overcome by its development team, can or should, be told even now. The UK is bound by its commitments to the Treaty on the Non-Proliferation of Nuclear Weapons and other international agreements not to assist other states to acquire nuclear weapons and, in some contexts, their delivery systems. Judgements in this area are difficult, and must also be tempered by the uncertain strategic WMD future we appear to be moving into. Thus while the end of the Cold War has allowed wider access to relevant public records, these commitments and the emerging threats will continue to impose limitations on the chronicling of the Chevaline story in both its nuclear and non-nuclear technical aspects. However, having said this, I can assure those of you who like myself had no direct involvement in the programme that you will have to wrestle with many new acronyms, as well as code words such as Falstaff which may indicate that some of those involved had had a sound Grammar School education!!

You have much ground to cover today, and much less time than would ideally be allocated to cover it. The organisers also wish to communicate relevant information to you in a structured manner, as a consequence will run all the presentations consecutively to allow for a wide ranging question and answer session at the end of the day.

The Royal Aeronautical Society will be producing the proceedings of the Symposium, including texts prepared by the speakers which will be of greater length than time permits today. Now, I am very pleased to ask Bob Ridley to start today's proceedings.

Politics and Strategic Background. 1964-1982.

Dr Frank Panton.

Other papers have given a factual account of the discussions about, activities regarding, and decisions made concerning the British independent nuclear deterrent from the policy point of view in the Ministry of Defence and Whitehall more generally in the years 1967-1975/6, and have critically examined the conduct and the conclusions of the House of Commons Public Accounts Committee 1981/2 Enquiry into Chevaline. (1, 2). This present paper complements the information in the earlier two, examining the political and strategic background to the UK nuclear deterrent programme, using mainly the written memoirs of prominent politicians of the period, relevant official papers being as yet unavailable.

The period covered by this board review stretched over a Labour Government (1964-1970), Conservative (1970-1974), Labour (1974-1979), and Conservative (1979 -). Each government brought a different perspective to the problems posed by the maintenance of a credible UK strategic nuclear deterrent force, and it is therefore convenient to review the political background in the four different periods. For completeness, short sections comment on the differences of view within government departments and between government advisors, and summarise the import of and reactions to the Public Accounts Committee Report. A final section attempts to summarise conclusions that may be drawn from the evidence presented in this and the previous papers.

1964-1969.

Immediately on taking office in 1964, only two years after the conclusion of the US/UK Polaris Sales Agreement, the Labour government reassessed the programme in the light of its election platform to de-negotiate Polaris. According to Denis Healey's memoirs (3), George Brown was at first for cancellation, but then changed his mind to argue for a cut to three boats. Harold Wilson wanted to be able to allow Polaris to continue, on the grounds that the progress of the programme had passed the point of no return. Healey was for continuing Polaris in some way or other, on the grounds that possession of it would give the UK more influence in an uncertain world with the US, and that to run it would cost only 2% of the Defence Budget. Healey did not think it wise to trust the future of the human race to the mathematicians of the Pentagon, who "seemed to assume human characteristics only when they thought their institutional interests were at risk" Having found that the keels of two Polaris boats had been laid down, that long lead items for two other boats had been ordered, but that no substantial expenditure had so far been committed for the fifth boat, he decided to rely on a four boat force, and cancel the fifth boat. It would seem that no serious objection to this course was raised by the Royal Navy: according to Healey, the major concern of most senior admirals was to ensure that the cost of the Polaris force would not be born on the Naval vote at the expense of other ships.

One effect of this decision, which must have been realised at the time but could not have then been considered important enough to stand in the way of the cut of the fifth boat, was that with four boats the Royal Navy could not guarantee to keep two boats at sea all the time. In the worst scenario, the credible strength of the UK deterrent was that of one boat, 16 missiles each with three warheads, and future calculations of penetrability in the face of possible defensive measures had to take that fact into account.

By the middle 1960's, the UK Polaris system was well on the way to full construction and deployment. Cooperation from the US through the Polaris Sales Agreement and the 1958 US/UK Agreement on the Uses of Atomic Energy for Defence Purposes was all that could be wished for. However, in those years, exchanges with the US under the 1958 Agreement on forward-looking research into nuclear warhead design, including research into hardening against nuclear defences, began to dry up. One reason for this was that Sir Solly Zuckerman, who, as Chief Scientific Adviser, MOD, was also the UK Principal in the regular "Stocktake" meetings with the US DOD and AEC, had, in one of those meetings, announced that the UK had no further interest in working towards new nuclear warhead systems beyond Polaris. From that point, and until the early 1970's exchanges under the 1958 Agreement were effectively limited on the US side to material that had already been cleared for discussion with the UK. And the decision by the Labour Government, stated openly by Mr. Wilson in 1967/8, that the UK had no interest in Poseidon, did not encourage the US to open up on methods of hardening against and penetration of possible ABM defences.

The US did, however, inform the UK in 1967 that a hardened version of the Polaris Missile, A3T, had been developed, and could be supplied to the UK. That offer was accepted, largely because production of the unhardened A3 missile had been discontinued, and it would have cost more to start up the A3 assembly lines for UK production only, than to buy the A3T. At the same time, the UK was warned that consideration should be given to hardening the UK Polaris re-entry system. The implication that the UK Polaris system might need improvement even before it entered service was not an easy one to accept, and the whole issue was, for obvious reasons, subject to great secrecy. In order for an informed assessment to be made by the UK of the threat to the credibility and effectiveness of the UK Polaris in the face of possible Soviet ABM defence, and to assess what might be done to overcome vulnerability problems and improve the UK deterrent appropriately, it was essential to re-engage the US in the discussion of these matters, which had languished in the mid 1960s. With difficulty, Ministerial approval was obtained for AWRE to take the lead in an in-house, no-contractor, highly classified study to give a view on the problems and the way forward. Full cooperation from the US in this study took some time to gain the UK's stated lack of interest in Poseidon, and the known views of Zuckerman (who by 1967 had left MOD to concentrate on being Chief Scientific Advisor to the Cabinet), that ABM defences would not work and there was no need to improve UK Polaris, did not encourage the speedy release to UK of necessary US data, test and studies. Consequently, it was not until early 1970 that AWRE produced an evaluation to the effect that improvement of the UK deterrent would be needed in the face of possible Soviet ABM developments, and that the best option would be Poseidon, but that Super Antelope would have useful effectiveness. Just before the Election of May 1970, Mr. Healey authorised a year's work on a definition programme for Super Antelope.

Writing of this period in his memoirs, Mr. Healey records that the US decision in September of 1967 to go ahead with the development of an ABM system, and the fact that the USSR was proceeding similarly, compelled the UK to consider what, if anything, might be done to enable UK Polaris to penetrate ABM defences, even though these would be unlikely to be effective for a number of years. Poseidon was ruled out, partly because we would be responsible, as with Polaris, for producing the warheads, and we could not expect to master the MIRV technology, except at a disproportionate cost to our scarce scientific manpower. So instead, research into possible ways of improving the penetration capability of UK Polaris was started. At one stage of the discussions, records Healey, Harold Wilson got so discouraged he suggested selling UK Polaris submarines back to the US, but no one else supported this proposal. Healey concludes that it was left to the new Conservative Government in 1971 to order the development of a system to penetrate Soviet ABMs - Chevaline.

1970-1974.

The coming to power of the Conservative Government provided an opportunity to review all options for the improvement of UK Polaris. While there was no doubt that the new government would want to maintain a credible national nuclear deterrent, the review was not speedy. It had to take account of several conflicting factors. One of Mr. Heath's prime objectives was to take the UK into the Common Market. He could not achieve this without the support or at least the acquiescence of France, and would need to take care that the state of UK's relations with the US in the defence nuclear field did not unduly upset the French. Purchase of Poseidon, which was never a real option for the Labour government, was one that the Conservative government was willing to consider, but there was doubt that the US would at that time be willing to sell Poseidon with MIRV technology, and the French might see such a move as unhelpful in the context of the proposed entry into Europe by the UK. Overall, there was the question of how to meet the expenditure of any improvement option within the Defence budge at a difficult time for the economy of the country.

At the outset of the Conservative government, the Navy Department asked Lord Carrington, the new Secretary of State at the MoD to seek further information on Poseidon, to reconsider the fifth boat, and to continue Super Antelope work. Through Naval channels, it was made clear that a request to buy Poseidon was likely to be refused, and that therefore there was no point in asking for information on the system. Reconsideration of the fifth boat does not seem to have been seriously pursued, and it was not until October 1970 that further continuation of work on Super Antelope was agreed, after the US Government had officially indicated that the project was worthy of mutual interest. However, as my article on Chevaline in the Prospero magazine shows in detail, throughout 1971 to 1973, various options other than Super Antelope were considered and re-considered, with US assistance and advices, including a concept using the Poseidon without MIRV. The option of a joint development with the French was given serious consideration, but not found feasible as a solution to Polaris improvement, but not ruled out for future systems. I show now a slide (Appendix 1), which identifies the alternative options and concepts that were examined during those years.

Finally, Mr. Heath decided at the end of 1973 positively to proceed with Super antelope, re-labelled Chevaline, but to keep his decision secret until the publication of the impending Defence White Paper. The February 1974 election, however, forestalled that, and a new Labour government took over.

1974-1979.

When Mr. Roy Mason, the new Secretary of State for Defence was briefed on Polaris Improvement, he was asked either for full go-ahead for Chevaline, or for six months funding, with a nuclear test, while the new Government reviewed the whole issue. He agreed to put the latter course to the PM, but would not include Poseidon in the review. By April 1974 the US government was made aware of the review, with a hint that Chevaline would probably go ahead on Conservative plans. The Royal Navy remained opposed to Chevaline, but after another search for cheaper alternatives and after the re-election of the government with an increased majority in October 1974, the decision to proceed with Chevaline was taken in January 1975. The full implementation of the decision was delayed until last minute while Naval objections on safety grounds were disposed of, and the Navy had been given full development and production authority to manage the project. After three months spent in assembling a new management team, and a further three months reassessing the programme, Chief Polaris Executive finally took over management in April 1976.

As an indication that the Labour government decision in 1975/6 to go ahead with Chevaline was not taken without severe reservations, it is interesting to note that Mr. Healey in his memoirs written in 1989 concluded that he regarded it as one of his mistakes as Chancellor that he did not get Chevaline cancelled. At that time, he wrote, the Labour government found that its cost had escalated beyond control, and Russia had meanwhile agreed in the ABM Treaty not to extend its ABM system beyond Moscow. He commented that Wilson's suggestion in the late 1960s that UK Polaris should be sold back to the US was not so bizarre as it seemed at the time.

By 1977-8 the Chevaline programme was assessed to be far behind schedule and even further above its planned cost, and the Callaghan government held a Ministerial meeting to discuss whether to cancel the project, and what to do about a replacement or successor to it. Both Denis Healey's (3) and David Owen' s memoirs (4) refer to these discussions. Healey and Owen did not believe it necessary for a British deterrent to guarantee the destruction of Moscow; an ability to threaten the destruction of the dozen next largest Soviet cities would be sufficient to deter an attack on Britain, if the Alliance had disintegrated-"a contingency which was inconceivable in any event". Officials were instructed to look again at the "Moscow Criteria", but they produced a recommendation in favour of it, without, according to Healey, any serious argument, except that to cancel Chevaline would damage UK prestige in Moscow and Washington. Owen's view in 1978 was indeed that cancellation of Chevaline would raise military questions capable of destroying the political effectiveness of the UK Polaris system without an improved warhead. Since he believed nuclear deterrence is as much psychological as political and military, he therefore favoured continuing with Chevaline, and the system development was allowed to continue. No decision was reached by the Callaghan government on a successor to Chevaline, but Owen records that though he and his immediate colleague never doubted that Polaris should be replaced, none of them felt able to go out and argue the case positively to the Parliamentary Party, let alone the Party and the country.

Although no decision was reached by the Callaghan government on a successor system, at a meeting with President Carter in early January 1979 at Guadeloupe, Mr. Callaghan raised, without commitment, the question of replacing UK Polaris with Trident, and was assured that Carter saw no objection to transferring that technology to the UK. Callaghan saw to it that when Mrs Thatcher took office after the 1979 election, she was enabled to see all the correspondence between himself and the President on the matter.

1979-1982.

In opposition from the 1979 onwards, the Labour Party maintained its policy of not moving towards a new generation of nuclear weapons, or to a successor to the Polaris force. In the early 1980s the Labour party specifically opposed Trident, and under Michael Foot's leadership, the Party's policy seems indistinguishable from unilateral disarmament. The alliance between the breakaway Social Democratic Party and the Liberal Party with difficulty formulated a policy to maintain the minimum British Nuclear Deterrent, with necessary modernisation, until it could be negotiated away as part of world - wide agreements.

On the other hand, as soon as Mrs. Thatcher took office in 1979, she set about confirming Chevaline and planning for a replacement to it. In her memoirs (5), she noted that previous governments, Conservative and Labour, had pressed ahead with Chevaline, through costs had escalated alarmingly as development continued, and that the system would maintain full effectiveness into the 1990s, though not much longer than that due to a variety of technical and operational reasons. Cruise missiles as a successor system were considered and rejected, as was cooperation with the French. In December 1979, a decision was taken to buy Trident C4 with MIRV, having obtained a firm assurance that the transfer of MIRV technology would not be affected by SALT negotiations. Discussions with the US administration on terms of sale stretched on into 1980's and when President Reagan took office in 1981, he decided to equip US forces with the larger Trident D5 missile. The extra cost of the Trident D5 raised the question whether the UK could afford to continue with the nuclear deterrent. Mrs Thatcher records that she was "utterly determined to maintain a credible deterrent, and it had to be Trident D5". The total cost, including an R&D fixed fee with no risk of escalation, was estimated at £7.5Bn, probably about £1.58Bn more than C4. Some of the cost had to be found by reductions in the surface fleet, and the closure of Chatham dockyard. The First Sea Lord, Sir Henry Leach, argued vigorously the importance of surface ships, but Mrs Thatcher was not moved, and the conclusions were announced in the Defence review in June 1981. Subsequently, after the Falklands [War], in which the Navy under the leadership of Sir Henry played such a pivotal role, some of the cuts were reversed, but Chatham closure went ahead.

By 1982, and after the election of 1983, the future of Chevaline as the deterrent system into the 1990's to be followed by a Trident D5 force, was therefore politically assured.

Differences of Views between Officials and Advisers.

The ability of successive British Governments to reach a political decision on the need to improve UK Polaris, to maintain its credibility in the face of possible Soviet ABM developments, and, if improvements were needed, which option should be preferred, was not assisted by the scientific and military complexity of the issues involved, and by the differences of view among the scientists and between scientific and military (mostly naval) experts. The lack of unanimity among expert advisers, and the difficulties to which this gave rise in the management of the Polaris improvement programme, are aired in some detail in the two papers on Chevaline presented to BROHP (references 1 and 2 below). It might be suitable to add a few further remarks on this subject at this point.

The advice which Sir Solly Zuckerrnan gave on Polaris Improvement as Chief Scientific Adviser (MoD) to the Secretary of State at the MoD from 1964-67, and as Chief Scientific Adviser (Cabinet) to the Prime Minister from 1967-1972, was basically that ABM systems would not work, and that there was no need to consider improvement of UK Polaris. In his published works on nuclear deterrence, (6,7), he states that ABM systems would not work "for the good and simple reason that in any theoretical nuclear scenario it will always be possible to saturate an ABM system with an avalanche of missiles, not to strikes on those targets which may not be protected". He expresses the view that the "Independent" nuclear deterrent forces possessed by Britain or France conferred little, if any, real additional world power on their possessors. He asserts that the nuclear arms race was generated by the nuclear scientists, and that "the men in nuclear weapons laboratories of both sides have succeeded in creating a world with an irrational foundation, on which a new set of political realities had to be built. They have become the alchemists of our time, working in secret ways that cannot be divulged, casting spells which embrace us all". In a chapter on Chevaline in his book *Monkeys, Men and Missiles,* he details his determined attempts to prevent the adoption of the programme. It is not the purpose of this paper to engage in a discussion of Zuckerman's arguments, but merely to point out that although they did not in the end succeed, the process of decision making had to spend a deal of time disposing of them.

The determined and active opposition to the Chevaline project from parts of the UK Navy also slowed down decision-making and management of the project. It was mainly based, I think, on the understandable gut feeling that the UK Navy should keep in step with the US Navy, and follow down the Poseidon-Trident route. There may also have been a lack of faith in a project managed by scientists, which was only allayed when the project was given to the Navy to manage. However, a strong feeling persisted throughout the years 1970-1975 in the UK Navy that if the British Government could only be brought firmly to ask the US for Poseidon, the request would, with the strong support of the US Navy be granted. Alas, no British government, for different times, could be persuaded to try. At Appendix 2 are copies of letters published in 1991 in the Daily Telegraph, from eminent UK naval officers on the subject of Chevaline, which throw light on their feelings about the problem of Polaris improvement.

House of Commons Public Accounts Committee.

Enquiry into Chevaline 1981-2.

The enquiry of the Public Accounts Committee of the House of Commons in 1981-2 into the cost escalation, management and current status of the Chevaline Project coincided in time with debates on the Conservative Government's decision to replace Chevaline after the 1990s with the Trident system. We may surmise, therefore, that in presenting evidence on Chevaline, care would be taken that the proceedings would read across as little as possible to the debate on Trident. With that thought, it is not surprising that the evidence given by the MoD to the enquiry, both in a memorandum and in the PAC meetings, did not fully expose dissensions within Government which delayed decision-making and caused drip-feed financing, to the detriment of efficient management up to 1976. From the standpoint of history, the conclusions of the PAC ought not to be regarded as a guide to the events in the Chevaline project from 1967 to 1976. My paper "The Unveiling of Chevaline" critically examines the PAC report and I have nothing further to say on the subject in this paper, except that in my conclusions today, I will remind you of my summation of the PAC proceedings and Report.

Conclusions.

I can think of no better summary of the events in the UK Polaris Improvement Programme 1967-76 than that written by Victor Macklin in 1981. He called it a long and depressing record, and wrote, - "Political problems within the Labour Party allied with discordant scientific [and] political advice prevented any useful decision being made on improvements on Polaris, up to 1970, despite the clear operational need to counter Russian ABMs. Nevertheless a little study and research work was agreed, but subject to such restraint and secrecy, e.g. from the Navy, as to be of marginal value. Zuckerman's role in obscuring the issues was crucial and severely undermined US confidence in the UK's intentions. The change of government (Mr. Heath) was an opportunity for a full review, and the Navy, together with CSA, revived the request to buy Poseidon, which had been offered by the US to the UK but rejected by Mr Wilson in 1968. However, because of the advent of the Strategic Arms Limitation discussions between the US and the USSR, the US was now unwilling to supply the Poseidon MIRV system. Many alternative options were studied and considered but no decisions were made because of Defence Budget problems, and because of the need to consider some new options. In the meantime, Chevaline (Super Antelope) was funded on a six monthly basis in 1972 through to 1975. By the time the Conservative government had decided to go ahead with Chevaline (in 1973, but to be kept secret from everyone until the February 1974 Defence White Paper), they had lost the first 1974 election. The new Labour government (Mr. Wilson) also favoured Chevaline but, because of its precarious majority and the rump of unilateralism in the Labour Party, no decision was taken until after the October 1974 election. The last year was filled with further option studies and with further trickle funding of Chevaline. After gaining a working majority in October 1974, the PM finally agreed to go ahead with Chevaline in December 1974, the option of Poseidon or C4 (Trident) being finally ruled out. However the early months of 1975 saw renewed activity by the Navy in favour of a solution other than Chevaline, and finally the Secretary of State at the MoD (Mr Roy Mason) decided that Chevaline could never succeed unless it became a Navy department project.

This Ministerial indecision for party political reasons, a marked change in US policy, disagreement between Zuckerman and almost all other Defence scientists, coupled with a deeply-held Navy instinct to opt for Poseidon, combined in different ways and at different times to delay a decision, which ought to have been taken in 1967, until 1975-76, and left the UK with probably a second-best solution on technical, operational and cost grounds.

During this time, Morien Morgan, Cliff Cornford and finally myself were expected to pursue a complex and difficult task (Chevaline) at minimum cost, in strictest secrecy, often with opposition from CoS and the Navy, and with funding known to be only on a six month to six month basis. It was only due to the resourcefulness of all the staff on Chevaline and the risks we took in dealing with contractors, that the government had a Chevaline project to hand over to the Navy in 1975-76. Because of the secrecy, insufficient credit has been given to those who fought to keep Chevaline alive.

While we knew, and said, that a US MIRV option would be better than Chevaline, the alternatives were rarely, if ever a choice between those two, but rather a choice between Chevaline and doing nothing at all; a decision which could easily have meant withdrawal of the UK from the military political nuclear scene.

As we know, the Chevaline programme survived and progressed, though not without doubts and reviews, and entered into service in the late 1980s, hading over its strategic nuclear deterrent role to UK Trident in the mid 1990s.

To end this paper, some comment on the PAC's Enquiry of 1981-82 is, I think, necessary. In my estimation, the evidence provided by MoD to the PAC, both in the Memorandum and in the PAC meetings, did not expose the full effects in cost and time of ministerial indecision and consequential drip-feeding, nor did the negative influence on the project of the determined and active opposition to it by the Royal Navy up to 1976 receive any mention. On that evidence, the PAC's report placed the onus for shortcomings in the progress of the Chevaline project on the "poor management" and "lack of determination of those managing the project up to 1976." Those HQ MoD scientists responsible for the Chevaline project before 1976 had not been invited to participate in the preparation of the MoD memorandum, and were not called upon to give evidence to the PAC. They registered their total rejection of the PAC report in the only way open to them under the civil service code of conduct; by letter to the PUS MoD. No action resulted from their representations.

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PhD (Chemistry, 1952).
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Appendix 1.
Polaris Improvement Programme - Chevaline System.

Political and Strategic Background 1964 - 1982.

Glossary of Polaris Improvement Code Names.

TOPSY
US hardened A3 Missile - thus A3T.

ANTELOPE
US hardened Polaris ReBs with A3 [W-58] warheads and decoys.

SUPER ANTELOPE/CHEVALINE
UK Improved Antelope with super-hard ReBs and warheads. Decoys deployed from a manoeuvrable carrier.

POSEIDON
Second generation US SSBM with longer range, multiple MIRV warheads hardened to Antelope standards. No decoys.

MINI POSEIDON
A design concept to put up to 6 Poseidon [W-68] warheads on A3T Polaris without decoys but with wider warhead separation.

HYBRID / STAG

A design concept of Super Antelope front end on the Poseidon missile.

OPTION "M"

De-MIRVed Poseidon front end on Poseidon missile with Poseidon warheads.

C4

Trident One. US third generation missile with MIRV, longer range than Poseidon. Warheads of new design.

"POOR MAN'S DETERRENT"

Polaris A3T with warheads hardened and with wider separation.

Appendix 2.

Polaris Improvement programme - Chevaline System.

Political and Strategic Background.

Correspondence between Naval Officers. July 1990.

An interesting exchange of letters on the Chevaline system took place in the columns of the Daily Telegraph in July 1990. In the context of a NATO Summit Declaration of Defence Policy which had just been issued by Admiral or the Fleet Lord Lewin, former First Sea Lord and former Chief of Defence Staff, in an article on July 10th 1990 argued for the continuing need for an effective UK Strategic Nuclear Defence Force in the following words:- "the maintenance of our Strategic Nuclear Force must remain top priority. Those who suggest that the Trident force could be reduced ignore the lesson of recent history. The incoming Labour Government in 1984 cancelled the fifth boat, saving £60M and removing the margin for insurance. Ten years later it was necessary to develop the Chevaline system at a cost £1Bn because a four boat force could not cope with improvements in Soviet Ballistic Missile Defences."

On the 12th July, Commodore R.W.Garson (who as a Captain in the early 1970s was the senior UK naval officer in Washington in charge of the liaison with the US Navy on the Polaris system) took Lord Lewin to task as follows:- "Admiral of the Fleet Lord Lewin's excellent contribution to the debate on Britain's future defence policy regrettably misleads on an important detail regarding the necessary updating of our sea-borne deterrent system. Cancellation of the fifth boat by the Labour Government had no bearing on the need to update the system by the late seventies as he implies. Redevelopment of Polaris was always known to be necessary, whatever number of boats we possessed. But the decision to embark upon Chevaline - a British designed front end improvement to an American system - at an eventual cost £1Bn, was against the advice of many and unnecessary."

Garson's view was contradicted by Rear Admiral Sir David Scott in a letter of the 17th July 1990. (Scott as chief Polaris Executive headed the Chevaline management team, which the Navy took over Chevaline in 1975-5). He wrote; - "with a five boat force we would have been able to keep two constantly on patrol. The prospects of our warheads being able to penetrate the Soviet Union's anti-ballistic missile defences would have been enormously enhanced as compared with a four-boat force. The increased number of missiles would also have helped to offset the known limitation of the Polaris A3 warhead ... " [the UK design, not the US W-58].

The final salvo in these exchanges came from Vice Admiral Sir J.Roxburgh, a submariner who had been in charge of UK submarines and NATO East Atlantic Submarine Command in the early 1970s. On the 20th July 1990 he wrote;- "It is a pity that the seeming disagreement between Admiral of the Fleet Lord Lewin and Capt. Garson led to Rear Admiral Sir David Scott's inaccurate rejoinder on the discussion in the Seventies on the need for improvements to our sea-borne nuclear deterrent. Both these well-informed officers were in turn closely involved with deterrent developments, thus there was no need for misunderstanding between them. Redevelopment of Polaris was always accepted as necessary, whatever the number of submarines we possessed. To meet the shortcomings, the US Navy was already well advanced on the conversion of its own force with the Poseidon missile which could be fitted to the existing Polaris boats. Rather than embarking on the expense and uncertainty of developing the British Chevaline Front-End Improvement to Polaris the US Navy advised us to seek Congressional approval to update our Polaris force with Poseidon - a system whose development costs bad already been fully covered by the Americans. In due course Poseidon would be replaced in the US Navy by the Trident missile system consisting of a much larger missile and submarine. Outline drawings for this were already held by the Royal Navy in 1971. How right Capt. Garson was in commenting on the dismay many felt which this advice was not followed and the more expensive Chevaline improvements were adopted, thanks to the pressure of the Ministry of Defence scientists."

Comment.

We see here a clear indication of a Naval view of the role played by MoD scientists in the improving of UK Polaris, and a forthright statement of the policy which the Royal Navy fought for continuously until the unambiguous choice of Chevaline was made in 1975-76, with the management transferred to them. A policy of asking, with US Navy support, the US Congress for approval for the sale of Poseidon -Trident to the UK was, however, not one that a Labour Government which had already declared that it would not proceed to a second generation deterrent, nor that a Conservative Government which had already been told by the US Administration that Poseidon with MIRV could not be transferred to the UK could be expected to pursue. It was not until 1981-82 that the obstacles to such a policy had disappeared and UK Trident came into being.

Why Chevaline? Political and Military Context, 1966-73.*

Richard Moore.

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The Polaris improvement programme Chevaline remains one of the most controversial in postwar British defence. Its political and military rationale was in doubt for many years; its management arrangements and above all its cost eventually brought it to the attention of the House of Commons Public Accounts Committee. We are no longer entitled, however, to regard Chevaline, in addition, as shrouded in secrecy. Extensive declassified documentation relating to the programme is now available in the Public Record Office, and many of the major participants in the political and military debates have published memoirs putting their side of the story.[1] Lawrence Freedman and John Simpson published accounts in the 1980s of the political background to Chevaline, which have largely stood the test of time; John Baylis and Kristan Stoddart have recently given us a good deal of information on the technical side of the story; and Kate Pyne, the Atomic Weapons Establishment's technical historian, has presented an unclassified account.[2] This paper attempts to extend our understanding further, presenting additional documentary evidence, establishing a narrative for political decision-making on Polaris improvement up to 1973 - the current horizon of the 'thirty-year rule' - and finally considering where we now stand on the controversial questions of Aldermaston lobbying, project management and cost.

Labour and Nuclear Weapons.

As Kate Pyne has shown, scientists in the UK were concerned by advances in

Soviet ABM defences and the implications for the viability of a missile-based UK deterrent as early as 1961.[3] The political story of Polaris improvement began however several years later, under Harold Wilson's Labour government. Wilson's nuclear weapons policy was a balancing act between the unilateralist left and moderate right of his party. In 1960 his predecessor as Labour leader, Hugh Gaitskell, suffered considerable political damage at the Party's annual conference in Scarborough when a resolution was passed calling for "a complete rejection of any defence policy based on the threat of the use of strategic nuclear weapons."[4] Partly to appease this kind of sentiment, Wilson's manifesto for the 1964 election promised to "re-negotiate" the Nassau Agreement, under which Britain was to buy Polaris missiles from the US.[5] In December 1964, after coming to power, he made great play in Parliament of dismissing the previous Conservative government's nuclear policy - based on what he had referred to as "the so-called British, so-called independent, so-called deterrent."[6] He and his advisers referred back many times in subsequent years to this December speech, which, as he put it, had ended "the independent nuclear pretence."[7]

In practical terms, however, the re-negotiation of Nassau never amounted to much. Wilson liked to claim that the Polaris programme he inherited in 1964 had gone beyond the point where cancellation would have been economic.[8] In fact, on the Monday morning after the election, there was a brief on Defence Secretary Denis Healey's desk stating that only £50M out of £400M had been committed and that there would be a £200M saving if Polaris were cancelled and the submarines completed as hunter-killer boats.[9] The Royal Navy was at this stage far from keen to take responsibility for the British deterrent, and its visceral opposition can perhaps be seen between the lines of this brief.[10] Healey remembers in his memoirs, however, that Wilson told him to keep the information to himself.[11] Re-negotiation translated instead into two things: rather prolonged and eventually fruitless talks on committing Polaris to a NATO Atlantic Nuclear Force,[12] and cancellation of the fifth of the planned submarines. To go further would have been over-ambitious in Labour Party or indeed domestic UK politics.

