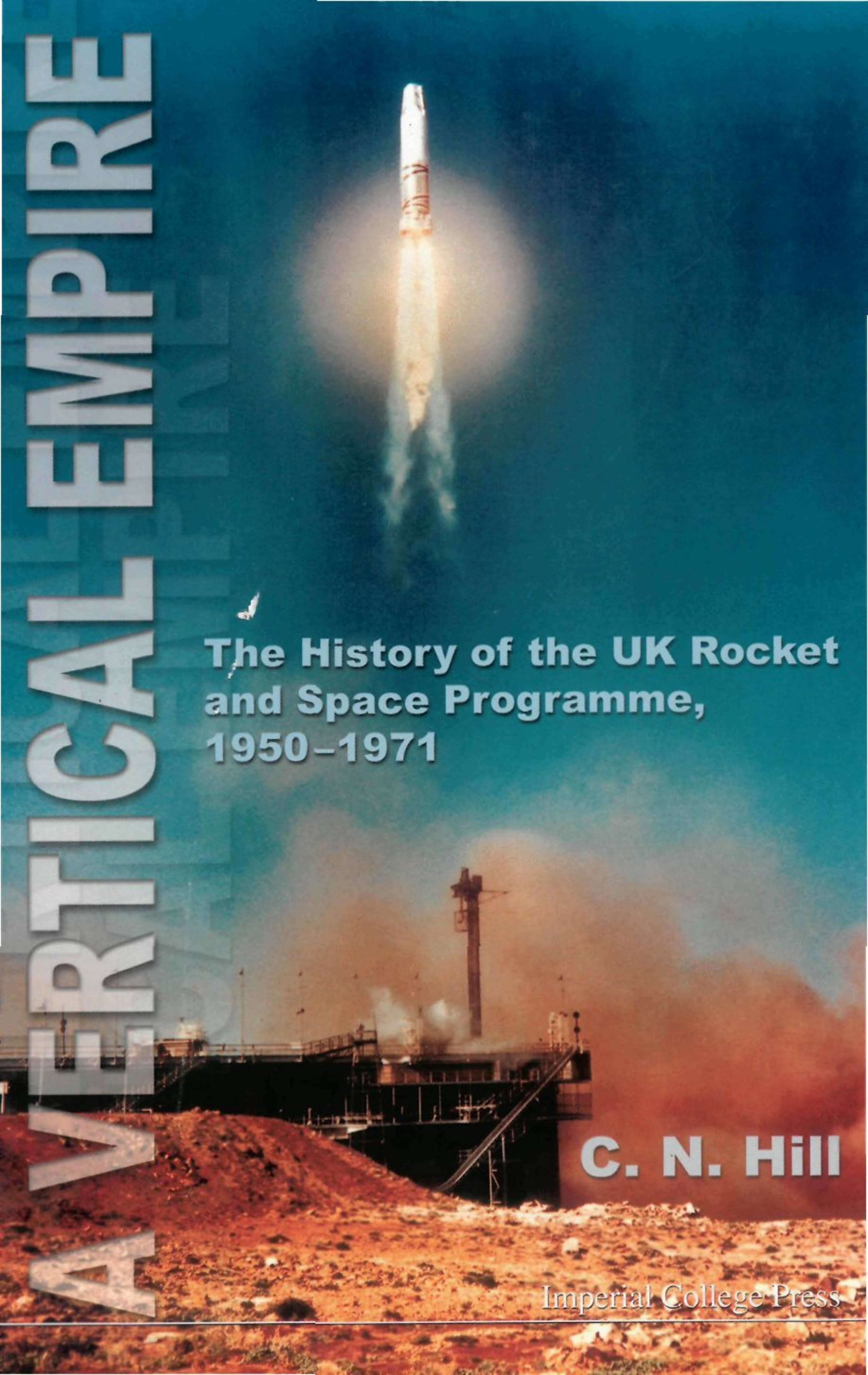
A VERTICAL EMPIRE

The History of the UK Rocket and Space Programme, 1950–1971

C. N. Hill

Imperial College Press



A VERTICAL EMPIRE

A VERTICAL EMPIRE

The History of the UK Rocket and Space Programme, 1950–1971

C. N. Hill
Charterhouse School, UK

ICP Imperial College Press

Published by

Imperial College Press
57 Shelton Street
Covent Garden
London WC2H 9HE

Distributed by

World Scientific Publishing Co. Pte. Ltd.
P O Box 128, Farrer Road, Singapore 912805
USA office: Suite 1B, 1060 Main Street, River Edge, NJ 07661
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Front cover photograph: The British Blue Streak rocket being launched at Woomera, Australia. Eleven successful launches of Blue Streak were made between 1964 and 1971. Blue Streak was originally designed as a Medium Range Missile, but later was used as the first stage of the Europa satellite launcher. © Crown Copyright. Reproduced with permission.

A VERTICAL EMPIRE

ISBN 1-86094-267-9
ISBN 1-86094-268-7 (pbk)

Printed in Singapore by Fulsland Offset Printing

Contents

Acknowledgements 3

List of Figures 5

1. Introduction 9
   Glossary 16

2. Rocket Motors. 25

3. Rocket Interceptors 43
   Designs in detail. 49

4. The Blue Steel Stand Off Missile 59

5. Blue Streak: the origins 69

6. Blue Streak: the cancellation 93
   Alternatives. 94
   The debate begins 97
   The debate ends 107

7. B.S.S.L.V. 117
   Black Prince 124
   A Liquid Hydrogen stage. 128
   Combination with Black Arrow. 130

8. ELDO and Europa 135
   ELDO B and C. 144
   Europa: from success to failure. 147

9. Black Knight 155

10. Black Arrow 189
    Prospero 203

11. The Could Have Beens 207

12. The U.K. and Space 223

Appendix A-History of the Saunders Roe S.R. 53 and S.R 177 239

Appendix B –Report on the Launch of F1 245

Bibliography 249

Index 251

Acknowledgements

This book would not have been possible without the help given by very many people. Acknowledgments are in alphabetical order.

Roy Dommett C.B.E., of R.A.E. and D.E.R.A., who was involved in much of the work detailed in this book, and whose sharp and percipient comments have thrown light on many of the ideas outlined.

Guy Finch for his encyclopaedic knowledge of aircraft, Blue Streak and the rocket interceptors.

Professor Edward James, who set me on this search following an interview when I applied for his M.A. course in Science Fiction at Reading University, and after reading his book "Science Fiction in the Twentieth Century", where he notes that Dan Dare "gave a whole generation of British boys ... a totally false impression that Britain was going to dominate the space race."

Doug Millard, Space Curator at the Science Museum, who with great kindness started me on my research by allowing me access to his filing cabinet. He also was the first to put the idea in my mind: why do you want to launch satellites anyway?

Kate Pyne, official historian at AWE Aldermaston, for answering blundering questions with tact.

Dave Wright of Manchester University, who has pursued Blue Streak with dogged perseverance, and without those endless telephone conversations this book would not have been possible. Many of the ideas outlined in this book originated from him. Thanks too to his wife Lesley for her patience!

Thanks also to David Cheek of GKN Aerospace, Susan Kinsella, Tom Lukeman, Barrie Ricketson, and the staff of the Public Record Office in Kew for their help and suggestions. Any mistakes are entirely due to me.

Images and copyright:

Thanks to GKN Aerospace for supplying images. Also images from the Defence Evaluation Research Agency: © (British) Crown Copyright, 2000 Defence Evaluation and Research Agency, reproduced with the permission of the Controller Her (Britannic) Majesty's Stationery Office.

List of Figures

Blue Streak and its Russian and American counterparts. 12
The SRA/1 23
The P2 test stand at R.P.E. Westcott. 24
The de Havilland Sprite. 25
A de Havilland Spectre rocket motor 27
Gamma 301 combustion chamber 29
The large chamber from the Stentor engine 30
A liquid hydrogen motor being fired at R.P.E. Westcott 32
Liquid hydrogen chamber 33
Injector head 33
"Downey thinks we would be nuts ..." 35
The RZ-20 rocket motor 36
RZ-20 test firing at Spadeadam 37
Gamma 201 as developed at R.P.E. Westcott 39
The Gamma 8 engine that powered Black Arrow. 41
XD 145 on an early flight. 50
SR53 plan view 51
SR53 crash investigation 52
The proposed research programme for the SR53. 53
P177: top view 55
P177: front view 56
P177: side view 57
The F177 as it might have appeared in German Air Force colours. 57
Blue Steel: a perspective view. 59
Blue Steel maintenance 62
The Stentor engine that powered Blue Steel 63
Blue Steel being fitted to a Vulcan bomber. 66
A Victor bomber carrying Blue Steel 67
Cutaway of Blue Streak. 79
The one sixth scale model silo 83
One sixth scale silo. 84
The K11 silo: architect's drawing 87
Blue Streak at Hatfield 91
The air launched ballistic missile Skybolt 106
King Hele's proposed Blue Streak/Black Knight launcher 118
Pardoe's Blue Streak/Black Knight launcher. 120
BSSLV: the Ministry of Aviation's view. 121

Black Prince schematic 125
Black Prince: from the Saunders Roe brochure 126
Black Prince's path to orbit 127
The Saunders Roe liquid hydrogen stage. 128
R.P.E.'s liquid hydrogen stage 129
Saunders Roe proposal for Blue Streak/Black Arrow. 132
Blue Streak static test firing 137
Europa 140
Europa third stage. 142
Blue Streak at Woomera 143
F1 tumbles 148
A Europa launch at Woomera 149
The Blue Streak launch site at Woomera 150
A Europa vehicle at Spadeadam 152
A single stage Blue Streak 153
The single stage Black Knight 157
An early model Black Knight 158
An aerial view of the High Down site on the Isle of Wight. 159
The gantries at High Down 160
BK03 on the launch pad at Woomera 161
BK03: the launch 162
Post flight debris. 163
The airflow around a re-entry vehicle at high speed. 164
BK04: re-entry head temperatures 165
BK04: re-entry 166
Innards of a re-entry vehicle 167
BK08 169
The two stage arrangement 170
The BK08 head 171
The Cuckoo motor 172
The control centre at Woomera. 174
BK14 175
BK15 177
BK15 head after flight. 178
A 86 foot diameter Dazzle radar dish. 179
The Gamma 301 motor 180
A Dazzle radar 182
BK20 183
Recovering the BK20 re-entry head. 184
36 and 54 inch Black Knights 185
BK03 and launch team 186
BK20 liftoff 188
Black Arrow in the static test stand at High Down 195
Black Arrow static firing. 196

Possible U.K. launch sites for Black Arrow 197
Black Arrow R0 198
R2 at Woomera 199
Orba. 200
Proposed meteorological satellite 201
Prospero 202
Prospero – cutaway view 203
Prospero being built and tested. 204
Black Arrow sectional view 206
Bristol Siddeley's I.R.B.M. 210
Bristol Siddeley PR27 engine 211
Bristol Siddeley's design for a satellite launcher 212
Bristol Siddeley's PR38 213
SLAVE and Black Arrow 215
Blue Streak with an American Centaur upper stage. 221
Bloodhound 224
The F1 launch 248

1. Introduction

The U.K. space program, or rocketry program, has always been so low key that the public perception is that the U.K. has never even had a space program. Yet for a time in the late 50s and throughout the 60s, the program was technically as advanced as any in the world. If it didn't achieve the high profiles of Sputnik, Vostok, or Apollo, it is in the main because the projects were less ambitious, subject to much greater financial restrictions, and usually had a more modest goal. Most of the work was driven by the needs of the military. This was true too in the U.S.A. and USSR, but there the civilian effort also became caught up in the Cold War propaganda battles. Kennedy's cry to arms "... to put a man on the moon before this decade is out..." had no resonances in the U.K., and the motives that drove many of the other projects in the U.S. were also very often military, if often in civilian guise.

It must be admitted at the outset that almost all the work described here is of military origin, and most of it with direct application to weapons of war, and usually of mass destruction, which is, of course, a euphemism for nuclear weapons. That means the obliteration of cities and its inhabitants. The biggest project of all described in this book is Blue Streak, whose sole initial function was to launch hydrogen bombs at the USSR. It was only later that its application to a satellite launcher was seized upon as a political figleaf for an embarrassed minister, and even then, many of the potential satellites might well have been military. Black Knight was a research vehicle whose initial function was to act as a test bed for Blue Streak and to research re-entry vehicles for nuclear warheads. Black Arrow was the only major project discussed here whose applications were intended to be solely civilian and scientific.

In the end, though, the British work on rocketry and satellite launchers died, mainly as a consequence of lack of funding, political vacillation, and a perceived lack of need either for satellites or other forms of space research, whether military or commercial. Although now there is a developing and thriving international commercial market for the launching of communications satellites in particular, the British rocketry programme is certainly now completely dead and there is no prospect of resurrection. It is ironic that the systems that were built and tested in the 60s, and then abandoned, could have been commercially highly successful in the 80s and 90s. It was, perhaps, a penalty paid for being too early in the field.

A good deal of material has come into the public domain fairly recently: the Thirty Year rule has applied to a great deal of it, and so has only been released recently. Other parts of it have been highly classified for military reasons. Thus a lot of the story which was not told then can be told now. But to understand it fully we have to go back half a century, to the early days of the Cold War.

During the Cold War era, the U.S.A. and USSR were driven by ideological pressures that the U.K. did not experience. Each feared the other and their systems of Government. In addition, when it came to development and production of hardware, they had vastly greater resources than the U.K.. Indeed, the USSR can be said to have "lost" the Cold War in the sense that it was driven into final collapse in part by the demands of the military and space programs on its shaky economy. In some senses that was true too for the U.K.: after Blue Streak, there was little further attempt to develop a purely indigenous deterrent system. Politically, rocketry, and the nuclear threat, meant very different things to the U.K. compared with the U.S.A. and USSR. The U.K. had no hope of "winning" a nuclear war, given its limited geography. America and Russia were driven by a paranoid fear that the one was intent on the other's destruction, and the ideologies of the two were so far apart as to be completely irreconcilable, despite ideas of "peaceful co-existence".

The U.K. had no such geopolitical or ideological dynamic. It had a considerable interest in the state of Europe and the Continental balance of power, as it always has had, but that interest was to be subsumed into NATO, whose purpose, in one phrase, was "to keep the Americans in, the Russians out, and the Germans down". The U.K. had also suffered tremendous economic damage in the 1939-45 war, from which it has never really recovered. In addition to the expenses of maintaining a far flung Empire, it also had to provide an army of occupation for Germany. One of the problems of wanting to be a Great Power is taking on the burdens and expenses of Great Power status, which increasingly Britain was less and less able to do after the war. And then the nuclear factor entered the equation.

The story of the development of the Bomb is a complicated one, but most of the theoretical and practical work was carried out by European émigrés, backed up by American know how and resources. The U.K. sent many of its atomic scientists to America. The U.S. and U.K. agreed to pool information, an agreement that was to fall foul of a later Act of Congress, the McMahon Act. But the British need for nuclear weapons in the immediate post-war period was not that pressing, since the only country that possessed such weapons at that time was America, which was Britain's closest ally. Possession of nuclear weapons by the U.K. would have been useful for the influence they may have carried but not at that stage essential to the strategic balance and would not have had much military significance. They have always been weapons of mass destruction, aimed at cities as much as armies.

As earlier noted, Britain's interests were in her Empire and in Europe. In neither of these areas were nuclear weapons necessary or desirable. But that picture changed in 1949 with the explosion of the first Russian nuclear device. This was to be the first of the many scares that the Soviet Union was reaching parity with or overtaking the West technologically. The need for a British nuclear device now became that much more pressing, since the Soviet Union was now perceived to be the most likely candidate for hostilities within the foreseeable future. Then came all the various nuclear scenarios that were so to bedevil military and political planners. In what circumstances would the U.K. need to use such weapons? In what circumstances might they be used on the U.K.? NATO doctrine held that an attack on one was an attack on all, but there was always the unspoken fear—would America risk nuclear annihilation for the sake of London? Or Bristol, or Birmingham? No one wanted to find out, and, fortunately, we never did.

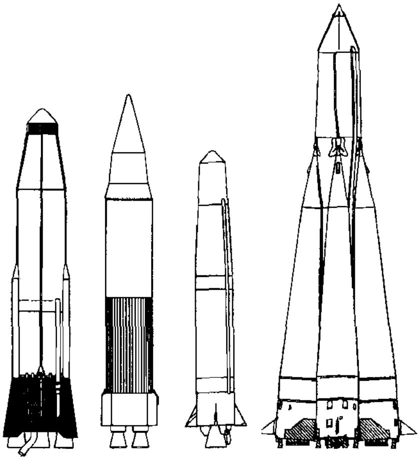
Another factor, which should not be discounted, was that, as mentioned earlier, Britain still regarded herself as one of the leading Powers. If the other two had the Bomb, then Britain should have a Bomb too, not from any intrinsic merit of ownership, but so as to keep a seat at the Top Table. The nuclear club was a club she felt she could not afford to be excluded from, yet could only just afford to join.

So work on a British nuclear device began very soon after the War. Soon Britain would have a working device. But there was the problem common to all three powers as to how the Bomb would be delivered. In the early post-war period, there was no alternative to the bomber, and the U.K. had produced some excellent jet bomber designs in the V bombers, the Valiant, Victor, and Vulcan, which were to give sterling service to the U.K. for many years. Indeed, the Operational Requirement was issued at the end of the war, and nearly 40 years later, Vulcans were used in the Falklands conflict in the bombing role, with Victors in the tanker role.

However, it was realised in the early 50s that with the increase in sophistication of missile defences, the V bombers, or bombers in general, would be increasingly vulnerable. Certainly it was expected that the likes of Moscow and other major cities would be surrounded by rings of guided weapons that could take out all but the most major bombing offensive. Hence the issue of Operational Requirement O.R. 1132 dated 3 September 1954, to develop a stand off missile, which would become Blue Steel. In 1954 the principal problem for such weapons was guidance over a long distance of flight, and with that in mind, Blue Steel was designed with an operational range of 100 nautical miles. This would keep the bomber clear of Moscow and its attendant defences, although still leaving them with a large amount of hostile territory to cross.

At the same time, the Americans were working on various air breathing long range missiles, precursors of the later cruise missile. Ballistic missiles were being worked on by von Braun's team, and by Convair under Brossart, but neither technology had advanced sufficiently to produce an effective weapons system that could deliver a nuclear device over a range of some thousands of miles. In 1954 Sandys of the U.K. and Wilson of the U.S. signed an agreement to share information on the development of ballistic missiles. By 1955 technology, particularly in guidance, had advanced far enough for serious design work to begin on a U.K. ballistic missile, Blue Streak, with range sufficient to reach Moscow (the criterion for any U.K. nuclear delivery system) and beyond. At the same time, a parallel programme, called Black Knight, was also started to carry out some of the basic research, particularly on re-entry vehicles. And America began work on a much longer range missile, Atlas.

At that time, thermonuclear warheads were much more massive than they would subsequently become, and so all the early missiles designed by the U.S., by the USSR, and by the U.K. turned out to be far larger than was in the end necessary. This was to have important consequences as far as the Soviet Union and Sputnik were concerned. The enormous ballistic missile that had been developed by the Russians turned out to be an equally effective satellite launcher. Neither the U.K. nor the U.S. had designed anything quite as big as the Russian R-7, or Semiorka. Western politicians, often technically ignorant themselves and with axes to grind, assumed these immensely powerful Russian boosters meant the Russians were that much further ahead in technology. In effect the reverse was true. The West hadn't built such large rockets because they weren't necessary.



Blue Streak and its Russian and American counterparts.

From left to right: Atlas, Blue Streak, Thor, and the Russian R7, which would launch Sputnik. This is diagrammatic only, but gives an impression of the scale of Blue Streak relative to its American and Russian counterparts.

All the early Western designs such as Blue Streak, Thor, Atlas and Titan I, were designed to use kerosene and liquid oxygen as fuels, as did the first Soviet designs. Solid fuel rockets had not yet sufficient size or range. Such large rockets were also very vulnerable to a first strike attack, so would have to be stored in and fired from underground storage silos, hardened against nuclear attack. This added considerably to the expense of the system, and meant in addition that the missile and silo complex itself became a target. Initially, the Pentagon were rather sceptical about the Atlas missile concept and design, but in the U.K., despite waverings, there was conviction in the concept of the missile. Development was carried on with Blue Streak as fast as funds allowed, although the whole project was bedevilled throughout its life by Treasury reluctance to release the necessary money. It could be said of the whole history of Blue Streak from 1955 to 1970 that the technical will was there, political will was there intermittently, and the financial will was never there. It is astonishing how well the morale of those involved with the project stood up in the face of such political and financial uncertainty.

But in 1957 came the shock of Sputnik. The psychological effect on the Americans was considerable, and Atlas, among others, became a crash program. In more than just the defence field, the U.S. felt it had been overtaken. This led, among other things, to a massive effort in science and technical education. Its effect on British opinion was very much more muted. They did not see themselves in any technological race, and were not perturbed by the thought of a satellite orbiting overhead. In the U.S. it was felt almost as an invasion of the country. Britain had suffered bombing of London as early as 1916, but the U.S. had never experienced hostile aircraft in its skies. Sputnik was perceived in those terms.

Curiously enough, the Rand Corporation had been undertaking studies into reconnaissance satellites, and had recognised that one legal problem might be that a satellite orbiting over another country may be taken as an invasion of the other country's airspace. This is one of the reasons why the first planned U.S. satellite was intended to be perceived as entirely civilian and part of the 1957 Geophysical Year. Sputnik had resolved this problem at a stroke. The Russians were in no position now to claim invasion of their airspace by American reconnaissance satellites.

Back in the U.K., by 1958 the Black Knight rocket programme, intended to provide a lot of the basic research for Blue Streak, was up and running. It would yield a lot of useful information for the U.K. and the U.S. on the physics of reentry vehicles, necessary for any ballistic missile system, and also for studies into possible defences against them. The first flight of Blue Streak was planned for 1960, when the decision was taken by the Macmillan Government to cancel the system for military purposes. The reasons for this are complex and will be explored further in the Blue Streak chapters. In the same way that the USSR was eventually driven out of the arms race, so too was the U.K.. It became increasingly reliant on the U.S. for delivering its deterrent.

Mainly, I suspect, to minimise the political damage that ensued from the decision, it was announced that although Blue Streak had been cancelled as a weapons system, work would still continue, albeit at a much reduced rate, on developing a satellite launcher based on the missile. At least £60 million (all costs are given as of the period), if not more, including large sums at Woomera by the Australians, had been spent on the project by this stage. A design, which would be known generally as Black Prince, or more inelegantly in official papers as the BSSLV (Blue Streak Satellite Launch Vehicle) had been under consideration for some time. It would have used Blue Streak as the first stage plus the proven technology of Black Knight as the second stage. Again, though, the major problem was money: one source mentioned that the development costs would amount to half the annual U.K. university budget, which even given the relatively small university sector in the U.K. at the time, gave pause for thought. And although the U.S. military had found many uses for satellites, there was not the same perceived need by the U.K. military, particularly since British Intelligence had access to a good deal of the U.S. information. Although the scientific community would have liked to launch various satellites (a stellar ultraviolet telescope was a favourite project), there were not the funds available in the civilian science research budget. Hence the U.K. was in danger of building a satellite launcher with no satellites to launch.

The decision was then taken to involve other nations in the project in the hope of sharing the costs. The Old Commonwealth countries were not interested, or lacked the finances and resources. France might be interested, but there was also the opportunity for France to acquire much needed data relevant to its own ballistic missile program, which led to some difficulties and embarrassment. In the end, the European Launcher Development Organisation, ELDO, was born with little enthusiasm from many of its members. And the ELDO launcher ran into considerable criticism almost from the start, being widely perceived as unnecessary and based on obsolete technology.

The latter criticism was unfounded, although the much slower pace of development in the cash strapped U.K. meant that the U.S. tended to be there first. But Blue Streak remained irredeemably tarnished by its cancellation for military purposes. It had, however, the potential to be the equivalent of almost any American launcher until the Saturn vehicles. ELDO was a political failure and a technical failure as well. Blue Streak itself performed almost flawlessly, but the same could not be said of the French and German upper stages. One of the reasons for this problem, however, was that the other European countries were that much less experienced; another was putting together a vehicle designed and built by three different teams of engineers in three different countries, speaking three different languages, was no mean feat. ELDO and its launcher died, never to be resurrected.

And what of the other project, Black Knight? After 22 successful firings, the project was declared at an end. But while the U.K. was still a member of ELDO, a decision was taken to proceed with an alternative, much smaller satellite launcher, and this would be based on Black Knight. The new design was called Black Arrow.

Two test vehicles were flown, one successful and one not, and then an orbital attempt failed by a small margin. On 29 July 1971, the announcement was made that Black Arrow was cancelled. However, the fourth vehicle was subsequently fired and achieved orbit on 28 October 1971. And then all further U.K. work on rocketry effectively stopped. There has been none since, and there is no likelihood of it ever being taken up again.

This account does not cover the work done using solid fuel rocket motors, and, particularly, Skylark. Although Skylark has yielded a tremendous amount of scientific information, it was never more than a sounding rocket, and does not really fit with the rest of this account. Instead what I would like to present is a portrait of the rocket and space programmes whilst they lasted.

Glossary.

Project names.

In the 50s, the fashion in the U.K. was to give many of the military projects two word code names, the first of which was a colour: thus Orange Herald, Blue Streak, Yellow Sun, Red Duster, Violet Club, Green Flax and so on. A good code name should reveal nothing about the nature of the project. However, Yellow Sun for an H bomb was a bit of a give away, since the Sun is a gigantic fusion reactor (or perhaps not: Mark 1 was not what is commonly understood by a "hydrogen bomb", so perhaps there was an element of double bluff).

The rocketry projects covered in this book are Blue Steel, Blue Streak, Black Knight, Black Prince, Black Arrow and the various rocket interceptors. The "Black" designations were applied, albeit unofficially, to research projects without a direct military application; indeed, Black Arrow was entirely civilian, but was named by extension from Black Knight, as probably was Black Prince.

Rocket fuels.

Liquid fuel rockets need a fuel and an oxidant. The U.K. used kerosene as a fuel almost exclusively, although a lot of work was done on liquid hydrogen, but sadly no use was made of this work. H.T.P. was the most common oxidant: this was an 85% solution of hydrogen peroxide (H_2O_2) in water. The hydrogen peroxide decomposes to steam and oxygen on a catalyst (silver mesh gauze) and kerosene injected into the resultant hot gases ignited spontaneously. However, Blue Streak used engines licensed from the U.S. and re-engineered, and these burned oxygen and kerosene.

The measure of the effectiveness of a rocket motor or fuel combination is called Specific Impulse or S.I. This is thrust times burn time divided by mass of fuel burnt. Another way of looking at it is the thrust obtained from each lb of fuel burned per second. The H.T.P./kerosene combination had a relatively low S.I., around 210-220 at sea level. Oxygen/kerosene gives an S.I. of around 245 at sea level. The effectiveness of a rocket motor is increased at high altitude or in vacuum. This is because the thrust from a rocket engine derives from the pressure difference between the pressure inside the combustion chamber and the pressure outside. In a vacuum there is no outside pressure. Thus S.I. is sometimes quoted at sea level and sometimes in vacuum. Vacuum S.I. is typically 10-15% higher than sea level. Hydrogen/oxygen is the most effective combination of all, reaching S.I.s of at least 400. This means double the thrust for the same weight of fuel. However, there are weight penalties in the use of liquid hydrogen, since it has a very low density and needs large tanks. It is also very cold, boiling at -253°C or

20K, so the tanks usually need extra insulation, which in turn implies a further weight penalty.

Thrust and weight.

The hot gases that exit from the rocket motor provide thrust. Rockets are launched vertically. The thrust must be bigger than the weight for the vehicle to start moving upwards. Usually, the ratio of thrust to weight is about 1.3, which means the initial acceleration is 0.3 times that due to gravity (the force driving the rocket upward is thrust minus weight). As fuel is burned off, the weight (and mass) decreases and the acceleration increases. The final velocity is governed by two factors: the speed of the exhaust gases (another way of expressing SI) and the ratio of the total weight of the rocket to the final, empty weight. This latter figure becomes very important for satellite launchers, where the payload may be 1% of the initial weight. If the weight of the design increases by only 1%, then there may be no payload.

Thus if the Blue Streak motors could provide a total thrust of 300,000 lb, its maximum lift off weight would be around 230,000 lb. If Blue Streak itself weighs 183,000 lb, then 47,000 lb is left for the upper stages and payload. A satellite launcher usually consists of 3 stages, and as each stage burns out, it is discarded. To make this staging as efficient as possible, the first stage should be around a half or two thirds of the total. This shows why Blue Streak as it was designed would not have been as efficient a satellite launcher as it might have been.

The same problem applied to the early U.S. launchers, but one way of overcoming the problem is to add strap on solid fuel boosters to augment the thrust for the first part of the flight. These boosters might then provide extra thrust for the first 30 seconds or so of flight, whilst fuel from the main stage is being burned off and so reducing its weight.

Liquid fuel motors usually use pumps to force the fuel into the combustion chamber: this means the tanks can be made of very thin metal and thus can be very light. The alternative is to pressurise the tanks: there is a trade off between having heavy, pressure resistant tanks and having heavy turbines and pumps.

Solid fuel rockets in the U.K. in the 1950s had a relatively low S.I. and were not very efficient due to their heavy casings. The technology improved rapidly in the 50s and 60s, particularly in the U.S., so that the comparatively small Polaris rocket could deliver its payload over 1500 miles.

Units.

The past being another country, they did things differently. I have kept entirely to the units of the day. Thus feet and inches. 1 metre is 39 inches. Weight is used where today we would (I hope) use mass. Mass is difficult to define, but can be thought of as the inertia of a body. Weight is the force of gravity. 1 pound, abbreviated lb [derived from Latin *libra*], is 0.45 kg. More annoyingly, force was also expressed in lbs, meaning in this context the weight of an object with a mass of 1lb. Modern usage takes the unit of mass as 1 kg and of force as 1 N. The force of gravity on 1kg is 9.8N on Earth at sea level. Thus rocket thrust was defined in pound force, sometimes abbreviated to lbf, or plain lb, which would now be written as 0.45 x 9.8N = 4.4N. A metric tonne is 1000kg, an imperial ton is 2,240lb. By a lucky coincidence they are almost identical. Orbit heights are usually given in nautical miles above the Earth's surface. A nautical mile is, strictly speaking, one second of arc of a Great Circle on the Earth, or around 2000 yards. A statute mile is 1760 yards. Thus a nautical mile is a little less than 2 kilometres.

After all this, the merits of the metric system appear obvious!

Political and Administrative.