Towards the end of 1966 Wilson created a new ministerial Nuclear Policy Committee "to coordinate and keep under review the principal developments in the Government's nuclear policy."[13] The membership of this committee varied slightly over the years, but the key personalities reflected the balance of Wilson's policy as a whole. In the blue corner sat the pro-nuclear Healey, and beside him the Prime Minister. Wilson isn't usually remembered as a conviction politician - the word "devious" appears more often in his biographies - but in fact his nuclear policy remained consistent.

As we have seen he was behind the decision in 1964 to continue the Polaris programme, a decision he had effectively taken before coming to power. He drew the line however at any new generation of strategic nuclear weapons system.[14] In the red corner sat the left-wing Minister of Technology, Tony Benn. Benn is not normally associated in the popular mind with the inner sanctum of nuclear weapons decision-making in the UK, and was at the time a fairly junior player. His memoirs give the distinct impression that he wanted to be seen to have nothing to do with nuclear decisions - witness his embarrassment at having to discuss the future of Aldermaston with trades union representatives.[15] This very reluctance may explain Benn's place on the Nuclear Policy Committee: the wily Prime Minister will have wanted the blood of his nuclear decisions on the hands of a prominent left-winger. Benn tried nevertheless in small ways to hinder the nuclear weapons programme. He found an ally in the interesting figure of Sir Sally Zuckerman. Zoologist, defence scientist and now the government's Chief Scientific Adviser, Zuckerman hated the open-ended technology commitment of the arms race and was a veteran opponent of the expensive elaboration of nuclear weapons and of any plans to make actual use of them in warfare. He was also a highly original strategist, liking to point out that it was quite irrelevant what was really in the missile tubes of a Polaris submarine so long as there was some doubt in the minds of the Russians.[16] Wilson appears to have taken some pleasure in the company of the brilliant and persuasive Zuckerman, whose lengthy briefs on nuclear issues bulked out his red boxes.[17] Wilson admired his mind and enjoyed his mischievousness,[18] although as we shall see the Chief Scientist was often outmanoeuvred. There is some evidence of skullduggery between the leading members of the Nuclear Policy Committee over such matters as granting each other access to papers.[19]

International and military context.

Beyond these shores Britain faced many other problems affecting nuclear policy in 1966. In Europe, General de Gaulle now had his own nuclear weapons and had recently withdrawn France from the NATO military structure. It would have been a brave British Prime Minister who left his nuclear defences looking weaker than his southern neighbour's. West Germany too was a rising power, and ministers were concerned amongst other things by the prospect of its getting its finger on the trigger of the many nuclear weapons now based on its soil.[20]

Further afield, Britain still had heavy military commitments in the Far East. The so-called Confrontation with Indonesia had just finished, but there were now serious nuclear proliferation problems. China had tested its first atomic bomb the day Labour took power in 1964, and India had begun its own bomb programme in the uncertain conditions following Nehru's death the same year.[21] Anglo-Indian relations were a matter of great concern to several members of the Labour government. The Vietnam War was also well underway, and Wilson was concerned to keep out of it. This and other things, including the response to West German rearmament and the poor personal chemistry between Wilson and President Johnson, made this a postwar low point in Anglo-American relations.[22]

Militarily, Britain's nuclear weapons were widely deployed in 1966, and committed to NATO in Europe, the Central Treaty Organisation (CENTO) in the Middle East, and the South East Asia Treaty Organisation (SEATO) in the Far East. There were eleven squadrons of RAF V-bombers in the UK with Blue Steel stand-off missiles and the new WE.177B, a hydrogen bomb for low-level use.[23] There were Canberra light bombers with the older Red Beard tactical atomic bomb at RAF Akrotiri on Cyprus and RAF Tengah in Singapore[24] Red Beard could also be used by strike aircraft operating from the Royal Navy's four carriers, one of which (at the end of 1966 HMS *Victorious)* was stationed East of Suez. Finally there were many US nuclear weapons in the UK and Germany pre-assigned for RAF and British Army use in wartime.[25] More nuclear weapons were to come: warheads were being developed for the multi-purpose low-kiloton bomb WE.177A and the Polaris missile.[26] After this, however, there was a looming gap in nuclear weapons research. This gap had already been discussed by officials, efforts had been made to fill it by interesting the Chiefs of Staff in new weapons developments, and options for future nuclear tests had been presented.[27] Wilson had already chosen in early 1965 however to put on hold a series of joint UK-US research tests at the underground site in Nevada. A final experiment to perfect the design of the Polaris warhead in September 1965 was to be the last British nuclear test for nearly a decade.[28] Wilson's line that there was to be no new generation of British nuclear weapons was gleefully relayed to the Americans by Zuckerman at a nuclear 'stocktake' meeting in 1965, calling future Anglo-American nuclear cooperation as a whole, not just testing, into question - much to the annoyance of nuclear scientists.[29]

Elsewhere, far from any concept of a looming gap in nuclear weapons development, the Arms Race was entering a new phase. The US was spending vast amounts to investigate anti-ballistic missile (ABM) systems: Nike-Zeus, Spartan, Sprint, Nike-X, Sentinel and Safeguard. At the same time studies were underway to improve US Polaris warheads in order to guarantee better penetration of Soviet ABM defences: a system called PX-1 was developed by Lockheed and put to sea on a small number of submarines, and others called PX-2, Exo-PAC, Mark-up, HEXO, Antelope and Impala were worked on but never deployed.[30] More importantly for the US there was to be in addition a whole new generation of strategic ballistic missiles: the submarine-launched Poseidon and the ground-launched Minuteman, both with multiple independently targeted re-entry vehicles (MIRV).

The USSR was also meanwhile deploying second-generation strategic systems: Yankee-class submarines and SS-9 heavy ICBMs.[31] For the first time these gave the Soviet Union a numerically significant strategic reach into the North American continent, raising the prospect of a 'nuclear exchange' between the superpowers, with events in Britain and Europe a sideshow. The USSR was also known to be working on ABMs. Was Britain falling behind?

Intelligence controversy.

It is worth digressing for a moment to consider what was known about Soviet ABMs in around 1966-7. As Lawrence Freedman puts it, "ABMs provided one of the most bitter wrangles in the history of the intelligence community,"[32] and one which is quite important to our story.

American spy-planes had photographed an ABM testing site at Sary Shagan, on the shores of Lake Balkhash in what is now Kazakstan, as early as 1960. Nuclear tests at high altitude had been observed in 1961-2 and (correctly) associated with work on ABMs. Soviet announcements had increased the excitement and suspicion in the West - Defence Minister Rodion Malinovskiy said in 1961 that "the problem of destroying missiles in flight ... has been successfully solved." In November 1964 a missile known as Galosh was displayed at the Revolution Day parade in Moscow, and (correctly) identified as a large, nuclear-tipped, exo-atmospheric ABM. Missile deployments were also observed around Tallinn in Estonia and Leningrad that were associated (we now know incorrectly) with a shorter range endo-atmospheric ABM.[33] In 1966 Secretary of Defense Robert McNamara told the US Congress that a Soviet ABM capability against ICBMs could be expected in 1967-8, and against Polaris perhaps a year or two later. Behind the scenes, there was a great deal of infighting behind this conclusion; the USAF and Army were playing up the story to justify weapons programmes of their own, while the CIA were playing it down.

Very little of this controversy can be discerned behind the carefully worded reports of the British Joint Intelligence Committee (JIC). In early 1964 the USAF and US Army line seems to have been current "probable ABM deployment around Leningrad" was underway.[34] By 1965 this was in some doubt, although "eventual deployment of such a system in defence of Moscow" was suggested.[35] But by 1968 early warning and target acquisition radars had been noted and the assessment was stronger: the system based on Galosh would soon offer Moscow "a limited defence against ICBMs launched from the United States and Polaris missiles launched from the intermediate area."[36] The words "limited defence" nicely covered a wide range of possible interpretations, and Zuckerman remained unhappy with certain intelligence details, as we shall see later. But it is clear at least that UK intelligence took the Soviet ABM threat to Polaris extremely seriously.

Polaris improvement.

Healey wrote to Wilson in November 1966 to raise, for the first time at this level, the question of research on a Polaris warhead "replacement," which he described as the best future guarantee of Anglo-American nuclear cooperation.[37] It is interesting that this point - made again and again over the many years of Chevaline's gestation - was seen as so important right at the outset. Ministers discussed improvements to Polaris at the Nuclear Policy Committee in January 1967, and again in April.[38] They decided to engage with the US in this area, spinning the line that the Atomic Weapons Research Establishment (AWRE) at Aldermaston was definitely "intending to engage in research" on Polaris improvement.[39] It was understood that the Americans would give no information without a definite commitment on the part of the UK, and so it was hoped the positive signal "would lead to a resumption of exchanges."[40] As a result, Healey and Zuckerman both embarked on discussions with their opposite numbers in the US, making it clear however that Britain was interested in improving Polaris, not in developing or procuring a new generation system such as Poseidon. Improvement was understood to include hardening of system components and work on decoys and penetration aids.[41] Also on the nuclear agenda at this stage was the possibility of basing Polaris submarines East of Suez, chiefly to extend coverage of targets in the USSR and also China, but offering the additional possibility of a 'nuclear umbrella' for India. Reactions to this idea were generally positive: there were "sufficient grounds for keeping open the option."[42]

The presumption against Poseidon was shortly announced in Cabinet and in Parliament, although Healey sidestepped a supplementary question on his discussions with the US.[43] Behind the scenes, Wilson had meanwhile agreed to buy new hardened missile bodies for Polaris from the US because the older design was going out of production. This created a significant precedent, because if the missile body were hardened, why would the UK continue to build to an unhardened warhead and re-entry vehicle (RV) design[44]?

The summer of 1967 brought horrendous problems at home and abroad for the British government, culminating in the devaluation crisis of November. This forced an urgent reappraisal of defence work, including an immediate decision to hasten military withdrawal from East of Suez. There was also a new look at nuclear weapons, with the option on the table of completely renouncing them; also of completing Polaris as planned, or of hardening it. The future of AWRE and the East of Suez option for Polaris were also seriously in question.[45] For the first time, costings for Polaris warhead hardening and decoys appeared in the papers for a Nuclear Policy Committee meeting in December 1967, coming to between £2M for warhead hardening only to a US design, and £40M or more for hardening and penaids developed entirely in the UK.[46] We can speculate that the £2M figure might have raised a smile had it been mentioned to the Public Accounts Committee fifteen years later. Not for the last time, the decision in December 1967 was to Wait and see. More information was called for on hardening options and the future size and cost of AWRE. But the East of Suez option, now looking very much more expensive given the planned withdrawal of other British forces, was more or less permanently ruled out at this point.[47]

A group of prominent people was commissioned to write an independent report on the future of Aldermaston under the chairmanship of the jet propulsion pioneer Lord Kings Norton, now Chancellor of the Cranfield Institute of Technology.[48] This four-month study considered the likely size and cost of AWRE under various assumptions of future workload: either simply the care and maintenance of the existing nuclear stockpile; or hardening of the Polaris warhead and RV, either under the US Antelope scheme or a British variant known as Super Antelope, which was said to differ mainly in the degree of hardening offered; or more exotic schemes such as a "small, superhard warhead," and/or a greater number of RVs - perhaps five - and/or a different warhead dispensing system somewhat akin to MIRV. The reference to Super Antelope in the Kings Norton report seems to be the first mention at ministerial level of the system that eventually became Chevaline. Kings-Norton came up with some fairly bland conclusions: some savings could be achieved, but the strength required at Aldermaston would hardly vary regardless of the option chosen.[49]

These conclusions were enlivened only by the minority report submitted by Lord Rothschild.[50] Another brilliant and independent mind - Cambridge microbiologist, MI5 officer during the war, now research director of Shell, Rothschild had been talking to Zuckerman, and came to similar conclusions. He could see no strategic need for hardening, and said so: " the conclusion seems inescapable that hardening is not worth the candle." He was also temperamentally inclined to challenge any scientific research activity that had outlived its usefulness or was providing no value to a customer.[51] I think he saw Aldermaston in this light. He certainly felt that the other study team members had been hoodwinked by AWRE managers. Zuckerman agreed, condemning the Kings-Norton report in forthright terms: "ministers are now presented with a white-washing report which carries them little further ... in order to keep the scientists happy [AWRE are meanwhile] shopping around for 'make-weight' work."[52] Rothschild, however, was outmanoeuvred.

Officials were able to point out, quite correctly, that his arguments had led him, in challenging the very future of Aldermaston, outside his carefully constructed terms of reference.[53]

When the Nuclear Policy Committee finally took the report in December 1968, almost five months after its completion, Kings Norton and Rothschild alike were thanked for their work.[54] But a decision on improvements to Polaris was no closer. Healey was already clear that pending the US election "we shall not be able to get any firm response from the US Government both as to their own intentions [regarding Antelope improvements to Polaris] and the extent to which they might be willing to help us."[55] Only in early 1969 did the new President Richard Nixon approve the release of full information to the UK on the Antelope system and its shortcomings.[56] Not only therefore was it important to preserve the working-level nuclear relationship with the US, but to understand the impact of US political decisions on the likely cost and difficulty of proceeding. The British were faced with a catch-22 in awaiting US information at various stages of the decision-making process on Polaris improvement: American officials would insist on a commitment to use the information before it could be passed, whereas British officials wanted the information precisely in order to help decide whether or not to commit.

Intelligence assessments of Soviet ABM progress had meanwhile been revised downwards. The Tallinn system, for example, had been reclassified by the Americans as a surface-to-air missile with no ABM capability, although there was still disagreement on whether it could one day be upgraded.[57] A cautious British assessment stated that "there is insufficient knowledge on which to base an estimate of the characteristics or capabilities of any ABM systems which have been developed."[58] In fact, a Soviet Ministry of Defence commission had already in October 1967 recommended against the full deployment of an ABM system and preparations were underway to offer its abandonment in arms control talks that began in 1969.[59]

The report of a MoD Technical Study Group on Polaris Improvement became available during 1969, and although I have yet to find a declassified copy it clearly recommended proceeding with Super Antelope.[60] At this point Super Antelope seems to have become the assumed answer to the Polaris improvement problem, although the documentary record is thin and another, more advanced option labelled Master Dispenser was certainly also being discussed.[61] By 1970 a new security codeword had been assigned to Polaris improvement work, and documents bearing the classification Top Secret Atomic Artificer began to appear.[61]

A revealing brief to Denis Healey in April 1970 discussed Polaris improvement as something one might do to "satisfy the Americans that we mean business" and to "keep our AWRE scientists happy."[63] Both were seen as desirable, but the result was more wait-and-see. A 'minimum' programme of feasibility studies costing £4M over two years was trimmed to £1M and one year. Now it was an impending British election that was creating delay - along with continued uncertainty over Soviet ABMs, especially as these were now on the table in the US-Soviet Strategic Arms Limitation Talks.[64]

Polaris improvement under the Tories.

The Conservatives' somewhat unexpected election victory in June 1970 injected new energy into what seem to have become rather unfocused discussions of Polaris improvement. Peter Carrington, the incoming Defence Secretary, very soon wrote to Prime Minister Edward Heath to request approval (again) for the two-year £4M Super Antelope project definition phase so recently put off by Labour. Extensions of Soviet ABM radar coverage and the deployment of a 54-missile Galosh system around Moscow meant, he reported that "the threat posed by our existing small force of A-3 missiles will be virtually eliminated by the mid 1970s unless the warheads are hardened and special decoys included to confuse the ABM defence."[65] Carrington also noted that there had so far been "no examination" of the possibility of acquiring Poseidon. Initially reluctant to decide, Heath eventually approved the two years of work in October, perhaps partly because commitment was urgently needed to a series of X-ray nuclear weapons effects tests in the US, and partly because by this time it had become clearer that the SALT talks were unlikely to result in a total ban on ABMs.[66]

Heath had the luxury of a less troublesome Cabinet than Wilson; there was no serious Conservative opposition to upgrading strategic nuclear weapons systems. In July 1970 Zuckerman sent Heath a long tirade, of just the kind he had produced many times for Wilson, against the “slippery slope of endless dimensions” that was Polaris improvement.[67] As one researcher put it to me, he got a "stiff ignoring" for his trouble.[68] Zuckerman spent some time and energy in the late summer on disputes with the intelligence community over what he saw as exaggerated assessments of Soviet ABM capabilities, but he appears to have played little part in serious decision-making on the subject after about October 1970, when a note from Carrington records that, meekly or not, Zuckerman did not now “dissent from the need to take action to keep our options open.”[69] Nor did Heath turn to Rothschild, head of his new Central Policy Review Staff, for scientific advice on nuclear or indeed wider defence issues.[70] Instead the more supportive Hermann Bondi, Chief Scientific Adviser in the MoD from March 1971, began to contribute in Zuckerman's place.

The story of Polaris improvement under the Tories reflects therefore the greater political freedom enjoyed by Heath than his predecessor, and perhaps as a result a slightly lesser formality in decision-making. Only one Nuclear Policy Committee meeting under Heath, for example, considered the subject.[71] The search began for more options - not just for short-term *improvement* but longer-term *replacement* of Polaris - and a series of diplomatic feelers went out. Interestingly, the new diplomatic offensive, although undeniably pursued more energetically with the US, appears to have begun with France. In April 1972, Carrington and his French counterpart Michel Debré discussed possible collaboration on a long-term successor system to Polaris,[72] only the following month did ministers discuss a strategy for engaging with the US government on Polaris improvement, and only on 28th July did Sir Burke Trend, the Cabinet Secretary, have talks about talks with Secretary of State Henry Kissinger.[73]

Heath's interest in nuclear cooperation with the French - indeed his enthusiasm for the European ideal in general was unusual in a British Prime Minister. This was a tricky area to approach, however: partly because of the web of Anglo-American agreements surrounding much specific British technical knowledge of nuclear warheads and weapon systems; partly because of a lack of French enthusiasm; partly because of American political sensitivities - under a "Mildenhall agreement" Heath and Wilson appear to have been bound to discuss all approaches to the French with Nixon.[74] In addition there was specific opposition, especially within the British military: the Chiefs of Staff agreed in March 1971 to write to Carrington "stating plainly for his information and for the record their grave reservations" about any French connection.[75]

The diplomatic round continued: Patrick Nairne, a senior MoD official, visited the US for discussions with Kissinger, US Atomic Energy Commission Chairman James Schlesinger and others in August 1972; Heath, Trend, Nixon and Kissinger spoke at Camp David in February 1973 while Schlesinger and Bondi talked in London; Victor Macklen, a veteran MoD nuclear official, spoke with Schlesinger in March and Heath with the French President, Georges Pompidou, in May.[76] One is struck by the variety and *ad-hoccery* of the channels used during 1972 and 1973; there were conversations in the margins of international meetings, parties of officials were across the Atlantic to look at technical questions, opportunities were taken to revise the agendas for pre-planned talks. Trend played a significant part in opening channels of discussion, but apart from successive ambassadors in Washington (Sir Thomas Brimelow and Lord Cromer), the Foreign Office seems hardly to have been involved. Service-to-Service discussions appear to have been discouraged. To some extent this pattern of contacts appears to reflect Kissinger's peculiar eighteenth-century diplomatic style.[77]

The aim of the British participants seems to have been to generate options - preferably cheap options - and to gauge the level of commitment to these options in the US and France. The motivations of US and French participants are less clear, and a mature judgement will have to await work in their respective document archives, although Trend may have been correct to suggest "that the real motivation of the United States ... is ... our virtual elimination as an independent nuclear power within a few years"[78] - and perhaps, if at all possible, also that of the French. Cromer also speculated that the US wished "to get a grip on the French (and to perpetuate their grip on us) by initiating Franco-American or triangular talks about future nuclear cooperation."[79] In June 1973 Trend picturesquely reported Pompidou's telling Kissinger, in response to such an offer of US-French cooperation, that he wouldn't swap French strategic autonomy for "this pot of lentils."[80]

The search for options.

The Heath government appears to have begun simply by considering Super Antelope and Poseidon as alternatives, although it remains far from clear that Poseidon was ever a real political possibility and, as a result, a number of half-way-house options had also to be generated. Battle lines were now drawn within British officialdom, not on whether Polaris should be improved or not, but on which option was best. A scientific group, personified for Zuckerman by Macklen but also including Bondi and another of his deputies, Frank Panton, put the case for Super Antelope. The Royal Navy meanwhile favoured Poseidon, largely on the grounds that Polaris had been successful as a straight purchase from the US with maximum commonality of systems, and that by contrast there could be little confidence in the achievability or even safety of Super Antelope. This latter point, based on the use of dangerous liquid propellants in the penetration-aid carrier and associated subsystems, became highly significant. At some point during the 1960s the Navy seems to have lost its anti-nuclear prejudice, and its enthusiasm for Poseidon was genuine. Only General Sir Michael Carver, Chief of the General Staff, was now prepared to question at senior level the need for significant expenditure on the deterrent. Carrington was keen to improve Polaris, but favoured neither Super Antelope nor Poseidon in particular.[81]

A brief for the Defence Secretary in late 1971, prepared at the behest of the Chiefs of Staff, reiterated the need for Polaris improvement based on the view that by 1975 the original system could no longer guarantee, in the face of Soviet ABM deployments, "the approved deterrent criterion (based on the JIC advice of 1962) of the destruction of the five largest Soviet cities, including Moscow." The paper went on to describe the possible advantages of Poseidon over Super Antelope, including penetration against a possible future endo-atmospheric terminal ABM defence and making economic use of the full hull-life of the Polaris submarines. However, "informal advice" received from US officials had suggested "that it would not be in our interests to raise the question of Poseidon in Washington for the next few months,"[82]

In August 1972, in discussion with Naime in Washington, Kissinger emphasised the "political problems posed by a British Poseidon option," but also his willingness to help the UK. Schlesinger presented Naime with four options to underline this US willingness: increased help with Super Antelope, Poseidon RVs for Polaris, Poseidon RVs and missiles (but not MIRV dispenser bus), and even provision of ULMS-1 (the later Trident).[83] All of these options explicitly excluded any transfer of MIRV technology from the US to the UK because of likely Congressional and Russian opposition - the latter important at a delicate stage of SALT. Macklen challenged what he saw as the optimistic cost estimates behind these options: "the costs stated by the US side ... are so misleading that they should be ignored except as indications of White House willingness to be helpful."[84] By September a report was circulating in the MoD that indicated naval support for a so-called Hybrid option involving a Poseidon missile with a UK non-MIRV front end based on Super Antelope. This Hybrid, later known as Stag, was thought to offer similar advantages to Poseidon in extended life expectancy and penetration of terminal defences, but also greater missile range and therefore greater searoom for submarine operations.[85]

By November 1972, when the Super Antelope project definition phase came to an end, the political waters had therefore been muddied somewhat, and a quick decision to go ahead was impossible given confusion over the cost and political commitment behind the several options now available. Despite what Carrington described in a letter to Heath as "overriding political and financial objections" to Poseidon,[86] Trend raised it again with Kissinger, hearing the most positive message yet: "if the decision rested with him alone he might incline towards letting us have the full Poseidon weapon."[87] At Camp David in Feb 1973, Nixon told Heath "if we can find a way of dealing with this Poseidon thing, I would be for it,"[88] but when he subsequently sent Schlesinger to the UK for discussions, instead of a resolution, a further complication emerged. Schlesinger thought penetration of terminal defences would be improved by the UK's adopting "Option M" - essentially a complete Poseidon, including the US Mk.3 RV and warhead with its high re-entry speed to defeat terminal defences, less only the MIRV dispenser bus. Option M appears to have become a favourite with the Chiefs of Staff,[89] but more questions had to be resolved as a result: was this offer based on definite US intelligence of a future Soviet terminal defence? What yield could Aldermaston get out of the Mk.3 warhead?[90]

Poseidon, despite support from the Royal Navy, had a number of specific drawbacks. The development itself was not without problems in the US;[91] its adoption would stretch supplies of fissile material in the UK, as a greater number of warheads would be required;[92] and politically it "would postpone Anglo-French cooperation into the next century."[93] Their remained just enough interest, however, in the possibility of full Poseidon with MIRV to plan another voyage around this particular buoy. This is likely to have been at least partly because both Stag and Option M implied the need for a new and extremely expensive non-MIRV bus for Poseidon. Cromer "gained the very strong impression" after a further conversation with Kissinger in June 1973 "that the President [now under pressure because of Watergate] would be mightily relieved if we did not press the MIRV question,"[94] but in July when Macklen visited Washington he was still getting hints that a fully MIRVed Poseidon might be on offer.[95] At this point we reach the horizon of the documentary record - until at least 1 January 2005 when more files will be released. We cannot quite say whether full Poseidon with MIRV was ever formally requested by the UK, or offered by the US, but the indications are that the difficulties were such that it was always better not to ask. A refusal, after all, sometimes offends.

Why Chevaline?

It may be worth highlighting that while all this diplomatic manoeuvring was going on a drip-feed of funding for Super Antelope, now known as KH793, continued: £9M in April 1972, £14M more in October and £17.5M in May 1973.[96] This drip-feed was highlighted as a problem for project managers by the Public Accounts Committee. On the other hand it did keep Super Antelope alive, whether or not it remained the favoured option of any individual or group, and one of the laws of project management is that the longer one goes on the harder it becomes to cancel. At any point after about 1969, so much more was known about Super Antelope than about any other option that rival ideas were at a specific disadvantage; for want of sound information they *could not* reliably be chosen over Super Antelope.

A full answer to the question "why Chevaline?" would have to address the subsequent history of the programme and its survival through various reviews. Conclusions are impossible to draw. But some points of interest certainly emerge. One relates to the persistent allegation, originating with Zuckerman, that Chevaline was built to keep the nuclear scientists happy and preserve the Anglo-American nuclear relationship, and moreover depended on lobbying efforts orchestrated by AWRE.[97] It is undeniable that that the future of Aldermaston and its American link were matters of some political importance over many years (this was odd, in one sense, given the enormous amount of work necessary at other establishments, for example RAE Farnborough: Chevaline presented problems of space science just as much as nuclear warhead design, and provided work for a large number of scientists and engineers outside AWRE).[98] References abound in the declassified documents to the need to restore and maintain Aldermaston and its US relationship: "the key problem was whether the programme suggested ... was sufficient to ensure the effective continuance of the Atomic Weapons Research Establishment"[99] ... without Polaris improvement "we should be unable to ensure the continued flow of US information on nuclear weapons."[100] Peter Jones, then Director of AWRE, strenuously denied before the Public Accounts Committee in 1982 that Chevaline had been some kind of 'make-work' scheme.[101] Graham Spinardi's close study of Aldermaston lobbying concludes however that, although in general British scientists were not guilty of creating and sustaining the nuclear weapons industry, in the particular case of Chevaline - which underlies the 'Zuckerman thesis' - there was some truth to the allegation: "Chevaline is the prime example where advocacy by nuclear weapons proponents may have sustained a development lacking sound political support.[102]

Cost is another aspect of continuing controversy: did the programme spiral out of control due to poor management? Inflation of cost estimates is another constant of project management, but in the case of Chevaline the increase from £2 - 40M in 1967, through £85M in 1970, £200 - 600M in 1972 and £699 - 876M in 1973, to the extraordinary £1Bn announced to Parliament in 1982, does seem remarkable, even at a time of high inflation and even higher defence-equipment inflation. Initial over-optimism on the part of the programme's supporters, especially concerning the space engineering elements of the system, fuelled the later controversy.[103] Equivocal political support also contributed, through several years' drip-feed of funding and consequent lack of committed project management In the absence of more detailed work on costs, we are not yet entitled however either whole-heartedly to condemn the programme's management or to reject the Public Accounts Committee's version of events as unfair.[104]

Significantly absent from the vast majority of Whitehall documents is any consistent logic based on Soviet ABM developments. These were a secret, after all, and so was the British response. In no sense were the British explicitly signalling to the Russians that our deterrent remained credible, that we could destroy Moscow at any time we chose, This is not to say that there was no logic of action/reaction to Soviet ABMs at technical level, just that it seems not to have been important to policy-makers. On the contrary: if the British were trying to convince anyone of their credibility by improving

Polaris, it was their allies. The likely Russian reaction to any loss of credibility was both less obvious, and less immediately bothersome, than the likely reaction in the West. A defence qualitatively inferior to that of the French, and little better than that of the Germans, was surely unthinkable, but although Bondi on occasion mentioned the Germans,[105] the documentary evidence we have suggests these assumptions, if made, were unspoken. Meanwhile however the late 1960s and early 1970s were a low point for Anglo-American relations, and there was a clear feeling that Polaris improvement one of the few remaining reasons for the US to take the British seriously. As Wilson commented, of his reasons for keeping Polaris in 1964, "I didn't want to be in the position of having to subordinate ourselves to the Americans."[105] This, for me, is the key to understanding the origins of Chevaline.

** Earlier versions of this paper were presented to the Charterhouse conferences of the British Rocketry Oral History Project in 2002 and 2004, and I am grateful to participants, especially Roy Dommett and Frank Panton, for their helpful and illuminating comments.*

References.

1. See for example Tony Benn, *Out of the Wilderness: Diaries* 1963-7 (London 1987), pp. 483, 513, and *Office Without Power: Diaries* 1968-72 (London 1988), pp. 5-6, 56, 96-7,115-6,130, 149; Solly Zuckerman, *Monkeys, Men and Missiles: An Autobiography* 1946-88 (London 1988), ch. 32; Denis Healey, *The Time of My Life* (London 1989), pp. 313,455-6; Hermann Bondi, *Science, Churchill and Me* (Oxford 1990), pp. 107-8; Eric Grove, ed., *The Battle and the Breeze: The Naval Reminiscences of Admiral of the Fleet Sir Edward Ashmore* (Stroud 1997), pp. 21721; Frank Panton, 'The Unveiling of Chevaline: House of Commons Public Accounts Committee 1981-2' and 'Polaris Improvements and the Chevaline System *1967-7516'* in *Prospero* Spring 2004, pp. 91-128.

2. Lawrence Freedman, *Britain and Nuclear Weapons* (London 1980), ch. 4-5; John SImpson, *The Independent Nuclear State: The United States, Britain and the Military Atom* (2nd edn, London 1986), ch. 8; John Baylis and Kristan Stoddart, 'Britain and the Chevaline Project: The Hidden Nuclear Programme 1967-82' in *Journal of Strategic Studies* Dec 2003, pp. 124-55; Kate Pyne, *'Dark Horse: The Chevaline Project 1961-82,'* presentation to the Charterhouse conference of the British Rocketry Oral History Project, April 2002.

3. Pyne, 'Dark Horse.'

4. Andrew Pierre, *Nuclear Politics: The British Experience with* an *Independent Nuclear Force* (Oxford 1972), pp. 201-7.

5. Wilson sometimes used the word "de-negotiate" but it was "re-negotiate" which appeared in the 1964 manifesto and in Hansard - see Pierre, *Nuclear Politics*, pp. 262-5. Pierre's book remains the best published account of Labour nuclear policy in these years.

6. Quote from *Hansard*, House of Commons Debates, vol. 687 col. 437, 16 Jan 1964.

7. Wilson, *The Labour Government* 1964-70: A *Personal Record* (London 1971), pp. *5516* and quote from p.175; Benn, *Out of the Wilderness*, p. 197; several refs by Zuckerman in papers in London, National Archives

- Public Record Office (hereafter PRO). PREM *13/1316*. The speech itself is in Hansard, House of Commons Debates, vol.704 cols.701-4, 17 Dec 1964.

8. Wilson, *The Labour Government*, p. 40.

9. PRO, DEFE *13/350,* PUS(RN) to PUS, 19 Oct 1964 (seen by Healey on 20 Oct).

10. Richard Moore, *The Royal Navy and Nuclear Weapons* (London 2001), ch. 5.

11. Healey, *The Time of My Life*, p. 302.

12. A rival to the American Multilateral Force (MLF) proposal - see e.g., Pierre, *Nuclear Politics*, pp. 276-83.

13. Terms of reference in PRO, PN(66)1 of30 Sep 1966 in CAB 134/3120.

14. See Philip Ziegler, *Wilson: The Authorised Life of Lord Wilson of Rievaulx* (London 1993), pp. 42-4, 105-6, 124-5, 208-10.

15. Benn, *Out of the Wilderness*, p. 462. Benn also claims, quite falsely, in a footnote to his diaries, to have heard nothing of Polaris improvement between 1966 and 1974 *(ibid*, p. 517; *cf.* p. 513).

16. Zuckerman: *Monkeys, Men and Missiles*, p.387.

17. See for example the flurry of papers dated 11 Sep, 21 Oct, 6 and 19 Dec 1968 in PRO, PREM 13/2493.

18. Ziegler, *Wilson*, p. 183.

19. Benn, *Office Without Power*, pp. 96-7; brief for and record of a meeting 5 May 1970 in PRO, DEFE 13/770.

20. John Le Carre's novel A *Small Town in Germany* (London 1968) shows a little of the more general unease caused in Britain by West Germany's resurgence.

21. Pierre, *Nuclear Politics*, pp.286-7; Bhatia, *India's Nuclear Bomb* (Sahibabad 1979); Kapur, *India's Nuclear Option* (New York 1976); Perkovich, *India's Nuclear Bomb* (Princeton NJ 2001).

22. See e.g., David Dimbleby and David Reynolds, *An Ocean Apart: The Relationship between Britain and America in the Twentieth Century*

(London 1988), ch. 13 ("Drifting Apart"); but *cf* Saki Dockrill, 'Forging the Anglo-American Global Defence Partnership: Harold Wilson, Lyndon Johnson and the Washington Summit, December 1964' In *Journal of Strategic Studies* Dec 2000, pp. 107-29.

23. Humphrey Wynn, *The RAF Strategic Nuclear Deterrent Forces: Their Origins, Roles and Deployment* 1946-69 (London 1994),

24. Richard Moore, *'Where Her Majesty's Weapons Were'* in Bulletin of the Atomic Scientists Jan-Feb 2001, pp. 58-64.

25. Wynn, *RAF Nuclear Deterrent Forces*, pp. 262-70.

26. PRO, ND(65)1 of20 Jan 1965 in CAB 13412241.

27. PRO, Cook. to CDS, 26 July 1966 in DEFE 25/123; ND(66)2nd mtg of 16 Sep 1966 in CAB 13412241.

28. PRO, ND(65)1 of 20 Jan and ND(65)1st mtg of 22 Jan 1965 in CAB 134/2241; also papers on testing in PREM 13/123 and esp. DEFE 241291. Barbara Castle recalled the cursory - and retrospective - Cabinet discussion of the final test in *The Castle Diaries 1964-70* (London 1984), p. 107.

29. Graham Spinardi, 'Aldermaston and British Nuclear Weapons Development: Testing the "Zuckerman Thesis" in *Social Studies* of *Science* Vol. 27 (1997), pp. 547-82, esp. pp. 559-60; PRO, undated Zuckerman brief (July 1970) in CAB 168/27.

30. Spinardi, *From Polaris to Trident: the Development of US Fleet Ballistic Missile Technology* (Cambridge 1994), pp. 66, 68, 72-4.

31. Pavel Podvig, ed., *Russian Strategic Nuclear Forces* (Cambridge Mass. 2001), pp. 127-9, 294-8, 319-22.

32. Lawrence Freedman, US *Intelligence and the Soviet Strategic Threat* (London 1977), quote on p. 86; see also John Prados, *The Soviet Estimate*: US *Intelligence Analysis and Russian Military Strength* (New York 1982).

33. For the true progress of Soviet ABM work, see Podvig, ed., *Russian Strategic Nuclear Forces*, pp. 412-9, 470-1.

34. PRO, JIC(64)3(Final) of 28 Feb 64 in CAB 158/51.

35. PRO, JIC(65)3 of 18 Feb 1965 in CAB 158/56.

36. PRO, JIC(68)3(Final) of 24 Jan 1968 in CAB 158/68.

37. PRO, Healey to Wilson, 7 Nov 1966 in PREM 13/1316.

38. The record of the January meeting, PN(67)1st mtg of 9 Jan 1967, has not been declassified, but the fact that Zuckerman wrote to Healey about Polaris improvement the day after the meeting does suggest that a discussion had taken place (letter of 10 Jan 1967 in PRO, PREM 13/1316); this is confirmed by the account in the minutes of the April meeting, PN(67)2nd of3 April 1967 in CAB 134/3120.

39. PRO, Healey to Wilson 20 Mar 1967 in PREM 13/1317.

40. PRO, PN(67)2nd of 3 Apr 1967 in CAB 134/3120.

41. See Healey's conversations and correspondence with McNamara of April 1967 and Zuckerman's trip report of9 May 1967 in PRO, PREM 13/1317.

42. PRO, PN(66)4 of 14 Dec 1966 in CAB 134/3120. See also note of S of S mtg 8 Jun 1967 in DEFE 11/437.

43. Barbara Castle asked at the Cabinet Defence Committee on 30 May 1967 about the next generation of nuclear weapons and Wilson replied "if you mean are we going to acquire Poseidon, the answer is no" - as she commented tartly in her diary, "that is as far as one can get on these top secret matters in Cabinet" (Castle, *The Castle Diaries 1964-70*, p. 260); for the announcement in Parliament see Hansard, House of Commons Debates vol. 747 cols. 223-4, written answers for 7 Jun 1967; *ibid*, vol. 748 col. 299, oral answers for 13 Jun 1967.

44. PRO, PN(67)3 of 15 May 1967 and subsequent correspondence in PREM 13/1317.

45. PRO, PN(67)6 and 7 of 1 Dec 1967 in CAB 134/3120.

46. PRO, PN(67)6 in *ibid;* also extracts in PREM 13/2493.

47. PRO, PN(67) 4th mtg of 5 Dec 1967 in CAB 134/3120. Polaris deployment East of Suez was to be possible from 1972, or at three years' notice, whichever was the later; this was later put back still further to five years' notice - see PRO, draft for S of S to PM of 5 Jun 1968 in DEFE 25/107; COS.38/68 of 13 Jun 1968 in DEFE 13/548.

48. Terms of reference in PRO, PN(67)8 of 15 Dec 1967 in CAB 134/3120. The study began in April 1968 and reported in July to Benn and the Chairman of the Atomic Energy Authority, Sir John Hill. Kings Norton's team members were Lord Rothschild (see below), the trades unionist Lord Carron and Sir James Taylor, recently retired Deputy Chairman of the Royal Ordnance Factories Board.

49. Report in PRO, ES 13/1 and under cover of PN(68)9 of 5 Dec 1968 in Pt. 2 of CAB 134/3121.

50. Filed with the main report, *ibid.*

51. See for example his speech in April 1968 to the Imperial Defence College, reprinted in his *Meditations of a Broomstick* (London 1977), esp. pp. 45-8.

52. PRO, Zuckerman to Wilson 11 Sep 1968 in PREM 13/2493.

53. PRO, PN(68)9 of 5 Dec 1968 in PI.2 of CAB 134/3121.

54. PRO, PS/Mintech note of 7 Jan 1969 in AVIA 65/2198.

55. PRO, Healey to Wilson 5 May 1968 in PREM 1312493.

56. PRO, note of technical discussions circulated 19 Feb 1969 in PREM 13/2439.

57. Freedman, *US Intelligence*, p. 94.

58. PRO, JIC(68)3(Final) of24 Jan 1968, pp. 109-10, in CAB 157/68; see also JIC(68)37(Final) of 18 Apr 1968 in CAB 158/70.

59. Podvig, ed., Russian Strategic Nuclear Forces, pp. 414-5.

60. PRO, Perm Sec/Mintech note of 15 May 1969 in AVIA 65/2198; brief for S of S mtg 4 May 1970 in DEFE 13/770.

61. PRO, note of S of S mtg 12 Feb 1969 in DEFE 13/548; also papers in AVIA 65/2198. See e.g.,

62. PRO, report of mtg 5 May 1970 in DEFE 13/770.

63. PRO, Jaffray to Healey, 28 Apr 1970 in ibid.

64. PRO, numerous papers in ibid.

65. PRO, Carrington to Heath 16 Jul 1970 in PREM 15/1359.

66. PRO, Carrington to Heath 21 Oct and Armstrong to Jaffray 27 Oct 1970 in CAB 168/27.

67. PRO, Zuckerman to Heath 17 July 1970 in ibid.

68. Conversation with Jerry Stocker at Charterhouse, April 2004.

69. PRO, Carrington to Heath 21 Oct 1970 in CAB 168/27 (there is also a final reference to Zuckerman in a note from Robert Armstrong of 26 Oct 1970 in PREM 15/1359).

70. Kenneth Rose, Elusive Rothschild: the Life of Victor, Third Baron (London 2003), p. 187.

71. PRO, NP(70)1st mtg 20 Jul1970 Confidential Annexe in CAB 134/3018. PRO,

72. Carrington to Heath 11 April 1972 in PREM 15/1359.

73. PRO, Carrington to Heath 15 May 1972 and subsequent correspondence in PREM 15/1359; Patrick Nairne note and draft brief of 10 Aug 1972 in DEFE 24/896.

74. PRO, GEN 69(71)1st mtg 13 Dec 1971 in CAB 130/544.

75. PRO, COS.10th/71 of 9 Mar 1971 in DEFE 32/21.

76. PRO, numerous papers in DEFE 24/896, PREM 15/1359 and 1360.

77. PRO, Nairne note of discussions with Kissinger dated 11 Aug 1972 in DEFE 24/896; record of Heath/Nixon talks at Camp David 1 Feb 1973 in PREM 15/1359.

78. PRO, Trend to Heath 1 May 1973 in PREM 15/1360. PRO

79. Cromer note of 12 May 1972 in PREM 15/1359. PRO

80. Trend to Heath 11 Jun 1973 in PREM 15/1360.

81. Interview with Sir Hermann Bondi, 24 April 2004. For Carver see also PRO, COS.41st of 1971 Confidential Annexe of 30 Nov 1971 in DEFE

32/21.

82. PRO, undated brief (among Nov 1971 papers) for S of S in DEFE 11/470. The 'Moscow criterion' appears to have been modified subtly during 1972 when Trend noted Carrington's agreement with a new JIC assessment that "the destruction of the Moscow area alone would be regarded by the Russians as an unacceptable price to pay for anything that they might hope to gain by a nuclear attack on the United Kingdom and that our deterrent will therefore remain credible so long as it is capable of destroying Moscow" (Trend to Heath 10 Nov 1972 in PREM 15/1359).

83. PRO, Nairne to ACNS(P) and ACSA(N) 11 Aug 1972 in DEFE 24/896.

84. PRO, Macklen note of 8 Sep 1972 in ibid.

85. PRO, DEPC(N) 2 of 72 also ORC(N) 2/72 of 7 Sep 1972 'The Way Ahead for Polaris' in Ibid.

86. PRO, Carrington to Heath 6 Nov 1972 in PREM 15/1359 (Heath queried the word "political" in a marginal note).

87. PRO, Carrington to Heath 19 Jan 1973 in ibid.

88. PRO, record of talks at Camp David 1 Feb 1973 in ibid.

89. PRO, Carrington to Heath 2 May 1973 in PREM 15/1360.

90. PRO, Carrington to Heath 21 Feb 1973 and subsequent correspondence in PREM 15/1359.

91. Spinardi, From Polaris to Trident, pp. 104-7.

92. PRO, Carrington to Heath 11 Apr 1972 in PREM 13/1359.

93. PRO, Trend to Heath 1 May 1973 in PREM 15/1360.

94. PRO, Washington telno 2055 by signal 011930Z July 1973 in PREM 15/1360.

95. PRO, record of Macklen's visit and Trend to Heath 31 Aug 1973 in ibid.

96. PRO, various papers in PREM 15/1359 and 1360.

97. Zuckerman, *Monkeys, Men and Missiles*, pp. 388-91.

98. This was occasionally noted at the time: e.g., PRO, Cabinet Sec brief to PM 1 Jan 1967 in PREM 1312493; note of26 Nov 1969 in AVIA 65/2198.

99. PRO, COS.43rd/66 Confidential Annexe 17 Aug 1966 in DEFE 25/123.

100. PRO, Carrington to Heath 16 Jul1970 in PREM 15/1359.

101. Ministry of Defence: *Chevaline Improvements to the Polaris Missile System* (London, HMSO 1982), p.11.

102. Spinardi, *'Aldermaston and British Nuclear Weapons Development,'* p. 574.

103. Interview with Sir Hermann Bondi 24 April 2004.

104. Frank Panton gives one side of the story in *'The Unveiling of Chevaline.'*

105. PRO, CoS.41st of 1971 Confidential Annexe 30 Nov 1971 in DEFE 32/21; interview with Sir Herman Bondi 24 April 2004.

106. In conversation with Peter Hennessy: Hennessy, *Cabinet* (London 1966), p. 149.

The Requirement and Early R&D Programme.

R.G.Ridley.

This paper is based on a paper presented by Peter Jones to The British Rocket Oral History Conference in 2003.

Introduction.

Prime Minister Harold Macmillan obtained the agreement of President John Kennedy in the meeting in Nassau in December 1962 to the UK purchase of Polaris. The resulting Polaris Sales Agreement of 6 April 1963 led to the UK building four nuclear submarines, each to be fitted with the US Polaris weapon system and 16 US launch tubes and US Polaris A3 missiles. Each missile carried three re-entry bodies (ReBs). AWRE was given the task of developing, producing and service acceptance of a UK warhead to fit in a US re-entry vehicle. In 1964 and 1965, two UK underground nuclear tests in Nevada provided the necessary nuclear performance data.

Nuclear Effects.

AWRE had been aware of the extensive US and USSR nuclear testing programmes. In 1957 and 1958 the US conducted some high yield, high altitude tests; in 1960 and 1961 the USSR did the same. The connection of these to ABM applications does not seem to have been made until, in January 1966, AWRE was asked to consider the implications of the US change from the A3 missile to the A3T 'Topsy' missile where the missile guidance system had been hardened against the effects arising from the exo-atmospheric detonations of ABM nuclear warheads. The initial concern in AWRE was the vulnerability of the warhead electronics. This soon changed to an additional concern about the vulnerability of the UK Polaris ReB and warhead.

Antelope.

In February 1967 presentations on vulnerability were made to Sir William Cook, Deputy Chief Scientific Adviser, MoD (Deputy Director, AWRE until 1958) and Sir William Penney (Director AWRE until 1959). Theoretical modelling, a few laboratory experiments and some palliatives were presented. The potential implications were already seen as serious and Bill Cook briefed the Secretary of State on the need to improve the ReBs and warheads; a high level meeting with officials in the US was arranged for March. At this meeting with Sir Solly Zuckerman, Chief Scientific Adviser, Cabinet Office, Bill Cook and Ted Newley, the US revealed that they were developing a minimum change improvement for their Polaris re-entry system codenamed Antelope. The ReBs were improved, one ReB was replaced with a Penetration Aid Carrier (or PAC) and penetration aids were added. This increased the number of ABMs needed to intercept each missile payload. The US noted that their current projection of the Soviet ABM force was that it could be overwhelmed by the number of missiles in the US stockpile, so they did not envisage deploying Antelope unless this assessment changed. Later a further briefing on Antelope was given in the US for John Challens, AWRE, Chief of Warhead Development, Fred East, RAE, Head of Projects Weapons Department and S.Chard, Director Atomic Weapons (Production and Factories) (DAW(P&F)).

Polaris re-entry study group.

In early October 1967 John Challens told Peter Jones, AWRE, Senior Superintendent Warhead Electronics, that Bill Cook had tasked AWRE to coordinate a Polaris vs. ABM study. The study was to be kept totally secret even within MoD and work within industry was forbidden. He, in turn, tasked Peter Jones that, in addition to his normal duties, he should lead a team from the various MoD R&D Establishments to support this. The first meeting on 26 October 1967 included Don Harper and Roy Dommett for RAE, Denis Dracott for AWRE, Sandy Murray for Royal Radar Establishment (RRE) and representatives of Chief Polaris Executive, Director Atomic Weapons Development (DAWD) and Director Scientific and Technical Intelligence

(DSTI). The group became known as the Polaris Re-entry System Study Group (PRESSG) nicknamed the 'press gang'.

During the preparation for the meetings in the US had it become clear that RAE had been researching penetration aid systems for some time but always with the expectation that the ABM system would be based on endo-atmospheric intercept, high acceleration missiles with nuclear warheads killing individual ReBs. This was the basic premise for a Study HR.169 led by Fred East to study possible improvements to Polaris. In view of the sensitivity of the topic, AWRE was not involved as they did not have a 'need to know'. Three unimproved ReBs were retained but a variety of penetration aid types were deployed from the equipment section.
The Terms of Reference of the PRESSG arrived on 14 December 1967. They were as follows:

1. To assess the threat to Polaris from likely ABM development in the next 10 years.
2. To propose the necessary modifications, with options, to overcome this.
3. Modifications to be confined to the 'front end' (i.e. not affecting guidance, equipment section, or motor stages below the ReB mountings.)
4. To estimate the work, cost, and effectiveness for each of these.
5. To consider relevant aspects of the HR.169 study.
6. To examine the feasibility of payloads of many smaller warheads.
7. To include SSBN deployment considerations.
8. To report by 31 May 1968.

Peter Jones recalls being called to Bill Cook's office four days later to report progress. AWRE's first briefing on radar capabilities was received from RRE four days before Christmas. Three days after Christmas and again ten days later, Peter Jones was called to Bill Cook's office to report progress. Peter Jones led the Study and reported monthly to DAWD, to a committee set up in headquarters by Victor Macklen, Deputy Chief Advisor (Projects and Nuclear) to monitor progress, and internally to John Challen's Warhead Development Committee for interaction with engineering and other divisions of AWRE, and the Technical Policy Committee, the Director/AWRE's senior technical committee. Don Harper had similar arrangements for RAE but his access to aerospace engineering support was hampered by lack of extramural funding. RAE had overall responsibility for coordinating the work of the non-nuclear establishments and for ongoing work with the contractor EASAMS. Clearances delayed intelligence briefings until February and discussion with the US Navy contractor for Polaris, Lockheed Missile and Space Corporation (LMSC), until April.
There was an enormous technical backlog to make up; there was no equivalent ABM research programme in the UK; research as well as projects in ballistic missiles, nuclear effects and ABMs had lapsed years ago. Some

AWRE staff made specialist contributions, e.g. Denis Dracott and Pat Flynn on ionisation and radio attenuation, others stayed on to develop offence/defence interaction modelling. e.g. Syd Barker and Ray Shepherd, and this activity grew to form the Systems Group. RAE contributed the background to the HR.169 Study. The PRESSG studied the limited information available on Antelope.

The PRESSG Report.

The report was in seven thick volumes, most of them issued in June 1968 but two re-issued in August 1968. It consisted of a Technical Report overview supported by volumes on system criteria, ABM warheads, effects of nuclear explosions, penetration methods, system assessment and programme costings. The main issues covered were:

Polaris A3T Vulnerability.

Fig.l shows a diagram of the Polaris A3T system. After nose fairing ejection, the three ReBs tilt out (Fig. 2) and the second stage continues thrusting until the velocity is such that the ReBs would hit the intended target. The ReBs are then ejected from the second stage which continues to motor between them. In the late stages of exo-atmospheric flight, the ReBs are about 10 miles apart in space. The main PRESSG conclusion was that one ABM missile with a megaton class nuclear warhead could kill all three warheads on one UK Polaris missile with interception at considerable range from the target. Thus the ABM system then under development with, say, 100 Galosh missiles would reach the point where it could neutralise the payload from one boatload of 16 UK Polaris missiles.

Radar Blackout.

The effects of nuclear explosions could blackout or degrade radar performance but the distributed sites and planned interception timing would allow the system to cope with successive ABM interceptions.

Super Antelope.

One option recommended for further study was Super Antelope with the ReB further improved compared to Antelope and retaining a PAC and penetration aids.

Other issues.

A number of specific topics were identified for further study.

Continuing PRESSG and System Studies.

Headquarters was aware that this short timescale and late access to information had been a severe constraint and the PRESSG was kept in being, still on a secret basis, to continue study of Antelope and Super Antelope. During the PRESSG study and later, Peter Jones and a few of his embryo systems group were given access to the US/UK official exchanges at high level, where Poseidon or mini-Poseidon (six Poseidon ReBs on the Polaris missile) were being mooted, and tasked by Victor Macklen with answering specific system questions for Bill Cook.

US Exchanges.

LMSC.

In December 1968 a visit to LMSC on Antelope gave answers to many questions on the PAC, separation dynamics, re-entry and flight trials.

Pentagon.

In July 1969, in a typical Bill Cook move to check on the competency of advice given to him, the UK paid a one-day visit to the Pentagon seeking a US critique of the PRESSG work. Presentations by the UK were made on the ABM defence, exo-atmospheric discrimination, blackout physics and tactics, and improved ReB design. The US did not exchange their information in these areas but they did respond with general agreement on intelligence interpretation and a promise to supply a US computer model of the effects of nuclear explosions on radars.

US/UK Technical Exchange Groups.

In September 1969, Frank Panton, then Assistant Chief Scientific Adviscr (Nuclear), began efforts to set up formal technical exchange under the terms of the US/UK Agreement of July 1958 on 'Cooperation on the Uses of Atomic Energy for Mutual Defence Purposes'. One for nuclear effects was relatively straightforward; Joint Working Group 26 (JOWOG 26) was set up and in December 1969 a visit under JOWOG 26 introduced the UK to the awesome complexity of an Underground Nuclear Effects Test (UGET). JOWOG 26 proceeded to establish regular exchanges from that point. JOWOG 27 was given the scope to cover exchanges on Antelope but as this was a modification to Polaris, information exchange was governed by the formal US/UK Polaris Sales Agreement. As this does not usually allow the release of US design information, it proved difficult to establish this JOWOG. It was to be a year before the UK was able to meet LMSC again under the auspices of JOWOG 27.

Systems Working Group.

In January 1970, John Towle and Bob Ridley joined Peter Jones as part of a systems group at AWRE. A permanent Systems Working Party, chaired by Peter Jones, was established which continued into the 1980s.

PRESSG Report update.

In March 1970 the PRESSG technical report was updated to note continued ABM system construction, as expected, and probable modification to give Galosh a loiter capability similar to US plans for Spartan. Loiter can give a good counter to fratricide or temporary blackout. The report reported on the progress made in all the areas of study.

Poseidon.

In separate studies the potential of C3 Poseidon in a UK context was estimated. It could achieve high penetration with lower technical risk than Super Antelope. The Poseidon option was well supported at official level in MoD but the Labour government 1967-1970 were against it for policy reasons. The US started Strategic Arms Limitation Talks with the Soviet Union in November 1969 and when the Conservative government came into office in 1970, the US was unwilling to provide Poseidon Multiple Independent Targettable Re-Entry Vehicles (MIRV) technology to the UK.

Continuing Research Study.

AWRE continued study of alternative ideas for penetration aids. RAE was updating an analytical capability on re-entry stability and ablation, developing theoretical and experimental techniques for separation gas dynamics and on exit heating, examining options for altitude control and with design support from Hunting Engineering Ltd (HEL) was considering options for optimum use of space and payload.

KH.793 Begins.

The Conservative government with Edward Heath as Prime Minister was elected in May 1970. The MoD spending review delayed consideration of initiating a project to develop Super Antelope until 27 October 1970. In the following month Controller Guided Weapons and Electronics (CGWL) in Ministry of Aviation Supply formally issued instructions for a project designated KH.793, limited funding for a one year project feasibility study and a one year project definition. He issued Terms of Reference tasking AWRE as the Coordinating Research and Development Authority (CRDA), to provide overall technical control of R&D, to direct system objectives and to report by November 1972. Peter Jones was appointed as Senior Superintendent Special Projects (SSSP), AWRE to undertake the CRDA role. He was given a Group for Systems and Assessment headed by John Towle and one for Project Programme Coordination headed by John Tomblin. Peter Jones set up and chaired the KH.793 R&D Coordinating Committee (R&DCC) and he allocated system objectives to the SWP which he also chaired. Further allocation of responsibilities was broadly: AWRE as Research and Development Authority (RDA) for threat payload, RAE as RDA for threat dispersal system and DDWP (Bath) as R&D agent for the US missile system. George Hicks now led for RAE, Ron Jennings came in for DDWP in the RN Polaris Executive, and Sandy Murray continued for RRE. Two months were then chopped off the timescale for some reason of urgency. The funding mainly expedited work in RAE's programme by increasing design and contract support and HEL was selected as their Coordinating Authority (CA); Sperry being selected as Design Authority(DA) for a digital electronic system to control the PAC. Funding also allowed AWRE to obtain more UGET results. Five further exchange meetings with the US had taken place including two JOWOG 27s.

The Naval Staff Requirement.

The project responded to a Naval Staff Requirement. In summary, the main items were:

a) The UK should have ability to penetrate an ABM defence for a continuous assured second-strike capability.

b) Any reduction in Polaris A3T maximum range was undesirable.
c) It was desirable to retain a good capability against undefended targets.
d) The submarine was not to be put at greater risk in safety terms than already existed for Polaris A3T.
e) Operation, maintenance and training should not require more service men.

KH.793 Feasibility Report.

The feasibility report was issued in September 1971. The report reviewed progress on design analysis of PAC variants. It also described US comment or criticism on designs. For a number of design options, trade offs were given between: simplicity and defence weaknesses; technical preferences and low risk development; and cost and defence insensitivity. Priorities were given for a firm set of technical decisions so that project definition could set in train a design and development programme with a very low risk of system modification. For instance, assurance of re-entry capability was given a higher priority than improved hardness.

KH.793 Project Definition Report.