Most of the projects covered in this book started life in a military guise. When a need for a particular weapon had been clarified, the Ministry of Defence or the Air Ministry issued an Operational Requirement, or O.R.. Thus Blue Streak was O.R. 1139, the warhead Orange Herald was O.R. 1142, and so on. The O.R. could be very specific about some of the requirements: thus for aircraft it might specify range, altitude, speed, maximum weight, and so on. Then the O.R. would be circulated to various firms, who would produce appropriate designs. The Ministry would then evaluate rival designs. Development was the responsibility of the Ministry of Supply, who dealt directly with the firms concerned. When the winning design had been selected, it would look after the timetable, finances and so on for the project. The major problem was the Ministry of Supply was not the end user, nor did it benefit or suffer directly from the success or failure of the project. Thus, Blue Streak files now in the Public Record Office can be found in various different forms: Supply files, Defence files, and Air Ministry files. Often material here is duplicated, as the same set of minutes of meetings were circulated to all relevant Ministries. A further complication is that the names given to a project by the Ministry and by the firm can sometimes be different: thus the Saunders Roe SR53 is known in Ministry files as the F138D.

There is a strong perception that this cumbersome bureaucracy did nothing to speed up projects, and that it would have made considerably more sense to give the function of overseeing development and production to the Ministry who would be the end users. This situation was never helped by continual Defence Reviews, changes of policy, and Treasury oversight. Whilst the latter three are obviously necessary, they can also cast doubts over projects which cannot have helped when it came to producing enthusiastic efforts to get the relevant project in service as swiftly and effectively as possible. Relations between firms and Ministries could also be difficult. Given directions as they were from Whitehall, the firms acted almost as Government agencies at times, free from normal commercial pressures. They were often at the mercy of the vagaries of changes in defence policy. Thus, as Saunders Roe were gearing up to produce 27 prototypes of the P177, together with work on Black Knight and the SR53, the work force approached 4000, only to be cut back drastically with the cancellation of the 177. This is always a problem when a company relies too much on Government work.

Politics.

Whilst many of these projects were pursued for defence purposes, their value for space research, exploration and exploitation has never received significant political or popular support. The strongest political personality that looms out of this story is Duncan Sandys, who made an early reputation for himself during the War in the context of German guided weapons. He was an effective if abrasive Minister, being Minister of Supply in the early 50s, then Minister of Housing and Local Government. In that context he was also responsible for setting up the Civic Trust. In 1957 he was appointed Minister of Defence by Macmillan, and was arguably the first to get a grip on the Ministry with its divergent Service interests. Before Sandys, there had been a rapid turn over of Ministers, who did not have time to stamp their authority on their Ministry. Certainly, he retains a considerable notoriety among aircraft buffs for the 1957 Defence White Paper, with its unspoken "no more manned aircraft" philosophy. Given the speed of the 1957 White Paper, he was probably implementing policy that had been already laid out by others, principally Sir Frederick Brundrett, Chief Government Scientist at the Ministry, and also Chairman of the influential Defence Research Policy Committee, the D.R.P.C.. A further motive behind Sandys' appointment was to cut the cost of defence in general, and he was not a man to be easily deflected from his objectives. Certainly, he reduced defence expenditure to 7% of GDP, at which level it broadly remained for many years. Part of the increased dependence on nuclear weapons was to cut the cost of conventional defence.

Sandys started the ball rolling for Blue Streak whilst Supply Minister, and he remained a vigorous proponent whilst at Defence. At the end of 1959, he was moved to a new Ministry, Aviation, which took over many of the functions of Supply. It has been asserted that Macmillan appointed him to this post to start the rationalisation of the aircraft industry. It also cleared the way for a new Minister of Defence, Harold Watkinson, to cancel Blue Streak. Watkinson's ministerial career was relatively short. It is quite likely that the fall out from the cancellation led to Sandys' sideways move to Colonial Secretary, although this too was a post that would require a man not afraid to take unpopular decisions. As Aviation Minister he was succeeded by Peter Thorneycroft, who had previously resigned from the Macmillan Government as Chancellor over the level of Government spending, and it was Thorneycroft who began the Anglo French talks which later led to ELDO. Thorneycroft later become Minister of Defence.

The Wilson Government, despite its rhetoric of the "white heat of technological revolution" cannot be seen as a government that pushed British technology. Beset by economic problems, R & D is an easy target for politicians looking for economies. Few in his Government were scientists or technologists: to make Frank Cousins, a trades union boss of the old school, Minister of Technology was no doubt politically astute, but can be seen as typical of the political cynicism with which Wilson operated. Crossman, another important Minister of the Wilson Government, writing in his diaries, bemoans time spent in cabinet discussing Black Arrow. Technology had no appeal for him either. But how was Britain going to survive in the latter part of the twentieth century without exploiting advanced technology?

And any discussion of the political scene would be incomplete without considering the role of the Treasury. One of the functions of the Treasury is to keep a tight grip on public expenditure. Defence and related areas of research such as space exploration came in for particular scrutiny. It does seem, however, that Blue Streak came in for a disproportionate amount of Treasury attention: true, it was, together with the nuclear programme, the major defence programme of the time. However, the V bomber programme, the nuclear effort and the Polaris programme were equally expensive, but did not seem to attract the same degree of hostile Treasury scrutiny.

The Wilson Government from 1964 onwards brought a number of economists in to evaluate programmes on a cost benefit analysis basis (Wilson himself had been an economics don at Oxford). The problem was that research programmes were analysed for their economic benefits, and this is a difficult if not impossible task. One of the points of starting research programmes is that their outcome is not always predictable, since the object of research is to look at matters that are uncertain or unknown.

Surprisingly, the greatest number of files on Blue Streak in the Public Record Office relate to the Foreign Office. This is as a consequence of the attempt to convert Blue Streak into a European satellite launcher. Hence it is not surprising that the Foreign Office were firm advocates of the project irrespective of any technical or economic merit.

The United States comes into the picture indirectly, since, with its vastly greater resources, it had covered most of the ground in space and rocket technology before the U.K.. The warheads that would equip Blue Steel and Blue Streak were of American origin, as was a good deal of the technology that went into Blue Streak. Competing with the U.S. in space research or satellite launching was also often thought by those in Government to be pointless, given the progress that had been made in America. The closeness of the U.S. and U.K. defence, intelligence and research establishments also often meant that the U.K. concentrated on certain rather narrow areas (for example, re-entry research) so as to have useful information to trade with the U.S..

The politician who closes the final chapter of this book is Frederick Corfield, who announced the cancellation of Black Arrow at the start of the Heath Government. But this decision coming from an otherwise colourless politician was almost certainly the culmination of years of Whitehall scepticism—as will be discussed later.

Officials.

Whilst the major policy issues were the province of the politicians, the day to day, or month to month work was carried out by officials at the various Ministries. One of the most influential, by virtue of his post, was CGWL, or Controller of Guided Weapons and Electronics at the Ministry of Supply and its successors.

For almost all the period, with a break of two years, Sir Steuart Mitchell held the post. From the Ministry papers he appears to be a sensible and capable administrator. Dr. Robert Cockburn filled the break. However, delving deeper into the Ministries, one drowns in a soup of alphabetic titles: in the R.A.F there was VCAS (Vice Chief of the Air Staff, who dealt with nuclear matters); DCAS, the Deputy Chief; DCAS (OR) Deputy Chief of Air Staff (Operational Requirements). There was DRAE (Director of the Royal Aircraft Establishment); DDRAE (his deputy); DAWRE (Director of the Atomic Weapons Research Establishment) and DDAWRE, his deputy. Then there are all the Ministry and Establishment departments with their heads: Guided Weapons, Space Department, and so on. Ministries have Private Secretaries, PS, Permanent Under Secretaries, PUS, and varieties of subordinate secretaries. It was part of their job to turn policy into hardware. But they were also responsible for the papers that went to Ministers, and, as a result, a good deal of the policy was made at a lower level than is often supposed.

Places.

The Royal Aircraft Establishment (R.A.E.) at Farnborough, Hampshire, provided the guiding hand behind most of these projects. Together with the Rocket Propulsion Department (R.P.D.), later the Rocket Propulsion Establishment (R.P.E.), based at Westcott, Buckinghamshire, R.A.E. carried out all the preliminary research for the ballistic missile, and also initiated and oversaw the Black Knight programme. It was also responsible for all the further studies that culminated in Black Arrow.

Spadeadam in Cumbria was chosen as the site to test and develop the Blue Streak engines, and here Blue Streak vehicles were assembled for static firing before shipment to Australia. Rolls Royce ran the site as an agency.

Woomera was, of course, the test range, jointly funded by the U.K. and Australia. It was run by the W.R.E. (Weapons Research Establishment) based at nearby (relatively!) Salisbury, South Australia. The airfield at R.A.A.F. Edinburgh was used for the V bombers during Blue Steel trials and for transport generally.

Firms.

de Havilland Propellers (later Hawker Siddeley Dynamics) was of course the largest contractor, building up to 18 flight models of Blue Streak (not all of which were completed) as well as several non flight vehicles. Large test stands had also to be erected at Hatfield for proving purposes. Rolls Royce developed the prototype RZ-1 engines (copies of the American S3 engine) then designed and built the RZ-2.

De Havilland was also responsible for the Sprite and Super Sprite, designed to assist take off for the likes of the Comet and the V bombers, and also the Spectre, used in the rocket interceptors and early test models of Blue Steel.

Napier was also involved in H.T.P. work, producing the Scorpion, installed in Canberra reconnaissance aircraft, and a rocket pack intended for the Lightning fighter.

Many other firms were also involved as sub contractors, and in particular Sperry and Ferranti were responsible for inertial guidance platforms.

All these were mainstream aircraft manufacturers, and as such, their involvement in these projects is immediately obvious. What is less obvious, however, is the large part played by an otherwise rather obscure subcontractor and builder of somewhat indifferent flying boats: Saunders Roe.

Why Saunders Roe? Their previous history had been that of a small but enterprising firm, involved both in marine work, and in aviation, and thus, not surprisingly, concentrating in the main on flying boats. It would be fair to say, however, that many of the flying boat designs were rather indifferent. It would also be fair comment to say that later, from the 1950s onwards, throughout their existence as Saunders Roe and later in various Westland guises, they worked on idiosyncratic and often quite advanced projects that would reach prototype stage, but rarely ever reached production. A review of the projects they undertook reveals programmes with technological fascination, but which were often dead ends. Among these can be listed:

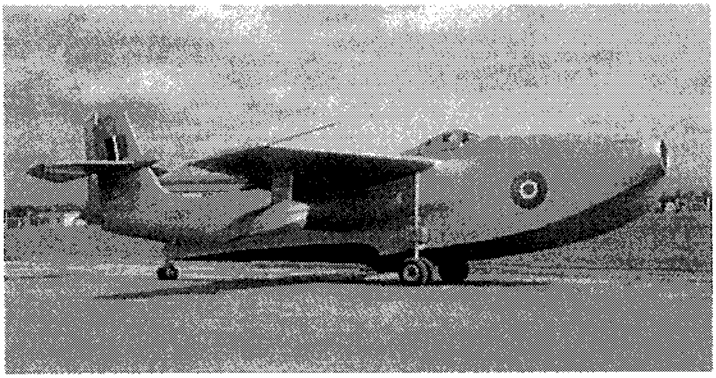
- the SRA/1, a jet engined flying boat fighter. Three prototypes were built, the first of which flew on 16th July 1947.
- the Princess, a very large turbo prop passenger flying boat. Three prototypes were built, the first of which flew on 22nd August 1952.
- the SR53, a mixed power plant (rocket/jet) supersonic interceptor. Two prototypes built. The project had its inception in 1952, and the first flight was on 16th May 1957.
- the SR 177, an extended version of the above. Prototypes were being built at the time of cancellation. Inception 1954, cancelled 1957.
- a design for the specification of F155, producing what would have been the very last word in rocket powered interceptors.
- a "hydrofoil missile" for the Admiralty. This was a design for a large hydrofoil craft, powered by a jet engine driving a large wooden airscrew, under radio control, and carrying sonar and a torpedo. Design study 1957.
- the Black Knight research ballistic rocket. More than 25 built; 22 flown. Inception 1955, first flight 1958, last flight 1965.
- the design brochure for Black Prince (see later) 1960.
- a design brochure for a liquid hydrogen stage for the Blue Streak satellite launcher (1961).
- the Black Arrow satellite launcher. 5 vehicles built, 4 launched. Inception 1963, first flight 1969, last flight 1971.
- the SRN-1, Britain's first hovercraft. Indeed, the firm for some years was known as the British Hovercraft Corporation, developing and building all the British hovercraft.

This is not an exhaustive list! Ironically, all these projects fulfilled their requirements. If Saunders Roe were asked to produce a design, they did so, and it would be fair to say that the designs were exactly what was asked for.. If that is the case, then it has to be asked whether the requirements were reasonable to begin with. Hindsight is very valuable, but it is pointless to castigate others for not foreseeing the future. However, a more polite way of rephrasing this would be to say that the projects investigated possibilities which might have had a fruitful outcome, and which were worth investigation for their potential.

In addition, the firm undertook a large number of design studies for other projects. Any firm of this sort will always be thinking of new designs, many of which will never see the light of day, but the Saunders Roe team produced an astonishing array of ideas. Again, most of these, like the ones listed above, are noted as much as anything for their eccentricity. Highest on such a list, second only to the hydrofoil missile, might come a study for a nuclear powered flying boat undertaken for the U.S. Navy.

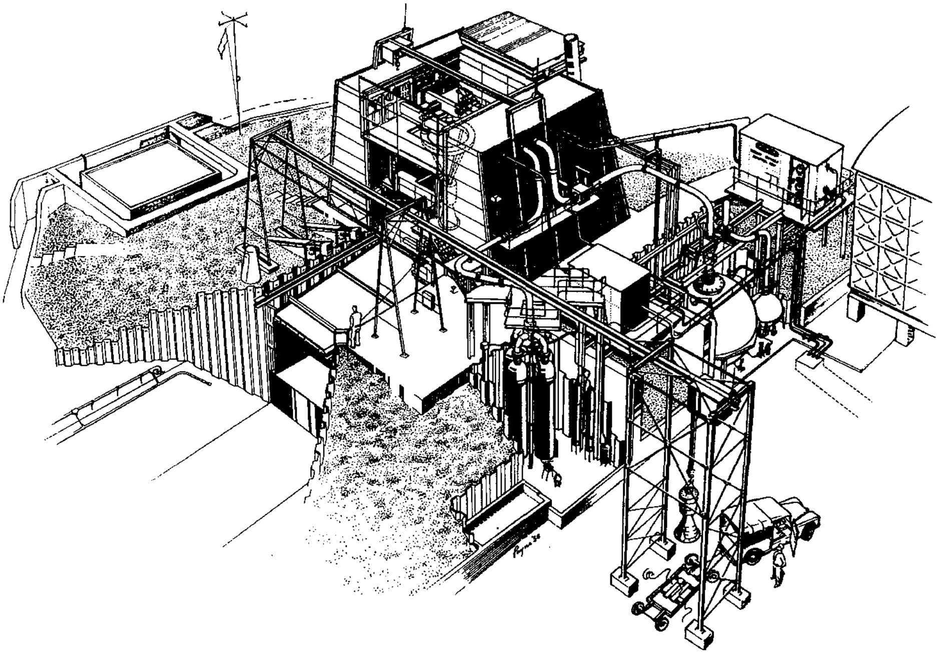
Money values.

It is almost impossible to convert from 1950s and 1960s prices to current prices. At a very rough estimate, multiply by 20. Thus, Black Prince at £35M could be obtained for the price of the Millennium Dome!



The SRA/1

This was a jet powered flying boat fighter designed by Saunders Roe near the end of the War. The remaining survivor is on display at the Aviation Hall of Fame in Southampton.



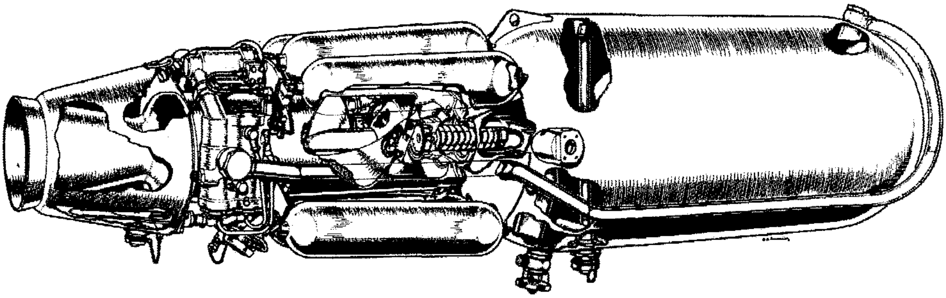
The P2 test stand at R.P.E. Westcott.

At bottom right a new rocket test chamber is being delivered. The motor would be fired in the main block top centre: the outline of a chamber is shown inside. Below the test chamber is the deflector bucket. The ancillary equipment around the test area would carry fuel and high pressure gas.

2. Rocket Motors

The technology of liquid fuel rocket motors.

The heart of a rocket motor is the combustion chamber, where fuel and oxidant are mixed and burned. Very occasionally, monopropellent motors are found, which decompose some unstable compound. The British used H.T.P. (High Test Peroxide, 85% H_2O_2 and 15% water H_2O) for this purpose in the Sprite and Super Sprite motors. The resultant gases are produced at high temperature and pressure, and expand out of the combustion chamber through a nozzle. There is usually an expansion cone—cone or bell shaped—to channel the flow further. This provides thrust: giving the hot gases momentum in one direction will also give the rocket and motor momentum in the other direction.



The de Havilland Sprite.

This was intended to assist the take off of the Comet airliner on high altitude airfields.

However, not surprisingly, there are various problems associated with all of this.

In the combustion chamber of a liquid fuel rocket motor, pressures are high—perhaps 30 times atmospheric pressure. In pounds per square inch, that would equate to around 450psi. In SI units, it would be 3MPa (3 megapascals). The fuel supply has to be at a higher pressure still, to force it into the combustion chamber at a sufficient rate. This might then be 600psi. The tanks of the rocket therefore have to be pressurised to more than this level, which means a sturdy and therefore heavy tank. In addition, the gas necessary to do the job has to be carried too, also in large heavy containers. This can be seen in the Sprite motor illustrated above. Alternatively, the propellants can be pumped into the combustion chamber. Such a pump is essential for any degree of efficiency in a rocket design, since there is a very large weight saving with the fuel tanks. Using pumps meant that the tanks can then be thin and lightweight.

A turbopump is comprised of two parts: first, a gas turbine, which then drives the second part: the two pumps, one for the oxidant and one for the fuel. Since they will not be needed in exactly the same quantities, the pumps may be of different sizes or driven via a gearbox. The gas for the turbine may be generated in many ways: one of the simplest is merely to burn the two propellants (but then they have to be forced into the turbine somehow!). The exhaust then drives the turbine. The pumps themselves are usually of the centrifugal type, rather like a turbine in reverse.

The figures below of fuel flows and combustion chamber pressures for some British rocket motors illustrate the need for pumps:

Screamer:	LOX: 23lb/s	Kerosene: 9lb/s	Chamber: 600psi
Gamma:	H.T.P.: 35lb/s	Kerosene: 4.4lb/s	Chamber: 450psi
RZ-2:	LOX: 390lb/s	Kerosene: 170lb/s	Chamber: 525psi

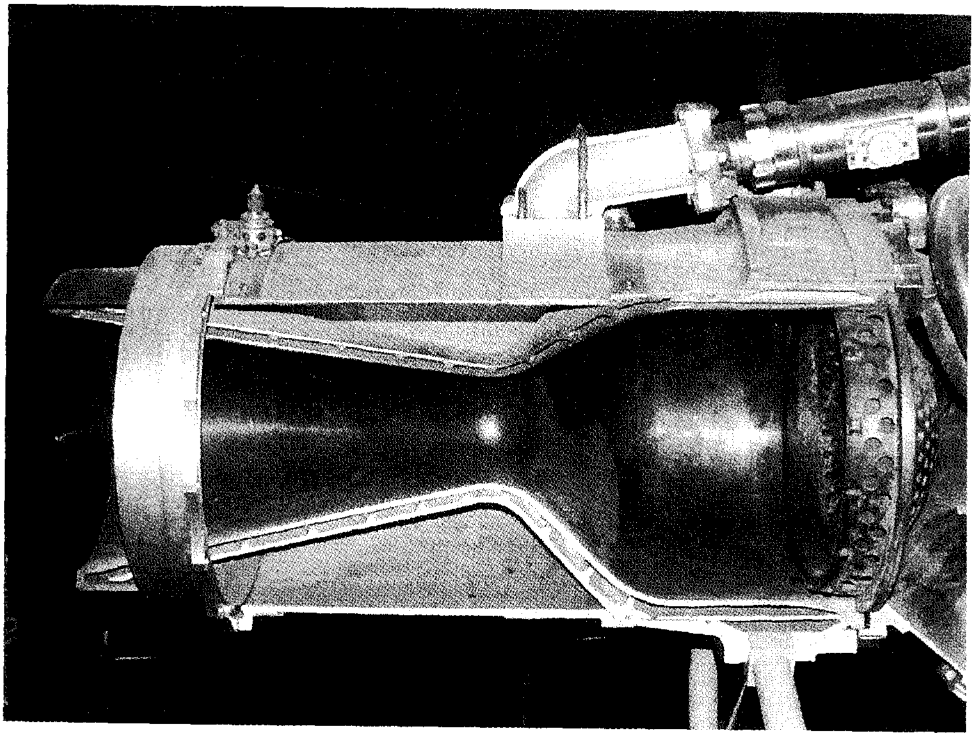
(for Blue Streak)
[*LOX = liquid oxygen*]

Moving such large quantities of fuel for Blue Streak requires powerful pumps. Early in the development of Blue Streak, tests were carried out at Hatfield on non flight models to ensure that it was possible to empty the tanks as quickly as this: with 2 motors, nearly half a ton of propellants per second were being consumed.

Having pumped the fuel in, it then has to be mixed efficiently before it can burn. The configuration of the injector plate is rather like a shower head. The two fluids then have to vaporise and mix.

A further problem is heating: burning hundreds of pounds of kerosene and oxygen each second in a confined space would melt the chamber walls very quickly. There are two solutions to this problem. One is film cooling: pure fuel is injected at the sides of the chamber so that there is a layer of insulating gas. The second is to cool the chamber with the propellants before they are burned—regenerative cooling.

The simple way of doing this is to make the chamber twin walled, and this approach can clearly be seen in the de Havilland Spectre motor shown in the photograph below. However, there is another, more efficient, method, which is to from many thin tubes into the correct shape, then braze them together. Reinforcing bands then usually strengthen the resultant chamber. This was the approach used for the RZ-2 motor used to power Blue Streak.



A de Havilland Spectre rocket motor

The Early Development of Rocket Motors in the U.K..

Lubbock and his co-workers at the Fuel Oil Technical Laboratory in Fulham, London were the first in the U.K. to work on liquid fuelled rocket motors. Their first design, called Lizzie, was fuelled by LOX (liquid oxygen) and petrol. It was a very simple device: the propellants were forced into the combustion chamber using high pressure nitrogen, so no pumps and other ancillary equipment were needed. It was intended for rocket assisted takeoff in aircraft such as the Wellington. In 1946 it was the first liquid fuelled rocket motor to be test fired at R.P.D. Westcott, and was eventually developed to give thrusts of up to 2000 lbf.

Lizzie was used to power the Liquid Oxygen Petrol/Guided Aerial Projectile, or LOP/GAP, which was an early test vehicle, fired from Aberporth in Wales, and later, the Rocket Test Vehicle 1 or RTV-1. Problems cooling the engine led to a change of fuel to a methanol/water mixture. This propellant was also used for the early rocket propulsion unit called Snarler, designed as a boost and climb unit for the Hawker P1072 in 1946. As a consequence of work with Lizzie, it was realised that hydrocarbons did not act as good coolants for rocket engines, and that their flame temperatures are also relatively high, exacerbating the cooling problem.

At this time, there was considerable investigation into different rocket fuels. Each had its advantages and drawbacks. For military purposes, solid fuel rockets are much to be preferred, as there is not the problem of sealing noxious liquids in their tanks. But in the late 40s, solid fuel rockets gave considerably inferior performance to liquid fuels, as their S.I. (Specific Impulse) was low, and the rocket cases, designed to contain high pressures, tended to be very heavy. They were also difficult to steer since the nozzles are fixed. Liquid fuel motors can be swung round, or gimballed. Hence for one of the U.K.'s earliest missile projects, the Navy's Seaslug, Red Fuming Nitric Acid and kerosene were chosen.

Liquid hydrogen and liquid oxygen are by far the most effective propellants, but liquid hydrogen is not easy to handle, boiling as it does at 20K or -253°C. Alternative fuels were considered—even liquid ammonia at one stage—but in practice kerosene was almost always chosen. Hydrazine and its derivatives have been widely used elsewhere, but not in Britain.

The most common oxidant for rocket motors is liquid oxygen, but alternatives that have been used are nitrogen dioxide (again, not in Britain), nitric acid and hydrogen peroxide.

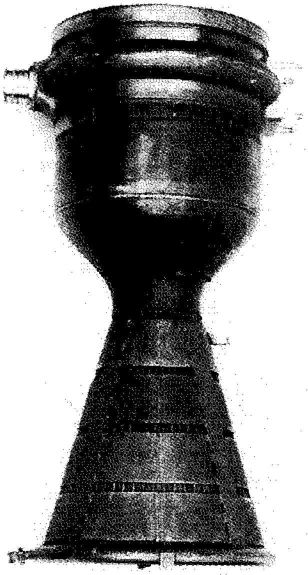
Kerosene and LOX were used as fuels in another rocket motor intended for a rocket powered manned interceptor, the Avro 720. The engine, called Screamer, designed and built by Armstrong Siddeley Motors, was to be of variable thrust, up to a maximum of 8,000lbf, and was first static tested in March 1954. It was, however, cancelled before being test flown in an aircraft.

At the same time, other research work was going on at Westcott. Their first experimental unit using H.T.P. and kerosene was christened Alpha, then, over the years, came Beta, Gamma and Delta. Alpha was again used for RATO, or Rocket Assisted Take Off. Beta was for a model aircraft propulsion unit and was the first U.K. engine to use a gas generator turbopump.

But in late 1952 the technical decision was taken by the Rocket Propulsion Department (R.P.D.) at Westcott that the preferred oxidant for all liquid propellant rockets was to be either LOX or H.T.P.. H.T.P. was reckoned to be the safest to handle in large quantities and in manned aircraft and so was preferred despite its relatively high cost. Storage was relatively easy, it was neither cryogenic nor corrosive, and did not produce toxic fumes. Having said that, it was not very stable, and had to be handled with great care. Any alternative suffered from one or more of these problems. H.T.P./kerosene engines also had the advantage that they were effectively hypergolic (self igniting) which had the further advantage that it could be easily restarted, which was certainly a useful feature for a manned rocket interceptor.

The Germans pioneered the use of hydrogen peroxide as a rocket fuel in the early 1940s, powering the Me163 rocket fighter, and the V2's turbine and fuel pump. British work was to take this much further. The key to a successful H.T.P. motor is the choice of catalyst. When the H.T.P. is passed over a suitable catalyst, it decomposes into steam and oxygen, and the decomposition is sufficiently energetic for the H.T.P. to be used as a monopropellant. However, it is much more effective then to inject a fuel into the steam and oxygen. In British rocket motors this was always kerosene. The kerosene ignites spontaneously in the hot gases.

Silver plated nickel gauze was used as the catalyst, and such catalyst packs could be easily inserted into the rocket chamber. The ratio of H.T.P. to kerosene was around 8 to 1. Although the combination does not give a very high Specific Impulse compared with many other fuel combinations, it has other advantages. Not being cryogenic, it can be left in the vehicle and does not needed topping up. Nor does it need insulation as liquid hydrogen does: the insulation adds to the vehicle weight. Further, H.T.P. is quite dense, 1375 kg/m^3, as opposed to 80 kg/m^3 for liquid hydrogen. This makes for a very much smaller volume and thus smaller tanks, again saving on vehicle weight. The later rockets developed using H.T.P. technology by the U.K. were structurally very efficient.



Gamma 301 combustion chamber

Other engines were then developed using this combination: Spectre, Scorpion, Stentor and Gamma. These were initially for aircraft use, although Spectre would be used in the Blue Steel standoff missile, and Gamma would go on to power Black Knight and Black Arrow. Most of these were developed by commercial firms: Scorpion by Napiers; Sprite and Spectre by de Havilland; Stentor and later Gammas by Armstrong Siddeley, as they were then. Sprite and Super Sprite were designed to assist the take off of large aircraft such as the V bombers and the Comet, but the increase in effectiveness of the jet engine meant that these units were obsolete before entering service in any major fashion. Scorpion and Spectre were intended for aircraft, to augment the jet engine. However, the H.T.P. combination was to represent the principal British contribution to the rocket field.

The U.K. was to make hydrogen peroxide technology very much its own: no one before or since has made use of it on such a large scale. Early German and British work used compounds of manganese in one form or another to decompose the peroxide, often injected with the fuel, leading to a very messy exhaust. The secret lay in a metal gauze, through which the H.T.P. was passed, and as it did so, decomposed to steam and oxygen at a temperature of around 500^{O}C. Into these hot gases a fuel could be injected, and at that temperature they burned spontaneously, meaning there was no further ignition needed. This was very convenient, particularly in the rocket aircraft and the Blue Steel missile.

The gauze was made of silver coated nickel, and a catalyst pack was fitted at the top of the combustion chamber. The space where this would be fitted can be seen in the photograph of the de Havilland Spectre engine above.

The Gamma 301 above derived from the small chamber of the Stentor engine for the Blue Steel missile. It was used in later Black Knights and went on to be the basis of the motors for Black Arrow.

The ring at the top of the motor was where the H.T.P. entered the motor, which was made of thin tubes formed to the shape of the chamber and brazed together. The bands around this are to strengthen the motor. The H.T.P. flowed down alternate tubes up the remainder to act as coolant, before being injected at the top. Around the combustion chamber, further down, is a ring where the kerosene was injected. Below is the largest such chamber made using this technology, capable of around 25,000lb thrust, made by Armstrong Siddeley for the Blue Steel missile.

The large chamber from the Stentor engine.

But Delta was to be one of the major projects at Westcott for some years. In the early 50s thoughts were being given to ballistic missiles, even if at that time they were still inchoate. Given the problems encountered with hydrocarbons, liquid ammonia was thought of as a possible fuel, with good cooling properties and a reasonable flame temperature. However, visits by the Westcott staff to the U.S.A., and observation of the work being done there, caused them to rethink the use of hydrocarbons. And so Delta was born. Delta was not a particular design, but rather a family of rocket motors for research, with no real specified application. The family comprised:

	Chamber	Thrust (lbf)
Delta 1	spherical	50,000
Delta 2	spherical	135,000
Delta 3	cylindrical	185,000
Delta 5	cylindrical	13,500
Delta 7	cylindrical	12,500

The Bristol Aeroplane Company now became involved in the work. Initially, in April 1955, it was given a contract for Delta 2, although this was soon abandoned in favour of Delta 3 (spherical combustion chambers had been used in the V2 motor, but were found not to be effective). With the licensing by Rolls Royce of U.S. technology for Blue Streak, these motors effectively became redundant other than for research. Hence the smaller engines were built for development trials. Work on Delta 3 started to run down, as it was no longer needed for the long range missile, but work continued on these motors for some time: the last firing of a Delta engine was in 1966.

The idea of the spherical combustion chamber was not proceeded with as it had too many drawbacks: all subsequent chambers would be plain cylinders. Delta 3 is the most interesting in that it would have been the starting point for a ballistic missile. Indeed, reasonably detailed sketches were made for a design of such a missile. However, when the Operational Requirement for Blue Streak was issued, it was realised that there was still too much development work to do on Delta. North American Aviation in the U.S.A. was by now well ahead of Westcott in the designing and development of kerosene/LOX engines. It was realised that to keep to the time schedule needed for Blue Streak, it would be necessary to take an existing American design and work on that. Hence an agreement was signed in August 1956 between North American Aviation Inc (N.A.A.) and Rolls Royce Ltd, which provided for the exchange of technical information on rocket engines over a period of 10 years. To licence this technology, Rolls Royce paid a capitol sum of $500,000, with an annual payment of $100,000 to N.A.A.. The N.A.A. engine licence was the S3, which Rolls Royce copied and renamed the RZ-1.

Early U.S. rocket motors used LOX and alcohol, and were V2 improvements and derivatives. A program began in 1952 to evaluate the use of hydrocarbons, effectively jet fuel, in place of alcohol. The Navaho cruise missile was the earliest test bed for this new motor. In the summer of 1954 NAA was given a contract to design a gimballed engine for Atlas, which was extended to include engine systems for Thor and Jupiter. Thor and Jupiter engines were to give 135,000lb thrust as opposed to 150,000lb for the main Atlas engines (this uprating can be done by increasing the pressure inside the combustion chamber, burning more propellant). The S-3D was intended for Jupiter, and the first engine tests were made in November 1955, with the first working engine being delivered in June 1956, and the first Jupiter launch in March 1957. It was to be a variant of this motor, rather than Delta, that powered the Blue Streak missile. Indeed, one of the sadder aspects to R.P.E. is that most of the work it undertook never found a direct application, from Delta to the silo research to the liquid hydrogen work.

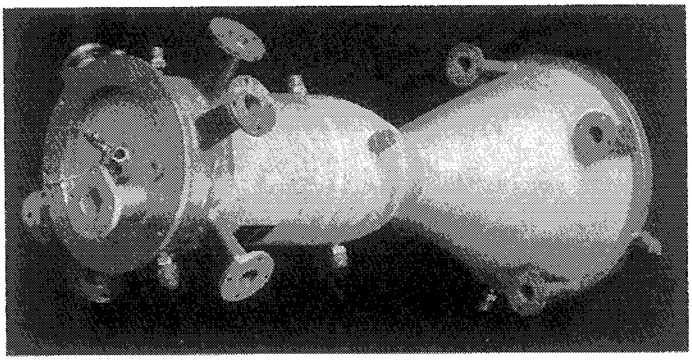
Liquid hydrogen motors.

For rocket engineers, the use of liquid hydrogen as a fuel is one of the Holy Grails. For British rocket engineers, it turned out to be like the crock of gold at the end of the rainbow, which always faded elusively away the closer they got to it.

A liquid hydrogen motor being fired at R.P.E. Westcott.

Liquid hydrogen is taken as one of the ultimate fuels as a consequence of its very high Specific Impulse (SI), the highest of all chemical fuelled rockets. This is the thrust obtained per unit mass of fuel burned per second. Under the old Imperial system of units, it was measured in seconds, but in the SI system is more correctly measured in metres/second. To convert, multiply by g (9.81N/kg).

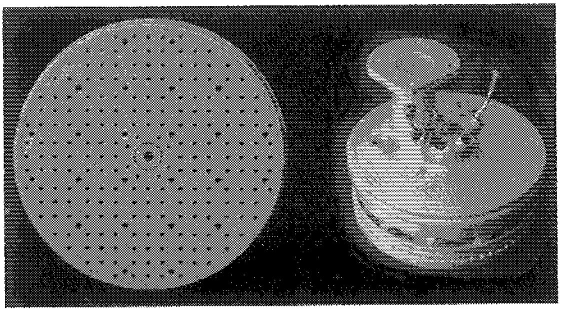
Although liquid hydrogen has this immense energy advantage, it has two properties which make it extremely inconvenient: an extremely low density of 80 kg per cubic metre, (as opposed to 1000 for water) and an extremely low boiling point (20K or -253°C). The low density implies a large volume of liquid and thus large tanks to hold it in, and as a consequence, an increase of the structure weight. Such a low boiling point means adding insulation to the tanks, increasing the weight further. Indeed, it is so cold that it has to be insulated even from liquid oxygen!



Liquid hydrogen chamber

This chamber is the one seen being fired on the previous page.

Work on hydrogen combustion chambers was being carried out at R.P.E. Westcott in the 50s by Jeffs, Ricketson and others. A long Technical Note was published on the experiments they had been doing using small combustion chambers of about 2kN or 450 lb thrust, at pressures of around 60N/cm^2 or 90psi, increasing to 100N/cm^2 (150psi). These were just experiments, however: no practical designs for motors emerged at that stage.



Injector head

This is from the motor above: the left hand view shows the holes through which the gases were injected into the chamber.

The first real practical interest comes in a proposal for a liquid hydrogen upper stage for Black Knight, a project that had its genesis in 1960. The advanced nature of this stage is illustrated by comparison with the U.S. programme: the first liquid hydrogen stage produced in America was Centaur, designed to fit on top of Atlas, and initially intended for a communications satellite. It was initiated late in 1958 by the Advanced Research Projects Agency at the Department of Defense and transferred to NASA in July 1959. The first launch was in 1962, but was a failure. Its role as a communications satellite launcher for geostationary systems meant that it needed a restart facility and the ability to coast in a parking orbit. For geostationary orbits the system is usually placed in a parking orbit, relit to put the stage into a highly elliptical transfer orbit, then fired yet again at the apogee of this orbit to convert the elliptical orbit into a high circular orbit.

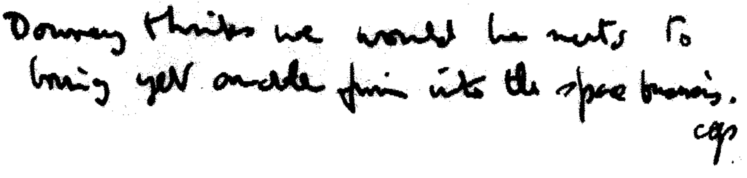
The liquid hydrogen Black Knight design was taken far enough for Saunders Roe to be making calculations on such matters as the lateral bending modes and the like in a technical publication of September 1962. However, the design is bizarre in one or two aspects: the first stage is a virtually unmodified Black Knight with 3 foot diameter but reference is made to the thrust being uprated to 50,000lb, although it doesn't say how. Also the 3 foot diameter and the large volume hydrogen tank makes for a vehicle around nearly 60 foot tall! This compares with around 34 foot for the single stage vehicle. There would have been a solid fuel third stage and the vehicle was estimated to be able to put 150lb in low earth orbit. In hindsight, the criticism would be that even with "tweaking" and solid fuel boosters, it would be difficult to get a substantially greater payload from the vehicle. A more useful design would have used a larger diameter vehicle, but this would have meant extra cost in redesigning the Black Knight part of the project.

The next time liquid hydrogen propulsion was considered was in the Blue Streak context. It is interesting that one of the most carefully considered early designs comes again from Saunders Roe (Technical Publication SP510 April 1962). Its origins lay in the Black Prince design and the need to increase payloads for communications satellites: specifically, to put at least 600lbs in a 5,000 nautical mile circular orbit. Hence in 1960 the R.A.E., Saunders Roe, and Bristol Siddeley Engines combined to produce the design criteria, which were taken as being a third stage of around 7000lb, of which 5000lb was propellant; that the engines should produce an SI of 400; and, most interestingly, that the vehicle should have two thrust phases: a boost phase of 3,500lbs for 8 minutes followed by 44lb thrust for 2 hours! The point of the low thrust stage was to work the vehicle up from low earth orbit in a series of spirals to the final altitude. In the end, the design study concluded that it would be possible to put 900lb in the 5,000 mile orbit, or 600lb into a 9,000 mile orbit. The engine would have 2 boost chambers that were turbo pump fed, and 2 cruise phase chambers running at a much lower chamber pressure; so low that they could be pressure fed. It might be thought that the low pressure chambers would be less efficient, but in the vacuum of space it makes no difference. At sea level however, the air pressure acts against the combustion chamber pressure, so that a high pressure differential is essential.

The paper goes into great detail as to the specifics of the design, considering various alternatives for each design feature, such as whether the insulation for the hydrogen tank should be on the inside of the tank or the outside? How should the tanks be insulated from each other? And so on. It is an impressive piece of design work.

At the same time, it is realised by the end of the design phase that Black Prince is not going to happen, and so the stage is designed to have a diameter of 70.8 inches to fit with a French 2 metre second stage. It is also slightly unusual to design a rocket stage entirely around one particular satellite orbit!

Further liquid hydrogen studies were undertaken for ELDO, and any useful satellite launcher derived from Blue Streak would need liquid hydrogen fuelled upper stages. But by this time, there had been forced amalgamations within the industry, and Bristol Siddeley engines had been taken over by Rolls Royce, who produced a design designated the RZ-20. Bristol Siddeley Engines, based at Ansty in Coventry, had produced several designs for liquid hydrogen motors and submitted them to the Ministry of Aviation in 1961. One such design would have powered the Saunders Roe third stage mentioned earlier. Having two firms interested was an embarrassment. Handwritten in the margin of one memo is the comment "Downey thinks we would be nuts to bring yet another firm into the space business" [*referring to William Downey, Under Secretary at the Ministry*].



Downey thinks we would be nuts to
bring yet another firm into the space business.
cap

"Downey thinks we would be nuts ..."

Throughout the 60s Farnborough and Westcott were maintaining their interest in liquid hydrogen. Below is a memo of 1963 showing the programme that was planned:

"2 Year Feasibility Study on Rocket Engine.

It is proposed that the main features of this programme should be studies and experimental work leading to the design of:-

(1) 4,000b thrust chamber
(2) 8,000lb thrust chamber
(3) Turbo pump for 8,000lb thrust capable of operating on the 'topping turbine' principle
(4) the use of a gas generator for turbo pump drive to be considered
(5) a separate turbine for each pump to be considered

(6) a control system for the engine of 8,000lb thrust including thrust and mixture ratio control

(7) all necessary valves, flowmeters, seals, piping etc.

Engine design should be such that the engine would be self operating ... and that repeated starts should not be precluded. Some components would require altitude testing conditions.

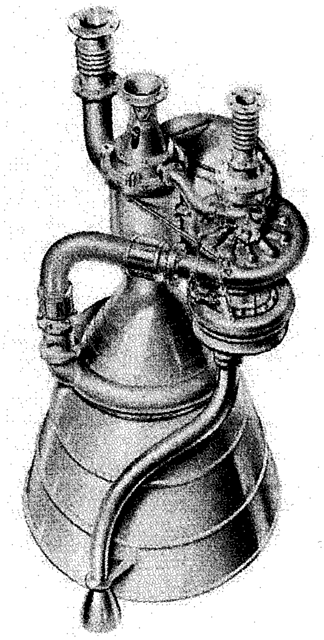
The choice of thrust level for the engine leads to a flexible arrangement such that one or more engines could be used for the following vehicle stages:-

(1) Present BK (Gamma 301 25,000lb thrust)
2 chambers or 1 chamber 8,000lb thrust 1 turbopump

(2) Suggested enlarged BK (Gamma 401 50,000lb thrust)
2 of above engines (16,000lb total thrust)

(3) Blue Streak ELDO Launcher
LOX/LH2 third stage one engine 8,000lb thrust)

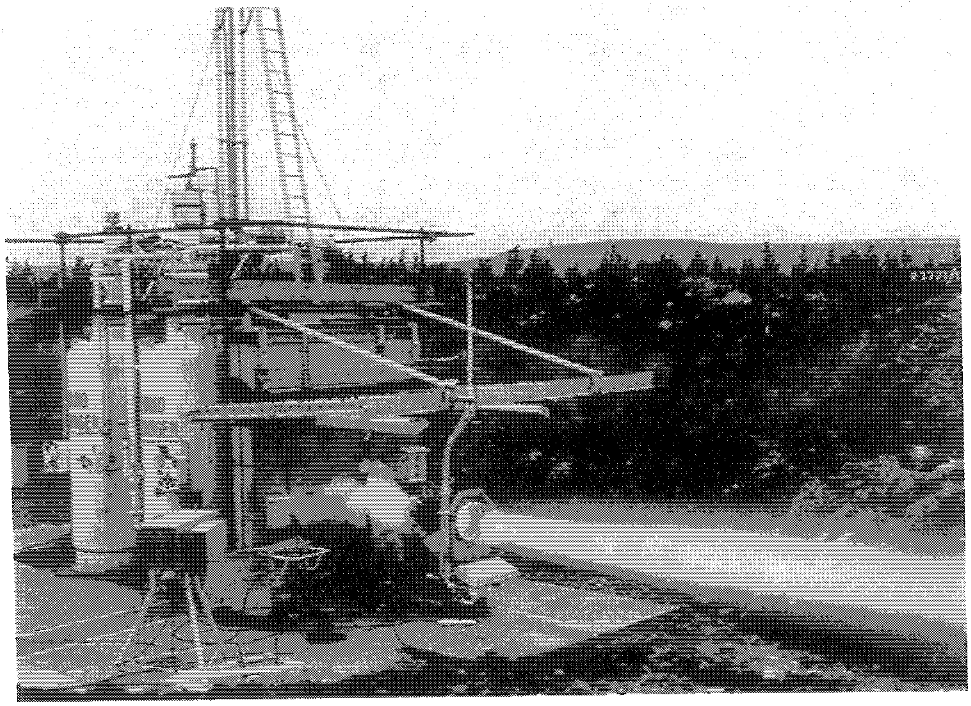
(4) Blue Streak ELDO Launcher LOX/LH2 second stage 6 engines 48,000lb total thrust."



The RZ-20 rocket motor

Within the context of the work to date this was quite reasonable: however, there was never the budget to develop any of these proposals into satellite launch vehicles. If these proposals had gone ahead, however, the U.K. would have been able to produce considerably more useful and powerful satellite launchers. Using the less advanced H.T.P./kerosene technology meant cheaper and possibly more reliable launchers, but restricted the payload considerably.

Work at R.P.E. began to wind down, but Rolls Royce was awarded a design study for a 60 kN vacuum thrust chamber by ELDO in 1965. Some of the work on this engine, the RZ-20, was carried out at Westcott as well as at Spadeadam.



RZ-20 test firing at Spadeadam

At 60kN thrust (equivalent to around 13,500lb) this gives more than twice the thrust of the Gamma motor as used in Black Knight or Black Arrow, or about half that of the large Stentor motor. However, liquid hydrogen/oxygen is much more effective than the H.T.P./kerosene combination; its specific impulse is nearly double. To put this another way, a liquid hydrogen stage would give the same thrust but burn for twice as long as an H.T.P./kerosene stage for the same weight of fuel. As a result, the payload from any liquid hydrogen stage could be very much greater.

But with British withdrawal from ELDO, funds for liquid hydrogen work decreased, and the company eventually produced only 2 chamber prototypes of the

RZ-20. Some of the preliminary work for this was done by R.P.E.. Using its own money, Rolls Royce constructed a test site at Spadeadam where one of these chambers was twice fired. But then the money finally ran out, and all further development work on the motor stopped, along with all the other U.K. rocketry work.

However, all this discussion cloaks one important point: by around 1960, the technology being explored by the U.K. was becoming mature. No doubt many of those employed in the firms at the time might disagree, but fundamentally, apart from the liquid hydrogen work, all the fundamental work had been done. For the next eleven years, what would follow would be merely further development work.

The major rocket motors used by the U.K. from 1950 to 1971 were, in order of size:

RZ-2 Rolls Royce)	5,000 -150,000lb thrust	Blue Streak
Large Stentor chamber (Armstrong Siddeley Motors)	24,000lb thrust	Blue Steel
Spectre (de Havilland)	8,000lb thrust	SR 53, test models of Blue Steel
Gamma 301 motor (Armstrong Siddeley, derived from small Stentor chamber)	4 - 6,000lb thrust	Black Knight, Black Arrow
Gamma 201 chamber [derived from R.P.D.'s Gamma motor]	4,100lb thrust	Black Knight

All these, with the possible exception of the Gamma 301 chamber, were developed in the 1950s. Developments of the Gamma motor continued for Black Arrow, but they were incremental in nature rather than any new major design.

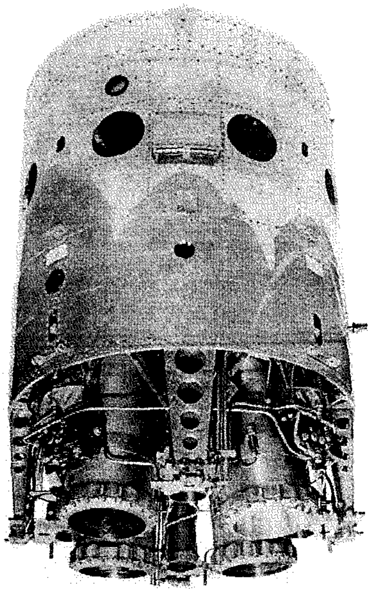
For comparison, the U.S. used very similar motors to the RZ-2 (which was derived from the U.S. motors) in Thor, Titan I, Jupiter and Atlas. Up until Saturn 5, the Apollo launcher, all the first stages of American satellite launchers used motors of this size. Typical motors for the second stage were:

Agena	16,000lb thrust
Able Star	7,730lb thrust
Centaur chamber	16,000lb thrust (2 per stage)

Thus, in the early 60s, U.S. and U.K. motors were comparable. It is Saturn and Apollo which leads to the very large liquid hydrogen motors that have gone on to power the Shuttle.

As a measure of the work being done by British firms on rocketry, the following figures were given in 1961 for the total expenditure to date (i.e., effectively, since the war):

	£ in millions:	dates
Napier:		
Double Scorpion	1.486	1955-59
de Havilland:		
Sprite & Super Sprite	0.881	1947-61
Spectre	5.576	1953-61
Research	0.254	1954-
Bristol Siddeley Engines Ltd:		
Snarler	0.226	1946-53
Screamer	1.222	1946-53
Stentor	3.4	1956-
PR 37/2 (Jindivik)	0.029	1960-
Gamma	1.6	1956-
Research	0.39	1955-
Rolls Royce:		
Blue Streak	5.379	1954-
Supply of H.T.P.	3.5	1946-



Gamma 201 as developed at R.P.E. Westcott
This powered the earlier Black Knights.

These costings do not include the work done at R.P.E. Westcott, which was considerable. The series of motors leading up to Gamma (Alpha and Beta) were developed there in the late 40s and early 50s. Rolls Royce used Westcott's facilities for early RZ-2 work, and R.P.E. also had its own on going liquid hydrogen work. In addition, Westcott was a major centre for the development of solid fuel motors.

However, by 1968 the picture had changed radically. Napier no longer existed, de Havilland were doing no more work on rocket motors. Bristol Siddeley and Rolls Royce had been amalgamated. There was just the one firm, and work was shrinking. Val Cleaver, in charge of the rocketry work at Rolls Royce, wrote to the Ministry of Technology to ask how he could keep his team together: "In this atmosphere, it is hard to maintain staff morale, or to retain the good people. Many of our best men have gone out of rocket work over the years (apart from a few who have left our projects, only to emigrate to the States), and we have been able to justify the recruitment of only a mere handful of bright youngsters in recent years."

The Director General (Engineering) at the Ministry of Technology then wrote to CGWL to explain: "My object in encouraging Cleaver to write to you was the conviction that the presently foreseen programme of liquid rocketry development implies the winding up of Rolls Royce's R&D activity in this field by the early seventies, and the facts need to be faced now, both by Mintech and by the Rolls Royce management."

He then went on to give the following figures for future planned expenditure, based on no further commitments to ELDO, one Black Arrow firing a year, and a limited programme on packaged propellants:

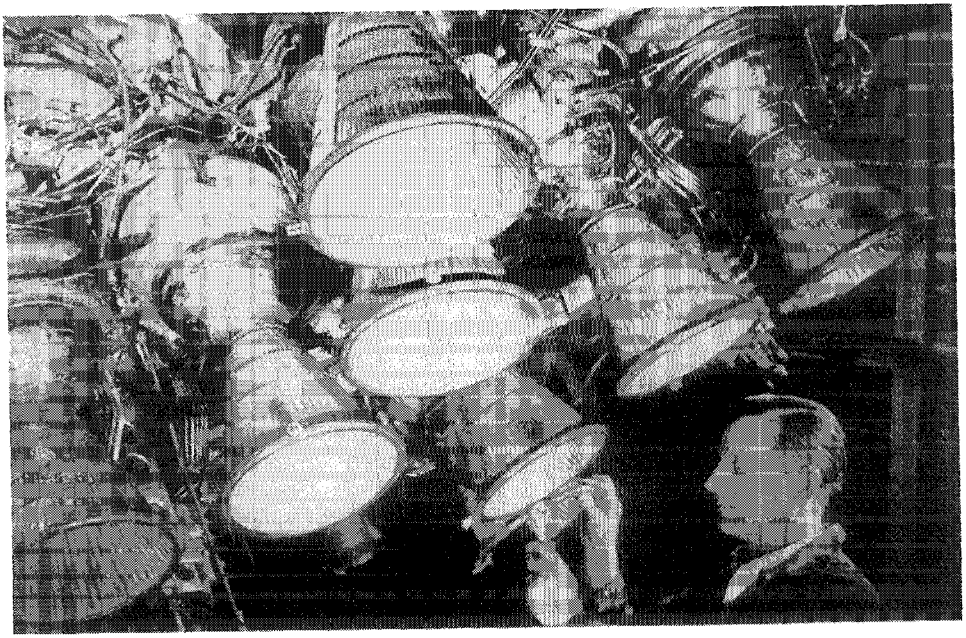
Year:	67/8	68/9	69/70	70/1	71/2
Black Arrow	.460	.390	0.85		
Utilisation	.276	.287	.287	.287	.287
RZ-2 1-10	.695	.400	.170		
RZ-2 11-13	.115	.550	.350	.280	
Thrust chamber	.027	.200	.120		
Stentor	.049	.035	.020		
High speed Pump	.028	.025			
Cryogenic pump	.004	.004			
Project K	.002				
Packaged propellant	.010	.085	.100	.150	
	1.656	1.900	1.117	.667	.437

[all these figures are £million]

It is not clear whether this includes work on the RZ-20 liquid hydrogen motor, which was being carried out under an ELDO contract (and part of the funding had came from Rolls Royce itself). But it does show very clearly that virtually no new work had been initiated since the early 60s, and what work was left would soon end.

Indeed, one of Cleaver's complaints was that it was all obsolescent technology. The RZ-2 had been designed in 1955, 13 years earlier, and although since refined, there was nothing further to be done with it. Similarly with the H.T.P. work: all that was left was derivatives of the Gamma motor, which had started life again in the mid 50s as the small chamber from the Stentor engine. The liquid hydrogen work was being run on a shoe string.

In the event, work effectively finished in 1971, with the demise of Black Arrow and of Europa. Since then there has been no significant rocketry work done in the U.K..



The Gamma 8 engine that powered Black Arrow.

3. Rocket Interceptors

An Overview.

In 1945 the R.A.F. and U.S.A.F. had indisputably the world's most powerful strategic bomber fleet, yet they were on the point of becoming obsolete, and the factor that was driving them obsolete was the jet fighter. The increase in performance that the jet engine gave to interceptors rendered the likes of the Lancaster and its derivatives hopelessly vulnerable. If airborne radar and guided weapons are added to the armoury of the fighter, the balance tilts even further away from the bomber.

One answer, of course, was to build jet powered bombers. The Air Ministry had been aware of this for some time, and before the war had ended, had issued the Operational Requirements that would lead eventually to the V bombers, which were probably, apart from the development of atomic weapons, the major part of the post war defence programme. Similarly, the Americans, while having pushed their propeller driven designs as far as feasible, were also busy designing jet bombers in the 1950s, culminating in the B52, still in service.

In post war Europe, the strategic focus for the Western Allies switched very rapidly from Germany to Soviet Russia. The Soviet Air Force was also a formidable fighting machine, although it had evolved along lines more tactical than strategic. It had on the drawing board, some impressive interceptor aircraft such as the MiG 15.

The first rocket powered interceptor of all was the German Me 163, which was used in the latter stages of the War against the high flying daylight bombing raids by American B17s. They were small and simple, using a wheeled trolley for take off, and a skid for landing. Their endurance was extremely limited, but they had by the standards of the time a phenomenal rate of climb. However, despite their impressive performance, they had very few "kills" credited to them.

But the Me 163 obviously impressed the British Air Staff, and proposals for a very similar aircraft began to emerge in the late 40s. The designs being considered were for a very similar aircraft: a rocket motor with no other means of propulsion, a simple skid for a dead stick (i.e., unpowered) landing, and a battery of unguided 0.5" rockets. It was intended for point defence: e.g., for airfields and the like. With its limited endurance it was not suitable for much else. Such an aircraft would have been able to carry enough fuel for only 3 or 4 minutes powered flight. In effect, it was almost a manned guided missile. In addition, an unpowered landing technique would not have made it popular with pilots.

In 1945, the whole strategic equation had been rewritten with the advent of the atomic bomb. There was no great urgency for the rocket interceptor in the immediate war years, since the Russians had built a formidable tactical air force, but had almost nothing in the way of heavy bombers. In addition, in 1945 it was thought that the Russians would not have atomic weapons until the mid 50s. In the event, the first Russian fission bomb was exploded in 1949. And a further difficulty was that any jet atomic bomber would be flying very high, very fast. Up until the 60s, the bomber's best defence had always been height. The higher the aircraft, the more difficult it is to detect and the more difficult it is to hit with conventional antiaircraft shells. For interceptor fighters, the choice was either to loiter at high altitudes, which, given their limited endurance, was not usually a feasible option, or to reach these heights as quickly as possible. In the 1940s, the performance of the jet engine was not sufficient to do this. The problem was to get an interceptor to that height quickly enough, and to give it sufficient speed differential to be able to manoeuvre into a position in order to be able to attack. It was further realised that such attack would probably be made by guided weapons of some form—either infrared, heat seeking, or radar controlled.

There was a fundamental problem, however, with an aircraft that small, in that it would have been able to fly only in daylight and reasonably good weather. This would be a problem that would plague all the designs until the later P177 and F155 designs. It is curious, given these limitations, that there was so much interest in the design. When Churchill was returned to Government in 1951, he took a personal interest in the project, asking Lindemann, his scientific advisor and eminence gris, to look further into the idea. But the R.A.F strategic offensive had been entirely night based, and the R.A.F had rarely encountered the Me163, and knew of it mainly by reputation. Similarly the German offensive against the U.K. had been mainly night based after the early attacks in 1940. It was only the Americans, with high flying well armed Flying Fortresses who attacked during the day. So why were the R.A.F so interested in a fighter that could be used only in daylight? One answer, of course, is the defence of the airfields where the V bombers would be based—effectively point defence.

But despite this, the Air Ministry issued Operational Requirement 301. The main points of the designs requested were that they should be relatively simple and would use rockets for the main propulsion. However, quick calculations would show that the endurance of such an aircraft is extremely limited. Let us do some order of magnitude calculations.

Given a rocket motor with an S.I. of 200 seconds and mean thrust of 4000 lb (the Spectre was rated at up to 8000lb thrust, but could be throttled) then the fuel consumption is around 20 lb per second. Given that the aircraft might carry 6000 lb of fuel, this gives a powered flight time of 300 seconds or 5 minutes! This is not long in which to take off, intercept, and shoot down an incoming aircraft at an altitude of almost 10 miles.

There are other problems too: high speed, supersonic, aircraft make very poor gliders! If the pilot's interception takes him too far from his base, then he will be forced to eject. Similarly, every landing will have to be one chance only. And landing such an aircraft unpowered would be a pilot's nightmare. It soon became obvious that an auxiliary turbojet would have to be fitted. This extended the post interception phase and enabled the pilot to "go round again" if there was a problem on landing.

But there can be other criticisms of the basic concept. The OR stated "in order to facilitate ease and speed of production, the aircraft and its equipment are to be as simple as possible." This, however, was a mistake. Although it is very tempting to go for a simple design on these grounds, any such design would have some fatal flaws. The first is that there was no inbuilt air to air radar, which would have been no novelty in 1952, and the lack of it would be a severe handicap for high flying interceptor aircraft. It can also be argued that owing to the limited nature of the O.R. that obsolescence was inevitable. The aircraft would be restricted to ground control and daylight interception. Would ground control be readily available in a nuclear war scenario?

Again, to quote from the O.R.: "Current day interceptor projects are expected to be adequate in performance to match the enemy threat in normal circumstances, but may be unable to destroy enemy aircraft carrying out special operations at exceptional heights.

"An aircraft to fulfil this requirement must have an outstanding ceiling and altitude performance. So far as is known at present, the characteristics can only be provided by rocket propulsion, and, although aware of the probable operating limitations of this method, the Air Staff consider that the promise of tactical advantage more than outweighs other considerations."

It is surprising in other ways that the O.R. was put in this way. As mentioned, Bomber Command throughout the Second War carried out the vast majority of its raids at night. Indeed, in the late 40s and early 50s a considerable amount of work was carried out on a radio controlled weapon carrying a television camera—Blue Boar. But one of its problems was that if used at night, the TV camera was useless, which is one of the reasons the project was dropped. It was only the U.S. Air Force, accompanied by escort fighters, that carried out daylight raids. So O.R.301 was in danger of becoming a requirement for an interceptor without a target.

But another key phrase is, of course, "special operations at high altitudes". This is an oblique way of referring to the nuclear armed bomber, and there is one crucial difference between a conventional and a nuclear bomber. With conventional bombing, it is acceptable that most get through the defences. Indeed, during the Bomber Command offensive, the German defences would be congratulating themselves if they inflicted 10% losses. In nuclear terms, this is completely reversed. Even 90% losses on a bomber fleet could mean devastation. This was the philosophy behind the rocket interceptor.