The Project Definition Report was issued in September 1972. It started off with a re-evaluation of the requirement against the 1972 ABM Limitation Treaty and an update of the ABM deployment. The report set out the design decisions and included many design drawings to underline them. Super Antelope with a PAC similar to Antelope was considered too sensitive to discrimination. A more complex PAC was selected. One ReB and UK designed penetration aids were carried on a PAC which, after second separation, manoeuvred to deploy the payload. (Although this option was the main focus of future project R&D, some still referred to the project as Super Antelope until later it was given the name Chevaline.) The manoeuvring PAC made trajectory discrimination unlikely. In June 1972, the front end had been subjected to another US critique at a meeting arranged by Cook before he retired. The US, including senior LMSC designers, agreed the feasibility but said that, because of the complexity, the programme would require more flight trials. The Report included details of the programme with estimated time scale and costs for development, sub-system and system ground and fight trials, and production together with PERT charts.

1972-1976.

Other Options.

Under the Conservative government in the period 1972-1974 other options continued to be assessed in headquarters some of which were referred to the AWRE systems team for effectiveness assessment. In February 1972 four options were considered in MoD[2]: Super Antelope, Poseidon or Trident C4, collaboration with France or a 'poor man's deterrent' with simply harder warheads on Polaris A3. The 'poor man's deterrent' option was ruled out later as unlikely to be effective. In February 1973 the US said that they could not supply the Poseidon with its Multiple Independent Targettable Re-Entry Vehicles (MIRV) capability but they were willing to supply the Poseidon missile with a deMIRVed bus and Poseidon warhead design information. This option was designated option 'M'. A further alternative, the Poseidon deMIRVed bus with the UK Chevaline payload, was designated 'Stag'. In the spring of 1973, Option 'M' was favoured by MoD officials on operational, technical and logistic grounds but Super Antelope on cost, but no ministerial decisions were promulgated before the General Election of February 1974 when the Labour government with Prime Minister Harold Wilson was elected.

Trickle Funding.

While this was happening only six-month extensions were approved in April 1972 and October 1972. In May 1973 the approval was only for a four-month extension; in September 1973 six months. Under the Labour government in March 1974 an extension was given of six months and in September 1974 one year. In January 1975, a decision to support Chevaline was taken but funding continued to be drip fed until a final ministerial decision was made some months later and a new team was constituted in CPE to manage Chevaline and take it into service with the Royal Navy. From a project point of view this was frustrating asking Industry to commit resources on this basis was fraught with difficulty. The funds allocated were never appropriate to that of the timescale of the last estimate of completion so a programme slip was inevitable. This again sent the message to contractors that MoD was lacking in commitment to the project. The Treasury required a re-estimate to project completion before each six-month extension so that each re-estimate had to start before the previous period was finished, thereby encouraging repetition of down stream errors. Treasury rules forbad inclusion of a contingency.

Technical progress.

However, in the 1972-1976 period a large programme of activity of ground tests, renovation and creation of test facilities and manufacture of novel prototypes was carried out. Development is to find out what goes wrong and to design it out; otherwise there would be no need to do it at all. This must be done before expensive tests are entered into, especially flight tests or nuclear tests where it is difficult or impossible to diagnose a reason for a failure. The system needed to survive and function reliably while subject to the service environment, and to remain safe including stringent nuclear safety requirements. These all required careful analysis and planning to collect appropriate evidence for Approval and Acceptance and to meet the needs of the various MoD Safety Committees. In 1974, the project was given the code name Chevaline. Between 1972 and 1976 many problems were found, lessons learned on instruments to detect faults and detailed design changes made. Progress was particularly slow with missile aspects controlled by SSPO due to lack of a formal UK decision. The high classification placed by the UK on the work with their contractor LMSC had major cost and timescale implications. RNAD, Coulport was late in realising the extent of the changes needed there to prepare Chevaline outloads for service deployment on the SSBNs.

AWRE Management change.

In 1974 John Challens was appointed Director AWRE and Peter Jones succeeded him as CWD. Eric Warnke became SSSP until his untimely death in 1975 when Stan Orman succeeded him.

Costs.

The existence of the Chevaline project was first announced publicly by Francis Pym, Secretary of State for Defence, in February 1980 and the Public Accounts Committee began hearings on the project in December 1981. Table 1 gives the estimated costs to completion of Chevaline as presented in a memorandum by MoD to the Public Accounts Committee.[3] The conversion to 1972 prices was done under Treasury rules. The lack of early detailed interaction with the US Navy meant that the costs for missile modifications and flight trials in the US were subject to review and steady cost growth through to 1975. The PAC was a sophisticated space vehicle and the trickle funding meant that RAE contractors, often dealing with state of the art development, were slow to produce teams to allow realistic estimates to be made in the early years of the project. As the MoD memorandum to the Public Accounts Committee said 'The technical complexities accounted for a major part of the real increase in the project cost estimates. But they were also due in part to a lack of confidence at the contractors and in Establishments about the future of the project in earlier days and their consequent unwillingness to deploy resources on the scale and of the quality that was needed.' During the evidence presented to the Public Accounts Committee, it was stated that the total expenditure to 1972, the end of initial project definition, was approximately £7.5m whereas the commitment of £140m by 1975/76 more nearly met the C.S.Downy (Comptroller and Auditor General) recommendations of a 15% spend on an advanced project definition in an ideal project. (Downey called this project definition 2.) It was noted that the estimate in 1982 included a rise in contingency funding to £70m in 1977 and a further increase in contingency funding of £35m in 1978.

Handover to Polaris Executive.

Handover of DCA (PN)' s responsibility to Fred East, Chief Weapon System Engineer (CWSE), Polaris Executive, occurred in April 1976. Some nuclear testing was done in 1974, realistic non-nuclear hardware began to appear in 1974, and development test hardware during 1975/6. The concept and the basic design decisions made in 1972 held good from that point and were sufficiently developed when the Polaris Executive took control so that in July 1978 the US A3T Polaris missile and the UK improved front end flew well together. Other presentations will detail Chevaline technical developments by the RDAs and DAs and management of the project from 1976 until successful introduction into service with the Royal Navy as UK Polaris A3TK.

References.

1. P.G.E.F.Jones, British Rocketry Oral History Conference at Charterhouse April 2003.
2. F.H. Panton, Polaris Improvements and the Chevaline System, PROSPERO The Journal of British Rocketry and Nuclear History, No.1, 2004, p.109.
3. Ninth Report of the Committee of Public Accounts, Session 1981-82,Ministry of Defence, Chevaline Improvement to the Polaris Missile System, 17 March 1982.

Year	Estimate to completion £m	Ec
1972 Project Definition	175	
1973	235	
1974	337	
1975	503	
1976	594	
1977	810	
1981	1000	

Table 1. Chevaline Cost Estimates.[3]

Dr. Robert G. Ridley: Biographical details:

King's College London, London University from 1951 to 1957. BSc Physics, Ph.D Physics, AKC.
Joined Atomic Weapons Research Establishment, Aldermaston in 1957 working on Mass Spectrometry for Dr. F Morgan and Prof. H.W. Wilson.
Transferred within AWRE in 1970 to work for P.G.E.F. Jones on Systems Analysis and Assessment.
In 1980 promoted to post of D.Sc.6 in the Ministry of Defence working for D.Fakley, Assistant Chief Scientific Adviser (Nuclear).
In 1982 transferred back to AWE as Head Electronics and Systems. In 1984 promoted to post of ACSA (N) in MoD. In 1990 retired.

An Introduction to Chevaline.

S.C. Metcalf & R.L. Dommett.

Introduction

1. The Royal Aeronautical Society held a symposium in 1999 which provided a comprehensive overview of the development of the UK nuclear deterrent from the days of the V bomber force through to the deployment of the Polaris A3T medium range strategic ballistic missile system that was deployed on the specially developed Resolution class SSBN (Figure 1). The timescales for these events are shown in Figure 2, with the time domain of the present paper highlighted.

2. Bob Ridley's paper in this Symposium gives an account of the evolving Soviet ABM defences that posed a continual challenge to the UK strategic force in meeting the Government deterrence criteria. It was evident soon after the UK Polaris force was in service that there was a potential risk of not meeting the criteria, and an intense debate took place in UK Government and military circles as to whether A3T was adequate, or an improvement in UK capability was required to maintain the deterrent. An insight these events is given in Frank Panton's paper, and in to the choices potentially available to the UK, ranging from do nothing, to purchasing a newer US weapon system, or undertaking a development of the A3T in the UK.
3. The second Bob Ridley paper provides an, overview of the MoD R & D establishments input into the PRESSG and the feasibility and project definition studies KH793/Chevaline to counter the Soviet ABM system with an improved front end (IFE) on the Polaris A3T missile. The RAE as RDA played a key,role in all of these activities from the formation of the PRESSG in 1967. The system criteria as defined by AWRE as the CRDA were translated by RAE into performance specifications for a sophisticated manoeuvring space vehicle, the PAC, designed to carry one of the ReBs and the penetration aids, with the other ReB still

launched from the Second Stage, in such a way that discrimination by tracking radars could be avoided.

4. This paper provides an overview of the engineering design and testing of Chevaline, and the organization set up post 1975 which managed the project through to acceptance by the RN. It thus provides an introduction to the subsequent papers presented at the Symposium, including the RAE and AWE contributions to turning the system criteria into a fully engineered system that is amplified later by Mike Rance and Kate Pyne, The paper also identifies the consequential crucial changes to the missile, submarine and shore facilities, which were the responsibility of .DDWP for CSSE, and other established RN branches. These aspects will be expanded;ny;rater paper on the role of the RN, which also identifies the important role played by US government agencies 'and industry. It will also introduce the extensive flight trials programme in the USA and Australia which the UK had to undertake to successfully develop and prove the IFE.

5. Kate Pyne's and Mike Rance's papers on the role of AWRE and RAE will provide a much greater depth of information on the technical aspects of Chevaline, and the management session papers, led by Dr Stanley Orman's paper on the not inconsiderable management challenges, will give further insights into the technical and non-technical challenges.

6. Chevaline was undoubtedly a major technical achievement. A lot has been said elsewhere about the management and costs of the programme, some of it not strongly founded, mainly because we have all been short of facts in the public domain, perhaps not unexpected given the essential secret nature of the undertaking. However, this series of papers and presentations provides much of the missing information, and should help provide a more informed judgement on the project team's response to the management and cost control challenges, especially post the setting up of the CSSE/CWSE organisation, and the provision of long term funding for the first time, to undertake what was a very large and complex project. UK industry played important and vital role in that achievement, which is addressed in David Reade's paper on the role of BAe as CDA and FTA, and Mike Rance's paper on the role of UK industry other than BAe.

7. The Government has already announced that there will be an official history of Chevaline, which will provide the in depth account and assessment of the project; this Symposium is a step along the path to providing greater public information that has been available to date.

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Requirement.

9. To summarize the Requirement for Chevaline introduced and discussed by Bob Ridley, it was to provide a system that.

- Was sufficiently hardened against Soviet ABM nuclear warheads.
- Provided significantly improved penetration of the ABM defences.
- Met stringent safety requirements in production, handling and deployment:
- At least 3 independent safety breaks.
- No risk to SSBN or crew.
- Met demanding environmental specifications.
- Met high operational reliability after long periods of deployment or storage.
- Minimised changes to A3T Missile and Equipment Section.
- Provided low risk by maximising use of existing technology.

10. This and subsequent papers examine how well these requirements were achieved.

Table 1: US SLBM ballistic missile development. (Blue Streak is a UK ground based-missile shown for comparison)

Missile	Blue Streak	Jupiter Initial Concept	Polaris A1	Polaris A2	Polaris A3T/A3TK	Poseidon C3	Trider 1 C4
Date conceived or deployed	(See ref)	April 1956	Mar 1957	June 1962	Sep 1964	Mar 1971	1979
Length (ft)	~80	41.3	28.5	31	31	34	34
Diameter (inches)	120	120	54	54	54	74	74
Mass (lbs) Mass (kgs)		162'000 73'636	28'000 12'727	32'000 14'545	36'000 16'364	64'000 29'091	73'0C 33'18
Range (nm)		?	1200	1500	A3T/2500 A3TK 1950	Varied with payload	>400(
Warheads	1	1	1	1	A3T = 3 A3TK = 2	MIRV	MIR'

The Polaris A3T Weapon System.

11. Given that Chevaline was an approved modification (SPALT) to the Polaris A3T missile system front end, some understanding what it is and how it works is critical to understanding Chevaline. A fuller account of the submarine and the changes required to it to operate with Chevaline (Polaris A3TK in service) is given in the paper on the role of the RN.

12. The original Polaris missile (A1) was the first practical two-stage rocket. It had to use solid propellants that hitherto had been of relatively low Specific Impulse and used in small sized motors. To shorten the length, each motor had four short nozzles, partially buried in the motor. Both payload and the guidance system had to be exceptionally lightweight. To gain a quick capability the first two versions were of short range, a maximum of 1,200 nm for A 1 and 1,750 nm for A2, both with unfortunately a rather low reliability, for A 1 as low as 50%.

13. Table 1. compares the Polaris missiles the evolution of US submarine launched ballistic missiles.

14. Polaris A3 (and hence A3T, the UK version designation) was the third generation strategic system developed by the USN through Special Strategic Projects Office (SSPO). The system is illustrated in Figures 3 and 4, the latter showing a set of photographs of a US Polaris A3 missile, essentially visually identical to the A3T. It remained powered by a solid fuelled 2-stage rocket motor, but now of increased length, mass and thrust over A1 and A2. The mounting of the ReBs on the front of the Equipment Section (carried by the Second Stage motor) is illustrated in these Figures. The three individual bodies are mounted on a delta frame, and are locked in a tilt-in mode whilst the Nose Fairing is present, and tilt out to a locked position for release as soon as the Nose Fairing is ejected. More detail is given in the next section.

15. A particular Royal Navy achievement must be noted, the Polaris A3T programme completed with the design and build of four submarines, the integration of missiles with new warheads, the extensive range of shore facilities, and personnel training exactly to the initially predicted time, and under predicted cost. This fact influenced some Naval attitudes to the change to Chevaline as opposed to the purchase of a US successor system.

Polaris A3T Engineering.

16. The UK POLARIS A3T missile was a nuclear hardened version of the US A3 missile, and carried ReBs fitted with UK warheads. It was deployed on the UK designed and built Resolution class SSBNs, and was designated Polaris A3T. (The information in Figures 3-4 has already been mentioned.)

17. Figure 5 illustrates the deployment sequence of the A3 missile. The ReBs shown in the previous Figure tilt out as soon as the separation ring attaching the Nose Fairing to the second-stage is cut by a line charge, and the Nose Fairing Rocket Motor is fired. The Polaris missile is unusual in that it ejects the ReBs at different times from the still thrusting second stage to change the range. The ReB ejection needs high acceleration, and is achieved using rocket motors. Even the longest range, achieved by latest time for ReB ejection, still undertaken with the second-stage motor burning (to ensure a repeatable maximum range). This procedure means that the second-stage post payload separation, being suddenly lighter, will overtake the ejected ReBs, flying through the middle of the group, with its exhaust plume washing over the bodies, causing a disturbance to each ReB to tumble.

18. The problems of the hot gases from the Nose Fairing rocket motor and the second-stage rocket motors exhausts on the ReBs were not very severe for A3T; they were designed to survive more severe re-entry heating. But this fly-by phenomenon was to be the source of very significant problems in the design of the Chevaline system.

Chevaline.

19. Chevaline represented a major UK engineering development programme. The rest of this paper concentrates on the engineering achievements of the project, which we judge to have been considerable.

20. Engineering of the Missile System.

21. The solution adopted by RAE and AWRE to meet the systems criteria was to replace the 3 ReBs fitted to the POLARIS A3T system with 2 ReBs and a Penetration Aid Carrier (PAC) to carry and dispense penetration aids.

22. The POLARIS A3T 2-stage booster was retained, together with the existing missile guidance and control system and the Nose Fairing. Some changes were made to the second-stage booster flight electronics to accommodate the PAC, and the changes in mass, and mass distribution. A new Nose Fairing eject motor was

developed to improve the clearance of fairing from the much bulkier front end.

23. The A3T mounting and deployment system for the ReBs (Base Frame or Delta Frame in Figure 3) was adapted for Chevaline.

24. Figure 6 shows the overall scheme, to be compared with A3T in Figures 4 and 5. One of the remaining ReBs is mounted in the original C position (ReB-C), visible, and the other, the ReB-P, is carried on the PAC (on the other side of the PAC in this view).

25. The design of the PAC was led by RAE as the RDA, with the engineering realization of the PAC being achieved by a team led by Hunting Engineering (now InSys), and by Sperry for the control system.

26. As Mike Rance will describe, the driving requirements in the development of the PAC were low mass to retain missile range, rigidity to dispense the payload under control, and performance sufficient to meet the systems criteria.

27. Figure 7 shows the packaging of the PAC and C-Body under the Nose Fairing, both mounted on a modified Base Frame similar to A3T. Because, like A3T, both the PAC and the C-Body is rocket ejected, the Thermal Barrier was modified to protect the flight electronics in the second-stage. As for A3T, the PAC and the C-Body tilt-out to their ejection position immediately following Nose Fairing eject. A photograph of an IFE mounted on a second stage, Figure 8, shows the mounting of the P-Body within the PAC, released later when the Blast Shield has been opened. The major additional features visible are an opening blast shield and thermal skins to protect the PAC and ReBs from nose fairing eject, aerodynamic heating and second separation, and the ACS nozzles. The basic concept, and much of the basic structure and component layout was kept, with refinement, from the early design conception through to deployment of a tactical standard.

Threat Deployment Sequence.

28. A deployment sequence of the PAC and C-Body is illustrated in Figure 9 (compare with A3T deployment in Figure 5). The PAC and the C-Body tilt out as the Nose Fairing clears them. The maximum time of it's eject, remained unchanged, as the UK rejected the replacement of the timer as too expensive, but it might have increased the maximum range a little. The consequence, unrecognised at that time, was that aerodynamic and shock wave heating in the upper atmosphere would still be sufficiently high to require extensive thermal protection on the

PAC.

29. The next challenge was ejecting the PAC and the C-Body from the still thrusting missile. Powerful, short burn rocket motors were used, but they exhausted into complex, small spaces, which changed continuously as the bodies separated. Mike Rance describes this gas dynamic problem in his paper, and the large trials and analysis effort it took to understand and predict the consequences.

30. One residual problem from A3T explained earlier, was the fly-by consequences of the second-stage, still burning, accelerating rapidly after it's payload release, overtaking the just dispensed PAC and C-Body. This was of little consequence on A3T, but for Chevaline, the ejection of the PAC and ReB without loss of control due to the exhaust wake of the second-stage passing close by, or even a collision, was one of the significant technical challenges. This is also dealt with by Mike Rance.

Ground trials.

31. What evolved as a concept, encouraged by BAe when they were appointed as the CDA, was to adopt a spacecraft approach rather than the then established one used to evaluate guided missiles. Thus, extensive ground testing of full-scale replica hardware was conducted, rather than extensively testing the flight hardware, in addition to sub-scale and full-scale development trials.

32. Mike Rance's paper shows that a very large number of ground trials (and, indeed, flight trials) were required to gain sufficient confidence that such a radical concept would work accurately and reliably under a wide range of environmental conditions. The test programme became a major, undertaking in its own right, both before the final build standard of the hardware to be tested on flight trials could be determined, and to help interpret the results of the flight trials. A critical trials logic was established by the MEG) in order to prioritise the trials, set the critical path, and allocate hardware, especially full precious scale hardware.

33. Safety was of paramount importance, and all tactical/flight trials hardware was tested to the appropriate parts of the environments defined in the Stockpile-to-Target Sequence prepared by AWRE.

Flight trials.

34. A significant part of the overall cost of the Chevaline programme was spent undertaking a series of sub- scale and full-scale flight trials, under the direction of DT(P). Such trials were essential, as the full high altitude and re-entry environments were not fully understood, and could not be simulated in ground facilities other than on small scale models, and also to prove the whole as a complete system.

35. From early in the Chevaline programme CWSE made a major decision concerning these flight trials. This was to use the full-scale system flight trials, which could only be conducted at the Eastern Test Range (ETR) Cape Canaveral, Florida, as a major programme event driver, another part of the effort to prevent programme drift. This also had a specific value to the programme, because the slots in the US ETR programme had to be booked well in advance, before the trials hardware was built. A parallel decision was to limit the number of major IFE build standards that would be allowed (PA, P1 and PT), restricting development time, helping to control costs, and ensuring that sufficient flight trials of a similar build standard were undertaken to provide statistically meaningful reliability and confidence data.

36. The consequences of undertaking precision manoeuvres, with extremely small tolerances, under near zero gravity conditions, cannot be fully simulated on the ground, and flight trials of instrumented representative part and full systems of the IFE was essential to resolve uncertainties and gain confidence in the complete approach.

37. Computational Fluid Dynamics (CFD) was in its early stages of development, and the project used, and helped develop, this approach wherever possible. A comprehensive programme of aerodynamic measurements, particularly heating, was undertaken using detailed scale models in UK and US wind tunnels (some of the UK tunnels had to be very significantly upgraded in size and performance), CFD and other analytical techniques, and sub-scale and full-scale flight tests at different velocities, to produce new theory allowing accurate prediction of heating in hypersonic, high altitude flight.

38. Two major trials programmes were undertaken at the direction of DT(P), one on the Woomera Range (WRE) in Australia, which had the great advantage that it was over land, and the flight hardware and data packages could be recovered. The other programme was undertaken at the Eastern Test Range (ETR), Florida, USA, which was a sea-impact range, but which was much more comprehensively instrumented, and where flight range was unlimited. The development trials were launched from flat pads

at Cape Canaveral, and the evaluation flights from submerged SSBNs off of the Florida coast. RAE led the flight trials programme at WRE, and the FTA managed and staffed the ETR trials, involving all of the DAs.

39. The total programme for the flight trials is illustrated in Figure 10. Other papers give some more detail, especially David Reade, Mike Rance and our later paper on the role of the RN agencies in the project, and more awaits a future publication. However, some observations on the integrated programme shown in the Figure are required. The programme consists of 4 main phases:

- Precursor concept-proving trials as part of Polaris A3T DASO.
- Sub scale and full scale flight trials at WRE Woomera.
- Full scale flight trials at ETR Cape Canaveral.
- Proving flight trials and subsequent DASO's from SSBN at ETR.

40. The precursor trials involved the replacement of a ReB shell with a candidate Chevaline shell.

41. The vehicles launched from Woomera in Phase II) were Jabiru, Skylark and Falstaff, Jabiru (a WRE test rocket) and Skylark (provisioned by Bristol Aerojet from the UK), were important to the development of elements of the payload concepts, to obtain high velocity, high altitude aerodynamic and heating data to help extend the wind-tunnel based assessments, and develop instrumentation. Falstaff was a RAE-RPE development which gave a payload bay of similar dimensions to Polaris, and thus allowed full scale trials of the PAC and payload release. The WRE flight trials were managed by RAE on behalf of DT(P).

42. The ETR flight trials, however, were managed by DT(P) directly, supported by BAe as the FTA, leading a joint team of the major UK contractors, with AWE and RAE. These are described in more detail in the paper on the role of the RN agencies.

43. Post development flight trials were made for Acceptance purposes to gather more accuracy and reliability data on the tactical standard hardware built at RNAD and outloaded by the RN at the Submarine depot at Faslane to satisfy the Royal Navy that the whole system was now fit for purpose and could be loaded with nuclear warheads. These are also addressed in the RN agencies paper.

44. The development and build of the IFE had consequential impact, and required modification programmes, in many other areas, nearly all of which were the responsibility of the RN, especially

DDWP and DGST(N). These modifications included those already mentioned to the missile, but additionally very significant changes were needed to the SSSN to handle the new PAC data in Fire Control, and particularly to add a flood system and leak system to protect the crew from a toxic fuel leak. Major improvements were also made to the shore facilities such as RNAD. These will all be addressed in the paper on the RN role, but a little more detail is given herein.

Missile.

45. The policy of minimum change to the missile was largely achieved. Some changes were essential to the flight electronics to accommodate the PAC and the changed mass and mass distribution arising from replacing the three ReBs with the IFE. The latter, although heavier than the A3T ReBs, and with different vibration characteristics and Moments of Inertia, and hence vibration levels, moments and forces, etc., was constrained to prevent them going outside the Polaris A3T specification.

Submarine.

46. The requirement from the outset was to make the absolute minimum changes to the SSSN to accommodate Chevaline.

47. In the event, a major additional system had to be added to the SSBN, and missile system, to minimize the risk, and in the event detect, any leaks from the liquid fuels used in the TCPU and ACS, since a leak of such toxic and explosive substances could put crew and boat in great danger. Liquid fuels could not be avoided because of the need to get enough energy into the PAC at an acceptable mass, and to be able to restart the ACS motors between stops. The liquid fuel tanks on the PAC were double skinned to minimize the leakage risk. This topic is addressed in more depth in the paper on RN support.

48. It must be said that the Navy were throughout the programme very reluctant to accept liquid fuels on board this, or any, submarine, having previously experienced disasters with liquid fuelled torpedoes.

49. Some essential changes had to be made to the Fire Control system of the SSBN to prepare and pass targeting information to the modified payload.

Shore facilities.

50. The introduction of Polaris A3TK required the provision at RNAD of another range of new buildings, together with new processes and staff training to assemble and test the PACs and to load them with a large amount of ordnance, rocket motors and liquid fuel tanks. They also integrated the PAC and ReBs to the Polaris missiles and outloaded/offloaded them to and from the submarines. This was a major programme in itself, and will be addressed in the paper on RN agencies support.

Management of the Programme.

51. As has already been pointed out, a major change was made in the management organisation in 1975, following an intensive review of the tasks, costs and responsibilities. This marked the recognition and endorsement of Chevaline as a project, with agreed funding through to deployment with the RN. This reorganisation pulled together the contributions from the many organisations already working on the programme, providing clearer lines of authority and responsibility, producing a much more cohesive team.

52. Figure 10 illustrates the resultant management structure, which was retained until the Acceptance of the system by the RN. A Chevaline Steering Committee was set up to oversee the project, and CPE, renamed CSSE, was made responsible for all aspects of the planning and programmes, finance, and coordination of the other Government agencies involved in the project, particularly those in the Navy Department, together with responsibility for the critical interface with the US through the Polaris Sales Agreement. A new three-star post was created, CWSE, filled initially by Fred East, with a team of three one-star Navy and civilian managers (Director Missiles (DMis(P)), Director Trials (DT (P)), and Director Weapons Systems (DWSP) (ex DDWP - harnessing the Navy resources located in Bath), together with three one-star technical advisors. Some perceived that a somewhat uneasy relationship might be left between CWSE and CSSE, with the former having a parallel reporting line directly to CDP.

53. The responsibilities for nuclear aspects remained with CSA, with his interface with the USA though the 1958 Agreement; as far as the project was concerned these were mostly discharged through AWE Aldermaston and Burfield, and DAW(P&F). AWE had already been acting as the CRDA, and this was adopted into the project organisation, giving a reporting line to CWSE via DMis(P), to include the warhead programme. A number of RDAs, virtually all of which were already deeply involved in the programme, and involving most of the R&D Establishments, particularly RAE, RARDE and RPE, where coordinated by the CRDA, reinforcing the reporting line to CWSE. AWE and RAE responsibilities are identified in the Figure. Underneath this, there was strong cross linkage and cooperation between the Establishments through shared responsibilities, interdependencies, coordination

meetings, specifications, etc., with a tremendous amount of joint work being successfully achieved without the need for heavy formal intermanagement.

54. As already identified, there were critical interfaces between the IFE and the missile, and thence the SSBN and shore facilities. These are addressed in the Navy agency role paper, but it is important to recognise here the roles of DDW(P), identified in Figure 10, for the changes to the missile and its configuration control, for Fire Control and other on board systems, for the specification and audit of the shore facilities, and as the technical interface with SSPO.

55. Figure 10 also identifies the UK industry contributors to Chevaline who now became contracted to DMis(P), or DT(P). David Reade's and Mike Rance's papers give much more detail. However, the role of BAe as a Coordinating Design Authority, and a Flight Trials Authority, must be recognised, as it was crucial to the successful achievement of the project from this point in time.

56. In practice, the review and setting of the programme to achieve the project to time and cost at the onset of setting up the new organisation involved DMis(P), DT(P), CRDA, DDW(P) and the Head of Special Weapons Dept, RAE. Dr Stan Orman, on moving from the post of CRDA to DMis(P), expanded this group into the MEG, as is recounted in his Symposium paper, providing a more direct management path than formally existed.

Support from the US.

57. The cost paper by Phillip Pugh shows that a large fraction of the total money (35-40%) was spent in the US for missile and SSBN components, major ground trials, and of course the ETR trials, and many services. Most of this money was spent through the Polaris Sales Agreement, and channelled through the suspense account arrangements managed by DDWP. More detail will be found in the RN support paper.

58. Little mention and appreciation has so far been made to the contribution made to Chevaline by US government agencies and contractors. A paper on the US contribution was planned for the Symposium but could not be realised. Figure 10 identifies some of the more important US contributors, but does little justice to their role in Chevaline. Other papers give a little more insight, but there is clearly a need to draw together, and assess, the

US contribution as part history of the project.

Polaris A3TK.

59. Chevaline was designated the name Polaris A3TK by the Royal Navy after it passed the Acceptance process for operational use. It was deployed on all four Resolution class SSBNs. One SSBN, and often two, were continuously on patrol for periods of 30-45 days throughout the period 1983 to 1995, with some overlap with Trident at the end.

60. During the in service phase of POLARIS A3TK, there were a number of improvement studies or programmes, the major ones of which were to overcome previously unseen aging problems on the first and second-stage booster motors (at a cost of about £300M), also addressed in the RN agency paper. This is another aspect of the Polaris A3TK programme (not Chevaline) which may be worthy of further research and reporting.

61. The Royal Navy undertook POLARIS A3TK weapon system flight tests regularly during DASO exercises at the ETR during its operational life.

Conclusions.

62. As should now be clear, the Chevaline programme was a very major technical development for the UK to undertake, despite the benefits from the earlier R & D programmes. A complex, lightweight spacecraft was successfully developed by the UK to very demanding requirements laid out in the systems criteria. Whilst there were undoubtedly significant challenges early in the project, post the reorganisation in 1975 the efforts of all concerned, management, technical, government and contractors, UK and US, combined to make the project a success.

63. By the end of the development programme Chevaline could fully achieve the specified performance and effectiveness requirements, albeit always a little range limited by the additional payload mass, when extra operational range would always have been welcomed.

64. Despite the original intention of minimum change, significant modifications to the submarine were required, as well as some vital changes to the original Polaris missile system.

65. The development and proving of Chevaline needed a large number of trials to gain confidence in the hardware functioning correctly, and safely, under all stages of the build, assembly,

transport, out load to, and carriage on, the submarine, through the launch sequence to impact to the target.

66. It was a programme that made a major contribution to the defence of the UK and NATO for a period of some 12 years, until it was replaced by Trident D5, carried in the Vanguard class SSBN.

Chevaline Deployment Sequence from nose cone ejection.

Figure 6: Chevaline flight trials programme at Woomera and Cape Canaveral.

Figure 7: Organization and Management of Chevaline post 1975.

AWRE contribution to the Chevaline payload.

Kate Pyne.

Part 1: The Beginnings.

The Chevaline payload consisted of two nuclear warheads, one of which sat on a sophisticated rocket propelled space-craft equipped with penetration aids, the actual means of getting the warheads through the ABM defence to the target. AWRE, the Atomic Weapons Research Establishment, developed re-entry bodies, warheads and penetration aids and provided assistance to other agencies and contractors in the work.

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For a brief period beginning in the nineteen fifties, Britain had started to consider the possibility of developing its own anti-ballistic missile capability before going on to consider the threat such systems would pose to its nuclear weapons. It is possible to catch sight of Chevaline's early beginnings in this work and during the course of it see how AWRE came to be involved with penetration aids.

In November 1957, the first meeting of the Working Party on Anti-ballistic Missiles was told that that, "... (Ballistic Missile) Defence was not[2] considered to be, impossible", Indeed the RRE; (the Royal Radar Establishment), was "... examining the problems and assessing the sort of things necessary to solve them". This remark summarises just about all that could be done in the next ten years or so as scientists began to confront the multifaceted problems of ABM defence. Only one thing was certain, to paraphrase Edward Teller, physics was the same on either side of the Iron Curtain, and this at least allowed rational technical analysis. The Working Party had to admit there was considerable guess work involved, (another keynote of work in this period!) and the RRE., "... awaiting confirmation (about various things) from intelligence sources", an absolutely essential factor in shaping conclusions about ABM systems. The chief defence problem arose from the ease which the incoming delivery vehicle for the warhead or warheads, could be "... broken up into a number of pieces of equivalent (radar) echoing area to the warhead". Reference was then made to what seemed to be "... the most promising approach to the problem of discriminating between warhead and (penetration aids)" Thus, we can already see familiar language, twenty-five years before Chevaline entered Service.

In 1958, the RAE, the Royal Aircraft Establishment, began looking at ways to reduce the vulnerability of the Blue Streak missile re-entry body to ABM defence. A year later, the British learned that the Americans were investigating ways to intercept hostile warheads outside the atmosphere. So by 1960, the major features of the ABM scenario were known in principle in the UK.

In March 1961, the Soviets launched an experimental missile which intercepted and destroyed the warhead of a large ballistic missile in flight.[3] It used a high explosive fragmentation warhead, not a nuclear device. Although a significant technical achievement, it was little more than proof that a relatively slow ballistic missile could be intercepted. It was also proof of course that the Soviet. Union was actively working on anti-ballistic missile defence. Just over a year later, the Americans intercepted the warhead of one of their own Atlas intercontinental ballistic missiles. At the same time, 'known' Soviet interest in anti-ballistic missile systems was causing concern over Skybolt, an American air-launched strategic nuclear missile ordered for the Royal Air Force for which AWRE were 'Anglicising[4], its American warhead design.

It was thought that it could be attacked by a variety of means including blast and neutrons. Countermeasures were possible against blast, and Aldermaston knew a great deal about neutron attack thanks to Project R.l, '... (a) method of ... neutralising the warheads of incoming missiles'. It had already proved possible to make warheads 'immune' from this form of attack. However, the RAE concluded that re-entry body survival could only be improved by, 'saturating the defences with (penetration aids)'. The Americans '... appreciated the benefits ... (of penetration aids) ... described by RAE' and also laid less emphasis on hardened re-entry vehicles, but for different reasons. They would have enough warheads to saturate an ABM defence many times over, in contrast to the planned British total delivered by Skybolt missiles. But this seemingly meagre number would be the creative touchstone that eventually led to Chevaline's capability and the continuous interest in it by the United States, to this day. In any case, the British thought they should still press for a hardened Skybolt re-entry body. Roy Dommett recalls that penetration aids would have been included in a bay behind the ReB, the re-entry body[5]. But in December 1962, Skybolt was cancelled and the UK ordered the submarine based Polaris system.

The vulnerability issue transferred to Polaris and in November 1964 the RAE produced the HR.169 study. It examined the penetration capability of the UK Polaris re-entry body and suggested ways of improving it. In the face of advanced ABM defences '... an improved re-entry body, along the lines of the Blue Streak re-entry body, with penetration aids to match, might well be the most satisfactory long-term solution'. It admitted that '... the grave lack of intelligence' resulted in much speculative data being used in (the) analysis.' So far, penetration aids were the RAE's concern.

At the end of July 1965, AWRE began researching threats to warheads and electronic systems. In August 1966, the Physics Working Party at AWRE began to organise experimental work on warhead vulnerability. This became a regular feature of research and development at AWRE and specifically arose over concerns about the credibility of the Polaris deterrent, still to enter Royal Navy Service. The intention was to expose samples of materials and complete re-entry bodies to the effects of a nuclear device to see how resistant they were. By January 1967, the UK was preparing to ask the United States for the facilities needed for such a test at Nevada. Apart from wanting experimental information, AWRE was also seeking to expand collaborative study with the Americans on vulnerability. One of the objectives would be, '... to obtain data for future hardened systems'. The problem was the usual one. Unless the British asked questions about a specific proposal, American colleagues were reluctant to respond and the British did not have a specific proposal to talk about. As the AWRE Director Ted Newley had said, the Americans wanted some indication that, '... we intend to stay in the weapon business.' A year later Newley was also concerned in case the United States thought the UK was not serious about vulnerability. So what could AWRE do? It was suggested that ideas on materials, the possibility of a UK test and what were called new 'provocative deterrent" systems' might help. Also mentioned later as part of this debate was the idea of work on possible new techniques to improve penetration aid performance, another indication of early interest in this subject by AWRE. While the US might not be interested in helping the UK harden Polaris, they might '... be interested in UK technology if it were applied to a completely new system', the same subject cropped again a year later during a visit to AWRE by the American Brigadier-General Giller. The US took the position that it would only discuss future collaboration after the UK had made a decision on its nuclear programme, a protocol that regularly appeared in AWRE documents of the time. This is not surprising. Since August 1958, the United States and Britain had been partners in the 1958 Bi-Lateral, 'An Agreement on the Uses of Atomic Energy for Mutual Defence Purposes', to give it its official title.[7] The Agreement refers to both countries having made 'substantial progress' in the development of nuclear weapons If the American side advanced further, the British side felt obliged to match this, otherwise there would be what the AWRE Technical Policy Committee called a 'serious imbalance' - with the possible consequence that a particular exchange might eventually stop altogether.[8]

In early March 1967 AWRE began to think that the present Polaris system would not be 'valid' without penetration aids'. Of concern also was a feature of the British Polaris warhead that might have to be changed in order to produce a hardened version. If this was the case, there would be little chance of hardening the present system. However, studies had suggested another approach that would eliminate some of the vulnerability problems. So a year before it went into Service, AWRE already had a strong sense that further work on the vulnerability of Polaris could be required.

In May 1967, the newly established Anti-Ballistic Missile Working Party discussed possible modifications to certain components that would be needed to harden the present ReB design without delaying production. But these would not be possible within the time available for the present programme and there were technical reasons for not buying a hardened US 'sock' to slip over the ReB. But if the weapons were not used against the Moscow ABM Defence ' ... they may be viable in present form' So apart from the Polaris missile itself, the system entered Service, unhardened, on that basis.

In December 1967, Ministers decided a further technical study was needed and AWRE was asked to run it and the 'Polaris Re-Entry Systems Study Group' was formed. With initials 'PRESSG, it was inevitably christened 'The Press Gang'. Its first job was to assess the capability of the Soviet ABM system and its second was to look at countermeasures. It would report at the end of May 1968.

In early April 1968, AWRE staff paid a visit to the Polaris missile maker, Lockheed, to discuss UK ideas on Polaris improvement. They would also present UK views on the American Antelope Polaris improvement scheme in which a penetration aid carrier or PAC replaced one of the warheads. The British thought that Antelope would not be credible after 1975 if it came up against the known Soviet ABM system. It would also be 'sensitive' to any improvements in the Soviet system. One UK Polaris improvement scheme featured multiple ReBs deployed from a maneuverable 'master dispenser system' or MDS. This had been 'designed' on the spot by the UK team, since Lockheed would only respond to specific proposals. The MDS would separate from the Polaris second-stage, accelerate along a prescribed path, dropping off ReBs as it went. A month later, Lockheed told the British that of the various options described by the UK team, only Antelope and the MDS were 'worthy of serious consideration'.

An early draft of the PRESSG study was completed in May 1968 and follow-up studies continued at AWRE, RAE and the Royal Radar Establishment. Amongst other things PRESSG concluded that warhead hardening would not be enough to counter ABM defences - an improved Polaris system must include penetration aids to confuse the defence. In early October 1968, AWRE was told that supporting research and development should be extended to include work aimed at solving problems associated with ' ... damaging environments, old or new, within or without the atmosphere'. This was a very broad remit that would enable work on the problems of ABM attack to widen in scope at AWRE. It became part of an Atomic Energy Authority Weapons Group 'Self Initiated Research' Programme which was funded through the Atomic Energy Authority. So in mid- November 1968, for example, a working party was set up to study the problems of protecting a nuclear warhead from all foreseeable stockpile to target environments, including those provided by possible defensive systems.

At the end of January 1969, AWRE's Sid Barker, one of the PRESSG team, made the case for a significantly different penetration aid philosophy, explaining the idea that would be used in the future Chevaline penetration aids. By early April 1969, the Physics Working Party programme included the construction of devices to simulate ABM attack mechanisms.

The following month, John Challens, Assistant Director of AWRE and Chief of Warhead Design, voiced concern about the level of research and development on penetration aids to Ted Newley, the AWRE Director. ' ... It was not commensurate with their importance to the Super Antelope system' Super Antelope was the name given to the further elaboration of a Polaris Improvement scheme suggested in the PRESSG Report. The RAE, following on from their previous work, would have designed its penetration aids. Challens' initial concern seems to have arisen from a letter on 'penaid' effort at RAE by Roy Dommett, an RAE member of the PRESSG team. The RAE confirmed that it had no effort for penetration aids, which ' ... they regarded as an AWRE responsibility'. If a project to improve Polaris went ahead, RAE would be 'happy' to see AWRE nominated as the Design Authority for the penetration aid system and indeed in September 1969, this was officially confirmed. But the RAE would still provide advice as necessary. This of course was still some time before the start of Government funding for the Feasibility and Project Definition work on Polaris Improvement and it shows the continuity of work in this period. Apart from 'self-initiated research', other resources for work in this area at AWRE came from the peculiar circumstances of AWRE itself. When British atmospheric nuclear testing had ended, a big reduction in the AWRE workload had taken place. Changes to the warhead programme following the 1958 Bi-Lateral had a similar effect. Another reduction took place when work on controlled thermonuclear fusion was transferred to Culham. The headcount fell and continued to fall through natural wastage. Nevertheless, 'a viable AWRE' had been recommended and the Prime Minister had given assurances about work of 'national importance' for AWRE. By 1969/70, the headcount was expected to stabilise at 6,000, the suggested minimum 'viable' figure, including 2,000 support staff for all the facilities, houses and hostels.[9] But if more professional staff left, the 'viable' nuclear weapon capability might be harmed. If further support staff left, the nuclear weapon capability might not be able to function properly. Since there was insufficient weapons work for the remaining professional staff, a large increase in non-nuclear diversification work, already in hand at Aldermaston, would be needed. In July 1968, the Kings Norton report on resources at AWRE was submitted.[10] Lord Kings Norton's investigation had been carried out against the backdrop of a possible Polaris Improvement Programme. The substantial effort needed '... could come from part of the diversification capacity'. The report accepted that AWRE had to maintain its numbers of professional staff at close to present levels with adequate support. Thus for some time there had been capacity that could be used in areas such as penetration aid development.

At the beginning of July 1969, the current view of Super-Antelope was presented to the AWRE Technical Policy Committee. Super-Antelope was basically similar to the US Antelope scheme but with the minimum changes necessary to ensure two principal improvements. The first was an increase in ReB hardness to raise the exchange ratio the number of anti-ballistic missile interceptors needed to knock out an incoming threat from one missile with two ReBs, protected by penetration aids. At this stage of development, the PAC did not include one of the ReBs. The second change would be a new system of penetration aids, resistant nuclear attack and discrimination by radar. Super Antelope at this time retained the Polaris warhead, despite the view that it might be vulnerable. ReB aerodynamic design would be closely similar to Antelope and thus extensive flight trials could be avoided.

Within two years, it was thought the Soviet defence could deploy some 128 Galosh ABMs, NATO codename 'Galosh', controlled by a sophisticated radar system. The limited attack possible by the British Polaris force would therefore place great emphasis on penetration aids and an advanced system of these would have to be developed to go with one or two hardened warheads. Once again, it was noted that the Americans appeared reluctant to talk about penetration aid design unless the UK opened discussions with specific statements or queries.

At this time, government departments were divided on whether the expense of improving Polaris would be worthwhile. Various options were discussed by the Defence Review Working Party, including that of giving up the deterrent altogether. One of the considerations included in that particular debate was that '... to abandon British nuclear weapons would present great difficulties for our policy'. The 'difficulties', were then explained. By early April 1970, the PRESSG report had been submitted to the Secretary of State along with a recommendation that a two-year programme on the feasibility and definition of Super-Antelope was ordered. The political decision to go ahead was made and by mid-November 1970, the Feasibility and Project Definition phases of a Polaris Improvement Programme had been formally authorised. AWRE was asked to undertake work leading to a clear definition of the project by November 1972 and it was given the number KH.793.

Part 2: The Re-Entry Body.

In 1972 the United States and the Soviet Union signed the 1972 ABM

Limitation Treaty. A later protocol to it, ... limited ABM defences to one complex, ... either around ICBM sites or the national centre of administration', In fact, the Soviets only built about 60 launchers and these were all sited around Moscow. This had the effect of making the mounting problems of defeating the Soviet ABM Defence more manageable for the British. But understanding the often detailed technical nature of some of these problems and providing a solution was not an easy matter. In addition to its core tasks on Chevaline, AWRE also provided assistance and facilities in a collaborative approach to such difficulties.

Typical of these was the tendency to collision between ReB-C11[11] and a part of the PAC known as the 'scuttle' that first occurred during the first Chevaline Polaris flight, PA, in September 1977. Now there was also evidence that the second-stage had passed close enough to ReB-C for its motion to be influenced by the second-stage rocket exhaust plume. (Relieved of the mass of one ReB and the PAC, the second-stage would then accelerate past these two objects). At the beginning of November, it became apparent that the problem was just one part of a single, very interactive sequence of events. It was thought that colliding with the PAC scuttle at separation altered the direction of ReB-C's movement enough to reduce the second-stage fly-by clearance. The second-stage exhaust would then redirect ReB-C enough to move its impact point to the right of nominal - in other words, it would miss the target. This was serious.

AWRE Foulness provided facilities for the RAE to conduct a series of scale model trials. The results of these trials and modelling work at RAE resulted in a modification that might prevent the C-Body colliding with the PAC.

A review of the Chevaline Programme took place at the end of November 1977. Discussion on AWRE's contribution largely centred on the overloading of engineering resources. Urgent action was therefore in hand to produce a realistic programme for the approval submission.

At the end of April 1978, Chevaline flight trials were described as a high-risk programme. This concern was borne out in May 1978 when the long delayed Falstaff F1 rocket was fired but broke up with the loss of all subsequent flight data 30 seconds later. AWRE would need information from Falstaff flights about the behaviour in flight and response to radar of both the ReB and penetration aids. Fortunately F2, on September 13 1978, was 'a very successful trial' and it provided a comprehensive set of data on both.

Meanwhile, it was hoped that the PI and P2 Polaris trials would reveal more about the kind of flight environment expected on an operational mission. PI was launched on July 27 1978 and was described as 'extremely successful' and the separation events occurred without collisions. P2 was scheduled for November 30 1978, and it was hoped to keep to this date by taking short cuts in ground testing. But the dates for Polaris rounds P3-P7 were already in danger of being jeopardised due to supply problems with the hardware.

By this time, drawings for the 'tactical' ReB had been issued for manufacture. However, a progressive slip in activities leading to Stage I Approval for the ReB had taken place. Development was still going on and modifications to meet the system criteria still had to be carried out. The cause as far as AWRE was concerned was not hard to see. There was not enough professional staff and craftsmen for all the work now involved. In addition, new trials regarded as 'essential' in dealing with new problems had to be included. What were described as 'Extreme measures' were put in hand to prevent further slippage. Staff was transferred from other Divisions within AWRE, almost regardless of what they were doing. Contract staff were used to prepare the voluminous technical documentation and an attempt was made to recruit recently retired personnel. Priorities were re-allocated for short-term gain in the knowledge that this would have the effect of delaying vital activity after the Stage I Approval.

The Falstaff F4 Trial was launched as planned on Wednesday, February 14 1979 but the control system failed to stop the missile spinning. However, after the PAC had separated, the slow roll was brought under control by the 'PAC's own attitude control system and the programmed manoeuvers were completed successfully. Some radar information on the ReB was obtained and it was tracked for about six minutes.

By the middle of March 1979, there was an ever-worsening position on ReB delivery because of labour shortages. Enquiries into the possibility of getting craftsmen on detached duty from other establishments were made. But places like RAE and Porton Down were in a similar position to AWRE. However, some improvement had been achieved by 'streamlining processes' and better communications. To add to the problems, preliminary results from the Polaris P3 trial in April 1979, seemed to show that neither penetration aids nor the P-Body were ejected as planned, but the C-Body flight and impact position appeared to be satisfactory. It looked as if this particular problem was on the way to being solved. Ten days later on April 14, Falstaff F5 was launched and proved to be very successful indeed. There had been a possibility of the impulse from the AWRE designed explosive ring that separated the ReB from the P AC affecting the Space Reference Unit. This might have disturbed the PAC attitude, leading to a collision with ReB-P at the instant of its departure, but there was no evidence this had happened. Penetration aids and re-entry body were seen by radar but the usefulness of the information obtained was limited by the relatively short time over which it was recorded.

In early July 1979, Polaris P4 also had a successful flight and it seemed to confirm that ReB collision avoidance measures for that particular build standard were effective. It also suggested that the fly-by distance between ReB-C and the second stage was now large enough. A satisfactory model of ReB-P ejection from the PAC now existed and it matched flight data. Work could now begin on finessing the modification used to prevent the ReB-P-Body collision with the PAC for the Polaris PT trials of the proposed Service standard Improved Front End. If necessary, further slight changes would be made by AWRE staff after the ReBs had arrived at Coulport. Stage 1 Approval for the ReB had been granted, with provisos, by the middle of October 1979. Before Stage 2 and 3 approvals could be made a number of trials had to be completed and assembling the hardware for these was behind schedule.

Polaris P4's apparently normal separation events were crucial to preparing targeting data for the Chevaline Acceptance trials starting in November 1980. But the somewhat scanty nature of the flight information data-base and small but 'not negligible changes' in the new build standard for the PT and PS series fed more uncertainty about targeting that would be carried forward to the Acceptance trials and the first outload. This situation was not helped when the Polaris P5 second stage exploded.

Confidence in the final solution to the ReB-C collision problem, which as we saw earlier, involved targeting accuracy, also continued to wane. It was proving difficult to recognise trends in ReB-C motion from flight to flight and the problem was not responding to 'determined' investigation.

Fortunately, on November 6 1979, Polaris P6, with the last of the development standard 'front-ends', had a successful flight. It was followed four months later by PT2, brought forward to March 1980, which also, very encouragingly, had a successful flight with the first Service standard 'improved front end'. The 'threat' deployed as intended. But on PT1 in April 1980, the PAC failed to deploy ReB-P or the penetration aids.

The next series of trials, scheduled for November 1980, would be the all-important Chevaline Acceptance trials and they will be discussed after sections on the Chevaline warhead and penetration aids.

Part 3: The Chevaline Warhead.

Work on the warhead that would fit inside the future Chevaline re-entry body began in January 1972. In April, a British 'copy' of the American W-58

Polaris A-3 Warhead was recommended for KH 793, but with a new primary. The reason for this change can be seen in the history of the original British built warhead for the Polaris A-3, based on the same American design. In 1963 one of the options for a British built equivalent had been to produce, 'an exact copy' This would avoid the time consuming assessment of changes resulting from 'Anglicisation'[12]. (At that time, the Polaris Executive was not prepared to accept any changes to the warhead design, precisely for this reason). However, by mid July 1963, the first indications that an 'exact' copy could not be made had emerged. As a consequence, it would have to be modified and the designers would need to understand the implications of each change. In March 1964, the necessary changes to the warhead were specified, but there were questions over whether they should be embodied. Eventually, it was decided that the views of both the British Ordnance Board and the various AWRE weapon safety committees, backed by years of hard experience, should prevail. Amongst other things, a completely new British primary would be substituted for the American primary.[13] The origins of this new British device lay in the long hard effort to produce an 'Anglicised' version of the American warhead for 'Skybolt'. The British 'Polaris' warhead used an American design of secondary, with a few changes to component 'fits' and 'clearances'.

In March 1967, AWRE had discussed an approach that promised to eliminate some of the vulnerability problems of the British Polaris warhead. Amongst these, it seemed as if there was a possibility that the innovative British system for initiating the implosion in the primary was vulnerable, although there were dissenting opinions amongst the scientists.

By April 1972, the complexity of warhead options for KH.793 was laid out and AWRE requested authority for the development programme and for planning the necessary underground tests at Nevada. In June 1973, the first of these was proposed around the eleventh warhead design option! Two months later, after discussions with American colleagues, Option 13 was favoured.[14] At some point, this was eventually built and successfully fired in a comprehensively instrumented underground test at Nevada.

In mid April 1976, the KH.793 Quarterly Summary by the Aldermaston Co-ordinating Research and Development Authority noted that a significant increase in the mass of the tactical PAC was forecast. PAC mass was very closely monitored throughout the Chevaline Project and figures for the rise and fall in mass were circulated regularly, along with the resultant range. An agreed reduction below the accepted range of the Polaris A-3 system had been understood from the start because the Chevaline payload was heavier. But further increases in weight and reductions in range would bring the, submarines ever nearer the minimum depth of water which they could patrol and stay undetected.

The PAC itself was the responsibility of Hunting Engineering. But it carried rocket motors, penetration aids, re-entry bodies, electronic components and wiring designed elsewhere, subject at one time or another to increases and decreases in weight. Nevertheless it was agreed to study what was termed, 'penetration [aid]/mass/range/ trade-offs'. It was also agreed to identify further potential savings of mass in every component. In the quest for this, nothing was sacred - not even the warhead. As with everything else in the Chevaline Project, a high standard of design objectives had been maintained from the start in the knowledge that there would be some give in the system if a development problem became intractable and threatened the in-Service date. The same attitude was taken in the criteria for ReB hardness and in this case it was more than achieved. This had been an important factor in previously allowing the number of penetration aids to be reduced as PAC weight grew remorselessly. But changing the warhead design at this stage would have repercussions on the re-entry body production programme, and even more awful to contemplate, on the planned date for entry into Service. Nevertheless, the Royal Navy was asked to support a proposal for testing a lightweight version of the warhead at Nevada on the grounds that the problem of diminishing range was paramount.

From around the end of 1976. documents at Aldermaston suggest the almost fraught nature of discussions amongst physicists and engineers over the problem of reducing the Chevaline warhead weight in the struggle for more range. Peter Jones, Chief of Warhead Development at AWRE, was in charge of the effort. Full American support in the difficult design process was promised - possibly because it might create opportunities for learning *something about a new and innovative warhead design for a possible* Chevaline replacement which deliberately excluded as much American design experience as possible. Long discussions on the technical issues of the lightweight warhead proposal were held in the United States in January 1977 with representatives from both American nuclear weapon laboratories. They concluded the proposed lightweight warhead was feasible, but warned that measures being taken in the design had increased the risk of it not working at all!

A concept document for the new modified, lighter warhead design was issued in July 1977. Remorselessly driven by Peter Jones, it progressed to the hardware stage. With some urgency, the usual mathematical evaluation and hydrodynamic trials took place and a successful underground test was eventually conducted. In 1978, a study on the programme needed to introduce the lighter weight warhead into the Chevaline ReB began. But in October, AWRE had to withdraw when all available resources at AWRE were re-assigned to priority Chevaline tasks. Chevaline's warhead entered Service more or less as it was.

Part of AWRE's difficulties with Chevaline at this time stemmed from Sir Edwin Pochin's investigation into the discovery of plutonium dust in the lungs of laundry workers at Aldermaston. Several buildings had to be closed, two of which were vital for the production of components needed in Chevaline warheads. By March 1979, it became apparent that warheads for the first boatload could not be produced in time because of remedial activity in these buildings resulting from recommendations in Sir Edwin Pochin's Report. By mid-April 1980, resources in the area at Aldermaston where both these buildings were located became overloaded. The crucial plutonium facility could not be re-opened before January 1981 and even then, some of the remedial work was still in progress.

In mid-October 1981, the AWRE Director Colin Fielding wanted the timetable for building a completely new plutonium facility to be extended rather than deferred. Because of the Trident programme, AWRE could not afford to postpone completion dates more than the year now being proposed. Remedial work in the original buildings affected by the Pochin Report was related to ' ... highly critical Chevaline activities, not Trident, and [this] must proceed with all urgency'. By this time of course, as we shall see, AWRE was also heavily involved in the aftermath of the November 1980 Chevaline Approval Trials which will be discussed after the next section.

Part 4: Penetration Aids.

AWRE designed penetration aids used Skylark sounding rockets for their initial flight tests from a payload designed by the RAE. The fourth Skylark trial was successfully fired in February 1975 and as usual, an on-board camera photographed the behaviour of all the penetration aids. In April, more penaids were successfully tested in NASA facilities at Cleveland, Ohio, and again, correct operation was observed. Skylark S5 was launched in July 1975 and once more everything worked satisfactorily. Penetration aid work seemed to be going well. An assessment was then made of the effects on penetration aids from the 'battle ahead' scenario - what later Chevaline 'threats' would experience as they approached earlier engagements with the Soviet ABM defence in the target area. It indicated that one of the materials used in the penetration aid could melt under certain circumstances, a problem that was 'designed out'. As with ReB development and warhead development, the penetration aid workload at AWRE was high. Submissions for freezing the designs would be made by the end of May 1976, although development was about six months behind schedule.

The behaviour of one penetration aid immediately after departure from the PAC continued to be a problem. If not corrected, the capability for confusing the defence radar could be unacceptably degraded.

In June 1977, the S7 Skylark trial was successfully launched. But not every penetration aid behaved properly on launching.[15] One that did behave correctly failed in a different but quite crucial way. The problem was eventually traced to the rocket motor used to launch it. Modified motors were fired in the N62 chamber at AWRE to examine the motor's characteristics. But despite all the work, the problem remained. Time was getting short so motors for further Skylark trials and the first tactical outload would be redesigned on the best information available. The Propulsion, Explosives and Rocket Motor Establishment at Westcott hoped to provide an improved motor at a later date. However, by July 1977, another type of penetration aid had shown satisfactory behaviour in trials, and '... it would probably achieve the design criteria'.

By May 1978, AWRE had fully utilised its manufacturing capacity for penetration aids and the work spilled over to the Royal Ordnance Factory at Burghfield. In fact the whole manufacturing programme for penetration aids began giving '... cause for concern', the CRDA[16] report to CWSE's[17] June 1978 Review meeting gravely noted.