In any event, designs were sought from all the major aircraft firms—Blackburn, Westland, Fairey Aviation, Saunders Roe and Bristol, among others. Saunders Roe were not originally on the list, and given their previous work, this is not surprising. However, they had gained experience of modern aircraft with the

SRA1, a jet propelled flying boat fighter. Bizarre though this concept might seem (it was intended for the Pacific war against Japan), it had 2 axial flow turbo jets, and, given the limitations on the design posed by its aquatic role, had a very respectable performance.

These designs were passed through to R.A.E. to "score" them on a complicated points system. The two that fared best were the Saunders Roe P154 and the Avro 720. The basic difference between the Avro design and the others is that Avro chose liquid oxygen and kerosene as fuels, as opposed to H.T.P./kerosene. The Gamma and the de Havilland Spectre rocket motors were the H.T.P. choices. H.T.P. was undoubtedly safer in a crash, although any rocket aircraft was inherently dangerous, owing to the explosive nature of fuel and oxidant.

But the limitations of these designs became obvious. Saunders Roe then came up with the suggestion that the aircraft should carry an auxiliary jet engine, and have proper landing gear. The point of the jet was to supplement the rocket, and then to provide a limited cruise facility, followed by a return to base. The jet engine was of relatively low thrust compared with the rocket, but had high endurance. The Spectre was of 8,000lb thrust; the Viper jet engine of 1850 lbs. This suggestion was also under consideration by the Ministry, and so Saunders Roe produced modified designs. The SR 53 design then emerged from the various proposals.

Avro and Saunders Roe were instructed to build three prototypes each, before the first of many defence economy axes fell. The projects were put on hold. Eventually the Avro prototype, though nearly complete, was to be dropped. Saunders Roe was asked to build 2 prototypes of the F138D/SR53 (the first designation was the Ministry code for the project; the second was Saunders Roe's). But Saunders Roe pressed on with further designs. The SR53 was finally felt to be too limited, even though it was a great step forward from its predecessor, and Saunders Roe proposed the P177, with a much more powerful jet engine, and limited Air Interception capabilities, in other words, a radar set mounted in the nose. Both the R.A.F and Navy were impressed with this design, and for once, the two Services were in full agreement over a project. Saunders Roe were asked to produce an initial 27 aircraft. The 2 prototype SR 53s were proceeded with so as to give experience with the concept.

But a variety of factors led to the cancellation of the 177. The main reason, although not the commonly accepted reason, was a change in defence policy. At this time, the decisions about future defence projects and related policy were taken on the basis of reports by a committee chaired by Sir Frederick Brundrett, known as the Defence Research Policy Committee, or D.R.P.C.. The work that had been done on guided weapons, or surface to air missiles, was reaching fruition in the form of the Bloodhound missile. Further, it was proposed to defend the V bomber bases not with conventional warheads, but with nuclear tipped missiles. The rationale for this lay in an effect which the British had worked on under the name of the R1 effect.

Nuclear warheads are susceptible to radiation in the form of neutrons or X rays, and considerable work had been done at Aldermaston to render U.K. warheads immune to these effects. However, it was still thought worthwhile to attack the Russian equivalent of the V bombers with missiles armed with 10 kiloton warheads. The lethal range of these warheads to aircraft was given as 600 yards, but their effect on the bomb that the aircraft might be carrying would be much greater.

As it was, the nuclear Bloodhound defence system was itself abandoned a few years later, when it was realised that the threat had switched from bombers to ballistic missiles, although Bloodhound was still deployed extensively in a conventional role. However, even this would have rendered the P177 obsolete.

Almost co-incidental with this change of policy came a change of Prime Minister, when Eden resigned to be replaced by Macmillan. Macmillan wanted defence economies, and with that in mind, appointed Sandys as Minister of Defence. Very soon after the appointment came the 1957 Defence White Paper; indeed, so soon that most of the policy must have been established prior to Sandys. The 1957 White Paper become famous for three points: the abolition of National Service, considerable cuts in Defence spending, and cancellation of various aircraft projects in favour of missiles. On closer examination it is difficult to see how many other projects other than the rocket interceptors were cancelled, but it produced a considerable psychological shock to the British aircraft industry. There was a strong sense that there would be "no more manned aircraft" for the R.A.F..

So despite a bitter rearguard struggle fought by the Minister of Supply, Aubrey Jones, the P177 was cancelled. The Admiralty in particular pressed Sandys hard, and forced him eventually to admit that although the Navy needed the aircraft for its carriers, the Defence Budget could not afford it. Both Saunders Roe and the Ministry of Supply tried hard to sell the aircraft overseas: there was Luftwaffe interest, and Saunders Roe prepared brochures for the Australian and Swedish Governments. However, Brundrett was against even this idea, arguing that we were trying to sell an aircraft which was obsolete, and that the Germans would be better off buying missiles from the U.K.. At the end of 1957 the Germans decided not to buy the aircraft; instead, they bought the Lockheed F-104 Starfighter, which became notorious in later years for its accident rate. Lockheed also had ... persuasive ... selling tactics unlikely to be matched by a small firm on the Isle of Wight!

The Lightning interceptor remained after the 1957 White Paper: later marks had almost the same capability as the P177 (and the same weakness in terms of endurance). It also showed the usefulness of a manned aircraft in the many interceptions carried out along the north and east coasts of the U.K. against long range Russian aircraft probing British air defences.

Both the Lightning and the P177 fitted the specification for which they were designed more than adequately: the problem was not with the aircraft but with the specification and the changes in both technology and policy as the Ministry of Supply lumbered through its slow development procedures.

The apotheosis of the concept of the rocket interceptor was a design submitted by Saunders Roe for the Air Staff requirement F155. Saunders Roe‘s design brochure is very impressive, leading to a behemoth of an aircraft with two jet engines with reheat and 4 rocket motors. This was an interceptor capable of taking on anything. It was also immensely huge, rivalling in scale even the TRS2. Indeed, its size was to be its downfall. The original specification had been for an aircraft to carry 2 infra red guided missiles and 2 radar guided missiles. Issue 2 specified one type or the other, with an option to switch. But whereas the other firms submitted their modified design, Saunders Roe stuck to their leviathan, and it was promptly discarded by the Ministry on grounds of size and expense. Fairey and Armstrong Whitworth were the chief contenders, with machines half the size, but again the project was never completed, falling foul of the same change in defence policy.

So the end result of all the work was the two flying prototypes of the SR53, and these were never to be other than research machines. But more than anything else, the concept had proved fatally susceptible to "bracket creep" over a period of ten years, from an extremely simple, almost crude, initial concept, to a highly sophisticated final series of designs. There is a saying, attributed to Voltaire, that the best is the enemy of the good. If the R.A.F had wanted a good point defence high flying interceptor, it could have had such a machine with 50 or so SR53s by the mid 50s. The concept of the rocket interceptor never had a chance to prove itself, partly because the window of opportunity in the technologies available was relatively narrow. This window was never fully utilised by the often slow progress of Operational Requirements through the Air Ministry, Ministry of Supply, the budget limitations, and the desire to go one better as each design became finalised.

Rocket engines did have their drawbacks in the form of relatively limited operating time and use of exotic and expensive fuels. There must have been a question about their reliability, too. One of the 2 SR53 prototypes crashed after an aborted take off, but whether this was due to a fault in the rocket motor was never fully established.

The other factors leading to cancellations were the enforced defence economies, the constant improvement in jet engines, and the development of guided weapons. The role of interception was to be taken by the Lightning aircraft, which although it too had an impressive rate of climb to altitude, was also limited by range, at least, in the earlier marks. But it was the advent of guided missiles, principally Bloodhound, deployed along the East Coast V bomber bases and at R.A.F. bases elsewhere, which finally killed off the rocket interceptors.

Designs in detail.

The F138/SR 53.

As mentioned, the original Operational Requirement, O.R. 301, in July 1951 did not specify a jet engine; the aircraft was to be purely rocket propelled. A meeting of the O.R. Committee at this time said that "it would be a very local defence weapon" and so "The possibility of fitting a small turbine to assist the landing was then discussed but ruled out on the score of weight.". The armament was to be a battery of 2 inch air to air rockets. As an indication of the number of aircraft firms that there were at that time, tenders were invited from Bristol, de Havilland, Fairey, AVRoe, and Short Brothers. Copies for information were sent to Armstrong Whitworth, Blackburn, Boulton Paul, English Electric, Gloster, Percival, Saunders Roe, Supermarine, Westland, Folland, Handley Page and Scottish Aviation!

In the minutes of the F.124 tender Design Conference in July 1952, it was announced that "General agreement was reached that only the Saunders Roe, AVRoe and Bristol A design remained in the competition..." and that "Saunders Roe had submitted very good designs on two previous occasions and he felt that their design team were so good that it would be a mistake for it to be disbanded as would be the case unless the firm received a contract soon".

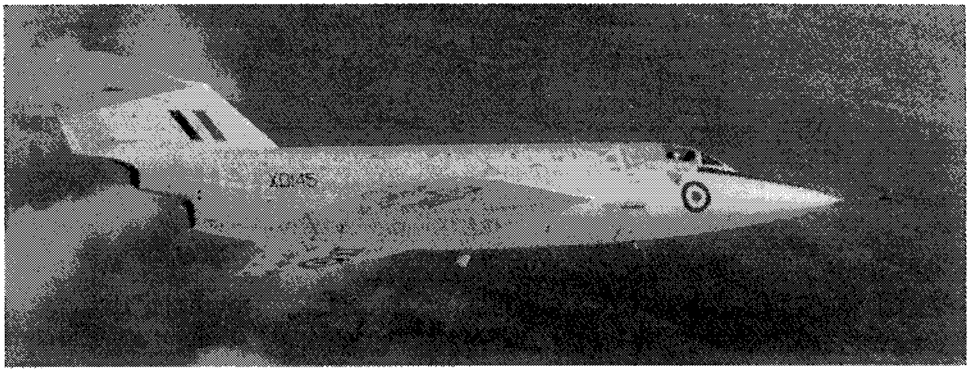
There are two curious points about this: the fact that it had taken a year to evaluate the designs, and the comment on Saunders Roe design team: contracts were often awarded for seemingly obscure reasons. So it was recommended that 3 prototypes be ordered from Avro and Saunders Roe.

However, the huge increase in the defence budget in 1950 could not be sustained, and economy again became the watchword. This meant that 3 prototypes could not be afforded; despite R.A.F. preference for the AVRO design, the Ministry of Supply decided to press on with the Saunders Roe design, but with only two prototypes.

But there is an interesting comment from the OR committee sometime later, in June 1953: "... the changes in requirement that have been brought in from time to time have moved the design some way from the basic conception of a simple rocket aircraft—and there is some danger, in my opinion, that the final weapon will be less effective than it might be ..". Indeed, in a sense this remark could be said to be the essence of the whole story.

However, work progressed rapidly with the SR53: in October 1952 there was a structures meeting between Saunders Roe and the R.A.E., and a preliminary mock up meeting in Cowes in September 1953.

The final delay in the completion of the first aircraft, XD 145, was delivery of the Spectre I motor: this could not be delivered to Cowes before mid December 1955. The motor had earlier been installed in a Canberra for flight trials. By mid-June 1956 the aircraft was completed, then dissembled for transport to the Aeroplane and Armament Establishment at Boscombe Down. Here it was put together again, and the first rocket engine firing was on 16 January 1957. The first flight took place on 16th May. The second aircraft, XD 151, was first flown on 18th December 1957.



XD 145 on an early flight.

This photograph shows what a graceful and good looking aircraft the SR 53 was.

But, the SR 53 was intended to be a lead in for the P177, and the cancellation of this aircraft, after long debate, meant that the aircraft had lost its purpose. However, it was felt that in many ways the SR 53 was a unique aircraft that could be used for aerodynamic research, rather as the X planes in America. Accordingly, proposals were put forward for enhancing the performance. It was estimated that the Spectre 1 rocket motor in its then state of 7,000lb thrust, and S.I. of 190s, gave a maximum velocity of Mach 1.8 at 60,000ft and a maximum height of 76,000ft. Thus a meeting in May gave some options for further development:

"(ii) Spectre 5 engine	95,000ft or M1.8
"(iii) Twin Spectre	125,000ft or M2.3

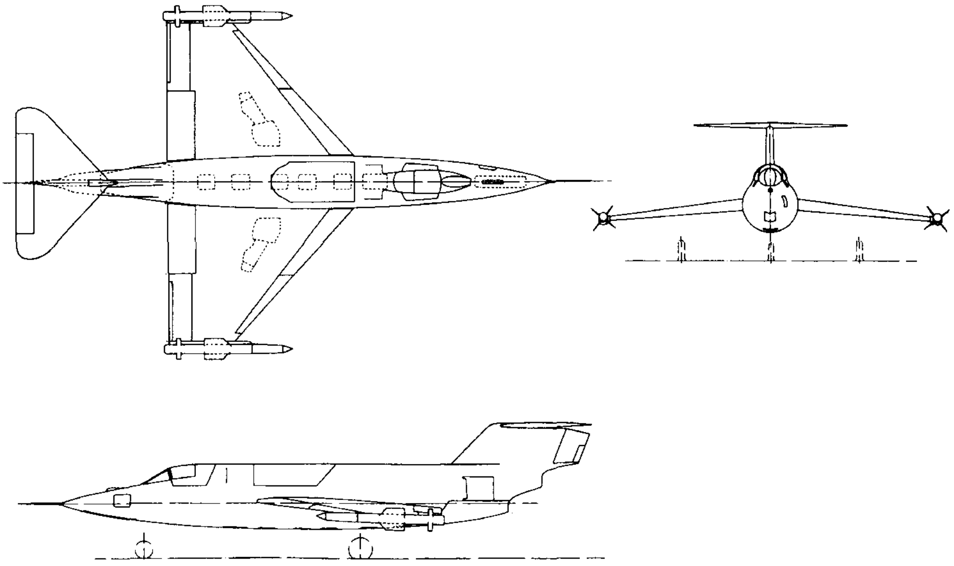
"(iv) Spectre 5 and airlaunch at 40,000ft and M0.8 gives 115,000 ft or M2.9"

The Spectre 5 was an improved version of the rocket motor; the Twin Spectre, as its name suggests, stacked two such motors together. But meanwhile the performance of the aircraft was being reduced by the inability of the Spectre to reach its target performance of 8,000 lb thrust.

Unfortunately, the SR53 as designed was not that well suited for the task, and most of this kind of research had already been done by 1958. As it stood, there were constraints on the airframe, being all aluminium. Kinetic heating meant that certain key parts of the airframe would have to replaced by stainless steel, and work was done on this by the design team at Osborne House on the Isle of Wight.

Several scenarios were sketched out: with no armament, more fuel could be carried. The jet engine could be removed, and with a more powerful rocket engine and still more fuel, the flight envelope could be extended further. Also suggested was the use of solid fuel Mayfly rockets to assist take off, and, in the piece de resistance, air launching from a Valiant was proposed. All this would have made XD 154 Britain's answer to the X-15! The Valiant could take the aircraft up to 40,000 feet at a speed of Mach 0.8. Unlike the American X-15, which was underslung, the proposal was to mount the SR53 on top of the Valiant.

Saunders Roe produced an impressive sheet outlining the possibilities. Again, all this took its time to work through the Ministry of Aviation's bureaucracy.



SR53 plan view

In the meantime, flight trials went ahead, with XD145's flying supersonic for the first time at around 45,000ft on its 31st flight, on 15th May. But disaster overtook the programme on 5th June when XD151 crashed during an aborted takeoff on its 12th flight. A long and thorough investigation followed. Here is an excerpt from the report.

"Circumstances.

"The aircraft taxied out at 1200, and the Spectre was started at 1203. Approximately 5 secs elapsed before the engine went 'hot' but this is understood to be normal. The aircraft lined up on the runway and after cockpit checks were completed, and 10° flap selected the aircraft commenced to take off. The aircraft accelerated normally and the nose wheel was raised. About 30 secs after the pilot had reported 'hot', he was heard to call "Panic Stations" and then a moment later "Come and get me will you". The anti-spin parachute was seen to stream, but the aircraft ran off the end of the runway. Upon impact with a runway marker light pole, a chain fence with concrete posts and finally a large marker light the aircraft broke up and caught fire. The pilot was killed.

"Technical Investigation.

"An analysis of the film shows that the take off was abandoned at a very critical stage when the aircraft was half way down the runway and on the point of becoming airborne. The rocket is shown to have ceased to run hot i.e. no flame, at this point. It could not be determined whether or not the rocket was deliberately throttled back by the pilot. There is no sign of the airbrakes having been opened and the aircraft left the runway at an estimated speed of about 145 knots."

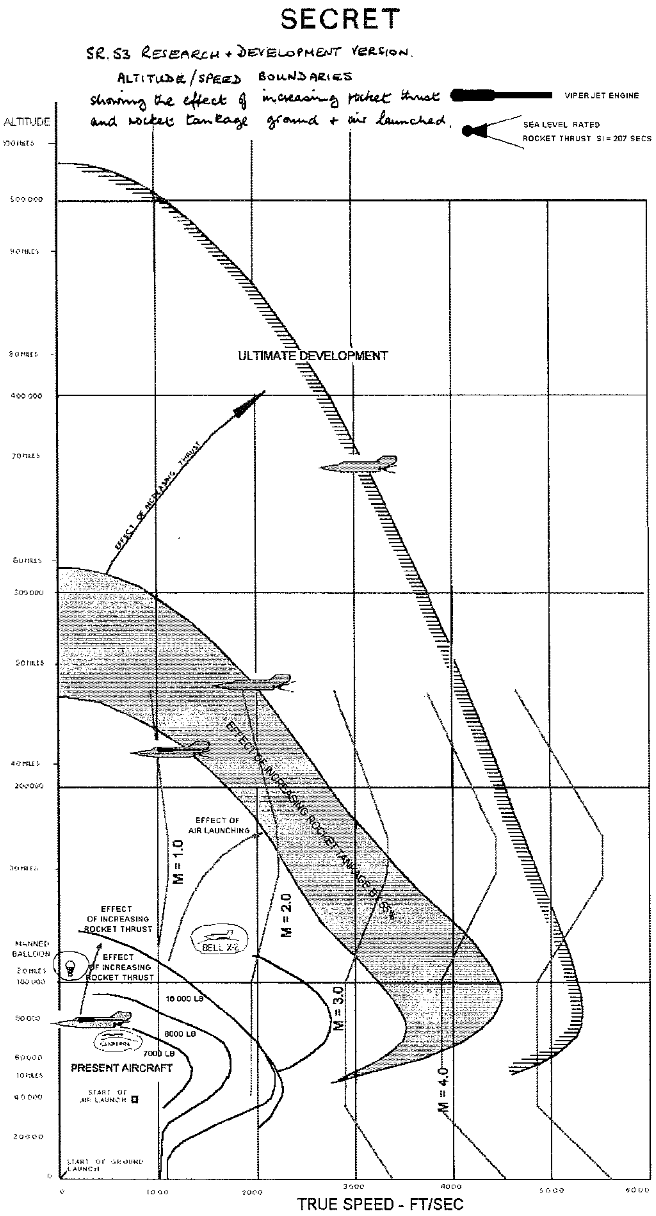
The aircraft was on its take off run, just becoming airborne, when the rocket motor abruptly cut. Whether the pilot took this action was never established, like so many other details of the accident. The aircraft braked hard, but overran the runway. It might still have survived but for a wing catching an obstruction, a runway lamppost. As the aircraft disintegrated, the rocket fuel ignited in a fierce conflagration. No cause for the accident was ever established, and there was no evidence of pilot error. Saunders Roe‘s chief test pilot, John Booth, was killed in the accident.

SR53 crash investigation

It cannot have been terribly re-assuring for Peter Lamb to have the wreckage in the same hangar!

With the investigation producing no clear result, the flight test programme continued, and XD 145 made a total of 56 flights, or 22 hours flying time. Peter Lamb, Booth's successor, described the SR 53 as "an extremely docile and exceedingly pleasant aircraft to fly", which, given the kick the rocket engine must have produced, says a lot about the aircraft. It reached a maximum speed of Mach

1.33, not an exceptional speed, altitudes up to 55,000 ft, but certainly lived up to expectations with a climb rate of 29,000 ft per minute.



The proposed research programme for the SR53.

By the time the Ministry had decided to go ahead with the possible research project, Saunders Roe had been taken over by Westlands. Westland's policy was to drop fixed wing aircraft development to concentrate on helicopters (and Saunders Roe would later become, for a time, the British National Hovercraft Company). Saunders Roe's Chief Designer, Maurice Brennan, responsible for all the fixed wing designs, had moved to Hawker Siddeley. The Ministry talked to Hawker Siddeley, but concluded "... it was not clear for some time whether Westlands would be willing to take on this work using the existing Saunders Roe team for the purpose, but they eventually decided to concentrate their activities on helicopter work and decline all fixed wing business. We had no alternative but reluctantly to accept their decision. However, Saunders Roe's Chief Designer had by this time joined Hawker Siddeley and asked the latter to consider taking the job on. Having examined the matter with them, we reached the conclusion that we could not obtain by this means the programme of work that we wanted within the amount we had set aside for it ....". The programme was finally closed in July 1960.

XD 154 was set aside at R.P.E. Westcott, and fortunately has been preserved. It is now in the Aerospace Museum at Cosford, with many other famous prototypes, including the TSR 2 and Bristol 188.

Facts and figures.

The SR 53 was a relatively small aircraft, only weighing 7,400 lb empty, but 18,400 lb fully fuelled. It was an extremely elegant aircraft, its only drawback in looks being a slightly tubbiness in the fuselage as a consequence of the large amount of fuel that needed to be carried. The wing span without missiles was 25 ft 1 inch, and it was 45 foot long.

The P177.

This project grew from the realisation of the limitations of the SR 53. It would have been a larger aircraft, with a much more powerful jet engine: the balance of jet and rocket would be almost equal. In addition, it was given a limited Air Interception capability, which extended the range of weather conditions and night time operations. Co-incidentally, the Navy were looking for a high flying supersonic interceptor at the same time, and both Services, rather unusually, concluded that the same aircraft would suit them both. Proposals were sent to the Ministry of Supply in March 1954 and a design contract was placed with the company in May 1955. With remarkably little fuss, development of the 177 began in autumn 1955, and work proceeded steadily throughout 1956.

A memorandum by First Lord of the Admiralty in April 1956 set out the navy's case for the aircraft:

"The P.177 is a single seat high altitude fighter capable of operating at a sustained speed of M=1.4 in the 40,000 to 60,000 ft height band; its ceiling will be in the region of 75,000 ft and it will be capable of reaching M=2 for short periods. It will be armed with 2 Blue Jay Mark 3 air to air Guided Missiles, with unguided rockets as an alternative armament. It will be equipped with A.I. [*A.I. = airborne interception*] and will have a limited capacity for night operations. ...

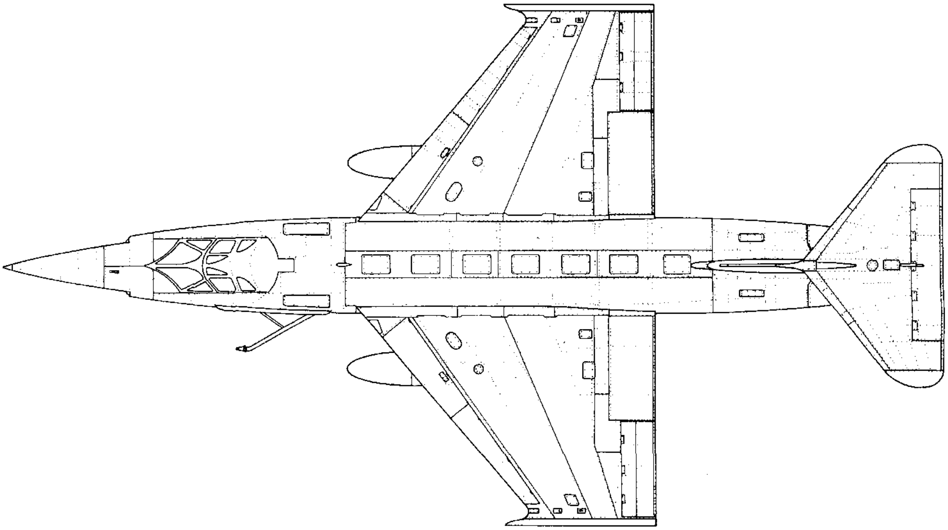
"The P.177 was selected by the Naval Staff because:-

(i) It is one of the very few British aircraft likely to be better than anything American when it comes into service.

(ii) It is the only aircraft required by both the Navy and the R.A.F.

(iii) Its engine, radar and weapons are already being developed for other aircraft, so that the development costs should be comparatively low.

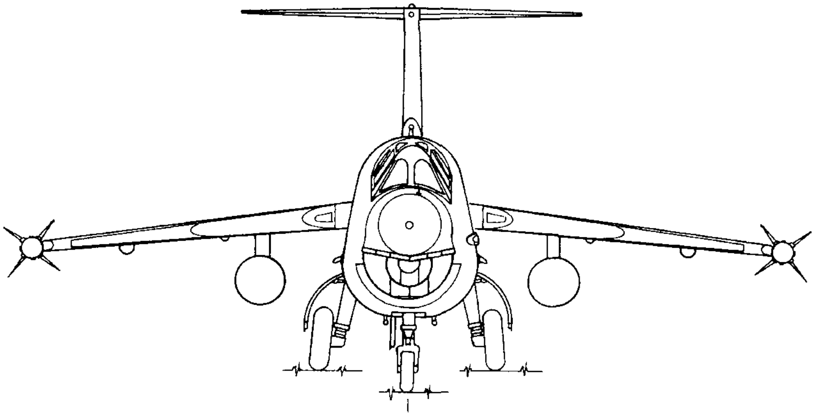
(iv) it is smaller and cheaper than the N.113 and its early substitution for that aircraft will save production expenditure."



P177: top view

However, two factors now intervened to threaten the project. One was a change in defence policy with regard to manned aircraft, and the second was a need to reduce the U.K.'s defence spending. With the arrival of Duncan Sandys at the Ministry of Defence, and the resultant 1957 Defence White paper, the R.A.F version was cancelled forthwith. As the White Paper put it: "Work will proceed on the development of a ground-to-air missile defence system, which will in due course replace the manned aircraft of Fighter Command. In view of the good progress already made, the Government have come to the conclusion that the R.A.F are unlikely to have a requirement for fighter aircraft types more advanced than the supersonic P1, and work on such projects will stop."

Given the extent to which the R.A.F was threatened, the 177 was relatively small fry, and the R.A.F was still promised the P1 interceptor, or Lightning as it became known in service.

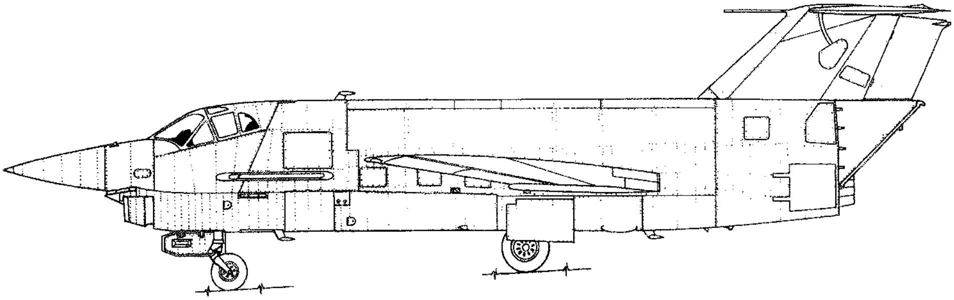


P177: front view

However, the Navy was still very insistent that they needed the 177, and at the same time, Aubrey Jones, who was Minister of Supply, wanted to keep the project going, as there was German interest in the aircraft. A prolonged Whitehall battle then ensued. Sandys told the Navy quite firmly that the aircraft, irrespective of merit or the Navy's need, could not be afforded. In the same way he told Jones that if the Ministry of Supply wanted to keep the project under way then it would have to go on his budget, not Sandys'.

All this wrangling cannot have helped the progress at Saunders Roe, or the prospect of trying to sell it to the German Air Force. After all, if the R.A.F. version had been cancelled and then the Naval version, this cannot have inspired confidence in the project. In addition, not everyone wanted to sell it to the Germans. Sir Frederick Brundrett, Chief Scientist at the Ministry of Aviation is on record as saying that the German requirement "was for a high-altitude quick climbing defensive weapon. There was no doubt that they would be best satisfied with a guided weapon and in his view the right course was to interest them in our own Stage 1 and Stage 1 and a half guided weapon developments rather than the P.177." The Germans didn't share his view however, and in December 1957 the project was finally cancelled.

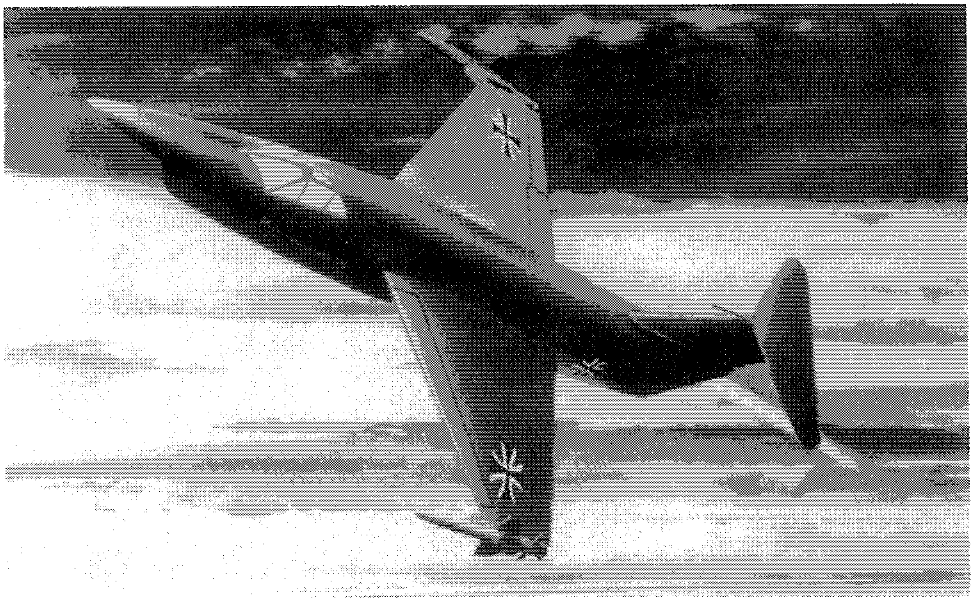
Would the 177 have lived up to expectations? There is a strong probability it would have done: its smaller sibling, the SR53, did all that was expected of it. The R.A.F were left with the Lightning; the Navy with nothing. It could be argued that the 177 would have been too specialised for the Navy: it would not have been able to maintain a continuous Combat Air Patrol, as its endurance was too limited, although it was intended to fit a probe for air to air refueling. But that was not its function: it was intended to by pass the patrolling function by its ability to reach high fast targets quickly. The concept was never put to the test—but by the late 50s it was becoming obvious that jets such as the Lightning with reheat on the engines could do the job as effectively as rockets.



P177: side view

The Lightning, however, went on to prove its usefulness against the Soviet aircraft that during the 60s and 70s attempted to probe British airspace. A manned aircraft does have some advantages over missiles, as the Falklands demonstrated. In reality, both are needed; they are complementary.

The Germans went on to buy Lockheed F104 Starfighters, as did many other NATO countries. Saunders Roe was a minnow by comparison with Lockheed. And whether as many 177s would have fallen out of the sky as 104s is also an interesting question. But the most fascinating image is of the 177 in Luftwaffe colours!



The F177 as it might have appeared in German Air Force colours.
An interesting but unlikely speculation!

Facts and figures.

The 177 was a good deal less elegant in appearance than the SR 53; the rather bulbous fuselage and pointed nose above the air intake detracting from its appearance. It was twice the weight at 14,500 lb empty, and 28,000lb at extended load. The span was 27 ft, and it was 50ft 6 inches long. It was within about 6 months of its first flight when the project finally cancelled in December 1957.

The F.155T/P187.

This chapter on the rocket interceptor would not be complete without a mention of the behemoth, the grandest conception of all, the P187, which was the design that Saunders Roe produced for the Ministry of Supply Requirement for a further rocket interceptor, the F.155.T.

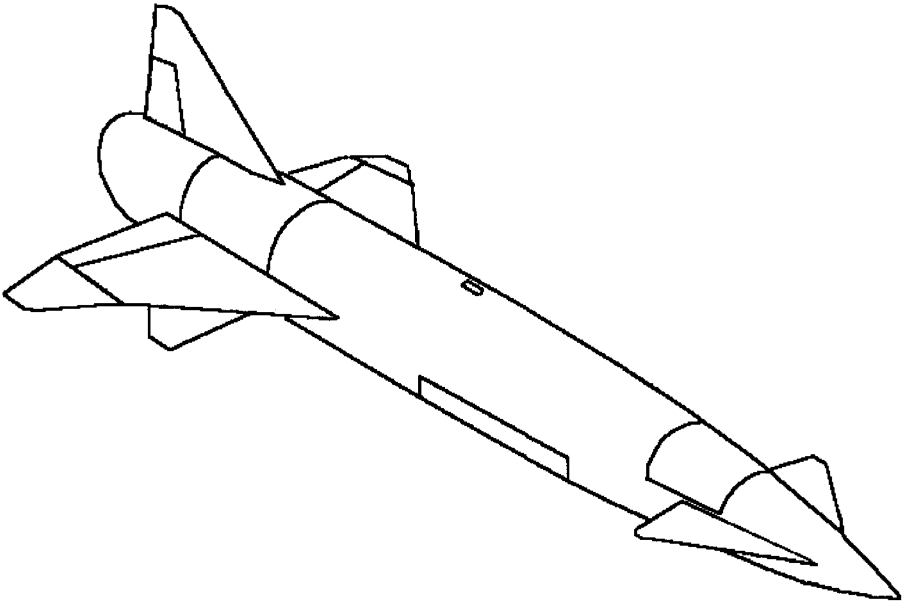
The P187 was a beast of take off weight 97,000lb and 83 foot long, carrying two Gyron jet engines with reheat and 2 Double Spectre (i.e., with 4 rocket chambers) motors, which would give it four times the rocket thrust of the SR53 or P177. It would have been armed with 2 Red Dean missiles, which were radar guided from the aircraft, and 2 Blue Jay missiles, which were infra red homing missiles. With an H.T.P./kerosene ratio of 2:1, it could intercept a Mach 3 target flying at 70,000ft over a front of 80 miles, and this in 1955! Its ultimate combat radius was 260 miles, and it carried 2 crew. It also had a sliding nose for better visibility for landing or for combat. Saunders Roe produced an extremely impressive and lengthy design brochure for the aircraft, but, sadly, it was to remain a paper project only. The project was a victim of Saunders Roe's desire to produce the ultimate interceptor, irrespective of size or cost. It was rejected almost out of hand by the Ministry of Supply as being too large and costly, in favour of designs from Fairey and Handley Page, but with the change in defence policy that had cancelled the 177, these two were never proceeded with, either.

Below is a comparison of the three aircraft, and shows the immense size of the P187. It is comparable in weight to the later TSR2, itself rejected on the grounds of size and cost.

	weight	length	span
SR53	18,400 lb	45 ft	25 ft
P177	26,000lb	50 ft	30 ft
P 187	97,000lb	84 ft	53 ft

A history of the SR53 and 177 projects written by the Air Ministry can be read in Appendix A.

4. The Blue Steel Stand Off Missile



Blue Steel: a perspective view.

If Britain had built the V bombers as strategic bombers capable of launching a nuclear attack, then it was logical to think that the countries threatened would take care to defend their own cities. In other words, that Moscow would be protected by guided weapons similar to the Bloodhound missiles that Britain was developing at the same time for the same purpose. Bloodhound was radar controlled, used a ramjet engine, and had a range of up to 50 miles. There were even proposals at one stage to equip them with nuclear weapons, since, in the early fifties, it was assumed that any nuclear threat would come from high flying, possibly supersonic, aircraft. Threat implies counterthreat, and the Air Staff was working on the assumption that from about 1960 onwards, the V bombers would be unable to penetrate the Moscow air defences.

The next question was then how to deliver the Bomb from this time on. In the early 50s, ballistic missiles were not yet an option. And Britain had invested heavily in the V bomber force, so that any ideas to prolong their active life would be very welcome. Hence the idea of a "flying bomb" evolved. Initial ideas soon after the War had centred on a system called Blue Boar, which was a television guided glide bomb. This however proved too limiting. Instead, thoughts turned to a longer range powered device. This was not a flying bomb in the V1 sense, whose guidance had been extremely limited, but one that would be able to deliver its payload with considerable accuracy. Nor would it be a cruise type missile, since the technology for long range guidance, terrain following radar or satellite navigation also didn't exist. Instead, inertial guidance would be used, which could be accurate enough at relatively short ranges. The missile would be released from the aircraft, immediately climb to a considerable height, cruise at high speed, around Mach 2, then dive down onto the target.

The theory was all very well, but the reality was something else in 1954. Britain was still working on its first fusion bomb, so it was difficult to estimate what payload size and weight would have to be carried. The next problem was the inertial navigation. As the U.S. was discovering with Snark, Matador and Regulus, navigation over considerable distances was a problem. This was one of the reasons why a range of 100 nautical miles was chosen for Blue Steel. The problem was made more difficult since it would be launched from a moving aircraft whose own position might be uncertain. A further problem with cruise type missiles is their relative vulnerability to enemy defences, unless they fly at a very low level, which was, again, not possible in 1954. Hence Operational Requirement 1132 specified a speed of Mach 2.5 at 70,000 feet or higher for the vehicle. But in 1954 supersonic speeds were an area still fraught with unknowns, and supersonic wind testing was still very difficult. Yet another problem was that at these speeds the skin of the vehicle would start heating up as a result of friction with the air. Aluminium airframes would not be suitable (this is one of the reasons why Concorde and similar aircraft are limited to Mach 2.2) and the only real alternative was stainless steel, which was difficult to work with. This was more unknown territory.

All of this was summed up by a memo from the Ministry of Supply, appropriately enough on 5th November 1954, by saying: "Present estimates are that medium range GW defences will make it excessively dangerous for the V bombers to fly over, or within about 50 miles of the target in 1960. ... The requirement is therefore for a flying bomb which will have its maximum use between 1960 and 1965. .... It is expected that a fusion warhead will be available by 1960 and it seems generally agreed that the bomb should be designed to carry this warhead."

The early files note that in some respects the project is almost equivalent to building a fighter aircraft. It would have no instruments and so on, but certainly was aerodynamically novel, and with an autopilot connected to the inertial navigator in place of a human pilot. As a further minute of November 1954 put it: "This bomb is indubitably much simpler than a fighter aircraft in the range of equipment that has to be provided. On the other hand it is a big step to go from the present speed range to Mach Nos. of 2 and above and again in comparison with the development of a manned fighter, it is to be expected that the production of the many vehicles required for firing trials will lengthen the development time." That was certainly an accurate forecast!

Accordingly, in September 1954 a letter was sent to the V bomber firms with data for a possible missile. At this point the design had not been thought through in any detail, and there were up to 6 different possible configurations under consideration—some with ramjets and solid boosters, others with liquid fuelled rocket motors. The V bomber firms had then to start thinking how they were going to carry the missile.

Vickers, who made the Valiant, were the initial favourites for the contract, which eventually, despite misgivings, went to A.V. Roe, but this, was now in early 1955. For a project whose time scale was so urgent, this was tardy behaviour. It has been said that the U.K.'s procurement policy at this time was seriously flawed: apart from anything else, there were three ministries involved in the development of a project such as Blue Steel: the Ministry of Supply, the Air Ministry, and the Ministry of Defence.

Sir Frank Cooper, later Permanent Secretary at the Ministry of Defence has this to say about procurement policy with regard to TSR 2 in particular, but the criticisms can be applied more widely.

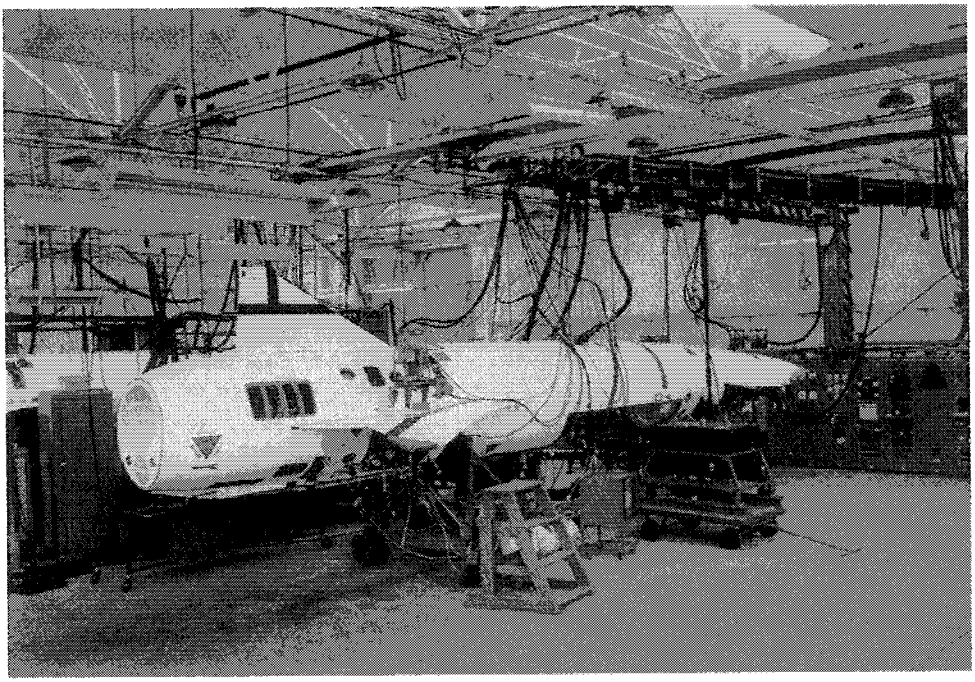
"There was no doubt that relations with the Ministry of Aviation/Supply and the Air Ministry went from bad to worse and that these poor relations spread increasingly to the Ministry of Defence as a whole. The breach itself was of long-standing. The basic cause was lack of trust, particularly as regards the information received by the Air Ministry. The trust was lacking because the Procurement Ministry stood between the Air Ministry as the customer, and industry as the supplier. Moreover nothing seemed to arrive at the right time and at the right price, let alone with the desired performance. The lack of trust was exacerbated by the financial arrangements under which the Ministry of Supply/Aviation recovered production costs from the Air Ministry but was left with the research and development costs. Hence, there was no clear objective against which the supply department could assess performance and value.

"The continual slippage of the forecast in-service dates added to the general air of despondency. All the changes were in the wrong direction and it hurt. Slippage contributed to the ever-diminishing credibility of the Ministry of Supply/Aviation and, indeed, of industry."

All this could equally be said about Blue Steel during its development, exacerbated by choosing a contractor not on the basis of their expertise, but on other, more diffuse grounds. Indeed the extant papers of the Ministry of Supply give no real reason at all for the choice. A.V.Roe had no guided weapons expertise, and had to set up a special department for the purpose, headed by R.H. Francis, who had previously worked at R.A.E.. His approach was the more measured one of a

Government department rather than the more urgent and commercial approach of a firm engaged on an urgent defence project.

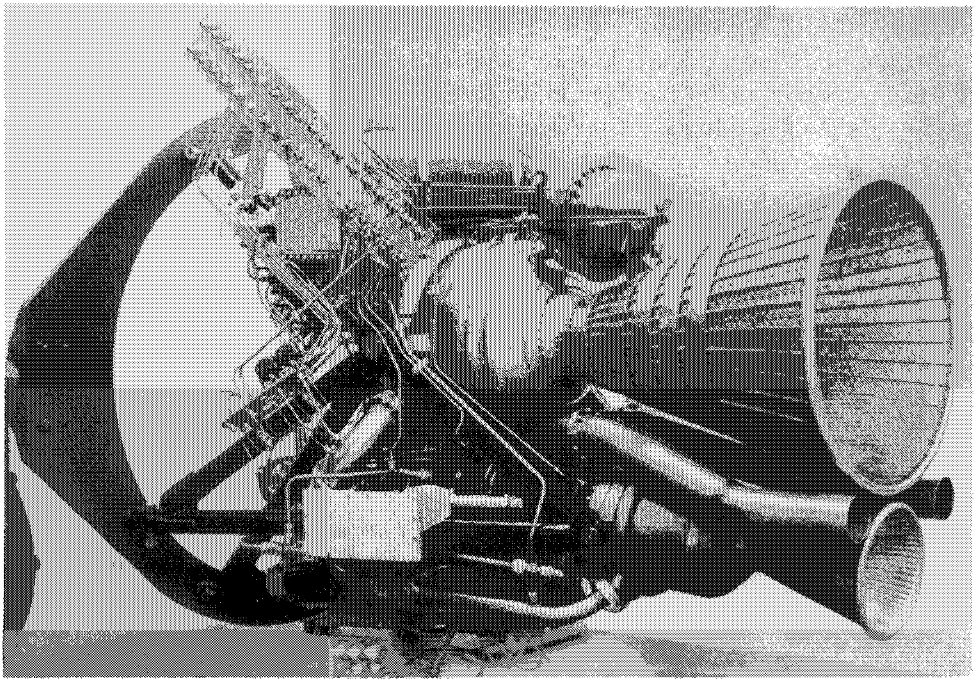
And A.V. Roe's time schedule began to slip. They had had no experience with guided weapons, and the division had been set up from scratch. Having built up a team, they produced a design, then tested the aerodynamics on a 1/8th scale model, moving up to a 2/5th scale model. These were tested by using solid fuel boosters at the R.A.E. range at Aberporth in Wales. Then variants made of light alloys rather than stainless steel were tested. For full scale missiles, the range at Woomera was brought into use—which entailed further delay as specially equipped Valiants had to be prepared. Although the Valiant was not to carry the operational weapon, they were used in early trials. The company intended to build and test missiles designated W100, which were effectively prototypes, and not the final design.



Blue Steel maintenance.

The problems were many and varied. The Auxiliary Power Unit, made by de Havilland, was particularly troublesome. The unit used H.T.P., which was catalytically decomposed, and the gases produced then drove a turbine that in turn drove the generator. Sloshing of the fuel caused problems too, and the missile went through some vigorous manoeuvring as it climbed, levelled off, then went into its final dive. Indeed, in April 1960—the year the missile had been due to enter service—the first 3 W100 rounds had been fired at Woomera and each had failed to follow the launch programme. And the minutes of the second meeting of the Blue Steel Management board talk about A.V. Roe's "dismal record at Aberporth" when talking of the delays in flight testing. The first round approximating to the final version was not successfully flown until 1962.

The problems led to the R.A.E. being called in to assess A.V.Roe's performance, and a series of Study Groups were set up. In December 1960 comments were made to the effect that the design of the missile was sound enough, but that "the standard of engineering is poor in a number of respects, with far too little emphasis on reliability studies." But eventually the final versions of the missile—late though they were—were much more reliable.



The Stentor engine that powered Blue Steel.

The engine has 2 chambers, the larger for boost, the smaller for cruise. The large chamber thrust is around 25,000 lb, the smaller is 6,000lb. The two pipes between the chambers are the exhausts for the turbine that drives the pumps.

In addition to the structural problems, the inertial guidance and autopilot, provided by Sperry, presented a new range of challenges. Despite the difficulties, particularly with gyros, the guidance was ready in time for the trials. Looking at the electronics with a modern eye gives pause for thought: all the circuits are pre-transistor, and use valves! This in turn led to high power consumption and associated heating problems.

The engine chosen for Blue Steel was designated the P.R.9, which became known as the Stentor, built by Armstrong Siddeley (later to become Bristol Siddeley). It had two combustion chambers, one of which was of fixed thrust of 25,500lb at 45,000 ft, the other was to be throtteable between 1,000lb to 6,200lb at 45,000ft. Burning H.T.P. and kerosene, it produced a S.I. around 220. The large chamber was intended for the boost phase to high altitude; the small chamber for the cruise phase thereafter. The motor turned out to be reliable and effective; so much so that when reports of the failures of the early rounds stated that the rocket engine had failed, the chairman of Armstrong Siddeley wrote a sharp letter pointing out that was not the case: the engine had been starved of fuel as a result of sloshing in the tanks. He did not want his company associated with the poor reputation the missile had at that time. Early test versions had used the de Havilland Double Spectre engine until the Stentor became available.

In addition to work being done on the missile, a considerable amount of work had to be done on the V bombers to prepare them for the missile. The large size of the missile meant that it was carried semi recessed into the fuselage. And then came a major change in policy: rather than flying high, tactics now dictated that the aircraft fly as low as possible. The V bombers were not designed for this, and the extra stresses produced led to metal fatigue in the Valiant. The sturdier Vulcan coped with no problem, however, and so now Blue Steel was launched at a much lower level than had been anticipated. But the intervening years had meant that design performance could be tweaked for the missile to cope.

Blue Steel was not a ballistic missile, but instead was controlled like an aircraft. It was intended for release from the bomber at around 40,000 ft. The aircraft would be travelling at around Mach 0.7 or so. It dived down, and after 4 seconds, at around 32,000 ft, its motors lit up. From there it climbed to around 59,000 feet, then increased speed to mach 2.3. After that, the missile began a cruise/climb, using only the small chamber of the rocket engine, to over 70,000 ft. When it ran out of fuel or arrived at the target, the motor cut, and the missile dived down to its target.

Around 1960, as the project began to reach maturity, there was a flurry of activity considering possible follow on projects. Sir William Farren of A.V.Roe came up with a proposal for a Mark II using hydrazine as the fuel rather than kerosene, and uprating the H.T.P. from 85% peroxide to 95%. This would increase the range from around 100 to 500 nautical miles, with the altitude and speed about 20 or 25% higher. Mark II was, however, cancelled by Watkinson soon after he took over as Minister of Defence on the grounds that the missile was not truly ballistic, but aerodynamic, and still too vulnerable to defensive missiles.. Throughout all the talks of upgrades ran the thread that any extension to the project would hinder the development of Mark I, already running very late. No dilution of A.V.Roe's efforts was to be allowed.

The Prime Minister also came into the picture, writing a minute to the Defence Secretary in June 1960 asking about a longer range version. All this activity must have come about as a result of the cancellation of Blue Streak. The American Skybolt was the chosen alternative, but was hardly off the drawing board. No doubt an extended Blue Steel looked to be an attractive alternative.

A version called the Mark 1S was proposed, which would have the Skybolt warhead with a weight of only 700lbs and a new navigation system. The exisiting warhead bay would be occupied by extra H.T.P. and kerosene tanks. Two small external jettisonable H.T.P. tanks would hold approximately 1100lb each. This would give a launch weight of 21,500lb (which was the limit imposed by the aircraft), a range of 400NM at a speed of M3.5 and a peak altitude of 85,000ft.

There was also the Mark I*, which externally was almost identical other than a slightly extended wing shape, but again used hydrazine/H.T.P., giving an S.I. of 292. This proposal would have entirely new engines: 3 boost and 1 cruise, although given that the engines had been one of the few trouble free areas of Blue Steel, this might have been tempting fate!

The problem with all these extended versions is that the accuracy became degraded. Indeed, the working party on Mark I* in July 1960 pointed out that the misalignment between missile and aircraft which was one of the major sources of error in Blue Steel became dominant for the new missile. There was an optical link between the missile and the aircraft in the bomb bay to help overcome this error, but the report comments that so far it had failed to come up to expectation and that an attempt to improve its performance would be desirable.

Much of this was summed up in a memo from the Deputy Chief of Air Staff to Watkinson, the then Defence Minister:

"You will remember that Blue Steel Mark 2 was cancelled on your advice primarily as a result of information from MOA [Ministry of Aviation] that work on it was impeding work on Blue Steel Mk 1 and equipment for TSR2.

"[There are] three possible methods (all using the same basic airframe as Blue Steel 1) which would produce ranges of 500, 350, and 250 miles.

"[The 500 mile version:] In the time available, we can only guess at a rough total cost of around £30 million. The timescale of development is estimated at 4.5 years. This improved version, therefore, could not be in service before mid-1965.

"[350/400 mile version] The rough guess of cost is £20M. Development would take about 1 year less. This version could therefore be in service by say mid-1964.

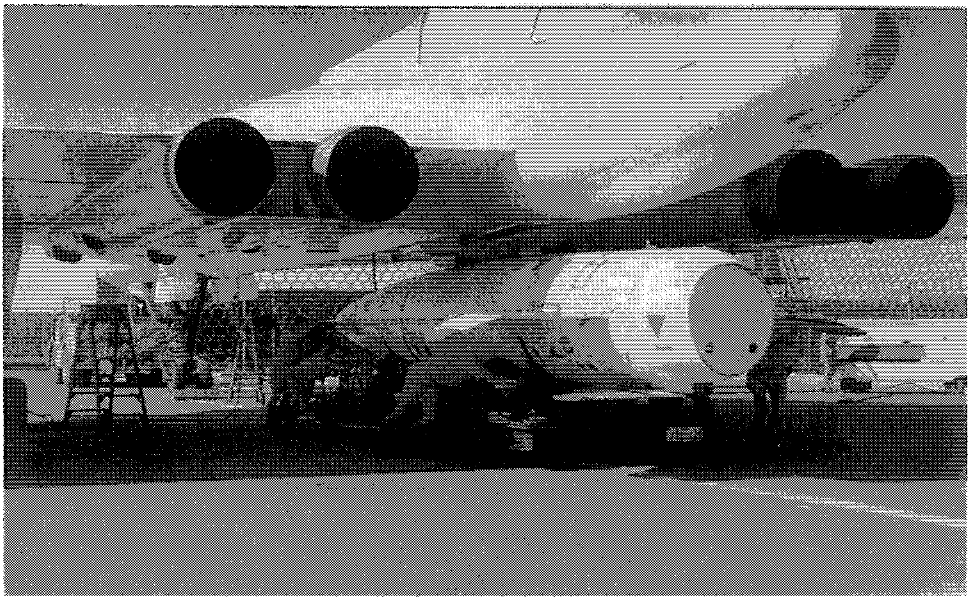
"[250 mile version:] The development of this version might cost £5/10M and it might be available by, say, the end of 1963. It is doubtful whether it would be possible retrospectively to modify Blue Steels already delivered.

"In considering Blue Steel and any possible developments of it we must take note of some pretty unpalatable facts. We first started thinking about this weapon in 1952. The OR was accepted by the Ministry of Supply in 1954 for an in service date of 1960 and events have I think proved that had this date been met the weapon would have had a useful and viable life. An in service date of 1963 for a weapon with a range of only 100 miles is however a different matter.

"In our submission to the Treasury in 1955 the total R&D was estimated at £12.5M. This is now estimated to be £55M ..

"In all the circumstances I cannot see that we would be justified in pouring more money into the development of a weapon which has made unsatisfactory progress to date and which remains dangerously close to being a non-viable weapon at the time of its introduction into service."

The technology advances from 1952 to 1960 meant that much of the weight that had gone into the warhead and into the power hungry, valve driven guidance system could be given to extra fuel. In addition, expedients such as strap on solid fuel boosts for the launch phase could extend the range. Whilst this would extend range, altitude, and speed, it simply wasn't worth it.



Blue Steel being fitted to a Vulcan bomber.

Then a letter from A.V.Roe in October 1960 gave details of their proposal for Mk1S. This would have the Skybolt warhead of 700lbs. and a new navigator. H.T.P. and kerosene tanks, together with two small external jettisonable H.T.P. tanks, each holding approximately 1,100lb, would occupy the present warhead bay. This would give a launch weight of 21,500lb (the limit imposed by the aircraft), a range of 400 n.m., a speed of M3.5 and a peak altitude 85,000ft, but the B.N.D.(S.G.) [British Nuclear Deterrent (Study Group)] dismissed all these Blue Steel variants as too little too late.

Blue Steel came into service with the R.A.F in a limited capacity at the end of 1962, although it was not until April 1964 that clearance was given for a filled and fuelled operational Blue Steel to be used with the Vulcan Quick Reaction Alert. However, its reliability was not good: in 1963 the R.A.F noted that the chances of a powered missile being fit for powered launch at the target was around 40%, and of these, only about 75% would reach their targets. The Victor squadrons were operational until 1968, when they were retired from the Blue Steel role. The Vulcans continued with the missile until 1970, when it was withdrawn from service.

From the wider perspective, the most useful contribution of Blue Steel to British rocketry were the two thrust chambers, which were the most successful part of the project. The smaller chamber went on to become the chamber that powered the later Gamma engines of Black Knight and Black Arrow. The larger chamber was suggested for various vehicles, but despite its apparent usefulness, was never exploited further.

A Victor bomber carrying Blue Steel

5. Blue Streak: the origins

The story of Blue Streak divides into 2 phases; phases which are very sharply divided from each other: the military and the civil. The civil phase was an afterthought, a by-product from the military. Blue Streak was cancelled as a military weapon in 1960, and its life as a civil project began with the intention of creating a satellite launcher from what had been intended as a Medium Range Ballistic Missile (M.R.B.M.). But after 14 years and hundreds of millions of pounds, neither programme yielded useful results ... but that wasn't the rocket's fault. Technically, the design was excellent. Almost every launch was flawless. But it spent most of its life in search of a role.

However, the original intent behind Blue Streak was to produce a guided weapon capable of carrying a megaton range warhead to the strategically important parts of the U.S.S.R.. Design work began in 1955, and the final result was a technological snapshot of rocketry progress circa 1957. In principle and design it was very close to its American and Russian counterparts, and very much their equivalent. But to realise this, we have to look briefly at the history of guided weapons.

The V2 was notoriously inaccurate, although good by the standards of the 1940s, and given in addition its limited payload (1 tonne of high explosive), it was not an effective military weapon. Following the war, both the Americans and the Russians pressed on with improved designs, based around the V2 concept. The British devoted relatively little effort to large rockets at this stage, and such work was, in the main, theoretical, although three captured V2s were fired off in Cuxhaven, Germany (Operation Backfire) in what was effectively a familiarisation exercise. However, the post war rocketry effort in the three countries began to solve some of the problems of guidance, accuracy, and range.

Most of the work done in the U.K. in the early 50s was studies of possibilities. One of the first significant British developments in this field of long range delivery systems was a report commissioned from the English Electric Company Ltd. Work on the report, entitled "Long Range Project", by L.H. Bedford, started in March 1952, and the completed report was delivered on 19th July 1953. The first consideration was that of range and accuracy. The report took a range for the weapon of 2,000 nautical miles with circular error probability (c.e.p.) of the order of 1,500 ft as the target to be aimed for (c.e.p. refers to the probability of 50% of the missiles landing that distance from the aiming point). Three types of missiles were considered: the ramjet, the glide rocket and the ballistic rocket. The guidance system for all of these was taken to be integrating accelerometers using gyroscopes. The times of flight were calculated as 16 minutes for the ballistic rocket, 25 minutes for the glide rocket, and 50 minutes for the ramjet. The significance of this was that the accuracy of the system decreased as time of flight increased. Thus the ballistic rocket was to be preferred on two counts: that of accuracy and that of invulnerability. Intercepting a warhead from a ballistic missile is a task that even today is extremely difficult. Indeed, if attempted operationally, on a system with even rudimentary decoys, it is well nigh impossible.

The two major problems of the ballistic rocket were identified firstly as obtaining a sufficiently high specific impulse from the rocket motors, and secondly the problems of re-entry into the atmosphere. In neither case were practical solutions offered, nor was there any attempt to suggest design features such as the fuel to be used. The report was still theoretical and speculative.

It is also curious that while a range of 2,000 nautical miles was being considered for the ram jet, with a predicted 25% chance of falling in the 1,500 ft circle. Blue Steel, the stand off bomb for the V bombers, was considered to be limited to a range of 100 n.m. on the grounds that the inertial guidance system would be too inaccurate at greater ranges. This lack of accuracy for Blue Steel was, however, due in part to uncertainties in the position of the aircraft.

At around the same time, in late 1952, a technical decision was taken by the Rocket Propulsion Department at Westcott that the preferred oxidant for all liquid propellant rockets was to be H.T.P.. This decision would lead to the motors that were to power the SR53, Blue Steel, Black Knight, Black Arrow, and other projects. The largest of these would be the large chamber of the Stentor engine, designed to give a thrust of 25,500lb at 45,000ft. However, this did not prevent speculation as to the use of other propellants for the proposed ballistic missile: ammonia and lox being one example, and there was one consistent advocate for the use of liquid fluorine! But it was felt that the advantages of the more exotic propellants were outweighed by the extra handling difficulties. Of all possible oxidants for rocket motors, H.T.P. is probably the easiest and safest to handle.

The R.A.E. was conducting its own studies into the same areas as the English Electric Report, and it is interesting to note the estimated all up weights of the three options:

Range:	Ram Jet	Winged Rocket	Ballistic Rocket
500	24	22	35
1500	34	56	105
2500	48	135	210

(Range is given in nautical miles; weights in thousands of pounds)

This has important implications for the design of any ballistic missile: a mass of 210,000lb implies a lift off thrust of at least 250,000lb. It was noted that the ballistic missile would be much heavier than the others, and that if it were to be chosen it would be because of its much greater chance of survival against enemy defences. The calculations were done assuming liquid oxygen and kerosene as propellants, and give a remarkably accurate prediction for the weight of what would become Blue Streak.

As a consequence of these deliberations, the R.P.D. at Westcott pressed ahead with design studies on larger motors. But even at the end of 1954, no formal summary had been made of the R.P.D.'s overall policy on the ballistic missile, as it was felt the position was constantly changing. At the same time, research was continued on a series of rocket engines that went under the generic name of Delta. Despite R.P.D.'s earlier dislike of kerosene as a rocket fuel, these were lox/kerosene fuelled, and mainly for research purposes. There was no firm design for a missile at this stage, although speculative drawings of how to fit several motors together for such a missile were made.