Falstaff F2 was launched successfully in mid-September 1978. After the disappointment of F I, F2 was a very successful trial and it provided a comprehensive set of data, but the trajectory was low. All penetration aids operated correctly, but the behaviour of some of them was still problematical. It was suggested that because they had not been built to the latest standard, the characteristics on the radar screen were not typical. Unfortunately, the low trajectory did not allow enough time for a full radar signature assessment of either penaids or the P-Body.

In early November 1978, AWRE learned that their part in Chevaline had come under some criticism following failure to meet certain agreed dates. One of the problems was a shortage of staff. New priorities in the Chevaline work had to be assigned. Engineers and supporting staff having suitable experience and employed on what could be regarded as less essential work elsewhere in AWRE would be transferred to the work.

Nevertheless, Skylarks S8 and S9 were launched on the planned dates of November 15 and December 13, 1978. Both performed well and the penetration aids operated correctly. The radars were able to obtain good information and the on-board camera produced a film record of good quality.

Falstaff F3 was launched on December 6, 1978. The payload consisted of a PAC and penetration aids and for the first time on a Falstaff trial, a re-entry body. But the planned sequence of events on the flight terminated prematurely because of a battery malfunction and neither penaids nor P-Body separated. But by late February 1979, testing a penetration aid of a new build standard had been successfully completed. This new standard included modifications to overcome difficulties that had previously developed after launch. The same build standard had worked successfully on Skylark S8 and had already been included in the design frozen for approval. But even so, some ground trials still had to be carried out. The S10 Skylark trial was also successful and good radar and film data were obtained. This trial and Falstaff F4, in addition to the successful PI and P2 Polaris flights, convinced everybody that the Chevaline concept was 'sound'. Falstaff F5 in April 1979 was also successful. Penetration aids and a P-Body were ejected from the PAC without serious anomalies. But the run of success halted in that same month with Polaris P3 when neither penaids nor P-Body were ejected.

In September 1979, assumptions about the Soviet ABM defence needed to assess the target tracking radar were presented to the AWRE Radar Signature Working Party. The somewhat 'arbitrary nature' of these assumptions was recognised and an endorsement by a special intelligence committee was deemed to be an 'urgent requirement'. After this, additional studies on the Soviet ABM defence radar would be necessary, using a set of alternative assumptions. It echoed the need by the 1957 Anti-Ballistic Missile Working Party and the 'urgent requirement' by the writers of the 1964 HR.169 study for an intelligence view on their respective technical assessments. It starkly underlined the point that the credibility of the entire Chevaline Project depended heavily on intelligence information and the judgements subsequently made on it.

In mid-September, the work involved in producing the service manual and approval documentation was proving to be much greater than previously anticipated. It was estimated that AWRE would have to print a quarter of a million sheets of procedures. An early IT enthusiast spoke in glowing terms about the value of word processors in preparing these documents as they would have to go through several drafts in the course of approval.

In the Polaris PT trials, only PT2, fired in March 1980 was successful in terms of getting information about penetration aids. On PT1, neither re-entry body nor penetration aids were ejected from the PAC. On PT3, most of the penetration aids failed, possibly due to the vibration encountered during missile flight. This failure thwarted plans to 'see' what the Soviet ABM radars might 'see' in a war situation. Research aimed at rectifying the problems began.

By November 1980, the RAE had completed tests in AWRE facilities of service standard penetration aids and the trial data had been processed. Detailed analysis by the RAE showed that, at long last, 'real' flight test data and data from these AWRE trials could be reconciled. The overall result was regarded as 'satisfactory', a word that perhaps that implied some relaxation from the exact requirements of the System Criteria. Nevertheless, it would all be included in the RAE final performance statement.

A Performance Review of Chevaline was completed on November 12 1980. It certainly looked as if all performance requirements as set out in the System Criteria would be achieved by the current tactical build standard of PAC and payload. The Review provided the required data for the RAE Special Weapon Final Performance Statement for the Stage 3 Approval. There were some minor shortfalls. Now system criteria had driven a high standard of design objectives. It would therefore be difficult to argue that slight reductions from the specified requirements made Chevaline a less potent and very capable weapon system in the ABM era.

Two days later, high hopes for the first shot in the Chevaline Acceptance Trial were dashed. The Polaris PS1, fired from Tube 1, HMS Renown, was a failure. Missile performance through launch and first stage flight was within predicted parameters but then a loss of control occurred and the second-stage pitch, manoeuvre did not take place. Nose fairing ejection and C-Body separation were satisfactory but subsequent PAC motion was uncontrolled and the In-Service Telemetry did not provide any information. Neither pre- nor post-separation events involving the PAC took place. Four days later, the next round, PS3, was launched from HMS Renown's Tube 12 and suffered a similar failure. Everything had worked as expected until the PAC separated from the second stage and went out of control. Again, the In-Service Telemetry did not operate and again there was no evidence of the pre-separation and post separation events. It was decided not to launch PS2. It would be taken back to Coulport where the Front End would be removed from the missile and disassembled under close scrutiny. It arrived there on December 13.

Part 5 - More Hard Work.

It was decided to produce three more improved front-ends and missiles for another trial. Each would be modified to include an additional telemetry system for electrical circuits suspected of malfunction. These rounds would be fired as PS4, PS5 and PS6, with an earliest flight date of June 1981 for P4. The programme came to be known as "PS Continuation'. Later a fourth round called A5 was added. A team was set up to identify and rectify the cause of the failures by February 1981. If this proved impossible, the improved telemetry would help in diagnosing any further failure. The first outload was still planned for the end of 1981 and all the modification and production work on Chevaline would proceed as if the outload dates had not been altered. In this way it was hoped to avoid a delay in freeing resources for the Trident programme. But at one stage, the Chevaline Steering Committee was forced to consider a temporary reversion to Polaris because of the delays being caused by the investigation into the PS1 and PS3 failures and AWRE's labour problems.

It proved difficult to pin-point a specific component as a possible direct cause of the failures. However, a number of areas were listed for particular scrutiny and analysis and the level of detail in these investigations was considerable. One area concerned switches designed to close after experiencing a period of acceleration. Tests showed that when a particular kind of vibration increased, it produced an unacceptable rise in the threshold at which the switch closed. By June 1981, a modification to reduce it was in hand. The switch contacts also tended to 'bounce' off each other as they neared closing. The effects produced in the circuit by this behaviour could risk the operation of the all- important telemetry system. However, by November 1981 it was thought that risks to flight were small and could be accepted. But this might have to be reconsidered if modifications to the switch increased the chances of it closing out of sequence. Statistical modelling of the way in which the switches operated still showed a disturbingly high 'scatter' in performance. It seemed to be related to the method of conducting the calibration. If Ferranti calibrated the switch, their results did not agree with EMI's or with the performance on flight trials. Varying acceleration and the time it lasted seemed to affect performance, '... in a way that was not understood' The age of the component might also affect its performance. When confronted by the possible consequences of an error, making a decision based on such considerations must have been a somewhat fraught process. In any case, at the end of September, Ferranti went ahead with a reduction in the arming level of one of the crucial gravity time sequencing switches.

By the end November 1981, processing the PS4, PS5, PS6 and AS Improved Front Ends was in full-swing at Coulport. Mating PS4 with its Polaris Missile began on Oct 21 and the remaining PACs followed at weekly intervals starting on December 13. Time was running short - the first boatload was scheduled for the end of the year.

Although no hard and fast conclusions about the specific causes of the PST1 and PST3 firings seems to be evident in the highly detailed reports on the investigations, one factor may have predominated. At stake here was an issue of the utmost seriousness the credibility of the most expensive nuclear weapon project yet attempted by the United Kingdom. In addition, the depth of the investigations showed that no fault, however small, could easily evade discovery. Together these may, consciously or unconsciously, have imposed a rigorous standard of quality control in the making of every component and over every action that was taken in the work to prepare the next rounds for the Continuation series. The result would have been the best possible quality of work achievable.

The four vehicles were out-loaded to HMS Renown by the week ending December 18 1981 and the submarine duly arrived without incident at Port Canaveral on January 21, 1982. Fortunately, the four launches were all almost totally successful. They confirmed that possible causes of the 1980 failures had been eliminated. On PS4, the Improved Front End performed correctly with pre- and post- boost separation occurring as expected except for the failure of a single penetration aid. On PSS, PS6 and AS, everything worked as expected. Radar data from the four trials showed a full threat could be set up as intended and the actual radarscope displays closely resembled prediction. A number of minor problems occurred but none of them were likely to affect tactical performance and operation and full approval for the Royal Navy's use of Chevaline was expected in the next few months. The likelihood of any new areas of concern was felt to be small. AWRE's Director Colin Fielding described the firings as '... an unqualified success' and praised all the participants in the Project. In mid-July 1982, he stated that the Chevaline programme was nearing completion. One submarine had already been for a short patrol and there would be a full patrol in August. The February trials, with full deployment of ReBs and penaids had reflected great credit on all involved over many years in '... stark contrast to the gloom prevailing last November when there had been much criticism of the Chevaline project. So Chevaline was finally in service, five years after the Moscow ABM system became operational. Almost twenty years had passed since doubts about Polaris warheads being able to penetrate an ABM defence had surfaced.

In 1998, the final Chevaline warhead was delivered to the AWE Burghfield facility for dismantling. Chevaline had squeezed another 14 years of useful life from the veteran Polaris missiles and submarines - and in providing a credible deterrent, served the perceived interests of this country very well indeed.

Note on sources. The sources consulted for this paper include 138 unpublished documents in the AWE Corporate Archive, details of which have not been included. Although not all of these originated at AWE, the majority did and inevitably, they might present a very different view of the same event as seen by other departments and establishments.

References.

1. For a project as large and complex as Chevaline, it was very difficult to identify the development status at a given instant.
2. Author's emphasis.
3. An 88-4.
4. The term given to the process of modifying the design to permit its manufacture in Britain.
5. Conversation with Roy Dommet, formerly of RAE Weapons Department.
6. Prophetic words from the distinguished AWRE scientist, Charlie Martin.
7. Cmd. 470, HMSO, July 1958.
8. An alternative explanation of this particular theme in British nuclear weapon history since 1958 can be seen in Solly Zuckerman's autobiography, 'Monkeys, Men and Missiles', Chapter 32, Chevaline, pp 386-339, New York, 1989.
9. Apart from managing a large number of houses built to house workers at the somewhat isolated AWRE sites, there was also a number of Hostels including Boundary Hall, adjacent to AWRE, with several hundred residents.
10. Report to the Minister of Technology and the Chairman of the Atomic Energy Authority by the Working Party on Atomic Weapons Establishments, July 1968, now in the National Archives at Kew The Chairman was Lord Kings Norton. The members were Lord Rothschild, Lord Carron and Sir James Taylor. [t had been set up in April 1968 by the Minister of Technology and the Chairman of the United Kingdom Atomic Energy Authority. Lord Rothschild's dissenting views were appended to it as a Minority Report. They make very interesting and thought provoking reading.
11. The ReB-C was the re-entry body that rode on the Polaris second stage. ReB-P rode on the PAC.
12. See footnote 3, p.5
13. These were thermonuclear warheads having two stages called a 'primary' and a 'secondary'.
14. American colleagues had been watching this work with interest and were providing much helpful comment under the 1958 Bilateral provisions and the JOWOG system.
15. That is to say a particular feature of its behaviour after launch compared well with the specification 16 Co-ordinating Research and Development Authority.
16. Co-ordinating Research and Development Authority.
17. Chief Weapon System Engineer.

Kate Pyne AWE Technical Historian. Biographical details:

In 1991, after spending 25 years in the aircraft industry, I went to London University. I graduated in 1994 with First Class Honours in Modern History and joined the Atomic Energy Authority as research assistant to Loma Amold, the Official Historian and author of various works on the British Atomic Energy Project. I worked with her on the History of the British Hydrogen Bomb until 1996 when my contract ended. I then joined the Atomic Weapons Establishment as Technical Historian. I write and lecture on the history of nuclear weapons.

RAE's Role in & Contribution to Chevaline.

Dr Mike Rance from material largely supplied by Roy Dommett.

Introduction.

I worked on Chevaline at the Royal Aircraft Establishment in Farnborough from 1971 until 1980, mainly for Ray Dommett. It was the most fascinating, engaging and stimulating period of my career.

In a short paper, and given the restrictions we are under, we cannot hope to do justice to RAE's contribution to Chevaline. Justice will have to wait for the official history. RAE played a central role in the conception of the system and in the project's development and I shall say what I can about it.

Let me first outline why RAE was so well placed to fulfil the role of RDA for the Penetration Aid Carrier, and many other aspects of the system.

Table 1. is a list of RAE's areas of expertise relevant to nuclear weapon delivery; I believe it gives a suitable sense of the breadth of RAE's capability. Some of these areas of expertise go back to the immediate post-war era, and many were also of course relevant to, and inherited from, conventional weapons activities at Farnborough.

Some, clearly, were not relevant to the ballistic missile delivery option, but most were brought to bear in the course of KH.793 and Chevaline, through the RAE Departments which, in those years, hosted the staff and the facilities. The relevant RAE Departments were: Weapons Dept, Space Dept, Aerodynamics Dept, Structures Dept, Radio Dept, Materials Dept and

Mathematics Dept. Over the years, department names changed, departments merged, but in the early 70s, these were their names. They all had something to do with Chevaline, even if it was just one man for just a part of his time. Weapons Dept led - initially a few people in a small section, and Space, Structures and Aero Departments had a substantial input and responsibility.
When it became clear that improvements would be needed to Polaris A3, not long after the UK bought it, RAE was deeply involved in the discussions, mentioned in Bob Ridley's paper, and in studying the improvement options. RAE had been working on penetration aid schemes for some time. And RAE had been involved in ballistic missile developments, such as Blue Streak, and nuclear weapon programmes as Roy has described at other times and in other places.

Initial involvement.

From the start, it was clear that Polaris improvements would require that the re-entry vehicles be hidden in a cloud of penetration aids to defeat the Moscow radars. The trick was to determine how to hide them, what the penetration aids should look like and how they would work that was AWRE's job - and how to engineer the deployment system - that was RAE's job.

The one year KH.793 Feasibility Study ran from late 1970. It was followed by two Project Definition phases, known as PD1 and a continuing phase, PD2. During this whole period, RAE's role was, primarily and formally, as the Research and Development Authority (RDA) for the Penetration Aid Carrier - the PAC. But RAE did much else besides, including all the dynamic issues of separations, ejection of the penetration aids and all aspects of the dynamic behaviour of the re-entry bodies, working to Aldermaston. The setting of objectives for and analysis of the flight trials programmes were also key RAE tasks.

The essence of RAE's role, in support of AWRE as the Coordinating Research and Development Authority (CRDA), was to:

Interpret the System Criteria, mainly in terms of:
- Error Budgets for Sperry & HEL
  - Penaid Ejection performance
  - Mass and Centre of Gravity Control
  - PAC Manoeuvres
  - Manoeuvre Timing and Sequence
- Generation

Specify Performance Requirements
Oversee PAC development

The main contractors at the Feasibility stage were Hunting Engineering Ltd, at Ampthill in Bedfordshire, and Sperry Gyroscope in Bracknell, Berks. Other contractors such as AirLog, EMI and ML Aviation were brought on board for specialised expertise and engineering capabilities. The Rocket Propulsion Establishment (RPE) at Westcott dealt with all the numerous solid propellant rockets and the bi-propellant Twin Chamber Propulsion Unit. There is more on the contribution of these organisations in the Industry Contribution paper.

The studies looked at the many options for generating the required confusion to the defensive system, as it was understood at the time and predicted to be. Some of the issues that were studied included: PAC design options; the design options for a PAC attitude and velocity control system; and options for propulsion of the PAC. There were also important interface issues with the existing Polaris missile, such as data transfer, electrical interfaces, system stability, and separation dynamics and environments. There were particular design issues and uncertainties in the early days concerning the separation process, the design of a suitable PAC structure, fitting in the desired number of penetration aids - AWRE always wanted more than could be included - and achieving the required attitude and velocity accuracy.
During feasibility, HEL looked at the options for the PAC layout. The best system choice appeared to be what was then called the Mono-PAC, later

simply the PAC, to obtain sufficient volume for the then required number and type (long and short) of penetration aids, and the flexibility to motor before dispensing the P-Body.

Sperry and Marconi each did a six-month study of a hypothetical Attitude Control System (ACS) suitable for controlling a space object whilst it manoeuvred. A strap-down navigation system rather than an inertial platform was chosen. The complex requirement needed an on-board computer, a digital control system - which was a "first" for the UK - and state-of-the-art control theory.

RAE recommended iso-propyl nitrate (IPN) for the Hot Gas control actuation system as being nearly off-the-shelf. (In the event, as we shall see, the IPN system proved to be too difficult.)

For motoring the PAC after separation, a number of options were examined. The System Criteria needed a large variety of achieved velocity increments, best suited to liquid propellant systems. Storable liquid propellants grew out of research initiated by Blue Streak, and a bi-propellant system was chosen, with two fixed thrust-line chambers. Again, more about this in my other paper.

This was the situation at the end of Feasibility. RAE had been at the heart of these Chevaline preliminaries and stayed at the heart throughout the programme. With a few exceptions, the Chevaline system design that emerged in 1974 changed little during development.

RAE'S contributions, activities and interfaces.

RAE's principal in-house contributions from Feasibility onwards were in these areas:

- hypersonic aerodynamics
- exit heating
- system performance requirements and analysis
- dynamics analysis
- management of complex technical programmes
- flight trials planning and analysis
- provision of many analysis and prediction codes for use by the other establishments and industry.

These were of course in addition to RAE's formal role as an RDA. The last two were areas of work which proved to be utterly vital, and which none of the other agencies, in the early days of the project at least, could undertake. The analysis and the modelling codes were at the heart of understanding the system.

RAE's reporting chain and responsibilities on Chevaline are summarised in Figure 1. The upper chart shows the reporting lines. As PAC RDA, RAE

reported through the Project Review Committee to AWRE as CRDA, attended the Physics Working Party and the Reliability Working Party, and advised Headquarters on the technical and programme issues.
AWRE created two fora where systems design and implementation issues were discussed, a Systems Working Party, the more senior forum, despite its title, and a Systems Committee. Ray Dommett attended the former, and Ray and Dave Albery attended the latter. Each penned numerous papers responding to actions on a range of topics.
The lower chart shows RAE's tasks and responsibilities which were.

- Technical responsibility for the major UK contractors, HEL and Sperry, involved with the PAC, and through them the minor contractors and suppliers.
- Provision of performance requirements and specifications.
- Organisation of themed committees, Working Groups and contract progress meetings.
- Without an industry prime contractor, RAE ran and monitored many project activities. This was not normal establishment practice. HEL, in addition to being a lead PAC Design Authority, was appointed Coordinating Authority by the CRDA, and on behalf of RAE were Trials Managers in the pre-1974 era, plus providing a secretariat.
- A strong lead on packaging, handling and emergency removal.
- Vulnerability assessments in conjunction with Sperry and US advisers.
- Characterisation of heating, aerodynamic and gas dynamic issues for ReBs, penaids and the PAC, involving Aerodynamics Department, who sponsored basic supporting research in industry's facilities and at universities; specification and coordination of the gas dynamic, aerodynamic and thermal trials.
- Structures Department, with John AEA Cook leading, formally looked after structural safety and provided definition of structural design practices and testing including structural modelling assistance and shock loading.
- Management and direction of the CQ.941 programme of test flights at Woomera, including Skylark trials, Falstaff Trials and the Jabiru experiments.
- Support to AWRE as RDA and DA for the payload items (ReBs and penaids), in respect of aerodynamics, dynamics and ablation, leading to ReB performance assessments, and, for penaid ejection in terms of accuracy and avoidance of collisions; also the full-scale and sub-scale testing; sometimes the cooperation with AWRE could become very complex, as with the Arming and Fuzing device for the warhead, for which AWRE made parts for RAE-led components, yet AWRE was also the system authority.

- Support to MoD(Navy), Bath, as RDA for missile and submarine systems, with the Flight Trials Authority, BAC, and later project CDA; including trials planning, flight sequence design, fit-to-fly reviews, models, modelling and the data base for targeting.
- Close liaison with LMSC was a constant feature, mainly on IFE interfaces with the missile. LMSC personnel, such as Gerry Cherf, Bob Goldman and Don Andersen were posted to RAE and became professional fixtures within the project. Our social life was pepped up too, with their families from California bringing a new style to the Farnborough area. They even got some of us going on poker.

So, in the development phase, the design was refined, the ground and flight trials took place, the models and simulations were developed and numerous problems were addressed and usually solved. Industry did most of the work, or at least that is what industry led RAE to believe. But seriously, at times it is difficult, at 30 years remove, to disentangle who made the key contribution in solving any particular problem. Even the cockups are difficult to assign.

Table 2 lists roughly what the main companies were responsible for on the Improved Front End, the IFE. I shall come back to them later and in the industry paper.

Some issues in development.

Some of the most interesting problems occurred at the various separation events, which involved the firing of rocket motors into confined and moving, expanding and leaking volumes, and which had given rise to the term "gas dynamics" - the forces and moments over and above what would happen in an ideal 'clean' environment.
Taking advice from the US, RAE led the modelling and trials work aimed at "Characterising" the gas dynamics effects, which were potentially serious enough both to affect velocity and body angular rates, and, as it turned out, also to cause undesirable collisions between separating bodies.
It was agreed that, for Chevaline, this was an issue which should be tackled early. Before and during the Feasibility phase, it was uncertain whether 'quasi-static' testing, with models in fixed positions, would be realistic, because of the transitory nature of the flow. RAE suggested a scale dynamic test facility and derived the scaling laws. In 1970, AWRE authorised the construction of a facility in a vacuum chamber at Foulness, capable of testing one-third scale models. LMSC gave assistance because senior MoD and AWRE staff wanted the reassurance of consultation with experienced people when striking off into the relative unknown. (Roy remembers the US experts being impressed with Foulness on a February visit with the wind blowing straight off the Urals!)
An important feature was mounting the models (of PAC and ReB-C on the model second stage) on a ram that could simulate the thrust of the second stage and which allowed the gas dynamics momentarily to slow the acceleration. The separating models had instrumentation packs to measure accelerations and external photographic coverage recorded the trajectories and angular motions.
Once the Foulness programme was underway, Tony Waterfall at RAE provided an analysis scheme which was customised for the tests. Computer models and the detailed analysis were eventually provided by HEL. The main problems were the lead time for model manufacture, and keeping the geometry up to date. (The gas dynamic forces and moments proved to be sensitive to the model detail underneath.) The accuracy obtainable in this dynamic facility was limited, although it was the basis of the data used for the early Chevaline development flight trials. Full-scale trials were mounted in the large vacuum chamber at AWRE Aldermaston. Here a limited number of tests on nose fairing, PAC/ReB-C and ReB-P separations were performed. An interesting feature was that the catcher volume was filled with

crushable, unfilled standard food cans.
One of the large vacuum dump chambers for the RAE Low Density Tunnel (LDT) was converted later for a quasi-static rig, designed by Steve Metcalf, which used the same 1/3 model scale as was being used at Foulness. The rig was massive to avoid any transitory movements induced by the start up shocks. The forces and moments were measured directly using load plates. Analysis was immediate on a linked Prime computer. Thus the trajectories could be predicted and models repositioned in a step-by-step procedure. This gave the effects as a function of separation distance. The match with flight data on the identical configuration became very close.
The overall purposes of the gas dynamic ground trials programme were.

- To characterise unknown gas dynamic effects prior to flight trials.
- To prove the design and produce evidence for design changes.
- To validate models able to predict performance at flight trial conditions.
- To examine performance across the envelope of operational use.

The gas dynamics programme involved many different organisations and was managed in one of several Working Groups set up by the project; this one was known as GASWOG. RAE led the activity - in fact, I chaired GASWOG. RAE specified and coordinated the work, which involved Huntings, Aldermaston and Foulness, RAE's Aerodynamics Department, Sperry, RPE/PERME and Lockheed staff from Sunnyvale - throughout the programme, close consultation was maintained with LMSC, particularly on scale model testing, instrumentation and analysis. I particularly remember "the two Bobs" - Bob Brown and Bob Krauss - whom we met frequently and who became invaluable advisers. In its lifetime, GASWOG dealt with innumerable issues on modelling, test time scales, collision events and their solution, flight test comparisons with ground test results and force and moment characterisation.
One of the major development issues, discovered during the scale testing, was a collision which occurred at Second Separation between the separating ReB-C and the PAC structure, due to the effect of the powerful and unpredictable efflux of the two PAC eject motors when they lit up. Following many trials in the facilities described above, and much analysis, a number of design changes were introduced. The detail of the solutions to this problem will have to wait for another occasion.
It was not only the Second Separation event in which gas dynamics effects occurred. The ejection of the nose fairing from the accelerating second stage, ejection of the ReB-P from the PAC (in free fall at that time), and the ejection of the penaids from their tubes all gave rise to gas dynamic effects which had to be characterised. As with Second Separation, these events were tested in various ground trials.
A back-up test on the survival of the thermal barriers and the possibility of

leaks through to the equipment section was conducted on the outside rocket sled alongside T70 Building, RAE. It was necessary to avoid external surveillance and all aspects had to be covered securely when warnings were received of the overhead passage of Soviet photographic satellites.

Time is one of the factors which does not permit a detailed description of the many other problems and design issues that RAE, with industry, faced and solved in development. A list and a short description will have to suffice.

- Jet Wake.
    - This was about characterising the effects, dynamic and environmental, on both the PAC and the ReB-C after ejection, as the second stage blasted between them.
- ReB-P Ejection.
    - Space was limited between the PAC structure and the ReB-P as it was ejected from the PAC in free fall, using a rocket motor. A number of palliative measures had to be taken to tune the ReB/PAC relative motion in the few milliseconds needed to get the bodies clear of each other.
- ReB Re-Entry.
    - Understanding the effects of atmospheric re-entry on the motion, the accuracy - and their predictability - and the survival of the re-entry vehicles was a major responsibility at RAE. The work was begun early in the programmed. Major contributors to this work were Jim Woodley, Chris Morton and Peter Marriott, one of those who was on loan from Huntings. Issues that were resolved included: the material for the heat shield; the drag profile during re-entry; and the dynamic stability of the body. Substantial use was made of scale models, wind tunnels (all over the UK) and extensive numerical analysis.
- Thermal Protection and the Blast Shield.
    - More on this is in the Industry presentation. The Committee in this case was known as THERMWOG. RAE's contribution was based on their expertise in re-entry aerodynamics and thermal modelling. The main contributor was Chris Morton.The issue was to protect the PAC and its sub-systems from the exit heating and nose fairing ejection environment as the missile, during and after nose fairing ejection, passed through the upper levels of the atmosphere. Heat transfer rates were measured in scale model tests, both in RAE's Low Density Tunnel and, at third scale, at NASA Ames. Cork sheet was used for thermal protection. The blast shield design, to protect both against the nose fairing motor efflux and exit heating evolved with time.
- The Hot Gas System.
    - At the feasibility stage the only viable system appeared to RAE to be based on Iso-Propyl Nitrate - IPN - which was supposedly an established UK technology with hot gas control valves and associated technologies.

Hydrazine technology was not thought to be mature enough, although it had been used in space systems for some years. RPE Westcott had supported the selection of IPN but wrote a memorandum recommending hydrazine soon afterwards. The IPN system was being developed at a Westcott site by a team led by Adrian Abbott of Sperry with the help of the RAE specialist George Eynon and monitored by John Flood. A number of explanations for the troubles faced by the IPN system development have been put forward, but it was proving too difficult to do the job in time. A two-week independent assessment by Brian Day at the request of Gordon Herring showed that an alternative should be considered. Sperry went to US consultants who suggested system changes. Dudley Lewis pushed for the switch to hydrazine which gave a higher specific impulse and could deliver thrust pulses on demand. A fixed price bid was requested against a preliminary draft specification hurriedly prepared by Dave Albery. Marconi made a hydrazine bid. The Bell Hydrazine Actuation System (HAS) was successful. Bell supported the system well throughout, with regular management level visits to the UK.

- Controlling the Mass of the system.
    - Growth in the estimated mass of system hardware bedevils every project. The initial PAC mass allocation was insufficient to allow for normal growth based on trials experience, and initial project guidelines and timescales prevented radical approaches. A major mass reduction exercise became essential by mid-development. All elements were reviewed, including the warhead. Close study showed that up to 25kg savings were possible in principle in the rest of the IFE, by major re-design, but this would have negated all the testing done to that point and would have delayed the project considerably. Major mass reductions that were approved included changing the Westcott eject motor casings and the EU to titanium. Lightening holes were made wherever there was little structural risk and the PAC thermal protection was reduced. HEL conducted all the modelling of mass, Centre of Gravity and moments of inertia of the PAC, the Re-Entry System - the ReS - and the IFE, and ran the Mass Control Committee throughout PD and Development.
- Ejecting the Penaids from the PAC.

- Ground and flight trials complemented mathematical analysis to develop engineering solutions for accurately ejecting the two types of penetration aids from their tubes, and for ensuring minimum damage from the rocket motors.