Commercial firms were also interested in the concept: during a meeting between R.A.E./R.P.D. and Rolls Royce, the company stated that: "In their own studies they had assumed a warhead of 10,000lb and minimum range of 2,500 miles and had produced a preliminary design. This design was a single stage missile with an all-up weight of 250,000lb and empty weight 18,000lb giving a mass ratio (empty/all up) of 0.072. Thirty three chambers of 10,000lb thrust each were used." Apart from the number of chambers, again this sounds very much like Blue Streak.

At around this time the ramjet and the glide rocket drop out of consideration. The glide rocket was never a very serious candidate. The ballistic missile with separating warhead and self contained guidance system has the great advantage that it was, and still is, almost invulnerable to defensive counter measures. A missile is also much better equipped to carry decoys, dummy re-entry vehicles or devices that would look the same as a re-entry vehicle to enemy radar. Decoys have been an on going area of research up to the present day.

The ramjet is not as vulnerable to guided missiles as the manned aircraft, but does not begin to compare with a free falling re-entry vehicle at velocities of several thousand feet per second. Height is also a factor here: today's turbofan subsonic cruise missile is designed to fly as low as possible, since terrain following radar and accurate guidance have subsequently been developed to make this possible. Supersonic ramjets would be high flying and more vulnerable to defensive missiles.

But in 1954 the Sandys/Wilson agreement was signed between the U.K. and the U.S., whereby the two countries agreed to collaborate on long range missiles; the British concentrating on medium range weapons whilst the Americans would aim for intercontinental ranges. However, to produce an effective military weapon, there were several important problems to be solved other than simply building a big enough rocket. For the missile to fulfil its function, all the systems had to work together. Loss of just one would render the weapon impotent.

The first of these problems was that of guidance. Radio/radar guidance during the launch phase was possible. However, such external guidance could easily be jammed or destroyed, particularly during a nuclear attack. The answer lay in internal inertial guidance, using gyroscopes and accelerometers to determine the vehicle's heading and speed accurately. The American Atlas missile used a form of radio guidance, but all other missiles carried inertial guidance. A form of radio guidance for Blue Streak was also developed for a time before being abandoned as too easy to jam and too easy to destroy, and also because there was an economy drive on! But a good inertial guidance system has many technical difficulties, and was even less easy in the 50s, without transistors but with thermionic valves for amplifiers. Suitable gyroscopes were difficult to manufacture, and eventually, partway through the project, gyros had to be bought from the American firm Kearfott. To give some idea of the accuracy which was needed over a range of 2,500 nautical miles, it was stated early in the programme that there was "a requirement for a 50% circular error no greater than 8,000 feet at all ranges. If this requirement should result in undue delay in the introduction of the missile into service the Air Ministry will be prepared to accept a 50% circular error of no greater than 3 miles at all ranges in the first instance." (8,000 feet is around one and a half miles.)

A novel feature of these designs for ballistic missiles was that at the moment the engines cut, some two to three minutes after launch, the warhead and its re-entry vehicle would separate from the empty rocket shell, and travel along a ballistic path outside the atmosphere towards its target. After a flight time of some tens of minutes, the re-entry vehicle would descend on its target at very high speed—perhaps as much as 15,000 miles per hour. It had to re enter the atmosphere at this speed, which led to the other unknown of the time: what would happen to such a vehicle? Would it survive re entry, or would it burn up like a meteor? In parallel with Blue Streak, the Black Knight programme was set up to investigate the problem. Guidance and re-entry were the two major imponderables, for which a good deal of work had to be done in parallel to the main project. But what of the rocket itself?

Westcott had been considering large rocket motors from the early 50s, without producing any real concrete designs. It took a visit to the U.S. to redirect efforts back to LOX and kerosene, and work began on a series of motors under the generic name of Delta. Some of these would undoubtedly have been suited to an I.R.B.M., but there was simply too much work to be done with too few facilities. It was felt that developing an indigenous motor would simply have taken too long.

After the Sandys/Wilson agreement had been signed, the U.S. and the U.K. set out to design missiles which were complementary to each other. Initially, the Americans were to produce the long range Atlas missile, the British the medium range Blue Streak. A team of Americans visited the U.K. in April 1955, to discuss progress. Sir Steuart Mitchell (CGWL) described the British plans, which involved the R.A.E. as the principal designer for the first two years, control being passed to the firms in the second year. The American team was not impressed by this idea; V.C.A.S. (Vice Chief of Air Staff) noted that he had been told in private that "They felt themselves that unless we give it to industry with a free hand it might delay the project greatly. They voiced the opinion at the meeting that the

British Technical Civil Service was of a much higher calibre than the American, but that a scheme such as that proposed by Mitchell would just never work in the U.S.”. Whether this was the case is difficult to judge, but certainly, progress in 1956 seems to have been slow.

It is also noticeable that the many Technical reports that came out of the R.A.E. at this time were speculative and academic. Typically, a half dozen different design solutions would be carefully evaluated in these reports, but they did not lead to a direct practical design in the way that an aircraft design team might work. British aircraft designers of the time would start with quite detailed sketches, which would be refined up to the final solution. A commercial firm was also under pressure to produce a prototype as soon as possible in a way that the R.A.E. was not.

At the same time, a British team from R.A.E. had visited America, and produced a report laying down the problems to be solved quite clearly. As a result of this, the Ministry of Defence felt sufficiently confident as to issue an Operational Requirement (O.R. 1139) for the missile in 1955, which stated a requirement to deliver a megaton range warhead over a distance of up to 2,500 miles. A Requirement is one thing, a design is another. Throughout 1955 and 1956, whilst work started on Black Knight and on other aspects of the programme, arguments went back and forward as to the details of the design. The crucial point, from which all else flowed, was: should it have one motor or two? The motor under consideration, an American design, had a thrust of 135,000 lbs. This implied a missile weight of no more than 100,000 lb with but the one motor. A two motor design could be double that mass. The critical factor, and an unknown factor, was the payload, and the payload was, of course, a megaton warhead and its re-entry vehicle.

The U.K. had, by this time, tested fission devices, but not fusion devices (hydrogen bombs) and was still some way from an operational fusion device in 1955. Full nuclear co-operation between the U.K. and the U.S. would not resume until after the testing of a successful fusion device by the U.K. in 1957, and after the scare given to the U.S. by the launch of Sputnik. Given the predicted accuracy of the guidance for Blue Streak, nominal fission devices (the size of device used against Hiroshima and Nagasaki) would be ineffectual. The missile would have to carry a much more powerful warhead. A bigger bang would also make up for errors in the guidance. Fission bombs would typically give yields of ten of kilotons, fusion bombs could reach tens of megatons. In addition to the warhead weight, there was the weight of the guidance system and of the re-entry vehicle. All three were unknowns, and so payload prediction was almost impossible. All that the Operational Requirement specified was that the rocket should carry a “megaton warhead”, without specifying the means as to how.

The original intention was that Blue Streak warhead would be a device code named Green Bamboo, which was probably a large fission device. Given the date of the Operational Requirement for the device (July 1955), it can only have been a unproven paper design. Another two years would elapse before any fusion weapons were tested. A contemporary paper from R.A.E. calculated that even with 2 motors and an all up weight of 203,000 lbs (nearly 91 tons), Blue Streak would only be able to carry a 4,500 lb payload a distance of 1,900 nautical miles. A single motor device of 102,000 lbs would have a range of 1,200 miles. The Air Staff considered 2,000 miles range as the absolute minimum. When Sir William Penney, Director of Aldermaston, was asked if he could produce a lighter warhead, the minutes of the meeting reported that:

"A small 1MT warhead for Blue Streak would be about 33" diameter and 2,200lb. weight; ... DAWRE (*Penney*) subsequently undertook to re-examine the design of this warhead and to say what could be achieved for a weight of 1,800lb. There is some development potential in Green Bamboo but little in the small warhead."

But Penney then had to write to C.A.W. (Controller of Atomic Weapons, Lt. Gen. Sir Frederick Morgan) to say that "... on current knowledge I could not guarantee to make a satisfactory warhead within the weight specified...". And "the figures of 1800 lbs weight and 30" diameter quoted for an unboosted fission bomb with a yield of about 1 megaton were purely estimates at this stage and could not be guaranteed." A fission bomb would need to use a good deal more of expensive uranium, as was noted by other participants at the meeting. "Although the much higher U235 content of the lightest warhead, and the subsequent reduction in the possible number of such warheads, were not discussed at the meeting, they are presumably of interest to the Air Ministry."

Eventually, the design weight for this lighter warhead was settled at 2,200 lbs. The Operational Requirement had to be amended from "thermonuclear" to "megaton range" device. ("Megaton range" does not imply a yield of 1 megaton, it was taken as being anything from 500 kilotons upward.)

The new warhead was code named Orange Herald. There is some confusion as to the exact nature of Orange Herald—the British Government has been very reticent as to the nature of the various designs that were tested in the 1950s, probably more so than the either the Americans or Russians. It has been stated that at least one of the three devices tested at Christmas Island in 1957 was a pure fission device, and there are other references to Orange Herald as a pure fission device, but other sources consider it as a "boosted" fission device.

Such a device has a large fission core, surrounded by lithium deuteride and a large and heavy U238 tamper. The fission core starts a fusion reaction in the lithium deuteride, but without the uranium tamper, it would be blown away before any appreciable fusion occurs. But in addition, the fusion reaction produces fast neutrons. U238 is not normally considered fissile, but it can be fissioned by very energetic neutrons. This has two consequences: the yield of the bomb is increased, and the fusion fuel is kept compressed by the exploding outer shell. However, there are drawbacks to such a design: it needs a large fission core, and it cannot be easily scaled up. In addition, since so much of the yield comes from fission, it produces a lot of radioactive fallout.

The large fission core was almost certainly the origin of another problem: such a core would need large amounts of fissile material (hence the cost) which is highly unsafe unless the weapon is very carefully designed. The amount of uranium would almost certainly exceed the critical mass, and in the event of an accident, could produce a nuclear explosion spontaneously. Such a device, of around 400 kilotons yield, was used by the R.A.F. as an "interim weapon", with 1,000 lbs of ball bearings as a safety device. This probably would not have been possible with Orange Herald.

There are several hints as to its nature in the Ministry of Supply file for Orange Herald, however: thus the DAW (Plans) [Director of Atomic Warfare] in December 1955. "One obvious change is needed in para. 2 (of the Operational Requirement), i.e., to delete 'thermonuclear' and substitute 'megaton'", and DGAW [Director General of Atomic Warfare] to CGWL [Controller of Guided Weapons and Electronics, Sir Steuart Mitchell] in June 1956: "... this warhead as at present planned is not a thermo-nuclear one..."

There is an interesting memo from the Director of Atomic Weapons (Plans) when, when asked "what is the present status of the official requirement for Orange Herald, and whether the Minister knows of the project" replied:

"Thus the answers to your questions are:

"(a) The present status of Orange Herald is that of a private venture by A.W.R.E., for the present Air Staff Requirement for a warhead for the O.R.1139 missile refers specifically to Green Bamboo. D.G.G.W. will inform Air Staff that the missile needs a lighter warhead; this should result in a revised O.R. calling in effect for Orange Herald, and we can then clear with A.W.R.E. the warhead parts of this O.R. in readiness for the eventual submission of O.R.1139/1142 to the Minister by C.G.W.L. and C.A.W..

"(b) there is no evidence that the Minister knows anything of the project beyond the code word and its definition."

(D.G.G.W. was the Director General of Guided Weapons, O.R. 1139 was the Requirement for Blue Streak, and O.R. 1142 was the Requirement for the warhead.)

Whatever its design, a version was successfully tested on 31st May 1957 at Christmas Island in the Pacific, although "...the cost of the material may be £2½ million." But the later success with the fusion devices meant that Orange Herald could be discarded. Whilst talking about in flight arming in November 1957, there were comments from the Ministry of Supply that: " ... it is not worth doing anything about Orange Herald as we hope we shall not have to use it.". And "... it was learned that no work was in progress on Orange Herald at AWRE [*Aldermaston*], nor was there any intention of doing any. Newley suggested that our work, based on Orange Herald, should be stopped, and that AWRE would offer instead a two-stage warhead of similar weight ... Orange Herald had very doubtful in-flight safety, and is highly vulnerable to R effects ...". (R effects were the code the U.K. gave to the vulnerability of warheads to X rays and to neutron flux, possibly resulting in premature detonation, and certainly disabling the warhead as a consequence of heating the fission core.) Aldermaston and the R.A.E. were not always good at talking to each other.

The later tests in 1958 at Christmas Island had led eventually to a satisfactory fusion device. By May 1958 a new design had emerged from the Grapple tests, with a weight of 2200 lbs, 6 foot long and 27 inches in diameter. To further confuse matters, however, joint U.S./U.K. nuclear weapon information exchanges had begun, and the proposal was for the U.K. to adapt the American Mark 28 as the principal design for Blue Streak, Blue Steel, and the Yellow Sun Mark II free fall bomb for the V bombers. This new device would be code named Red Snow. (Following code names of this period needs a clear head!)

Indeed, warheads were to become lighter and lighter: Polaris warheads, albeit with a smaller yield, had a weight of the order of 200 lbs.. Blue Streak would be grossly over engineered for those, but if used with warheads of that weight, could have extended its range, increased the number of decoys carried, or carried several warheads. Although the British fusion design would have been satisfactory, and could well have been developed into a fully fledged weapon, the American devices had the advantage of much more development work. Whereas the British devices at that stage were not developed to Service standards, the U.S. devices were operational weapons. Hence the decision was taken to drop the British designs, and produce Red Snow instead.

But to return to the design of the missile. Thus Air Vice Marshall Satterly A.C.A.S.(OR) [Assistant Chief of Air Staff (Operational Requirements); the alphabet soup of departmental posts is nearly as confusing as the various code names given to the weapons] in July 1955: “My views are that if we go for the single motor missile we shall always be in trouble over weight and range, and will find ourselves in the early 60’s [sic] still striving to catch up. Let us be bold and go for the twin motor and exploit any future saving in weight in the warhead, or anywhere else, by increasing the range. Let us then review the position in a years [sic] time, when we can put much more reliance on the small warhead and when we are due to consider parallel development of a second missile.“

And Sir Steuart Mitchell, CGWL, “reluctantly agreed that two motors would probably be necessary to guarantee a range of 1500 nautical miles“. Dr. William Cook, Deputy Director at Aldermaston, said that A.W.R.E. “had not realised how significant was the weight of the small warhead in reaching this decision.“ Reluctantly, given the uncertainties in the payload, it was then decided that to achieve the necessary range, two motors would be needed. A single motor missile would have been almost identical to the American Thor missile, but the heavier U.K. warhead coupled with the already limited range of Thor (1500 miles with the U.S. warhead) ruled out the use of Thor by the U.K.. This was summarised in a paper by Sir Frederick Brundrett, Chief Scientist at the Ministry of Defence, in June 1956:

“The co-operation between the Americans and ourselves on this missile development is extremely good except that which is limited by United States laws governing the passage of information on atomic weapons. We have, in fact, considerably more knowledge on this subject than we are supposed to have and *it is vitally important that the Americans are not made aware that we have the information that follows.*" [This passage is underlined in the original document.]

"The warhead for Thor is being designed to a weight of atomic core of 1500lbs, but the weight of the warhead itself must include the metal sheathing designed to act as a heat sink. The total weight including this sheathing will be 2,600lbs if the sheathing is of steel and 3,100lb if the sheathing is of copper. The comparable figures for our own design are 2,250lb, 3,600lb and 4,500lb. ....

"What this means, however, is that if an arrangement could be made for the Americans to provide vehicles to which we could fit our heads, which is a technical possibility, the range of the American vehicle with our head would be reduced to something of the order of 1,100 miles ..." (The 60 Thor missiles that were deployed along the east coast of England were fitted with U.S. warheads and re entry vehicles.)

However, there is no doubt that the single motor design would have been simpler, cheaper, and would have taken less time to develop. But, in a sense, the Air Ministry had painted themselves into a corner. The missile had to be as big as it was to achieve a range of 2000 miles with a megaton warhead. But no one appears either to have queried this requirement or even decided what the missile was for. Was it a deterrent? Was it actually intended as a weapon that could be used to win a war? Did it need a range of 2000 miles? The Strath Report, also concluded in 1955, looked at the effect on the U.K. of just five megaton warheads, and was deeply pessimistic about the result. And if the intention was to "win" a nuclear war with the USSR, how much destruction would have been necessary to annihilate it or, at least, force it to surrender?

The requirement could have been relaxed either in terms of range or warhead. Given the range as 2000 miles, why did it have to be a megaton warhead? Would 200 or 400 kilotons have been sufficient? And could Aldermaston have designed such a warhead within the weight constraints? Further, the payload weight was pushed up by inadequate knowledge of the re-entry head. It might have been worth putting more research into re-entry before finalising the design. It is possible that a single motor design might have had a better chance of ultimate deployment, being smaller, cheaper and quicker into service. But the assumptions on which the criteria were based never seem to have been questioned in depth.

So the issue of one motor/two motors having been settled, further design work could begin. It took some time for a more detailed design to emerge, however. Thus Joe Lyons of the R.A.E. wrote in February 1956: "It had been agreed in principle that it would be a thin steel missile with propulsion at rear and the warhead at front. Titanium had been considered for the skin but was not promising. A cylindrical structure of about 10 ft diameter and length of about 60-70 ft was generally agreed. It was probable that fins would be fitted but this was not completely certain yet." Even the use of the NAA motors was still to be debated. A note from Serby, DG/GW (Director General/Guided Weapons at the Ministry of Supply) in March 1956 reads: "Should the missile be designed as a single stage weapon using 2 x 135,000lb NAA motors since the AUW [All Up Weight] could be reduced and the requirement for thrust control could be eliminated if a number of smaller motors could be used?" The thrust control issue arose from the use of large rocket motors: towards the end of the flight, when almost all the fuel was consumed, accelerations became unacceptably high. Thus there was a proposal to throttle back the motors: not an easy task.

The firms detailed to do the work had been decided back in 1955. "It is proposed that Messrs de Havilland should be responsible for the airframe and general weapon co-ordination, Rolls Royce for the rocket motor and fuel system design, Sperry for the internal inertial 'guidance' and autopilot, Marconi for the ground radar launching system.".

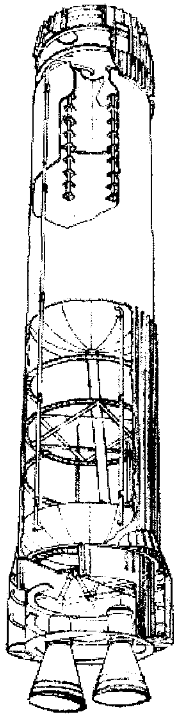
Whilst relationships between the firms and the Ministry were usually good, this was not always the case with de Havilland, particularly in the early days. There were considerable cost over-runs at a time of financial stringency, and at one stage the Ministry went as far as sending in Cooper Brothers, a firm of accountants from the City, to check the costs and management. And with reference to talks with Rolls Royce in 1958, the Ministry noted that "they share the view with everybody else that de Havilland can be extremely difficult and very unsatisfactory, but have no complaints to make over their immediate contacts in this particular connection. Indeed, at the working technical levels, they have a very high opinion of the de Havilland staff, but, here again, they fully share the general view about de Havilland top level people."

Rolls Royce initially copied the American S3 motor design and then refined and anglicised it, so that the motor could be built with purely British components. The S3 was being developed for the American Thor and Jupiter missiles, having evolved from the original V2 design via the Navaho missile. This motor burned kerosene and liquid oxygen, standard for the time, but a combination that might, in retrospect, have appeared out of date by 1960, although this is still a matter of controversy. A copy of the design, designated the RZ-1, was built by Rolls Royce and tested at Westcott. From this, the anglicised design, the RZ-2, evolved.

De Havilland licensed the techniques for building large stainless steel rocket structures from Convair, who were building the Atlas missile. The design for Atlas was unusual in that the tank structure was so thin that it could not support its own weight: it had to be kept pressurised, or in a special structure to keep it under tension.

Although these licences would save a great deal of time and efforts, they were only licences for the techniques and not for designs. There was still an immense amount of development work still to do.

The rocket structure, like Ancient Gaul, could be thought of in three parts: the engine bay at the bottom, the main tank structure containing all the fuel in the missile, and the ancillary equipment, guidance and payload at the top. The engine bay, containing 2 RZ-2 motors, was 9 ft in diameter (so designed for transport by air), but the elegance of the final shape of the missile was rather spoiled by two panniers either side containing nitrogen to pressurise the kerosene tank. The liquid oxygen tank could be pressurised by oxygen gas derived from the liquid via heat exchangers. So in June 1957, de Havilland stated that "the propellant tanks, constructed of 0.019 inch thick stainless steel, remained unaltered. External stringers on the rear (kerosene) tank would permit the weight of the head to be supported without pressuring the rear tank. This would in turn allow the kerosene to be drained from the missile in the event of a failure occurring on the launcher." The upper tank had to be kept pressurised at all times to prevent the structure collapsing under its own weight. These 48 stringers also helped to give Blue Streak its distinctive appearance. Inside the fuel tanks were various baffles to prevent the sloshing of fuel, but basically, missiles such as Blue Streak are gigantic thin-walled tanks.



Cutaway of Blue Streak.

For Atlas, skin gauges varied throughout the structure, being tailored to meet local stresses. The heaviest skin gauge was forty thousandths of an inch. By comparison, the skin gauge for Blue Streak was nineteen thousandths, but the lower section, the kerosene tank, was re-inforced with stringers. Blue Streak was simpler in being a pure cylinder, whereas the Atlas tanks tapered at the top. The most probable cause of the failure of such a structure in compression is what is known as Euler buckling—the process that occurs when you step onto an empty soft drinks can. But there were other reasons for the re-inforcements.

A structure such as Blue Streak or Atlas, particularly when transmitting large loads vertically, is very vulnerable to sideways bending forces. These can originate from sideways gusts of winds, and also from the act of swivelling the rocket motors off centre for control purposes. Indeed, the two motors were to be inclined inwards slightly so that their thrust lines passed through the centre of gravity of the missile. Although it is often said that Blue Streak performed impeccably for ELDO in the 1960s and 1970s, this is not quite true. Sloshing of the fuel towards the very end of the first flight, F1, on June 5th 1964, overcame the control system and caused the missile to tumble uncontrollably.

The most important parameter for a ballistic rocket using no aerodynamic lift forces is the engine thrust. Two of the S3 motors gave a thrust of 270,000lb. Given that the smallest practicable initial acceleration is 0.3g (and there is a good case to make this bigger in a missile) then the lift off weight is of the order of 200,000lb. Some of this, perhaps 4,000lb, is payload. The rest is divided between fuel and structure. So structure plus fuel amounts to 196,000lb. Given 10% as structure, as an arbitrary figure, then this gives fuel weight as around 175,000lb. Given the densities of the fuels, their volumes can be calculated. Given a diameter for the rocket—say 10 foot—then the length of the tanks can be estimated. Using these "back of the envelope" calculations, then the design of Blue Streak is quite easily arrived at. For comparison, the F1 vehicle with a dummy load of a ton, had a lift off mass of 205,000lb, 190,000lb of which was fuel.

A two stage vehicle could have been smaller and lighter, but a two stage design would also have been considerably more complex. A single stage vehicle was a good deal simpler, despite its greater size.

So from mid 1957, testing and development proceeded apace. At Hatfield in Hertfordshire, large structures were built to house the testing of early, non-flight, vehicles. These were for checking the strength of the vehicle structure, and for such tasks as determining whether half a ton of fuel could be pumped from the tanks each second. Engine testing was carried out separately by Rolls Royce, first at a test site at Westcott, and then at the purpose built facility at Spadeadam in Cumbria. Here, in addition to engine development, assembled vehicles could be static fired. When tested, they would then be taken apart for transport to Woomera.

Transport proved to be a difficulty. The large size of the tanks meant that very few aircraft would be suitable, and those which were, such as the Bristol Freighter, had limited range. This meant a great many countries would be overflown on the route from the U.K. to the Antipodes, and, given the nature of the cargo, political difficulties were foreseen. The problem was solved when the R.A.A.F. bought Lockheed Hercules aircraft: one of these could be leased from Australia for the purpose. And given the extra range of the Hercules, the overflying problem could be reduced by going westward round the world, over Canada and the U.S.. As it would turn out, the tank of the first missile was at Los Angeles when the cancellation was announced, and it was returned to the U.K.. All subsequent civil vehicles were transported by road and sea.

Another of the major problems in the early development was that of guidance. The contract had been given to Sperry, but they were struggling: " ... accuracies being demanded from the inertial equipment for this project are extremely high and very marginal. It does seem that these accuracies are just about obtainable ..." in January 1956. There is a despairing cry from the Director of Air Navigation in October 1956: "There does not yet exist, I believe, anywhere in the world a gyroscope suitable for Blue Streak." This was not quite true: American gyroscopes were very much more advanced, and Ferranti was eventually given the job of adapting Kearfott gyroscopes for the guidance system. Although these were probably not the best the Americans had under development, they were perhaps the best they were prepared to make available to the U.K.. And in November 1956: "It will thus be seen that, though the Blue Steel situation is parlous, the Blue Streak position is even more desperate...". A working design was finally produced, although in the end it was never used: the guidance system was cancelled at the same time as the missile. A satellite launcher needed a much less complicated system, and scrapping the Blue Streak inertial guidance could save weight.

As the 60s progressed, inertial navigation was to become much improved: a system designed for the TSR 2 was adapted for Black Arrow. Blue Steel was left to soldier on with a much earlier design, which, with its valves, was very power hungry. Again, a penalty was paid for being early in the field.

But, in addition to all the technical difficulties, the whole project was fraught with political uncertainty from the outset. It is impossible to look at this part of the programme without looking at the political background. Blue Streak was effectively in the hands of three Ministries: Defence, Supply and the Air Ministry, whilst the whip hand was held by a fourth, the Treasury. The set up seems Byzantine to modern eyes. The Ministry of Supply was a pre-war creation to produce as many aircraft as possible for the Air Force, and to develop designs and prototypes to a stage where they could be used by the Air Force. The major problem with giving Supply this Research and Development function was that they were not the final users, so no matter how conscientious they were, there was still not that final incentive to get things right. Secondly, they did not operate the obsolescent material that the prototypes would replace, and so here too lacked that final sense of urgency.

The Ministry of Defence was to supervise the overall budget, and to coordinate the three services. At this point in its history it did not have the powers that it would later have, and it was probably Duncan Sandys who first gripped the Ministry, and used the power at his disposal most effectively. The Air Ministry was subordinate to the Defence Ministry, being part of it, and not having a seat in Cabinet, but was the end user of the projects that emerged from Defence and Supply. The Defence Ministry did however control overall policy by means of the extremely powerful D.R.P.C. (Defence Research Development Committee). It was this committee that decided general defence policy needs and hence which projects should proceed. The cancellation of the interceptors described in Chapter 3 were as a direct consequence of a change in policy initiated by the D.R.P.C.

And the final arbiter was the Treasury. For a project such as Blue Streak, which could be considered as one of national priority, considerable delays were incurred as a result of Treasury refusal to release funds. The Spadeadam facilities were delayed for some six months as a consequence of Treasury reluctance, as this memo from the Ministry of Defence indicates. "You will remember that in February the Minister of Supply wrote to you in connection with the project to develop a rocket testing site in Spadeadam and emphasised the necessity of settling as quickly as possible the fate of our medium range ballistic missile project. We agreed at the time that nothing should be done about this letter since we had not yet settled the problems raised by the Long Term Defence Review. The Ministry of Supply, however, are now being held up by Treasury refusal to agree any expenditure at Spadeadam until the Financial Secretary has seen your reply to the Minister of Supply's letter of 15th February [1956]"

Sir Frederick Brundrett commented with regard to the same issue:

"There is no doubt whatever that the political uncertainties stemming originally from the reports of the meeting at Chequers, and particularly the bitter hostility of the Exchequer and the Treasury to the project, have contributed to the difficulties, and in particular, specifically caused the work at Spadeadam to proceed at a speed less than the maximum that would have been possible had money been available."

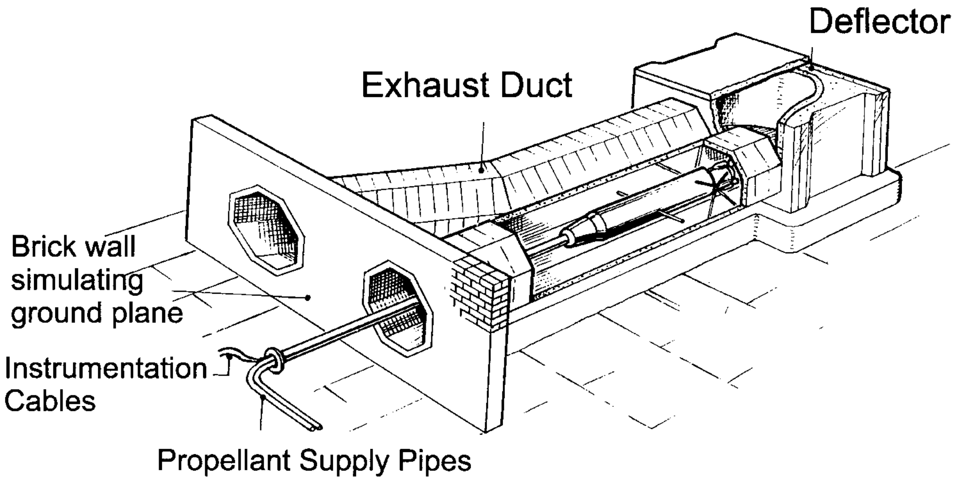
Similarly with the proposed Technical Assistance Agreement between de Havilland and Convair on Ballistic Missiles: "Treasury ratification of the agreement and the payment of the dollars has up to the present been withheld because of the uncertainties regarding defence policy." A letter then came from Thorneycroft, the Chancellor, agreeing to the release of funds but requesting economies of equal value.

Again, an excerpt from a minute to the Minister of Defence in October 1957 reads: "During most of 1956 we were defending the very existence of Blue Streak against savage attacks by the Treasury". But amidst the controversy the military case was being made that "the conclusion from these arguments is that of all the weapons under consideration only the ballistic missile looks like having a reasonable chance of remaining comparatively invulnerable by 1970. What is more the firing sites for ballistic missiles will be difficult targets to destroy. It is clear, therefore, that unless we change our present policy of maintaining continuously in being an effective contribution of our own to the strategic deterrent, we must retain in the program the ballistic missile."