- PAC Electrics.
  - Some of the electrical issues addressed during development are covered in the industry paper. Alan Ironside and Peter Hamer led RAE's work on the electrics.
- PAC and Missile Structures.
  - Mainly for structural reasons, the structure of the PAC evolved significantly from early aluminium and balsa wood sandwich schemes without blast shield or thermal panels. Structural modelling of the unusual structure was a problem, and Structures Department, RAE, was brought in; a Structural Safety Panel and a Structural Progress Panel were set up under John Cook. Materials department also advised on corrosion, salt-water immersion effects and IPN tank collapse. Problems involving different US and UK design rules had to be overcome and effort was expended on the exchange of geometry, mass characteristics and stiffness data. BAC Weybridge (Tony Dudman) was brought in in 1974 to advise on structural dynamic modelling, advising the project, industry and ST4 Division, RAE. The effect of underwater shock (depth charge attack) brought in the Ordnance Board to consider "Safe and Serviceability" criteria. The underwater shock case caused a base frame redesign. Other "abnormal loadings" that might lead to failure in the submarine led to concern and much analysis. One required action was a nose fairing collapse test in 1975. Five additional potential accident situations had also to be studied, and the studies led to a number of procedural safeguards, inspections and functional checks. RAE Specification WE.1763 was issued in 1977, covering all RAE requirements for safety. The RAE Panels were absorbed into the project Safety Assessment Committee in November 1977.
- Surface Support Equipment.
  - Flight test and in-service hardware is useless unless the system and its components can be delivered, stored, handled, mated, assembled and disassembled, and tested. In-service, each item of support equipment used

in the ordnance depot was uniquely tailored to its specific role and task. The components of the system were: equipment section, nose fairing, ReB with pedestals, bare PAC, electronics unit, twin chamber propulsion unit, hydrazine system, eject motors and penaids. A large range of surface support equipment was necessary. The equipment included the items on this list: stillages, lifting beams, cradles, headstocks, protective covers, sheaths, work stands, processing stands, mating rails, integration fixtures for ACS/Propellant Storage Assembly (hydrazine), propellant and gas storage assemblies, access stands, the turn-over stand for the PAC ("the yellow peril"), the transfer and upending stillage, equipment trolleys, the inter-building low canopy trolley, and the interbuilding flat top trolley, packaging for transporting, storage, monitoring and maintenance, a mass characteristics machine with load cell, frame slinging and head stock, the weighing machine, inert gas supply, atmospheric sampling kit, and X-ray equipment safety testing, toxic environment detection equipment, emergency removal equipment, electrical test equipment, notably Sperry's SPATE.

It's one of those lists that illustrate how complex the programme was, and how much detailed engineering effort went in to it.

Some Management Issues.

It wasn't only the technicalities that caused problems in development. This is a non-comprehensive list of Administrative and Management problems faced by everyone on the project, including RAE:

- Security, clearances, concealment.
- Shortage of skills, building teams.
- Documentation Requirements.
- Extensive Safety Requirements.
- Management Re-organisations.
- Fast project growth (companies were unable to grow, and recruit, fast enough).
- Committees - too many of them.

The high level of security caused enormous day-to-day difficulties which simply had to be lived with. The scale of the project meant that every contractor had to set up and maintain extensive procedures for clearances, for handling documents, for working and for concealing outdoor activity

from satellite observation.
Drip funding together with a history of under-investment in skills, plus the 3-day week, high inflation, security and Positive-Vetting requirements and project uncertainty led to real recruitment and team building difficulties. The documentation requirements, especially from the US, were enormous.
Extraordinary steps were taken over system safety. Many organizations were involved, the Ordnance Board, the AWRE Weapon Safety Committee, the Magazine Safety Committee, the RN Depot at Coulport and the Ranges all had different needs. And the Committees had to be obeyed.
The Management Re-organisation bullet above refers mainly to RAE, but of course, every organisation reorganises now and again. The changes introduced by Fred East in 1976 had their impact on everyone. Each contractor had to reorganize from time to time to handle the scale of the job. There is, I'm sure, a fascinating story to be told about the impact of Chevaline on and within the main establishments and contractors.
The RAE team grew from a sub-section in We6 division, under Henry Hensman to a division (We8) under George Hicks and then Roy Dommett. As the workload increased and the division doubled it was split between Roy and Norman Blight, who had a flight trials background, and became half of Air Armaments Department under Gordon Herring. The team was accommodated in the ARL area of RAE. The project had to fight for staff and resources against the rest of the RAE (which knew nothing about what was going on over the airfield!). It continued to grow; there was another re-organisation to form an Engineering Division under George Munns. As new tasks became evident, specialist staff were posted; for example, Roy Harmer for the Aerodynamic Test Vehicles, Chris Longstaff for the engineering of Falstaff, Sandy Stagg for structural matters, Mike Gage on software management, and, based on his experience on Martel, Rex Chase for the PAC Performance Approval Submission. In 1969 RAE's team was 6 strong; by 1976 it had risen to around 80.
Let's not dwell on the Committees. There was simply a vast array of meetings, working groups and committees. There were too many committees for monthly meetings, but the 6-7 week cycle that was deemed to be necessary still was unable always to maintain the trial dates.

The Falstaff flight trials programme.

Moving on from the general to a particular example. One of RAE's biggest responsibilities was to direct the flight trials in Australia. Apart from Falstaff, other programmes were the Jabiru series (examining re-entry issues) and the Skylark series (which looked primarily at the penetration aids).
The idea for a large unguided sounding rocket came when a search was

made for means to reduce the high costs of a programme based entirely on flights in the USA.
The 36 inch diameter solid propellant Stonechat motor had been produced at Westcott as a convenient step towards a programme for larger UK rockets, by developing casings, and filling and curing techniques. The proving flight of the Stonechat 1 at Woomera from the standard rail launcher in a single stage configuration was successful in October 1969. Later, this was referred to as F00. The vehicle could offer a significant flight time outside of the sensible atmosphere, as high as 2-3 minutes, but would be too slow for useful re-entry work. See Figure 2. In 1971 a programme of up to 10 launchings during 1974-5 was envisaged involving the manufacture of 12 sets of hardware, including proving rounds. A concept of operations was evolved which defined the vehicle configuration. Contracts were placed and serious design work started on Falstaff in 1972; a mock-up was assembled for inspection in the blister in Weapons Department's ARL compound at RAE. Chris Longrigg coordinated the engineering. He had come off the RAE's Urban Transport study team.
The new vehicle retained the large fin designed for the Hypersonic Test Vehicle by Structures Department, RAE. The fin sets were made by RAE and Airlog. The booster was attached to the 54 inch diameter, full-size payload by a reverse conical frustrum 'Adaptor Bay'. The payload was an early layout of PAC with a single ReB-P mounted, and only a few penaid ejection tubes, because it had to carry a bulky telemetry system compatible with the Woomera range facilities, and instrumentation such as a recoverable 70 mm cine camera.
BAe were concerned that the unstabilised booster could disperse too easily just after launch, before fin-based stability was fully established. This was solved by giving the vehicle spin rockets fired at launch, although they only turned the booster one or two revolutions, the huge fin area soon damping out any roll; but it was enough.
The payload had to be protected from the exit environments and was enclosed by a nose fairing. British Hovercraft (Saunders Roe/Westlands) had produced 54 inch base diameter split nose fairings for the UK Black Arrow which were easily adaptable. British Hovercraft also provided all the ground and test equipment that was needed for Falstaff.
At first it was suggested that a complete IFE would be flown. This proved to be too heavy even with a 7% increase in motor propellant in the Stonechat 2. The payload had to be orientated for ejections of the P-Body ReB and the penaids; an attitude capture and orientation scheme was evolved based on a beefed up sun-seeking MSDS Attitude Control Unit as used on Skylark. It was decided to stay with the normal WRE compatible telemetry system which was different from the tele system used on the Polaris shots. There were also changes to reduce impact dispersion and avoid the roll-yaw lock-in that had plagued Skylark. The differences between the tactical, Polaris flight test and Falstaff flight test PAC builds increased, workload was high and the

delivery time pressures grew from the various agencies. Greater commonality would have cost more but the evidence would have been more credible.
John Ray of RAE had overall responsibility for all the CQ.941 flight experiments, taking a particular interest in the on-board photography. The RAE team was able to include staff with Black Knight engineering experience, such as Jim Sedgwick and John Woolley, as well as perfomance staff like Jim Scott.
The experiments - the PACs - were assembled, measured, balanced, and checked out at the UK Assembly and Test (UKAT) facility in Farnborough. Then they were flown to Woomera while the boosters went by sea. All the handling gear and packaging was provided by Airlog. The payloads were checked out again at the Test Shop 4, the ordnance was loaded in the nearby explosives fitting shop or ordnance area, Test Shop 6, and then mated with the nose fairing. This assembly was taken to the launcher and mated to the Stonechat motor and the adaptor bay already mounted horizontally on the launcher. It was then elevated for launch. The launch angle chosen depended on the measured wind profile. The high acceleration off the launcher was very impressive.
Initially, ten firings were planned, all to be ahead of the first Polaris shot. This was increased to twelve and appropriate sets of hardware ordered, most on delivery time incentive contracts, against delivery dates which became increasingly unrealistic because of delays in design, manufacture, assembly and test of the special PAC build. (Marconi on a fixed price contract was threatened with a penalty for late delivery of their tenth unit when the first of the vehicles was not yet ready!) Six more sets of fins were made by Airlog and other vehicle components by BHC. From December 1971, the over ambitious Falstaff and Polaris flight trials programmes slipped 4 years. As the slippages continued, a programme logic linkage was made for F1 to precede and be a hold on P1. As F1 was a vehicle failure, even this had to be dropped. Eventually only five functioning flights were attempted and the other hardware was scrapped.
The programme did not go well. There were long delays with the first four vehicle payloads. Too often, the Falstaff trials were competing for hardware needed in other development programmes. A nominal 8-9 weeks of preparation in the UK stretched to from 30 to 51 weeks. Even in TS4 the nominal 7 weeks grew to 11 weeks for the first two rounds. However, most were launched on the day of the first attempt. Table 3 summarises the outcome of each trial.
The value of the Falstaff flights was:

- The PAC system was shown to work according to expectations, in exo-atmospheric conditions, without having to withstand the hostile disturbance of second separation.
- The ACS was exercised in simple angular and displacement

manoeuvres that were impossible with Polaris, directly comparable with the gimbal rig trials in the Pendine vacuum chamber which had been limited by the mass of the rig and the use of a cold gas, proving the control algorithms, and measuring the magnitude of the penaid ejection impulses on the PAC.

- P-Body ejection and its subsequent motion could be observed - this was not something that could have been demonstrated on the Polaris tests.

Concluding remarks.

There is so much more that Roy I and wish we could include. Let me just add another final list of RAE's work which I have not covered in this paper.

- Design of the night test and in-service PAC manoeuvre sequences.
- Provision of PAC system performance requirements document.
- Preparation of Approval Submission questionnaires.
- Design and oversight of databases such as Standard PAC Characteristics for Analysis (SPACCA).
- Characterising System performance.
    - Forces, moments, velocities, accuracies-, re-entry.
- Provision of the basis for the Targeting model.
- Integration of IFE with the Polaris missile.
- Over one thousand Working Papers dealing with all aspects of RAE's input.

The contribution of the Royal Aircraft Establishment to the success of the Chevaline project was immense. The work that was done was unique, both in a national sense and in relation to anything else in RAE's history, or in the subsequent history of DRA, DERA, DSTL and QinetiQ.
For everyone who played a part, the scientists and engineers, the senior staff, the clerks and administration staff, it was - if nothing else - a memorable phase in their careers; for most, it was a career defining one. For our spouses, partners, families and friends, who knew nothing about what we were doing for so many years, they were puzzling times. Perhaps they still are.
Michael Rance. November 2004.

Bomb ballistics	Bomb release mechanisms
Explosive release units and release disturbances	Parachute retardation
Ballistic missiles	Inertial navigation
Aerodynamics and wind tunnel testing	Re-entry dynamics and heating
Trajectory and motion analysis	Mathematical modelling
Structural design and testing, including vibration and shock	Radomes
Safing and arming systems	Fuzes and switches
Flight test planning and analysis	Ground handling
Materials, including carbon and plastics.	

TABLE 1. RAE'S EXPERTISE IN NUCLEAR WEAPONS

HUNTING ENGINEERING LIMITED, AS DESIGN AUTHORITY	PAC Structure,thermal panels, cork insulation, penaid tube stand-offs, base frame, thermal barrier, cables, connections,distribution boxes, opto-isolator, snatch plugs, some scale models for ground trials
HUNTiNG ENGINEERING LIMITED AS COORDINATING AUTHORITY	Trials managers, documentation, mass control, interface control, reliability data collection, PERT.
SPERRY GYROSCOPE LIMITED	Atitude Control System, Space Reference Unit (SRU), Electronics PROM, SPATE, and other test equipment, tests at Pendine and Holloman AFB.
BELL AEROSPACE TECHNOLOGY INC	Actuator system, HAS.
ROCKET PROPULSION ESTABLISHMENT (RPE),	Design and test of all solid and liquid motors, including

later PERME, then ROF Westcott	Nose Fairirg, ReB, TCPU, PAC and Penaid eject, plus secondary containment
BRISTOL AEROJET (BAJ) LIMITED	Manufacture of rocket motorcasings & carbon fibre penaid tubes
ML AVIATION LIMITED	RFACs, tilt -out mechanisms, latches and interlocks, thermal battery mounts.
MSA	Thermal batteries
AIR LOG LIMITED	Blast shield, handling gear,emergency removal gear, fins and barrels for Falstaff, Experimental clusters for Skylark, dummy penaids for trials, some scale PACs for gas dynamic trials
ERDE, WALTHAM ABBEY	Propellants, E-type fuseheads
RARDE	Pyrotechnics
AWRE	Vibration and shock testing, penaid ejection accuracy testing in vacuum, vulnerability testing, sub-scale gas dynamics testing (at Foulness)
THORN EMI LIMITED	Telemetry systems
IRVIN LIMITED	Ply tear webbing

TABLE 2. THE PRINCIPAL COMPANIES

	Objectives (cumulative)	Outcome.
F0 May 1975	Vehicle proving, in-flight separations MSDS ACU and EMI	Successful, functioned correctly, but transponder failed at 50 secs.

	analogue telemetry, range operation and tracking; minimum of on-board instrumentation.	
F01 Feb 1976	PLUS – EMI digital telemetry, on-board tape recorder and full instrumentation.	Successful, full correct functioning.
F1 May 1978	PLUS – PISUs, PAC functioning angular manoeuvres, penaid ejection reactions.	Failed, nozzle broke up at 30 secs following motor nozzle burn-out.
F2 Sep 1978	PLUS – lateral manoeuvres, first functioning TCPU.	Successful, correct functioning.
F3 Dec 1978	AS F2 plus P-Body eject.	Failure, payload activity terminated early.
F4 Feb 1979	As F3, no penaids.	Successful, experiment not roll-stabilised at start.
F5 Apr 1979	As F3, full PAC functioning.	Fully successful.

TABLE 3. OBJECTIVES AND OUTCOMES OF THE FALSTAFF TRIALS.

FIGURE 1. RAE: LINKS, RESPONSIBILITIES & REPORTING.

(Not shown)

Biographical details:

Dr Michael L Rance. Independent Consultant.

Dr Rance is an Independent Consultant specialising in ballistic missile defence, weapons systems and international defence co-operation. He writes and presents papers on missile defence issues, and advises companies, governments and academia. He has presented papers on missile defence at numerous conferences. He is a Specialist Adviser on BMD to the UK House of Commons Defence Committee. In December 2000, he retired from UK's Ministry of Defence where from 1995 he held the post of Director of the Directorate of Science (BMD) which was responsible for the US/UK technical relationship on BMD and providing technical advice in MoD on missile defence. From 1991 to 1995 he was a diplomat in the British Embassy in Washington as Counsellor for Defence Science & Equipment, dealing with the defence science and technology relationship between the US and UK. His long-term background was in weapons systems research at RAE Farnborough and weapon system procurement in the Procurement Executive. In addition to missile defence, he has specialised in strategic systems, including on the UK's Chevaline programme, stand-off weapons, air defence and anti-armour systems. His BSc was from Manchester University in Physics and his PhD from Imperial College in Electrical Engineering.

The Contribution of Industry to Chevaline.

Dr Mike Rance.

Based on material provided by Roy Dommett and staff past and present in Hunting Engineering (Insys), RPE / PERME and Sperry Gyroscope.

Introduction.

This paper describes the contributions of some of the companies involved on the Chevaline project. David Reade's paper deals with BAe's activities. The paper is not comprehensive, being based largely on personal recollections and not a thorough scrutiny of papers and files. I hope, however, that it will trigger other memories which can contribute to a more complete history. Any errors are mine. I apologise to those companies who only get mentioned in one table. I shall only be talking in any detail about Huntings, Sperry and the Rocket Propulsion Establishment. I hope that the contributions of companies such as AirLog, ML Aviation and Thorn EMI will get due recognition in a history.

Marking the start in 1970, the only contractors then associated with the Polaris Improvement programme were Hunting Engineering (HEL), Sperry Gyroscope and Marconi Space and Defence Systems (MSDS). Before the Feasibility Study, a few individuals in industry, notably Paul Cope at HEL, where work was done under a pre-existing fluidics contract, were in discussion with RAE on various studies. As Feasibilty got under way, the main contributors were HEL and Sperry, with smaller companies such as ML Aviation and AirLog, together with the Rocket Propulsion Establishment (RPE, later PERME) making inputs.

By the end, important pieces had been developed and built in addition by many companies including: Bristol AeroJet (BAJ), MSA, Bell Aerospace in the US, RARDE and DoVv1.y. For all the companies involved this was a big and important job, although there was not much prestige to be had. This was mainly because of the extreme security that flooded everything and everyone. But the contracts were all cost plus, so regular profits were probably made - although I haven't checked this point with company finance directors!

For many in industry as well as in government, especially those who were with the programme for many years, Chevaline became a highlight and a defining phase in their careers. Whatever they did afterwards, they always remember Chevaline, not always perhaps with unalloyed pleasure, but always with nostalgia.

Table 1 is a list of most of the companies that worked indirectly as sub~contractors, or directly with RAE on the Re-Entry system.

HUNTING ENGINEERING LIMITED.

Let's start with Hunting Engineering Limited, known either as Huntings or HEL, now under the name of Insys Limited.

HEL's involvement grew out of Percival's contributions to Aldermaston and Farnborough on the early UK nuclear free fall bombs. By the end of the 1960s, Huntings had established a role on Britain's nuclear weapons programmes as the preferred contractor for the delivery system - the WE177 free-fall bomb and its interfaces with the aircraft which carried it. They had also been involved with Blue Steel in the 1960s, and seemed suitably sized for what was perceived then as a UK version of the US Antelope concept. When ideas for improving the effectiveness and penetrativity of Britain's Polaris fleet were being discussed, HEL was brought in by RAE to assist with schemes and layouts.

One of the first decisions was to provide RAE with full-time staff to work- at Farnborough on secondment. It gave RAE invaluable effort and real technical expertise, largely in the modelling and simulation area, that was otherwise unavailable. It also gave Huntings an inside view of the technical debates and issues, although there were times when the company queried the cost benefit. The practice of seconding staff became common in many other areas of the programme. The earliest HEL man at Farnborough was Jim Simmonds from 1967 to 1969. Others, who all made significant contributions later, often in the modelling and simulation field, were John Simons, Peter Marriott, Steve Daley and Ron Peasley.

The first formal studies were Pre-Feasibility in nature, in which early layout options were studied and interfaces with and implications for the existing Polaris missile were considered. Relationships with staff at AWRE at Aldermaston and DDW(P) at Bath were started. In the lead at this time was Paul Cope, who later led the Special Systems Department at Ampthill. Paul reported initially to Dave Gilbert, the Director responsible for the Ampthill site, who himself reported to Geoff Dollimore, the Company Chairman. After Dave Gilbert, the Project Manager was Retired Air Commodore Ambrose

Eyre, followed by Dave Robertson and finally Chris Batten. The Huntings team was three men strong initially. At the peak, Huntings employed 625 staff on Chevaline.

Table 2 summarises the responsibilities of HEL on Chevaline.

During the one year Feasibility Study, from late 1971, the design options for the chosen Mono-PAC solution became more detailed, with structural design and electrical system layout work predominating. The design issues involved in carrying and dispensing penetration aids (penaids) from tubes were studied, and HEL became involved in trading-off requirements with practicalities. HEL began to plan the trials and to undertake the modelling and understanding of the various kinematic and dynamic requirements and constraints. Closer relationships were developed with the other principal contractors such as Sperry, and support to RAE remained a strong feature. Many meetings, working groups and committees began their lives in this period, and HEL acted often as RAE's right hand in planning and reporting them. By the Development phase, this role had grown into a Coordinating Authority activity which in time encompassed reliability, PERT, ground trials coordination and planning, flight trials work, mainly for Falstaff, quality assurance, build standards etc etc.

One of HEL's main tasks as PAC Design Authority was the design of the PAC structure. The Chief Designer was Dan Sharp.

The development programme needed several build standards as the timescales were too tight to allow completion of one phase before moving on; thus there were overlapping stages. Also, the different test vehicles and flight ranges required significant changes, calling for alternative designs. The growth in the number of build standards for trials purposes severely stressed the contractors, particularly HEL, and caused delays, especially for the Falstaff programme. The delays can be put down to a lack of resource - insufficient, irregular and intermittent funding and a consequent inability to recruit enough staff when they were needed.

The recognised variants of PAC build were:

- Experimental X PACs.
    - This preliminary design was produced for experience in packaging the sub-systems and for developing the various experimental test techniques. Examples were flown on the proving FO and F01 flights in the Falstaff programme, and another used by Sperry in the gimbal rig in the Pendine vacuum chamber. One was used for the early EMP trials. The structure was mostly in an aluminium encased balsa wood honeycomb. It was an open "book-case" arrangement without blast shield, side panels or thermal protection, which were introduced in later builds. The penaid eject tubes were in fibre glass. The SRU was mounted through one of the side diaphragms, which proved to be far too flexible for successful operation in a vibration environment.

- Development D PACs. The first realistic PAC design was produced in versions for:
    - The ground trials of a tactical build.
    - A build with the WRE telemetry system for Falstaff, for compatibility with the launch vehicle, with the features such as thermal protection not needed.
    - The simplified build for the first Polaris flights PA and PS, without a live TCPU, PAC ACS or separating payload items.
    - The early Polaris build for flights PI to PG, using an off-the-shelf telemetry system.

- Engineered E PACs. This was the first attempt at the final configuration and incorporated all the agreed mass savings. It was used for all the project approval ground and flight trials. It was fitted with the limited "in-service" telemetry used for all the submarine shots. To avoid requalifying the build, all production PACs also carried this telemetry package.

- Production PACs. The main production run used for DASOs and in-service.

- Reference Facility. To control the in-service build standard, to work out changes to procedures or establish the acceptability of proposed modifications to flight or ground hardware and support equipment, a Reference Facility was set up in an AirLog building in North Town, Aldershot. None of this could be done in the ordnance depot conditions of Coulport.

Unfortunately, we are not permitted to describe the final PAC design in any detail. It was a challenging design and development task for Dan Sharp and his team. Some of the challenges were:
- Accommodating the TCPU tanks and the thrust lines.
- Attaching the Space Reference Unit firmly on a stiff structure.
- Characterising the PAC's vibration modes.
- Fitting as many penaid tubes as possible - a continuous struggle.
- Fixing the ReB-P and its pedestal.
- The complex ordnance electrical system, requiring a number of innovations.
- The design of the separation mechanisms, including the PISUs, and,
- The tilt-out mechanisms on the modified base frame.

As Trials Authority, HEL had responsibility for the conduct of Ground Trials, and the associated analysis of results, and also the Flight Trials, before BAe as the Flight Trials Authority was brought on board. The Trials involved the use of a significant amount of Ordnance, and HEL was responsible for its safe installation.

A comprehensive ground trials programme was required, the principal objectives of which were to:
- Characterise unknown System Performance features prior to flight trials.
- Prove the design and produce evidence for design changes.
- Validate models able to predict performance at flight trial conditions.
- Examine performance across the envelope of operational use (wider than achievable in flight trials)

Many different trials were carried out, mainly in the UK, including:
- Investigation of the Gas Dynamics at Nose Fairing Eject, Second

Separation, ReB P Eject and penaid eject. This was a major HEL effort, performed in close coordination with RAE and others.
- Determination of Thermal Effects, Post-Nose-Fairing Eject.
- Evaluation of PAC Controllability for Sperry - on the gimbal rig at Pendine.
- Study of the ReB aerodynamics.
- Safety Investigations, too many too describe.

In addition, many other sub-system trials took place, including:
- Rocket motor characterisation, in conjunction with RPE.
- Shock/vibration tests, with the aid of RAE and Bae.
- Salt water immersion.
- Ordnance Board Trials (e.g. long term storage).
- EMP Susceptibility.

Let me take one example of Huntings' contribution to the Ground Trials programme - the PAC Heating trials and the thermal protection that was tested. I have already alluded to the exit heating trials at RAE. The modelling of the heating on the PAC was validated by full-scale trials at British Hovercraft Corporation (BHC) on the IOW. These were basically of three types: material evaluation trials; sub-system trials; and system trials. The material tests, using a flame test rig and a chamber with radiant heaters, were carried out on a range of cork thicknesses and back plates. The HEL Charring Ablator model to predict back plate temperatures was validated with the test data. The sub-system tests were carried out, for example, on the latches and the launch tubes. These tests demonstrated that the protection was adequate for these systems, which were not protected by the PAC thermal skins.

The major thermal trial was the full PAC system trial. A full-size PAC was used (painted a sinister matt black) and a special-to-purpose rig was built at BHC up the hill from Cowes. The rig enclosed the entire PAC with two large frames on each side that were rolled up to the PAC. Each held a series of copper reflectors and the radiant heating lamps. Where the highest heating levels occurred, the lamps had to be as densely packed as possible without touching. The blast shield was mounted on two frames, which, at the point of separation of the PAC from the second stage, swung aside driven by pneumatic rams, complete with the halves of the blast shield. A second frame then dropped down over the systems above the top diaphragm.

To avoid combustion in the air under the intense heat, totalling 1 MJ/m^2 in the worst areas, a Nitrogen purge system was used. This also served to blow away the large quantities of smoke generated. Temperatures and deflections on the PAC were measured. The entire heating sequence was quite spectacular. The results were used to validate a thermal model of the entire PAC and directly to provide confidence in the total PAC thermal protection scheme.

In addition to the trials at BHC, "rides were taken" on any other trials that could yield thermal data, such as the separation trials.

Given time and space, stories such as this one on PAC heating can be told about many of the other ground trials.

Chevaline relied more heavily on modelling and simulation, probably more than any previous programme. There was a feeling - this is a Huntings view - that an immensely ambitious programme was being conducted with the minimum of expensive flight trials, hence the need for sophisticated modelling techniques and exhaustive validation of the models in ground trials.

Computer technology, viewed in hindsight, was at an almost laughably simple level, and yet the achievements were remarkable. One worker using the structural model PAFEC recalls that, in the late seventies, it was impossible to run a full PAC structure simulation on the HEL computers since the largest programme they could handle at that time was 64Kb. Large jobs had to be ferried to the "super computer" at AWRE Aldermaston (how huge was that - 256Kb?). A typical job cycle would be: Day 1 - compile the job and programme it as six heavy boxes of IBM cards; Day 2 - transport boxes by car to AWRE, and, if lucky, collect job the same day; Day 3 - examine results.

The most likely result was a red ticket inserted about 10 cards from the front of the first box with the legend: "Job failed here". Fix obvious errors and repeat.

HEL played a key part in the modelling and simulation effort, developing many codes and performing analyses with codes developed by others, principally RAE Farnborough. HEL had the task of compiling the Chevaline Model Register on behalf of the programme as a whole.

The Model Register Issue 2 of June 1981, for example, numbers models from number 1 (the Chevaline Performance Assessment Model by AWRE), to number 455 (the Guidance and Tracker Error Program by LMSC). Models were originated by AWRE, RAE, DWS(P), PERME, SPERRY, BAe, LMSC, EMIE, and HEL. HEL were the originators of 61 entries, which were codes covering reliability, mass characteristics models, mass characteristics changes in flight, calculation of ballasting tables, tilt-out and nose fairing eject, structural dynamics, heat transfer and ablation (in the PAC cork thermal protection), gas dynamics, heating during second-stage fly-by along with numerous models to assist post-trial analyses of dynamic events.

There is much more that should be said about Huntings, including their work at UKAT - the UK Assembly and Test facility in Farnborough (it's the ASDA car park now) and on the Flight Test teams in Woomera and the Eastern Test Range. And some good stories. Another time.

SPERRY GYROSCOPE LIMITED.

Moving on to the developers of the so-called Attitude Control System - Sperry Gyroscope Company Limited, located then in Bracknell. Together with Marconi Defence and Space Systems (MSDS), Sperry was asked during the Feasibility Study year (1971/72), to submit a bid to design, and to write a proposal for, what was called an Attitude Control System (ACS) for an exo-atmospheric system. The contractors were not told what the system was for, but they guessed. As we shall see, the description "Attitude Control System" grossly understates the role and significance of the ACS in the performance, sequencing and control of the PAC.

The design of the Sperry system was masterminded by Tony Walpole, who is acknowledged as the principal system designer, and John Bourne.

John Flood at RAE led the selection process which decided upon the Sperry proposal, largely because the work would be focused on one site, which was preferred for security reasons. A strap-down system from Sperry was preferred to an inertial platform from MSDS based on the company's space experience.

The Sperry design employed a pair of in-house free-flywheel gyros to give pitch, roll and yaw angles from the gimbal resolvers, and three orthogonal, strap-down accelerometers. The design, although quite heavy, was probably lighter than a higher performance inertial platform, as had been proposed by MSDS.

The cylindrical Space Reference Unit (SRU) was (finally) mounted firmly on an extension of the bottom core structure - and contained the gyros and accelerometers needed to estimate the behaviour of the PAC from the start of second-separation.

The control system design used a 50 Hz sample rate, locking all timing functions to a master clock. The processor (designed in-house) generated the multitude of sequencing signals and computed the thruster demands for closed loop control.

The processor electronics and the power supplies were located in the Electronics Unit (EU) See Figure 1. This is the heart of the PAC system. Its complex box shape was made of a titanium alloy, machined from solid. There are cooling channels in the casing to allow extended periods of testing during assembly and before flight. The EU was half filled with the control system electronics boards; the other half contained the power supply conditioning as required by the units in the SRU and elsewhere in the PAC. The boards contained some 109 different types of components; some of new technologies, mostly supplied by the major electronics companies in the USA to high reliability specifications. A major feature was 'hardening' against nuclear radiation.

The overall system design, the control system algorithms and the hardware in the SRU and the EU were well thought through. The Hot Gas System design based on Iso-Propyl Nitrate (IPN) was more speculative, less well-developed at the Feasibility stage, and therefore more risky. There were substantial engineering and metallurgical challenges, which ultimately led to the change to hydrazine, provided by Bell Aerospace.

In the early to mid-project period, before 1976, Sperry's organisation was: a "Project Office", a Systems Department including Tony Walpole, an Electronics Department led by John Bourne, a Hot Gas Department, led by Adrian Abbott and a number of sections dealing, for instance with the digital electronics and the gyros.

Graham Lang as Project Manager gave way in due course to Les Darbyshire then Dick Sellings. Martyn Bennett (who had joined Sperry from MSDS) became the lead technical interface with RAE, with the Department heads still responsible for design and development.

Following the change from IPN to Hydrazine for the actuation system in 1976, the parent company sent Mel Feder and Karl Burfeindt to Bracknell to manage the UK programme. A new management style and processes were introduced. It was a no-nonsense, earthy New York style, which, though a culture shock to many, was soon accepted. (There were casualties of the new regime, and-other New Yorkers, such as Bob Shostak and Bob Taglia soon joined.)

The whole Sperry programme was reviewed thoroughly, and although the new programme, assessed by Feder to be realistic, moved many milestones to the right, it was agreed by the new project management under Fred East. As the programme progressed, the timescales outlined by Feder in 1976 were largely held.

As the EU and software design had evolved, it became clear at one point in development that both the processor speed and the memory capability were becoming inadequate; a major constraint on resolving the problem was lack of space in the EU. Sperry proposed that the computer system should be changed from discrete technology to microprocessor technology, and that additional memory boards be fitted into the space freed-up by the processor redesign. RAE agreed to the changes.

The instruction set for the new microprocessor-based computer was modified to simplify coding of the circumvention routines; this was a benefical change when software growth later was greater than predicted, and memory capacity was almost reached.

The PAC structure had a major resonant mode at a frequency which was almost exactly half the ACS sample frequency. The ReB-P and the PAC were "nodding". RAE brought in BAe Weybridge to measure the resonances and advise on control system stability. The builds of PAC were vibrated to obtain modal frequencies. Some disagreements arose between Sperry and BAe on the meaning of stability to an autonomous space vehicle. In the end, after looking at other ways to remove the resonance, Sperry decided to implement a digital notch filter.

It was the Hot Gas System that caused the greatest concern to the project. VVhen the decision was made to compete the development of the ACS actuation system, Sperry Gyroscope the parent company in Great Neck, New York - became more involved and demanded briefings and meetings to consider their response. It was at this time that Mel Feder came into the picture.

After the management reorganisation at Sperry and the introduction of the HAS, the general impression is that few difficulties arose. A casualty of delays and programme changes not Sperry's in this case - was that the linkage between the Falstaff Trials and the Polaris trials became less and less useful; for Sperry. the Falstaff programme became largely irrelevant. It confirmed the predictions and the modelling, but if anything serious had gone wrong, there would have had to be further delays - there was at that time, no programme slack.

Sperry played a key role in the success of Chevaline. The control system was at the heart of the total system, and the analysis and simulation tools were central in the trials programme. The American director installed a professional operation, relegating politics, promoting project success as the overriding objective and lifting standards across the company.

THE ROCKET PROPULSION ESTABLISHMENT.

RPE at Westcott, near Aylesbury in Buckinghamshire, was primarily a research and development centre for all forms of rocket propulsion. It had a liquid engine propulsion division, a solid motor division, and a materials/chemistry section. The solid motor division produced several types of rocket motor, such as the Skylark sounding rocket motor, in fair numbers. These divisions were supported by sections such as instrumentation, photographic, library and workshops. A number of contractors was used to provide much of the hardware, such as motor cases and propellants.

Westcott had been involved with Polaris A3T on the surveillance of ReB eject motors and with the firing of one second stage motor at Shoeburyness. Stan Green and Anne Tatem of the project group were involved in defining various conceptual motors to support the pre-feasibility studies. They showed that the optimum eject motor was in fact like the LMSC design with three embedded nozzles when overall length was a limitation. Westcott produced an outline design for a thrust terminating second stage motor, using information on Skybolt technology - a mechanism with blow off panels -- along with an estimate for the necessary production facility. Special low-spin ReB eject motors were produced for what became the PO and P01 DASO experiments.

Involvement in Chevaline started in 1970 with a request to the solid propellant division from RAE for some small motors for trials. At the time, RPE did not know what they were for. Other requests for various small scale solid motors followed - usually one-third scale for gas dynamics trials at Foulness and RAE -- and by 1972 there was a considerable commitment by the RPE solid motor division. Project codes were revealed, and staff began to be security cleared. Westcott gave support to the packaging and performance studies that led to the choice of the MonoPAC. It was finally settled that the PAC would have two high thrust solid propellant separation motors.

Flight trial motors, including Skylark, Rooks, and Stonechats, were required, all destined for Woomera. Much of the hardware was being made by Bristol Aerojet at Banwell who also provided project engineers to work at RPE. The propellants, both plastic and cordite extrusions, were being made at the Explosives Research and Development Establishment, ERDE.

By 1974 the solid propellant division and motor filling facility was heavily involved in Chevaline. The Nose-Fairing Eject trials motor was needed in two versions and the ReB-P eject motor was redesigned to halve the burn time with the same total impulse. Other motors designed by Westcott were the PAC and ReB-C eject motors, and the penaid eject motors.

By 1973, the workload was such that a Chevaline Project Offfce was formed with Stan Green heading the team. Staff numbers were augmented using outside contractors, including HEL, to cope with the compilation of test results and provision of test schedules. For most of the development period, Andy Jeffs supported Stan Green and John Rolfe did the engineering of each design.

As discussed elsewhere, the ACS initially planned to use the mono-propellant Iso-Propyl Nitrate, IPN. Sperry took over A-site and the adjacent buildings. A security fence was built around the enclave and Sperry provided the staff and test engineers. RPE had only an advisory role (Dr. A.Hardacre). As described elsewhere, the IPN design was abandoned. In the meantime RPE had worked on eliminating the principal problem with IPN, known as 'dieseling', and had managed to eliminate it and to keep the reaction going at a steady rate.

One of the key decisions about PAC design was whether to use solid or liquid propulsion technology for the motoring phases. Second separation certainly had to be done with solid motors, to achieve a rapid onset of high levels of acceleration. But liquid propellants are notoriously toxic and dangerous, and ill-suited to the submarine environment. Design work in the solid propellant division was undertaken to look into the feasibility of a PAC repositioning motor using a solid propellant; this was *possible* if a number of constraints were accepted in the performance, and there was some technical risk.

Peter Jones at Aldermaston commissioned a technical survey of the solid and liquid propulsion options from RAE, and Dave Albery was given the task. RPE advice was sought and a paper discussing the pros and cons of solid and liquid systems was prepared. Each factor was assessed. Every factor except safety gave the advantage to liquid propulsion. Peter Jones gave the decision, based on this assessment.

Until the requirement for a PAC repositioning system was formulated the liquid motor division was not significantly involved in Chevaline. However, a research project into packaged liquid propellants had been going on for some time, originating in the Blue Streak era, with significant success. This provided a technology on which to base a liquid propulsion·system. There appeared to be little technical risk as the research had successfully demonstrated the main components. The test facilities and hardware manufacturers were available.

A two nozzle design was chosen and the engine became the Twin Chamber Propulsion Unit, TCPU. The fuels were divided between two balanced tanks, and the propellants were ejected using pistons driven by gas pressurisation provided from outside. The pressurisation of the TCPU placed large demands on the ACS.

The Chevaline programme at PERME now had an additional 50 people on the TCPU, which incorporated a secondary containment system and a continuous leak detector monitor. With the late introduction of Hydrazine, the liquid propellant division now had the task of filling the tanks and other items supplied by Bell. Another group in the Liquid Propellant Division was formed to liaise with the US and put together a dedicated filling, integration and test facility. A further 30 to 40 people formed a group for the filling and test work. The leak detection system had to be linked to the Hydrazine storage tanks. Transport packaging for air transport to Woomera and Cape Canaveral and road transport elsewhere had to be developed. The packaging incorporated leak detection monitors to satisfy the safety requirements of the Air Force and Cape Canaveral authorities.

In the mid-70s, about half of RPE Westcott was directly or indirectly working on Chevaline, about 400 people.

During the Development Programme the establishment at Westcott changed from the Rocket Propulsion Establishment, RPE, to PERME, and was then bought by Royal Ordnance, which became a subsidiary of BAe, and was finally absorbed into what had been IMI at Summerfield, Kidderminster.

I'd like to thank everyone who helped me put this together, especially Roy. Also Brian Shepherd, Richard Clifton, Neil Cox, Neil Foster and Dan Sharp from Amphill. Martyn Bennett, ex-Sperry, now DSTL, and Andy Jells from RPE/PERME.

HUNTING ENGINEERING LIMITED, AS DESIGN AUTHORITY.	PAC structure, thermal panels, cork insulation, penaid tube stand-offs, base-frame, thermal barrier, cables, connectors, distribution boxes, opto-isolator, snatch-plugs, some scale models for ground trials.
HUNTING ENGINEERING LIMITED, AS COORDINATING AUTHORITY.	Trials managers, documentation, mass control, interface control, reliability data collection, PERT.
SPERRY GYROSCOPE LIMITED.	Attitude control system. Space Reference Unit (SRU), Electronics Unit (EU) including SPATE, PROM, and other test equipment. Tests at Pendine and Holloman AFB.
BELL AEROSPACE TECHNOLOGY INC.	Actuator system, HAS.
ROCKET PROPULSION ESTABLISHMENT (RPE) later PERME, later ROF WESTCOTT.	Design, fit and test of all solid and liquid motors, including Nose-Fairing, ReB, TCPU, PAC and penaid eject, plus secondary containment.
BRISTOL AEROJET (BAJ) LIMITED.	Manufacture of rocket motor casings and carbon fibre penaid tubes.
M.L. AVIATION LIMITED.	RFACs, tilt-out mechanisms, latches and interlocks, thermal battery mounts.
AIR LOG LIMITED.	Blast shield, handling gear, emergency removal gear, fins and barrels for Falstaff, experimental clusters for Skylark, dummy penaids for trials, some scale PACs for gas dynamics trials.
AWRE.	Vibration and shock testing, penaid ejection accuracy testing in vacuum, vulnerability testing, sub-scale gas dynamics testing (at Fowlness)
THORN EMI LIMITED.	Telemetry systems.

TABLE 1A. COMPANIES ON CHEVALINE.

MSDS.	Skylark ACU.
IRVIN LIMITED.	Ply tear webbing.
MSA.	Thermal batteries.
ERDE, WALTHAM ABBEY.	Propellants, E-type fuse heads.
RARDE.	Pyrotechnics.
ARA, Bedford.	Wind tunnel testing.

WARD ENGINEERING.	
WILMOTT.	
EPS.	Packaging.
ROF BRIDGEWATER.	
MRS.	
J.S. CHINN.	
HELLERMAN DEUTCH.	Connectors.
FERRANTI.	
PORTSMOUTH AVIATION.	

TABLE 1B. COMPANIES ON CHEVALINE

TABLE 2. MAIN RESPONSIBILITIES OF HUNTING ENGINEERING LIMITED.
(Not shown)

Glossary of Terms.

Introduction.

This glossary defines the abbreviations of the terms used in this paper and Annexes. It is based in the terms used during the development of Chevaline, and carried forward into the service life of Polaris A3TK.

3DQP	Three-Dimensional Quartz Phenolic. A material woven from quartz phenolic into a three-dimensional structure by US company AVCO and supplied to UK under the Polaris Sales Agreement for Chevaline and A3TK.
A3T	POLARIS A3T. US POLARIS purchased by UK, missile 'nuclear hardened' with US ReB shell and UK warhead.
A3TK (POLARIS A3TK)	POLARIS A3TK. UK operational Polaris A3T with the payload developed through the Chevaline programme.
ABM	Anti-Ballistic Missile. A missile designed to engage warheads before or after re-entering the atmosphere whilst on ballistic trajectories. Soviet (and now Russian) ABMs around Moscow assumed to carry nuclear warheads.
ACS	Attitude Control System. The system to control the attitude of the PAC after separation from the 2nd stage in accordance, with the demand of a pre-determined flight profile. It consisted of an Electronic Unit (EU), a Space Reference Unit (SRU) and a Hydrazine Actuation System (HAS).
AEK	Auxiliary Equipment Kit.
AFETR	Eastern Test Range. The US major Atlantic missile test facility at Cape Canaveral, operated by the USAF. ETR includes all of the range head facilities and sensors, those on islands down

range, the impact measuring equipment, and all support ships and aircraft.

AIFE Active Inert Front End. An assembly of the PAC, P-Body and C-Body (mounted on the base frame) with a fully functioning electrical and data system, but with inert rocket motors and all other types of ordnance used for ground testing.

AIT Assembly Integration and Test.

ALBM Air Launched Ballistic Missile (e.g. Skybolt).

Antelope USN POLARIS Improvement (A3A) that replaced one ReB of the three ReBs with a motoring countermeasure launcher; held in 'readiness' but not thought to have been deployed by the US.

ARIS Advanced Range Instrumentation Ship. A specially adapted ship (USS Vandenberg) fitted with a number of large radars operating at different frequencies which is capable of measuring the characteristics of the threat cloud prior to re-entry (representing ABM defence radars).

Artificer Security codeword used to protect aspects of Chevaline programme, now defunct.

AUWE Admiralty Underwater Weapons Establishment.

AVCO Aviation Corporation (US Contractor) Atomic Weapons Research Establishment.

AWRE Atomic Weapons Research Establishment, Aldermaston.

Base Frame (Delta Frame). A near-triangular beam structure at the top of the ES that supported the ReB tilt-out mechanism and the Thermal Barrier panels protecting the items within the section

BAC British Aircraft Corporation.

BAe British Aerospace.

BAT Bell Aerospace Textron.

BET	Best Estimate Trajectory.
Blast Shield	Device used on Chevaline and Polaris A3TK PAC to protect it and the payload items from efflux of nose fairing eject motor and atmospheric exit heating.
BROHP	British Rocketry Oral History Programmed.
C-Body	See ReB.
C&AG	Comptroller and Auditor General.
CDA	Co-ordinating Design Authority.
CEP	Circular Error Probable.
CFD	Computational Fluid Dynamics.
CGWL	Controller Guided Weapons and Electronics.
Cheval	Security codeword used to protect aspects of Chevaline programme, now defunct.
Chevaline	Development programme for payload of POLARIS A3T to improve penetrability of ABM defences by addition of penetration aids and new warheads; initial programme named KH793 from 1970.
CPE	Chief Polaris Executive.
CRDA	Coordinating R&D Authority.
CRES	Corrosion Resistant Steel.
CRF	Central Reference Facility.
CSDA	Control System Design Authority.
CSDL	Charles Stark Draper Laboratories (USA).
CSSE	Chief Strategic Systems Executive (successor to CPE when Chevaline development approved).

CTC	Coordinating Trials Contractor.
CWSE	Chief Weapons System Engineer.
DA	Design Authority.
DASO	Demonstration and Shakedown Operation. Crew proving exercise post-refit, conducted at the AFETR to demonstrate the readiness of SSBN weapon systems for fleet use. This operation provides a combined technical and operational evaluation of each SSBN weapon system while determining capabilities and limitations and demonstrating the reliability, serviceability, maintainability and safety of the system.
DAWD	Director Atomic Weapons Development.
DCCC	Documentation Change Control Committee.
DC(N)	Deputy Controller (Nuclear).
DCR	Document Change Request.
DDWP	Deputy Director Weapons (Polaris).
DGSWS	Director General Strategic Weapons Systems.
DGST (N)	Director General Supplies and Transport (Navy).
DMis(P)	Director Missile (Polaris).
DNOrdS	Director Naval Ordnance Safety.
DOF	Degrees of Freedom.
DPTCAn	Directorate of Project Time and Cost Analysis.
DRWP	Defence Review Working Party.
DSTI	Director Scientific and Technical Intelligence.
DT(P)	Director Trials (Polaris).

DWS(P)	Director Weapons Systems (Polaris) (successor to DDWP when Chevaline development approved).
Effectiveness	The estimates of the likely success of the A3TK system if used against the postulated defences, including ABMs.
Eject Motors	Motor(s) mounted on the Nose Fairing, ReBs, PAC to accelerate them clear of the second-stage of the missile. Also known as the separation motor for PAC and ReBs.
EMC	Electromagnetic Compatibility.
EMIE	EMI Electronics.
EMP	Electro-Magnetic Pulse.
ETP	Engineering Test Plan.
ETR	See AFETR
ES	Equipment Section. Part of the basic missile, situated between the Missile Second Stage, the ReB, delta-frame and the nose-fairing, it contained the missile Flight Control and Guidance systems and interface equipment for the IFE.
ESIP	Equipment Section Interference Package.
EU	Electronic Unit. A part of the ACS consisting of a computer processor, interface unit and power supplies. It accepts flight data from the SRU and computed the thrust demand on the HAS and TCPU. It also sends trigger signals to eject the payload.
Exit heating	The aerodynamic heating experienced in the very high altitude flight phase between nose-fairing eject and leaving the sensible atmosphere.
FCS	Fire Control System. The equipment on-board the SSBN, reproduced at the ETR, to prepare targeting data and to condition and launch the

missile.

FMEA	Failure Mode & Effect Analysis.
FTA	Flight Trials Authority.
FTAWG	Flight Trial Analysis Working Group.
Gas Dynamics	The collective term used to describe the dynamic consequences of firing the various payload rocket motors in confined space, resulting in large, strongly time-dependant additional forces and moments on all the ejected bodies, i.e. the nose-fairing, PAC and ReBs.
GASWOG	Gas Dynamics Working Group.
GHE	Ground Handling Equipment.
GSA	Gas Storage Assembly.
Hardness	The degree of resistance to the effects of radiation from ABM warhead nuclear explosions.
HAS	Hydrazine Actuation System. Provided thrust for the ACS and pressurization for the TCPU from the decomposition of hydrazine.
HEL	Hunting Engineering Ltd.
HLGG	High Level Gas Generator.
HPS	Head Program Secretariat.
HTV	Hypersonic Test Vehicle.
IFE	Improved Front End. The hardware of the UK side of the controlled UK/US missile interface, but also included the Base-Frame and changes to the ReB, together with a new Nose-Fairing motor.
IPN	Iso Propyl Nitrate.

IRBM	Intermediate Range Ballistic Missile.
IRFNA	Inhibited Red Fuming Nitric Acid.
ISS	In-Service Support.
IST	In-Service Telemetry.
JAIEG	Joint Atomic Information Exchange Group.
JRSWG	Joint Re-entry System Working Group.
JSTG	Joint System Task Group (the lead executive meeting between US and UK under PSA).
JWOG26	Joint Working Group 26 (under the 1958 Atomic Exchange Agreement between UK and US).
KH.793	Cabinet authorised study of adding penetration aids to Polaris A3TK, building on earlier UK experience. This programme was essentially the feasibility phase of Chevaline.
LCC	Line Cutting Charge. System used to release the Nose-Fairing and ReBs in flight.
LDT	Low Density Tunnel.
LLGG	Low Level Gas Generator.
LMSC	Lockheed Missile and Space Corporation.
LPLD	Liquid Propellant Leak Detection Equipment fitted on the missile, PAC and SSBN to detect the possible leak of toxic liquid propellants.
LTS	Long Term Storage.
Manoeuvrability	A flight ability involving programmed changes of course rather than a simple reorientation.
MDS	Master Dispenser System.
MEG	Management Executive Group.

MIRV	Multiple Independently (Targeted) Re-entry Vehicle. A scheme to carry several RVs on a thrusted bus that adds different amounts of velocity to each RV according to time it is ejected, which together with changes to the orientation of ejection, can send the RVs to different and widely spaced targets. Poseidon and Trident are examples.
MOD(N)	Ministry of Defence (Navy).
MSS	Military Space Systems (Division of BAe).
MSOSO	Missile system Pre-Launch Safety Plan.
MTBF	Mean Time Between Failure.
MTRE	Missile Test & Readiness Equipment.
NAO	National Audit Office.
NF	Nose-Fairing. The ballistic fairing which covers and protected a re-entry system during the exit flight and aids missile stability, and which was ejected on leaving the atmosphere.
NOTU	Naval Ordnance Test Unit.
NSWC	Naval Surface Weapons Centre, Dahlgren, USA.
NWMC	Nuclear Weapons Modifications Committee.
OHSA	Occupational Health & Safety Administration.
OP	Operating Procedures.
Operational Readiness launch order.	The capability of the SSBN to respond to a
OSTE	Ordnance System Test Equipment.
PI-P7	Designation of flight trials with Development Standard PAC used in Chevaline programme,
P-Body	See ReB.

PA, PB — Initial standard of Chevaline flight trial PAC with non-functioning, but separating PAC.

PAC — Penetration Aid Carrier. An attitude controlled and rocket propelled vehicle designed to carry a ReB (the P-Body) and a number of penetration aids.

PAC — Public Accounts Committee.

Pad — Shore-launch from test pad at Cape Canaveral.

PBRS — Post Boost Rocket System.

PCM — Pulse Code Modulation.

PCTO — Prime Contractor Technical Office

PDS — Post Design Services.

PEM — Polaris Evaluation Missile firing: this is a missile test firing at the ETR, Cape Canaveral.

PERME — Propellant & Explosive Research and Manufacturing Establishment.

PERT — Program Evaluation & Review Technique.

PISU — Pressure Intensified Separation Unit. Three units that held the PAC to the base frame via the hinges and tilt mechanism. These connectors rupture when a pyrotechnic charge is ignited after receiving a signal from a SFU.

PMMC — Polaris Missile Modifications Committee.

PO, PO1 — The pre-cursor POLARIS A3T DASOs which carried experimental Chevaline ReB shells.

POPSIN — Post PS Investigation.

POTS — PAC Ordnance Test Set.

PRESSG — Polaris Re-Entry System Study Group.

PS	Designation of the Chevaline flight trials (using tactical trials hardware standard) launched from Resolution class SSBNs.
PSA	Polaris Sales Agreement.
PSG	Product Support Group.
PT	Pad, Tactical Standard. Designation of In-Service standard PAC used in Chevaline flight trials and POLARIS A3TK DASOs.
PTA	Prime Technical Authority.
R&D	Research and Development programmed.
RAE	Royal Aircraft Establishment.
Range	Maximum/Minimum - longest/shortest design range. Optimum - range spread within which performance was most satisfactory.
RCA	Radio Corporation of America.
RDA	Research and Development Authority.
R&DCC	R&D Coordinating Committee.
ReB	Re-Entry Body. A ReB with its heat shield, containing a warhead and has an ejection motor and a separation ring assembly. The body is mounted on a pedestal that remains behind at separation. The flare is part of the re-entry body and is integrated with it. There are two types of ReB: • C-Body (or ReB-C) - mounted on the base frame. • P-Body (or ReB-P) - mounted on the PAC. The two ReBs are identical except for their rocket motors.
ReB SHELL	The thermal protection shell of the ReB. For Chevaline and Polaris A3TK it consists of a 3DQP

(Three-Dimensional-Quartz-Phenolic) hollow structure that is closed at its hemispherical end.

Reliability	Probability that the required design function will be performed under stated conditions at/for a specified time, and/or within specified limits.
REM	Rocket Engine Module.
Remotoring	Replacement replica solid propellant first and second stage POLARIS rocket motors introduced in the 1980s to A3TK.
ReS	Re-Entry System. Chevaline and POLARIS A3TK term. The ReS comprised the major assembly of all items, except the Nose-Fairing, attached to the missile forward of the ES. The base-frame assembly is included for design purposes but was treated as part of the short missile for configuration control purposes. For POLARIS A3T it refers to the 3 ReBs; for Chevaline the ReB-C and the PAC carrying the REB-P, even though the PAC did not actually function during, or necessarily survive, re-entry.
RESESSE	Re-Entry system Emergency SSE.
RFA	Radio Frequency Actuators.
RFAC	Radio Frequency Attenuating Connector. A device designed into the inputs of firing circuits to prevent stray electrical signals inadvertently igniting the low voltage fuzeheads and prematurely firing units in the IFE.
RFAC-C	RF AC-Cartridge.
RN	Royal Navy.
RNAD(C)	Royal Navy Armaments Depot (Coulport).
RPE	Rocket Propulsion Establishment.
RRE	Royal Radar Establishment. Became RSRE.

RSP — Range Safety Procedure.

RSRE — Royal Signals & Radar Establishment.

RV — Re-entry vehicle carried by ballistic missiles; for Chevaline and Polaris A3TK this was known as the ReB.

SAC	Safety Assessment Committee.
SEATO	South East Asia Treaty Organisation.
SEO	Senior Executive Officer.
SEP	Separations of missile stages and of the payload; for Chevaline and Polaris A3TK, this is the IFE. The RES separation is also known as second separation.
SFU	Separation Firing Unit. A device that provided a firing pulse to separation ring assemblies to initiate separation of NF, ReBs or PAC.
Signature Characteristics	Acoustic, magnetic, thermal, radiological, mechanical, radar reflectivity and electromagnetic properties associated with a device that provides a means of identification or discrimination.
SLA	Service Life Assessment.
SLE	Service Life Evaluation.
SMC	Safety Monitoring Circuit.
SMCT	Safety Monitor Control Testing.
SMS	Strategic Missile Systems.
SPACCA	Standard PAC Characteristics for Analysis.
SPALT	Special Project Alteration.
SPATE Equipment.	Special Programmable Automatic Test
SPRN	Special Projects Royal Navy (CSSE representative in US, housed as a lodger unit in SSPO Washington).
SPTR	System Performance Technical Requirement.

SRT	Slow Run Through.
SRU	Space Reference Unit. Equipment for the provision of actual attitude and velocity data for the PAC ACS, relative to conditions at separation.
SSBN	Ship, Submersible, Ballistic, Nuclear - formal classification of US and UK nuclear powered submarines equipped with ballistic missiles e.g. POLARIS and TRIDENT.
SSE	Surface Support Equipment. Shore-based equipment required for testing, handling, maintenance and support of the Missile and Weapon System and their component parts.
SSPAG	Strategic Systems Performance Analysis Group.
SSPO	Special Strategic Projects Office.
SSWE	Senior Superintendent Warhead Electronics.
STPP	Safety Test Programme Plan.
Super Antelope	The project name for early UK work jointly with the US (based on experience gained on the Antelope system) that was rejected as not being sufficiently effective for UK requirements, some concept elements subsequently developed into Chevaline.
SWISSC	Strategic Weapon In Service Safety Committee.
TCPU	Twin Chamber Propulsion Unit. Consisted of two propulsion chambers used to propel the PAC post separation.
Telemetry	System used to condition sensors and process and transmit data for flight trials. For Chevaline and POLARIS A3TK DASO two major standards were used: Development standard for Chevaline flights. IST (In Service Telemetry) for Chevaline PT flights and Polaris A3TK DASO.

TFR	Trouble & Failure Report.
Threat objects credible to the defence.	Objects placed in the threat cloud that appeared
Thrust, rocket motor	The resultant reaction forces resulting from the flow of hot gas out through the nozzle of a rocket motor.
TRAJWOG	Trajectory Working Group.
UGET	Underground Nuclear Effects Test.
UKAT	UK Assembly & Test.
ULCER	Underwater Launch Computer.
USN	United States Navy.

Ends.

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The History of the UK Strategic Deterrent: The Chevaline Programme. 28th October 2004

Following the success of the Royal Aeronautical Society symposium on the History of the UK Strategic Deterrent from inception to Polaris A3T, held on 17 March 1999, the Society held a one-day conference on 2& October 2004 to cover the conception, development and achievement of the Chevaline project. Chevaline was successfully deployed with the Royal Navy as Polaris A3TK. The aim of this conference was to provide an in-depth understanding of the need to improve Polaris A3T, and how this major weapon system was selected, developed and managed. The conference was the first public presentatlon of this important programme, and was intended to contribute to the future preparation of an official history of the Chevaline project already announced by HM Government.