Then came the financial crisis of 1958, when the entire Treasury team resigned in protest at the size of public spending. £100M had to be cut from Government expenditure, with the consequence that Macmillan wrote to the Minister of Defence and the Chancellor in December 1958: "on Blue Streak we should take all steps to reduce expenditure which can be taken without giving any wide-spread impression that the approved programme is being abandoned or retarded. ... of the order of £1M."

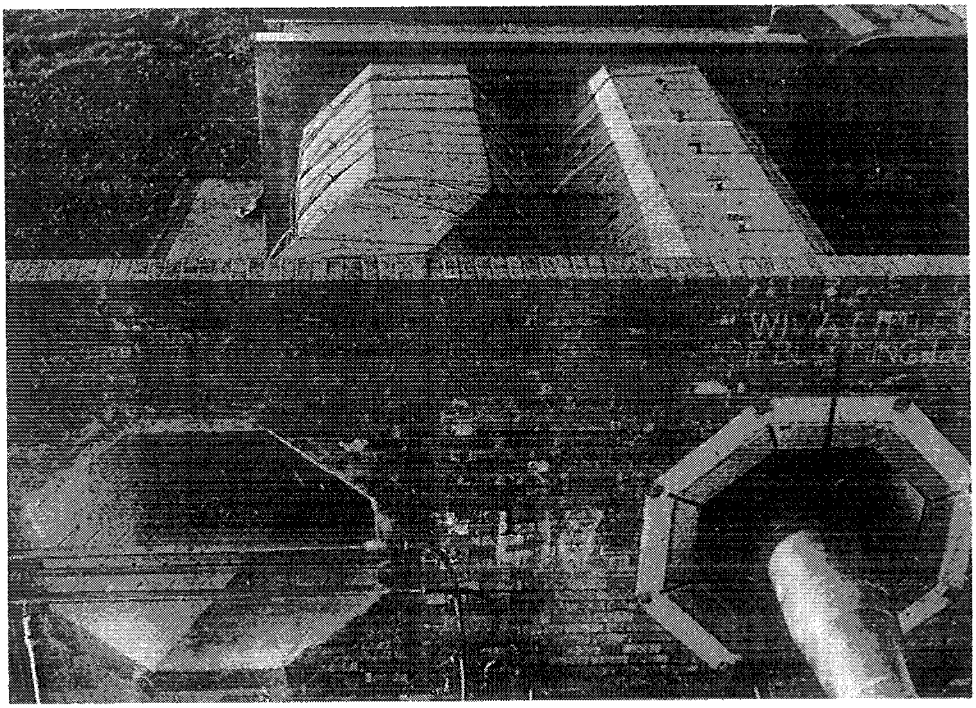
It is difficult to see why the Treasury seems to have opposed the project so bitterly: other defence programmes such as the V bombers or the nuclear programme had been equally costly. It is impossible to judge how such economies affected the project, but it would not be unreasonable to say that the first flight would have been put back by at least 6 to 12 months by the delays imposed whilst obtaining Treasury clearance. The point was also made more than once by Sandys that such economies would mean that as a consequence of the delays, the system would be late in service, and its useful service life concomitantly reduced.

But the next, and most controversial, point about Blue Streak was to be its proposed means of deployment. To have the missile sited on the ground in the open, as the Thor missiles were, was pointless. A pre-emptive strike by relatively few Russian missiles would have destroyed every site before a missile could be fired in retaliation. As all sides in the Cold War realised, land based missiles would have to be sited in "invulnerable" silos, although the word silo was not in usage in the U.K. at that time. Indeed, the two phrases used became code phrases, showing which side of the controversy you were on. "Underground launcher" was the phrase used by those in favour of the project, "fixed sites" if you were against. "Fixed sites" were perceived as being vulnerable. Airfields, somehow, were not so perceived—although they were as "fixed" as any missile launcher. (A proposal was made in 1958 to have the missiles mounted in floating launchers, but as someone noted: "I find it rather difficult to believe that these platforms can be produced, taken to site, and submerged to 90' without detection." In addition, the coastal waters of the U.K. rarely extend to 90 foot depth.)



The one sixth scale model silo

Given the sheer physical size of Blue Streak, putting it underground would be a problem, but there would be many other problems as well. Given its relatively slow lift off acceleration, what effect would its own hot exhaust gases have on the missile at launch? Confined as it was in a narrow tube, would the sheer acoustic energy be enough to damage the missile? No one knew the answers to these questions, so Dr. Barrie Ricketson, Head of the Gas Dynamics section at R.P.E. Westcott and his team were given the task of finding out. The launcher would have to be in the form of a U tube, with the rocket in one arm, and the hot exhaust gases would vent up the other arm of the tube. A 1/60th scale model of the missile and possible silo was prepared, with high pressure nitrogen to simulate the exhaust. Sound levels were also measured, and the results had then to be scaled up to give estimates of the noise levels on a model ten times larger. The gas flows and sound levels seemed to be satisfactory, so Ricketson went ahead and built a 1/6th scale model horizontally, in the side of a wall, as shown above.



One sixth scale silo.

A model missile can be seen in the "launch" tube, above which is inscribed the words of a song from "My Fair Lady": "WIV A LITTLE BIT OF BLOOMING LUCK".

A 1/6th scale missile was also prepared, with H.T.P./kerosene rockets, which were fired within the tube, so that sound levels and gas flows could be measured.

High temperature cement was used initially, which turned out to be a bad idea: it was scoured from the walls, and the resultant particles sand blasted the rest of the tube. Low temperature cement merely fused at its surface, and was better. Some of these test runs must have been interesting, reading between the lines of the report. When talking of the erosion of the concrete from the tube, it was noted that "the effect was cumulative ... pieces weighing two ounces or more were picked up about 50 yards from the launcher exit"! Acoustic liners were added to the tube to absorb some of the sound, with satisfactory results.

With this research, Ricketson validated the concept of the launcher. It is also of interest that the British design studies preceded any undertaken in the U.S., and Colonel Leonhardt, deputy commander for Installations, Ballistic Missile Installations, visited the U.K. to evaluate the design for the underground launcher. A similar research programme, which seems closely based on Westcott's work, was carried out in the U.S. in 1959, where again a one sixth scale model was tested. The Titan II silo design that resulted can be seen to have a family resemblance to the Blue Streak launcher (although similar problems lead to similar solutions). The last Titan silo was not taken out of commission until 1987, which tends to argue against any obsolescence of the U.K. design.

The silo design was entirely produced from within the U.K.: Blue Streak may have used American technology, but the design for its launcher, whose basic ideas were used by the U.S. and U.S.S.R., were entirely original. With this work, and the re-entry vehicle work carried out with Black Knight, the U.K. was breaking new ground, and with results that were as advanced or more advanced than the work being carried out by the two superpowers.

De Havilland was not the first choice for silo design: a minute in October 1957 said: "It should be clear that design of underground sites is in no way the responsibility of this firm, which is already showing itself incapable of carrying the load that has been put on it." However, despite this opinion of the firm's capabilities, it was left in their hands, and now that the concept of launching from within an underground tube had been proved, de Havilland could now press on with the design of an operational site. A paper prepared in 1959 gives some idea of the projected costs:

"The Ministry of Supply estimate that the total R&D cost of a below-ground Blue Streak would be £160—£200M", and the following cost estimates were given:

"Underground Deployment	
"100 sites at £2M per site	£200M
"100 missiles at £0.5M per missile	£ 50M
"10 years operating costs at £0.125M per missile per year	£125M
"R & D	£160-£200M
"Warheads	£100M
[Total]	£635-675M"

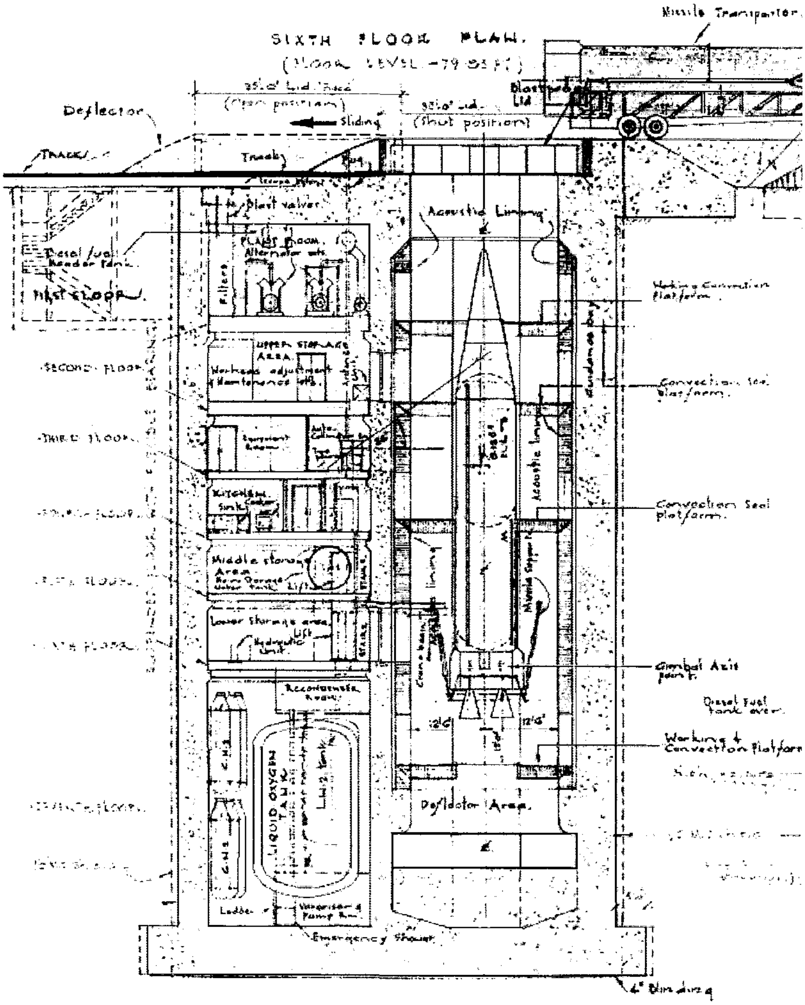
Even with only 60 missiles deployed, which would have been the probable final total, these are impressive sums for 1959. But they were only estimates, based on no hard data, and the history of such projects made it very clear to everyone except the Ministry of Supply that all such estimates were usually wild under estimates. The Treasury, of course, was more cautious: in January 1958 it gave authority to start work on Australian facilities. However "commitments on the part of the launchers related to 'below ground' aspect are to be kept to a bare minimum and no work should begin on the 'below ground' part of the launchers themselves."

The final design is indeed impressive, as the architect's drawing seen below shows. A description of the prototype launcher, code named K11, says: "Basically, the emplacement consists of a hollow re-inforced concrete cylinder, 66 feet internal diameter, extending downwards from ground level to a depth of 134 feet and divided internally into two main sections by a vertical concrete wall. One section houses a U-shaped tube, whose arms are separated by a concrete wall and are, respectively, the missile shaft and its efflux duct. The surface apertures of this U-tube are covered by a lid that can move horizontally on guide tracks. The other main section within the cylinder is divided into seven compartments, each with concrete floor and ceiling, for the various storage, operating, technical and domestic functions.

"The internal diameter (66 feet) of the concrete cylinder is determined solely by what is to be accommodated. Protection against [a 1 megaton explosion at ½ mile distance] is given by the lid and by the re-inforced concrete roof walls and foundations. The wall thickness will depend on the geological characteristics of the surrounding rock and may well be of the order of 6 feet. The depth of 134 feet is arrived at primarily to give sufficient clearance below the missile (itself 79 feet long) to allow for de-fuelling and re-fuelling the missile into and from the liquid oxygen and kerosene storage tanks located on the 7th floor."

The 400 ton steel lid could be opened in 17 seconds, and high pressure hoses would sweep it clear of debris first. Two firms, John Brown (S.E.N.D.) [Special Engineering & Nuclear Developments], and Whessoe Ltd of Darlington, were commissioned to produce designs. Whessoe's report is dated March 1960, so that it is obvious that the design of the lid had not been finalised by the time of the cancellation. This, combined with the problems of finding a site for K11, meant that the schedule must have been slipping seriously. To have produced a fully working prototype by 1963 or 1964 on this basis looks difficult to achieve.

Brown's lid was 56 foot by 36 foot, weighing 600 tons. Both were hollow, although with strong internal bracing, and in Brown's case, 5 foot thick. The Whessoe lid used 3 inch thick steel plate top and bottom. The lids were to be capped with 6 inches of concrete. The rails on which the lid was to run were also of steel, in Brown's case 7 inches square in cross section, and for Whessoe, "12 inch overall width by 5½ inch rail width".



The K11 silo: architect's drawing.

This is a section through the arm of the tube containing the missile, and the living quarters. The kitchen sink is on the sixth floor!

Provision was also made for keeping the lid free from debris, although the ground shock the silo was predicted to receive would be considerable. There are references in a de Havilland paper to "Ground shock ... in a vertical direction, an instantaneous step velocity of 2¼ ft/sec is induced, which decays at a uniform rate to zero in one second .... in a horizontal direction, an instantaneous velocity of ¾ ft/sec is induced which decays at a uniform rate to zero in one second", whereas Whessoe notes "Acceleration forces on Ancillary Equipment equivalent to accelerations of 2g". In addition, the rails would be exposed to heat from the fireball. The question this raises is whether the rails buckle under these loads. A silo whose lid cannot be opened would not have been much use.

Other aspects of the design were to cause concern: the various effects created by a nuclear explosion nearby. Whilst the silo might survive the blast, there were concerns as to the effects of Electromagnetic Pulse and of high energy neutrons. The R.A.E. Lethality Committee set to work to investigate these effects.

One effect, of course, is the thermal radiation or heating. Being underground, the launcher was relatively immune from this, although the lid and the rails would be exposed. This was not thought to be a significant problem.

The high temperatures and energetic radiation produced by nuclear explosions also produce large amounts of ionised matter that is present immediately after the explosion. Under the right conditions, intense currents and electromagnetic fields can be produced, generically called EMP (Electromagnetic Pulse), that are felt at long distances. Living organisms are impervious to these effects, but they can temporarily or permanently disable electrical and electronic equipment. Ionised gases can also block short wavelength radio and radar signals (fireball blackout) for extended periods.

The occurrence of EMP is strongly dependent on the altitude of burst. It can be significant for surface or low altitude bursts (below 4,000 m); it is very significant for high altitude bursts (above 30,000 m); but it is not significant for altitudes between these extremes.

This was the reason for the steel liner to the silo: it would act as a Faraday cage, whereby the strong magnetic and electrical fields pass through the liner without affecting anything inside. For this to be effect, the cage must have no openings through which energy could leak. Studies were carried out on the consequences of such details as pipework into and out of the silo, and what effect they might have.

The main radiation hazard came from high energy neutrons, which would not only affect the warhead but also the crew inside the silo. One of the purposes of the lid was to act as a neutron absorber.

In addition, the equipment in the silo might be protected against ground shock, but the crew themselves could be seriously injured. There was even a proposal to keep a spare crew suspended in hammocks ready to take over! The missile itself would be suspended on hydraulic cylinders to act as dampers against the ground shock.

All this research was also of considerable interest to the U.S. Air Force, who were designing their own manned silos for the Titan II missile. As mentioned, this bears several strong points of resemblance to the Blue Streak launcher!

Within the silo, there would be a crew of 3 officers and 5 men per shift, and the crucial point of the O.R. for the launcher was that: "the emplacement must be self-contained for an emergency period of four days (covering three days before an attack is expected and one day afterwards)."

This is the pivotal issue for the silo concept: early warnings, launch times, and the rest were irrelevant. Indeed, although much had been made of the fact it would have been impossible to launch Blue Streak between the time that an incoming attack was detected and the time when it arrived, this misses the point entirely. The U.K. would never have launched "on warning". There were no facilities for doing so. A man carrying the codes for a nuclear attack follows around the U.S. President throughout his time in office, but in the U.K. there has never been such provision. There would have been very many times when the Prime Minister would have been inaccessible, such as when he was in his car on the way to Chequers, for example, and authority to launch would not have been delegated to the military.

The point of Blue Streak was to act as a deterrent, so that if the U.K. were attacked with atomic weapons, it would have the ability to retaliate for a period of at least 24 hours after the initial attack, although there is no reason why this period could not be longer. The U.K. might not then be a functioning society any more apart from this one vital aspect, its ability to strike back at its attacker. That was the point of deterrence. But would the launchers in fact be capable of this? Some thought so, when the effect and accuracy of Russian missiles was been discussed. Thus, in a Ministry of Defence memo in June 1958: "This does not mean that a potential enemy attack with weapons achieving a c.e.p. of ½ mile would invalidate Blue Streak as a weapon. With a c.e.p. of ½ mile, one MT weapon delivered at each site would have a 50% probability of neutralizing a site. [This was an estimate based on the silo design and the known effects of nuclear explosions.] Thus to achieve an acceptable probability of destroying our retaliatory capability, a much higher ratio than one attack per site would be required; for example, more than 3 attacks per site would be required for a 90% probability and, if the reliability of the attacking weapons system is, say, 70% then more than 4 launchings against each target would be required. Alternatively, to give a 90% probability of putting a Blue Streak site out of action with 1MT delivered, a c.e.p. of ¼ mile would be required and again additional launches would be needed to offset the inevitable less-than-100% reliability." [c.e.p. is circular error probability; the chance of 50% of missiles arriving within this radius.]

So the Air Ministry was happy with the concept of silos, and work was proceeding on them both in Australia and the U.K.. But the Treasury was not so happy. Air Vice Marshall Kyle, A.C.A.S.(O.R.), had to write a note in 1958: "At our meeting on Monday, 21st April, in the Ministry of Defence, the requirement for underground launching for Blue Streak was queried and I confirmed then that this was the firm intention of the Air Council. From the attached note you will see that this has been made plain for well over a year and that the need for underground siting was envisaged in the original O.R. for the missile."

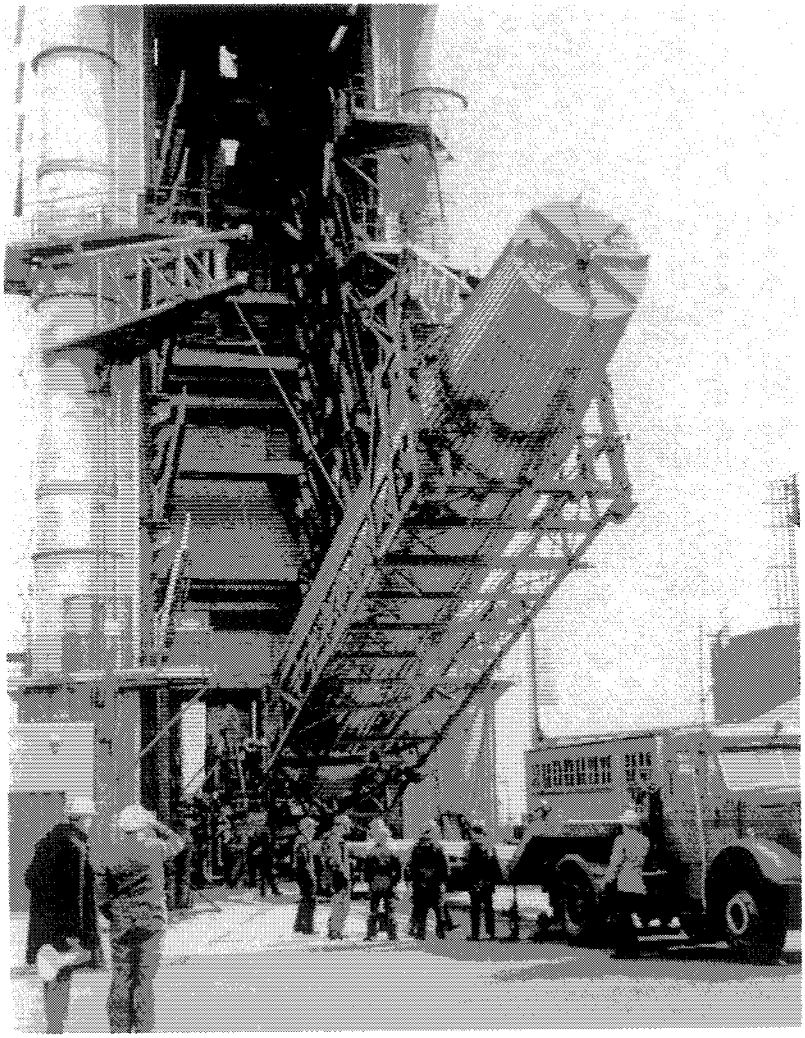
In Australia, a U tube launcher was to be built in the side of a ravine, to avoid unnecessary excavations. In the U.K., a full engineering prototype launcher was to be built, but finding a site for K11 and indeed for the rest of the silos was not easy. In June 1957 a list of 92 possible sites had been prepared, but only by looking at a map for disused MoD properties. In a stroke of lateral thinking, more than 40 roadstone quarries were looked at for suitability: after all, there was already a hole there, and roadstone was good and hard. Geologically, the silos had to be sited in hard rock, or other fairly rigid material such as chalk. By October

1958, there was talk of Duxford for the site of K11, with alternatives at Odiham, Waterbeach, and Stradishall. By January 1959, Castle Camp, Ridgewell, Sudbury, Raydon, and Lasham had made their way onto the list.

Although there was talk of building clusters of 6 silos at a time, the sites had to be well separated by distance of several miles, so that one site would not be affected by attacks on other sites. But in February 1959, there was a change in policy: "the first sites should be in the South of England, North of the Thames", and 12 disused airfields had been surveyed by March. A problem emerged at Duxford, however: discovery of the water table 40 foot down, and the resultant flow of water, rendered it unsuitable. Another site had to be chosen, and Upavon and Netheravon in Wiltshire were then earmarked for the job.

But now the Home Office intervened: they wanted the sites well away from any evacuation areas, and on the East Coast, so that fall out would be carried away by the prevailing winds. Upavon was dropped from the list of sites as a result. The 1959 election then intervened, holding up the progress, and after the election the emphasis changed: now the R.A.E. was sent up to Yorkshire and Durham to look at the likes of Acklington and Eshott as locations for the K11 site. Similarly, the Vice Chief of Air Staff favoured Ouston or Morpeth.

One thing was certain: by the time of cancellation, no site had been fixed upon, no excavation had been started, the design was not complete, and the chances of K11 being operational by 1964 were looking increasingly remote. But other problems were beginning to arise.



Blue Streak at Hatfield

Here it is being erected in a stand at de Havilland's works at Hatfield, where tests, such as pumping fuel from the tanks at the correct rate, were carried out. The photograph gives a good impression of the size of the vehicle.

6. Blue Streak: the cancellation

The political decision by the U.K. to become a nuclear power in the late 1940s implied two interlinked technical policies: the development of the nuclear device itself, and the development of a credible means of delivery. Credible in this context can imply a variety of different concepts.

Primarily, the threat of the nuclear deterrent has to be credible to the opposition, and as far as the U.K. was concerned, this meant Russia.

Secondly, the deterrent has to be credible to the armed services that have to deploy it, and also politically credible to the U.K. electorate.

Thirdly, in the U.K. context, it had to be credible to the United States, since the U.K. deterrent was perceived by the Government as essentially an adjunct to the U.S. deterrent, and also since the U.K. wished to have some influence over U.S. nuclear policy. This was not possible unless the U.K. had her own nuclear weapons. (The 1957 Defence White Paper described the U.K deterrent thus: "The free world is today mainly dependent for its protection upon the nuclear capacity of the United States. While Britain cannot by comparison make more than a modest contribution, there is a wide measure of agreement that she must possess an appreciable element of nuclear deterrent power of her own.")

A bomb without a delivery system is of little use. In the early 50s, the intended means of delivery was by a free fall bomb dropped from jet aircraft (the V bombers, which were the Valiant, the Vulcan, and the Victor), which were further to be augmented by Blue Steel. However, technological advances meant that many other means of delivery became possible as the decade advanced.

Principal among these was the ballistic missile, which, above all, seemed to have one overriding advantage. This lay in its apparent invulnerability: once the vehicle was safely launched, it would be extremely difficult to intercept. But there were various ways in which ballistic missiles could be deployed, and as the various possibilities unfolded, each one appeared to offer advantages over its predecessors. Thus, it was possible to begin development of one system, only to find that another system was becoming feasible, and which threatened to supersede its predecessor. Technological advances during the 50s were such that a new system could appear within a year or two of development having begun on an earlier system.

This was a particular problem for U.K. policy makers; those in the Cabinet and the Defence Ministry. For whatever reasons, development times in the U.K. were far greater than their U.S. counterparts. U.K. policy makers were put into a position where they had to take a decision on a system which might take ten years to develop, with an expected service life of perhaps another ten years. Thus they had to look twenty years into the future, and with little hard intelligence as to the capabilities of the Soviet Union. Much of this intelligence was based on erroneous assessment of the industrial capabilities of the U.S.S.R.. The launch of Sputnik in particular led the West to think that the U.S.S.R. was in many areas technically superior. In fact, the missile that launched Sputnik, the R7, was far too big and clumsy to be deployed operationally. However, Soviet nuclear forces from the late 60s onwards would be a formidable challenge to a country such as the U.K..

Political and Service tensions developed as a result of the development of potential rivals to Blue Streak. Proponents of one system often deliberately misused technical information to cast doubt upon another, and a good deal of the policy making was deliberately partisan. In other words, lobbying for a particular system was heavily influenced by particular Service departments who wished to control the means of delivery themselves, and whose budget would benefit accordingly. There were also other Service factions who wanted as little money as possible to be spent on nuclear weapons, to free up the Defence budget for conventional weapons.

The Operational Requirement for Blue Streak had called for a missile that could carry a megaton warhead over a distance of 2000 nautical miles. The weight of the warhead then available meant that a relatively large missile had to be designed, and in retrospect, this was a mistake. Given the long development time for the missile, it might have been reasonable to assume that warhead design might have made significant advances in the interim. However, hindsight is a wonderful thing.

The use of a cryogenic fuel for Blue Streak was also a potential limitation on its deployment, as the missile could not be kept in a ready to fire state indefinitely. However, it should be noted, in this context, that exactly the same constraints were to apply to contemporary Russian and American designs such as the R-7, Atlas, and Thor. Further, the structure was relatively fragile, and extremely vulnerable if deployed on the surface. Hence the intention at the outset was to site the missile in "underground launchers", already described. At the time the debate as to alternatives began, development of the missile was considerably advanced, at a cost of at least £60 million.

Alternatives.

Alternatives to Blue Streak began to emerge in 1958 and 1959. These were the Polaris submarine launched missile and an air launched missile code named WS138A, later to be known as Skybolt.

Polaris was a system developed by the U.S. Navy. It used solid propellant motors, and the early versions had limited range and payload. However, a decision had been taken by the U.S. Navy that since warheads would become much lighter as their design improved, the range/payload problem would be much less pressing by the time of deployment (warhead design in the U.S. was considerably in advance of that in the U.K.).

The U.K. had been involved with nuclear submarines when the U.S. Navy made available a design for a lightweight reactor for H.M.S. Dreadnought. Since then there had been close co-operation between the two services, and Admiral Arleigh Burke, in charge of the programme in the U.S., was eager for the RN to acquire the Polaris system.

Skybolt was designed by the U.S. firm of Douglas to be carried by an aircraft. Its range was intended ultimately to be 1500 miles, although with U.K. warheads of the early 60s it might be considerably less, perhaps as little as 600 miles. Unlike Blue Steel, it was a ballistic missile rather than a cruise missile. For the R.A.F., it held out not only the promise of an extended life for the V bombers, but also the possibility of future bomber aircraft. This was, not surprisingly, extremely attractive to the R.A.F., who preferred flying bombers to being confined to a hole in the ground. Hence in 1959, pressure began to be applied on the Ministry of Defence to reconsider its decision on Blue Streak.

Compared with the U.S., development times for U.K. projects were very much longer. By the time of cancellation, Blue Streak had been under development for around 57 months, with the first flight was still some months away. The Thor missile, albeit smaller but of the same technological sophistication, was 13 months from inception to first launch. There are various reasons for this.

The first is that the Americans had much more prior experience than the U.K.: missile development had proceeded almost uninterrupted since the war, whereas efforts in the U.K. had been much smaller scale and directed mainly at small defensive missiles.

A second reason was the means of procurement. In the U.S., specific teams were set up with considerable executive powers, and by comparison with the U.K., almost unlimited finance. In the U.K., the procurement ministry was the Ministry of Supply (later to become the Ministry of Aviation). A reading of the Ministry papers shows that the executive powers of the Ministry with regard to the industry carrying out the work were very much less.

Further, responsibility for the project was very much divided. The Ministry of Supply was the procurement Ministry. The Air Ministry would deploy the missile when it went into service. The Air Ministry however came under the control of the Ministry of Defence, who also then became involved. Finally the R.A.E. were to be the technical overseers of the project. Hence representatives of all these organisations, together with representatives from the firms, might all have been present at the various progress meetings. Such cumbersome bureaucracy cannot have helped the progress of the project. For example, an official in the Ministry of Defence wrote about the building of the facilities at Spadeadam: "I think the Minister of Supply ought to be shaken. It is up to him to warn us as soon as there is any administrative or financial difficulty to his not getting on as fast as he could with the project." The sending of memoranda back and forward from one Ministry to another must have been another time waster.

A third brake on the project was the Treasury, who took a much closer interest in Blue Streak than seems to be the case with many other defence projects. Thus in a minute to the Minister of Defence: "During most of 1956 we were defending the very existence of Blue Streak against savage attacks by the Treasury.". Such comments occur frequently in the Ministry of Defence files. By comparison, U.S. resources were incomparably greater, and American engineers could afford to launch missile after missile until the design was a success. The U.K. did not have this luxury.

However, the feature of Blue Streak that was to prove the most controversial was the means of deployment in "underground launchers". These launchers evolved gradually from relatively simple ideas into what today would be termed missile silos, although the term was not then in contemporary British use. The design of these launchers would give almost as many technical problems as the missile itself, and their size and complexity would have made considerable construction problems for the U.K..

However, these too came under Treasury attack. In April 1958 the Assistant Chief of the Air Staff (Operational Requirements) was forced to write to the Treasury: "At our meeting on Monday, 21st April, in the Ministry of Defence, the requirement for underground launching for Blue Streak was queried and I confirmed then that this was the firm intention of the Air Council. From the attached note you will see that this has been made plain for well over a year and that the need for underground siting was envisaged in the original O.R. for the missile." Further, a Treasury letter of January 1958 gave authority to start on Australian facilities, but "commitments on the part of the launchers related to 'below ground' aspect are to be kept to a bare minimum and no work should begin on the 'below ground' part of the launchers themselves."

But Blue Streak was running into other financial difficulties. In a sense, the Treasury's anxiety was justified, since the costs seemed to be open ended. The Ministry of Supply seemed to be unable to make any realistic cost estimates, and the time was fast approaching when firm decisions as to silos and their location would have to be taken. In addition, even the Home Office was becoming concerned, since their location affected civil defence decisions. The sheer size and scale of the silos was only just becoming evident: a site would occupy around 3 acres, and would have be a considerable distance from any habitation. (One potential site at Bircham Newton was ruled out on the grounds that it was too close to the Queen's residence at Sandringham!)

Stopping any such major project in its tracks is extremely difficult; very good reasons had to be found. There would be considerable political implications to cancelling such a major project. However, both the R.A.F. and the R.N. now had an alternative system. It is probable that the seed for the committee that was to cancel Blue Streak was planted by the Admiralty and watered by a faction inside the Air Ministry.

The debate begins.

The Navy felt it had come out of the cuts in defence resulting from the 1957 Sandys White Paper relatively lightly. But the deterrent and Blue Streak in particular was resented as it was felt that too much of the defence budget was being diverted towards it; money that could be used for new ships. However, attitudes began to change when the First Sea Lord, Mountbatten, was told of Polaris by Arleigh Burke, the originator of the system in the U.S.. Mountbatten and Burke were old friends, and a rather clandestine correspondence began between them. Soon the correspondence became more official. Burke was a formidable proponent for the system: he invented rather poorly scanning clerihews for the system along the lines of:

"Out at sea
"where the real estate's free"

to hammer the point that a submarine on patrol does not need fixed bases, and where it can remain undetected and thus invulnerable. The Navy took up Polaris with enthusiasm during 1958, but realised that the big obstacle was Blue Streak. The U.K. could not afford yet another nuclear delivery system. Accordingly a campaign began with the Admiralty, as an internal memo shows.

"I was surprised and encouraged today that amongst those who are advising both the PM & the Chancellor there is a pronounced feeling that if we are to go on with the deterrent it should only be on the basis of Polaris.

"I share your views that what we are most immediately concerned about is so to reduce the deterrent that we can maintain adequate conventional forces. I believe however that a decision to go for Polaris would give a large enough saving to guarantee the conventional forces we need. Further expenditure on Polaris would I think be less than future expense on Blue Streak plus fighter defence of the deterrent.

"If I am right that we can get an immediate saving by taking the decision now, I feel that we should present the economic advantages of Polaris rather more strongly. Such a presentation would it appears fall on fertile ground."

The Admiralty became even more excited when they discovered (and misinterpreted) a scheme for a U.K. A.B.M. system: "You would hardly believe it, but since sending you my note this afternoon we have unearthed further information which really does put BLUE STREAK out of court." The language used goes well beyond the simple evaluation of the merits of rival systems: it becomes distinctly partisan.

Sandys himself had had doubts about Blue Streak during 1958, but decided to press ahead on the grounds that he could see no alternative. The V bombers with free fall bombs would be adequate until 1960, with Blue Steel until 1965, but after that some form of ballistic missile seemed the only option.

The Navy's efforts had not gone unnoticed by the Air Ministry either, as this note in June 1958 from the Secretary of State for Air to Sandys shows: "The general conclusion that I come to is that the matter is of such fundamental importance and so complex that it might be more helpful to you if the Chiefs of Staff were asked to examine the requirement in all its aspects, strategical, tactical and technical, in the light of ... the First Lord's paper, and then to put forward a considered military opinion to you."

So were set into train events which would involve the three Service Ministries, the Ministry of Defence, the Ministry of Supply, the Treasury, the Home Office and the Foreign Office in a bitter struggle for the next twenty months. For the Services, the prize at stake was which of them would carry the deterrent for the foreseeable future.

Mountbatten, then First Sea Lord, was pushing hard for some form of report too, as a note to Sir Frederick Brundrett shows: "... we are all most anxious to see that the Powell enquiry is dealt with on the right lines, to be quite sure that it will lead to the right answer. This is a Defence question first and foremost, although it may have all sorts of secondary interests. We none of us can believe that Powell and two outside scientists can possibly arrive at the right answers if they have no Service views on the requirements represented at the Committee.

"For this reason, we are all convinced that we must have adequate representation on the Committee from each of the Services; and that is why we decided that the three Vice Chiefs should sit on it."

("Powell" refers to Sir Richard Powell, then Permanent Secretary at the Ministry of Defence, and a key figure in the story of the cancellation.)

This is a letter full of ambiguity: what is the "right answer"? Presumably, to Mountbatten, this meant Polaris. And it is interesting that Mountbatten is pressing for Service representation on the committee.

Accordingly, Sandys minuted Powell in December 1958:

"The Chiefs of Staff have no doubt been considering for some time the respective advantage and disadvantages from the British stand-point of basing our nuclear deterrent underground or under the sea.

"I think we ought to have a discussion of this matter at an early meeting of the Defence Board. I should, therefore, be glad if you would let me have a summary of the views of the Chiefs of Staff as soon as you can after Christmas."

But an internal Admiralty note written to the First Sea Lord in May 1959 gives another perspective:

"As I see it, the present Minister of Defence [Sandys] will do all in his power to prevent any alternative to Blue Streak from even being considered. I am also certain that the new Chief of the Defence Staff [Mountbatten], when he takes office, will do everything in his power to see that the merits of Polaris are brought to the attention of HM Government. Domestically, I am certain that we in the Admiralty need a much clearer picture than we have at present of the probable repercussions of the Polaris programme on the rest of the Navy before we start any official pro Polaris propaganda. Indeed, I doubt it is right for the Navy to undertake any such propaganda at all. I believe we would be in a far stronger position if we were (at any rate, apparently) pushed into the POLARIS project rather than have to push it ourselves."

Accordingly, Powell submitted a reply to Sandys outlining the form he felt such an inquiry should take, and suggested its terms of reference as being: "To consider how the British-controlled contribution to the nuclear deterrent can most effectively be maintained in the future, and to make recommendations."

But then he had to push Sandys for further action: "In a minute of 23rd March I submitted proposals for setting up a study into the future of the British deterrent ... you agreed that this should be set in action but subsequently asked me to do nothing, in order to avoid casting doubt on the future of BLUE STREAK.

"The Chiefs of Staff and Sir Norman Brooke [the Cabinet Secretary] have recently asked me about this study. Both felt that it ought to go on, since the future of the deterrent is bound to come up again after an election, if not sooner. I think they are right, and should like to have your authority to proceed ..."

It is difficult to judge whether Powell is being disingenuous or not: did he go to Brooke and the Chiefs of Staff, or did they, as he alleges, come to him? It is also noteworthy that the Cabinet Office has become involved. Whether this was Brooke acting on his own initiative, or whether Macmillan himself was taking an interest in unclear.

In any event, a note from Sandys' office to Powell shows that his hand is being forced: "The Minister discussed with you this afternoon the proposed Study Group on the British deterrent. He felt that we had only recently reached our conclusions on the need and form of the British contribution to the nuclear deterrent. Little further information would be available, and in his view, the time was not yet ripe for a further study of this problem. He asked that if this matter was raised in your coming meeting at Chequers, you should say that he was considering setting up a Study Group, and you should to leave this matter open. You agreed to discuss this further with the Minister after discussing it with Sir F. Brundrett and after your visit to Chequers."

The idea of the Permanent Secretary visiting Chequers (the Prime Minister's country residence) without his Departmental Minister is an interesting one. There is obvious speculation that Macmillan had some influence on the decision, and if so, it is possible that it originated from this visit. Certainly, Powell returned persuaded that all three Vice Chiefs should be on the study group.

Another reason for suspecting Macmillan's influence is the replacement of Sandys by Watkinson as Defence Minister after the October 1959 General Election, and it is certainly the case that Sandys appears to be unaware of the Study Group's thinking and conclusions until well after the event.

So the review of the deterrent was set up in July 1959 under the chairmanship of Sir Richard Powell. Indeed, the committee was controversial from the outset, by Powell's wish to exclude Sir Frederick Brundrett, then Chief Scientist at the Ministry of Defence, and a known advocate for Blue Streak, from the committee. The eventual composition of the committee, as well as Powell, included the three Deputy Chiefs of Staff: Vice Admiral Durlacher, Lt. Gen. Sir William Stratton and Air Marshall Sir Edmund Hudleston. There were scientific heavyweights in the form of Sir William Strath, Sir Frederick Brundrett, and Sir William Cook of Aldermaston. In addition there was Sir Patrick Dean from the Foreign Office and Mr. B.D. Fraser from the Treasury. The committee was to be known as the British Nuclear Deterrent (Study Group) or B.N.D.(S.G.). Given the composition of the study group, then any recommendations that it might make would carry a great deal of weight.

The committee was very successful in keeping their deliberations from the Air Ministry and the Ministry of Aviation. Throughout the report's gestation—deliberations began in July 1959—the Air Ministry seemed quite confident that Blue Streak would come out of it with a clean ticket, which was certainly not to be the case! It appears from correspondence from Sandys that he was not kept informed; certainly he made no submissions to the committee. In addition, Sir Steuart Mitchell, CGWL, had little input, as shown by a note of his to Sandys a month after the report was finished:

"Adequate opportunities did not occur during the drafting of their report by the Study Group for my Controllerate to brief you properly on the technical issues as they arose, nor to discuss with you the conclusions and recommendations of the report … now that I have seen the report I am seriously disturbed at the picture it presents in so far as the technical issues are involved, and ... I disagree with some of the conclusions. I am having those technical aspects of the report which lie in my sphere examined (for the first time) in detail." From the Government's principal expert on missiles to be kept in the dark in such fashion is revealing. Indeed, given that the Study Group consulted elsewhere, such an omission is very surprising—unless it was deliberate.

However, an interesting submission was put forward to the Study Group by the Air Ministry Strategic Scientific Policy Committee, made up of some extremely eminent scientists: Sir Solly Zuckerman, William Cook, Deputy Director of AWRE Aldermaston, Sir James Lighthill, Director of the R.A.E., and Professor William Hawthorne. Hawthorne was already a silo sceptic, as a note to CGWL, Sir Steuart Mitchell, in 1956 indicates: "I can imagine a few 'impregnable' subterranean fortresses being built at enormous expense, but not many, since politicians may find them hard to justify." Cook was also, of course, already part of the Study Group.

Here the first suggestion of the "vulnerability" of the underground emplacements is put forward. The Air Ministry committee's report is noncommittal, but clearly sceptical about the survivability of "fixed sites".

"Given that the enemy knows … where our fixed installations are, and … that he can launch a surprise attack of sufficient speed and accuracy, it must be concluded that by about 1970, and possibly before, the U.S.S.R. can neutralize all fixed U.K. static bases, whether they are airfields or above-ground or below-ground missile sites … it follows logically that any deterrent force whose location was not continuously traceable or detectable would be invulnerable to surprise attack … Were such a system possible, it would be as much the ideal weapon system today as it would tomorrow."

The phrase "fixed sites" was to become a code phrase for those who thought that Blue Streak in its underground launcher was not viable. "Underground launch sites" was the phrase used by the proponents of the system. Interestingly, the same idea of "vulnerability" is held true of airfields (with more justification), and the report is an oblique endorsement of Polaris. In its earlier musings on the deterrent, it bears the signs of Zuckerman's authorship.

The picture is further complicated by the close relationship between Zuckerman and Mountbatten. In 1959 Mountbatten became Chief of the Defence Staff, and Zuckerman was a highly influential Government scientific adviser. Zuckermann was adept at finding his way around the "corridors of power" (it has been reported that he was first choice for the post of Minister of Disarmament in the first Wilson administration. He was certainly heavily involved in many of negotiations about Polaris with the U.S. Government.), with very decided views on military matters and the deterrent. As well as being an active proponent of Polaris as against Blue Streak, he is supposed to have wielded considerable influence, in conjunction with Mountbatten, in the decision to cancel the TSR-2 aircraft. It is interesting therefore that the first suggestion of vulnerability comes from someone associated with Mountbatten.

The Treasury representative, Fraser, seized upon this suggestion of vulnerability, saying: " ... surely we would not decide to equip our troops with spear proof shields if we know that by the time we have made the shields the enemy is going to have fire-arms."

This rather tendentious description of the silos was the first shot to be fired in a Whitehall battle that would last for the next five months.

Excluded from the Powell report were the "political purposes for which British nuclear forces are required". Instead they were to look at "technical and operational factors". In discussion of the Russian capabilities, the report drew the conclusion that by 1965 the USSR would be able to launch warheads between 3MT and 8MT with "an accuracy of 0.55 n.m. at 1,000 n.m. range" [n.m. = nautical miles]. The key passage comes later in the report, however, when it says that: "If we assume that the Soviet attack would be made with ballistic missiles of an accuracy equal to that which we expect to achieve ourselves (0.55 n.m.) and that a warhead of at least 3 MT would be available, 95 per cent of the underground BLUE STREAK sites could be destroyed by between 300-400 Soviet missiles."

The arithmetic at this point becomes crucial. 300 to 400 missiles are needed since although the accuracy is given as 0.55 miles, this actually implies that only 50% of the missiles will actually achieve this result. The Air Ministry had made an estimate of the vulnerability the previous year: "With a c.e.p. of ½ mile, one MT weapon delivered at each site would have a 50% probability of neutralising a site. Thus to achieve an acceptable probability of destroying our retaliatory capability, a much higher ratio than one attack per site would be required; for example, more than 3 attacks per site would be required for a 90% probability and, if the reliability of the attacking weapons system is, say, 70% then more than 4 launchings against each target would be required. Alternatively, to give a 90% probability of putting a Blue Streak site out of action with 1MT delivered, a c.e.p. of ¼ mile would be required and again additional launches would be needed to offset the inevitable less-than-100% reliability." (c.e.p. is circular error probability. This is the distance from the target that 50% of the missiles might be expected to achieve.) Another Air Ministry view was that: "It is doubtful if Soviet attack on the Blue Streak sites will be worth while even in 1970 as, with a half mile nautical mile delivery acuracy, it is stated in (*a joint Intelligence Committee report*) that 11 missiles per site will be necessary to give 95% assurance of destruction."

It is not clear whether the Powell figure represents the number of warheads launched, or the number that actually have to arrive and explode. If the latter, then the number that would need to be delivered would have to be almost double, given estimates of reliability of Russian missiles. Further, the Powell report was talking about a pre-emptive attack, one where there would be no warning and hence all the missiles would still be in their silos. In addition, for an attack of this nature to be successful, all the warheads would have to arrive at the sites simultaneously. As CGWL would later point out, this is logistically almost impossible, since missiles from different locations in Russia and Eastern Europe would have different flight times, depending on their location and target, and so would have to be different launch times to ensure simultaneous arrival. In addition, there is another more subtle point ignored by the committee, but one which they should been aware of, which is called fratricide. If two warheads arrive in very close succession, then the explosion of the first will almost certainly disable the second. This occurs for a variety of reasons, not the least of which is the neutron and gamma radiation emitted by the initial detonation. The shock wave of the explosion and the atmospheric disturbance is also likely to affect the trajectory of other re-entry vehicles. Hence the analysis offered by the Study Group was, to say the least, highly simplistic.

The conclusion was further attacked on the grounds that 300-400 3MT weapons would create enormous problems in the form of fall out, increased considerably since most of the blasts would be ground bursts rather than air bursts. Indeed, given the prevailing westerly winds, such an attack could render most of the European mainland and the European area of the USSR itself completely uninhabitable. This was not a credible scenario.

However, these estimates were made on the presumed basis of the capability of Soviet missiles in the late 60s/earlier 70s. There is a tendency to assume a worst case scenario, and indeed any analysis must do so. Decision makers dealing with the future must deal with the most unlikely of events. The Soviet triumph of placing Sputnik in orbit in 1957 came as a considerable shock to the West and to America in particular, and thus may have fuelled a tendency to assume Soviet superiority in missile technology. However, much of the criticism of the Powell report that was to follow centred on the unlikely nature of the postulated scenario. There was a further point which also went overlooked: would the Soviet Union be prepared to expend so much of its arsenal on the U.K., when its main adversary was likely to be the U.S.?

Now that the Powell Report having disparaged Blue Streak in this unlikely set of circumstances, what did it make of the alternatives?

The only alternative directly considered by the report was the V bombers carrying WS-138, which would become better known as Skybolt. Of a Russian attack on the bombers and their airfields, the report concludes: "But, in any event, the arrival of the Soviet missiles would inevitably be spread to some extent and some of the bombers would probably be able to escape."

But this contradicts the Blue Streak conclusion that the Soviet attack could be co-ordinated almost down to the minute. Further, how many is "some"? Then there were the Russian defences. WS138A was reckoned at the time to have a range of the order of 600 miles, so the V bombers would not have to fly all the way to Moscow, but there were considerable Soviet air defences based in Eastern Europe. The suspicion is strong that the committee was not, to use a modern phrase, playing on a level pitch. In other words, the criteria that were applied to Blue Streak were not being applied to the V bombers with Skybolt. Furthermore, aircraft on the ground, or even in the air, are an order of magnitude more vulnerable to nuclear attack than a well designed silo.

But the key phrase was "[Blue Streak] would therefore effective only if it were fired first ...". This phrasing allowed the system to be ruled out on the grounds that no U.K. Government would ever dare to fire off nuclear missiles unless the country had already been attacked.

However, the report was to spark off a Whitehall battle of some proportions. Many in the Ministry of Aviation (which had taken over from Supply) up to, and including Sandys himself, attacked the report in trenchant language that was not the usual polished civil service vernacular. One of the first ripostes came from one of the most important figures in the Ministry, Sir Steuart Mitchell.

"The estimates of total costs ... are seriously misleading. In my view, if estimates of total cost to the taxpayer of the Blue Streak and WS.138A weapon systems until the end of their useful life (say 1975) were made it would be found that the Blue Streak system would total some £500-£600 million while the WS.138A system, including the necessary new bombers to follow the Vs would total £800-£1000 million. This very important factor of total cost is not, in my view, adequately presented in the report.

"The vulnerability of underground Blue Streak is, in my view, grossly overstated in the report. As a result, Blue Streak is presented to Ministers as exclusively a fire first weapon, with all the serious disadvantages thereof. This, in my view, is based on misunderstanding of the technical facts.

"The report, in my view, accepts much too light heartedly the technical concepts of the WS.138A weapon system. History is strewn with weapon system concepts in which U.S.A.F. expressed total confidence and which they pursued with great ardour for a year or two and then totally dropped. W8.138A today is where Hustler was four years ago except that the confidence and enthusiasm in

W8.138A today is less than in Hustler four years ago. Hustler today is dead. To any technician familiar with the problems of a ballistic missile fired off a fixed site, the thought of putting our deterrent shirt on an American plan to fire such things off an aeroplane and having them in Service operations in the U.K. by 1966 or soon after as stated in the report is alarming. In my view the plan proposed in the report is dangerously unsound."

"Seriously unsound", "grossly overstated", "alarming", "dangerously unsound": these are strong words indeed in this context, not phrases in common use in Whitehall. These are from the Government's chief expert on guided weapons! But despite all the challenges to the technical arguments, the supporters of Blue Streak missed a crucial point: the decision was to be reached on political rather than technical grounds.

And Mitchell raises a point that was echoed elsewhere: WS138A was merely a gleam in the eye of the American firm Douglas and of the Pentagon. Thus, in another paper by the Chief Scientist, Brundrett, entitled "The 1963-1972 Gap", he notes "the unreliability of American weapon policy (they might stop the project halfway through)". Mitchell and Brundrett were quite right: the cancellation of Skybolt at the end of 1961 was to prove highly embarrassing to the Macmillan government, leading as it did to the Nassau conference and the purchase of Polaris. (During the announcement of the cancellation in the Commons, a Labour member commented that buying Skybolt was buying "a pig in a poke". However, there was considerable Labour opposition to the deterrent *per se*.)

It is also noteworthy that Sandys, the instigator of the project, and the Minister responsible for the development of the project, was not better informed, for he wrote to the Chancellor on 25th January 1960 to say: "Therefore, unless the Defence White Paper contains an announcement that Blue Streak is to be abandoned, which I regard as inconceivable, and which I would, of course, strongly resist, I must ask you to give the 'all clear' so that further serious delays can be avoided." This was written nearly a month after the Powell report was finished.

But the Chancellor, Derek Heathcote Amory replied on 4th February:

"I do not think it would be reasonable, at a time when the future of the weapon is the subject of a searching review as a major question of defence policy, to accept that the programme should suffer no delay. ....

"I am afraid therefore that I still feel unable to authorise the further expenditure referred to ..."

He also cited a previous hold up of funds (the Prime Minister's note of December 1958) as a precedent.

Cost, however, did not seem, on the surface of things, to be an issue. Various deterrents were costed with results that seem to be inconclusive—partly because there was no way of costing many of these projects, partly because the costings depended on the numbers of missiles to be ordered, and partly because other factors (for example, would Skybolt imply a new bomber for the R.A.F.?) were or were not included. One of the weaknesses of all the various costings was that no-one really knew why they wanted a deterrent, and so estimates could vary wildly depending on the numbers of the particular system under consideration.

But the Ministry of Aviation now swung into action with a series of papers decrying the V bombers as a means of carrying the deterrent (it is curious to see an Aviation ministry attacking the use of aircraft!). Sandys and C.G.W.L. enlisted the help of the R.A.E. at Farnborough in an attempt to show the vulnerability of the V bomber force. Thus a note from CGWL to Sandys:

"Bomber Reaction Time to Ballistic Missile Early Warning.

"S. of S. for Air's Letter of 1/3/60 to Prime Minister... The Minister [*Sandys*] has asked for advice on the above ... I think that the S. of S's argument is open to serious questioning on the lines shown below.

"... Blue Streak is condemned because of alleged inability to withstand 300/3MT rockets directed against 60 sites. It is therefore fair to consider what 300 3MT bursts could do to our V bomber force.

"The Air Ministry claim that they can get '4 bombers airborne from an airfield in 4 minutes'—presumably four minutes from the local order to scramble....

"The disabling radius of a 3 MT airburst against a V bomber is approximately as follows:

"V bomber on ground ... 14-15 miles. (not tethered since it is about to take off)

"V bomber airborne between zero height and 12,000 ft ... 12 miles.

"One 3 MT burst over the airfield ... would therefore disable not only all aircraft still on the airfield but also all airborne bombers within 12 miles of the burst.

"Further, it would be reasonable to suppose that the Russians, in addition to the airburst directly over the airfield would at the same time lay on two additional airbursts along the direction of the bomber flight path...

"It will be seen that the combination of one airburst over the airfield and two airbursts about 14 miles away and about 30° to the axis of the runway would disable not only all aircraft still on the runway but also all aircraft that had become airborne during the preceding 3 minutes. If these rocket bursts occurred at any time within the period up to 6 (not just 4) minutes before the order to scramble, it is difficult to see how any significant number of the bombers could escape.

"I do not know the number of airfields which the V bomber force would use under dispersal conditions. But if one supposes the number to be, say, 50 at the most, [*in fact, it was considerably fewer, of the order of 36 airfields*] then to carry out the attack outlined above would require a total of 3 x 50 = 150 missiles.

"If the Russians were in any doubt as to the direction of take-off of the 7 bombers, they could remove the ambiguity by placing two other airbursts 14 miles at 30° from the other end of the runway to cover the reverse direction of take-off. This, for 50 airfields, would require a further 100 missiles, thus bringing the total missiles up to 250, which is still below the 300 postulated for the knocking out of Blue Streak.

"Further, a number of the dispersal airfields are understood to be sufficiently near each other for the damage radius of a burst on one airfield to overlap on to the neighbouring airfield, thus reducing the weight of attack required.

"Finally, it should be realised that the bomber bases in East Anglia would only get 2½-3 (not 4 minutes as commonly stated) warning by BMEWS of the Russian 1000 mile rocket if fired on a low trajectory from satellite territory.

"It should also be added that it is unlikely that, 'on the night' and for the first time ever, a delay of less than 1—2 minutes would occur between the first radar reception at BMEWS and the local order to Scramble on a bomber airfield. The S. of S's claim is therefore more correctly stated as being four bombers airborne in 5—6 minutes after first radar reception. The rocket however could burst in less than 4 minutes from first radar reception, and indeed a pattern of bursts as shown in the sketch could burst as late as 7—9 minutes after first radar reception and still catch all or nearly all the bombers...

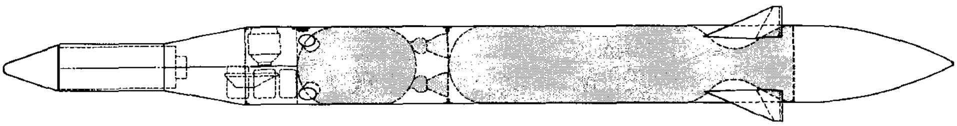
"CONSTANT AIRBORNE ALERT ... The Air Ministry, as far as I know, have never made say external statement on the logistics of maintaining a constant airborne alert. I suggest they should be asked to do so.

"In particular, they should be asked what C-in-C Bomber Command does, in a period of tension, if the Russians start jamming BMEWS. Does he fly off, or does he not?

"If he does not fly off, why have BMEWS? If, on the other hand he does fly off, then presumably he would re-land his force in shifts and shake them out on to a constant airborne shift basis. He should then be invited to say how he would handle the subsequent logistics if the jamming of BMEWS continued for, say, six hours, or twenty-four hours, or a week, or a month. It would, I think, be difficult not to be run ragged."

(BMEWS was the Ballistic Missile Early Warning System situated at Fylingdales in the Yorkshire moors.)

This is typical of the papers produced by Sandys and by Mitchell, all raising very valid points, but as far as the papers show, there was no real attempt at rebuttal to any of these arguments. Instead, it would appear that the papers go largely by default.



The air launched ballistic missile Skybolt

This was a 2 stage solid fuel airlaunched missile. Each Vulcan would carry two missiles, one under each wing.

However, in one sense, the argument had already been lost. Blue Streak had had sufficient doubt cast upon it that revival became impossible. (Similarly, later, when the U.S. Secretary of Defence Macnamara cancelled WS138A/Skybolt, but still offered it to Britain, Macmillan rejected the offer on the grounds that "the lady's virtue has been impugned". The same was happening to Blue Streak.)

Indeed, the battle went outside Whitehall with the publication of an article in the Daily Mail on 4th February 1960. The headline ran "Blue Streak is a damp squib" and went on:

"This is the key problem—one of the most critical defence questions this country has faced—that Mr. Harold Watkinson, a senior cabinet minister, was put into the Ministry of Defence last October to solve. ...

"His brief from the P.M. was short and to the point. First, Britain must continue trying by all means within financial reason to remain an effective nuclear power.

"Second, an attempt to do this by striking a new balance between the runaway costs of the deterrent and our obvious weakness in conventional forces.

"With this in mind, it follows inevitably that the first file called for by Mr. Watkinson in the Ministry of Defence was labelled "Blue Streak".

"In the days of his predecessor, Mr. Duncan Sandys, this file was the sacred cow. Mr. Sandys had made up his mind unalterably that Blue Streak, secure in its underground cells, was the answer for Britain.

"It is said that throughout last summer Mr. Sandys faced increasing pressure from financial and military experts to think again. Apparently, he was obdurate. Only in his successor has a ready listener been found.

"The most disturbing aspect of the cost of Blue Streak was strengthening military opinion that this fabulously expensive weapon would be secure underground only for a few years at most.

"Once the Russians could guarantee the accuracy of their rockets within half a mile, Blue Streak would be as vulnerable as today's Thors which stand plain for all to see fixed on their surface-launching pads in East Anglia. ...."

The most interesting feature of this article is: where did the journalist get his information? To be as well informed as this suggests a leak from very top levels—possibly even the Cabinet Office. And, further, although Blue Streak is portrayed as obsolete, there is no alternative mentioned.

Other newspapers also picked up on the political implications of the struggle: another article mentioned the constant redrafting of the Defence White paper, and noted of Sandys that: ".. if he wins this Cabinet battle his personal standing among Ministers will be immensely enhanced. If he loses, his resignation cannot be ruled out."

The debate ends.

But despite all the arguments between Ministries and their civil servants, the Chiefs of Staff were to short circuit the whole debate in a letter to Watkinson on 5th February, saying: "We attach no military value to Blue Streak as a weapon, and we recommend the cancellation of its further military development for this purpose, together with the planned deployment." The reason given was the "fire-first" nature of the system.

This was to put Watkinson in a very difficult position. He had only been Minister for Defence since the October 1959 election, and in his first Cabinet post (he would disappear from the Cabinet in the reshuffle known as "the night of the long knives" in July 1962). Irrespective of all the papers from the Ministry of Aviation, and from Sandys, a Cabinet colleague who had been in successive Conservative cabinets since Churchill's election victory of 1951, and who was the originator of the project, Watkinson had now received a memo from the Chiefs of Staff to say they had no confidence in the weapon. There was little he could then do. He wrote to Sandys on 9th February, and, unusually, the word "personal" is handwritten at the top. The letter reads:

"Dear Duncan,

"Rippon and Strath will have told you how things have been developing in your absence.

"The first development is that WS.138A seems to be doing well. You will have seen the messages sent to your Ministry by the Mission, which show that it has now been approved by the Department of Defense....

"This leads on to Blue Streak. The Chiefs of Staff have been considering their attitude to Blue Streak and have now given me their unanimous advice that they find Blue Streak, as a fire first weapon, unacceptable. I am afraid Dermot sold the pass here to begin with.

"If then it is open to us to obtain an American weapon on acceptable terms, we are faced with a disagreeable choice. Either we must go on with Blue Streak in the knowledge that the Chiefs of Staff advise against it as a weapon. Or we must cancel it in favour of an American weapon, with all that may be involved in the way of losing the ability to develop missiles on our own. No intermediate course seems to be feasible as I understand from your department that if Blue Streak is to go on at all there is no sensible way in which any significant sum could be saved. I am not sure that they have really thought this out enough, but you will know better than I about this.

"This then is the choice so far as spending defence money is concerned. It may be that the Minister of Science will conclude that he can justify financing the development of Blue Streak and converting it into a project for space research, primarily from civil funds. I have put this proposition to him but I should doubt whether he can find the money.

"All this presents us with a difficult choice and I am not yet clear what it is best to do in the national interest. In order to help me to form an opinion I have been asking your department for information about the consequences of stopping Blue Streak. Your department is directly in touch with the Minister of Science's office about the cost of the space research programme.

"I should very much like to know what you think, as soon as your people have finished setting out the consequences of stopping Blue Streak, or any possibility of saving something from the wreck."

"Dermot" referred to in paragraph 5 was the R.A.F. Chief of Staff, Sir Dermot Boyle. This is in itself an interesting note: Blue Streak was intended for the R.A.F., yet even the head of that Service had rejected it. Watkinson's implication is that Boyle's withdrawal of support for Blue Streak was the precipitating factor.

The phrasing of the letter is also interesting: Watkinson realises the implications for Sandys, yet cannot argue against the advice give to him by the professionals.

What were the motives of the Chiefs of Staff? Crudely, they could be summed up as follows.

The Army had no real interest one way or the other. Their only real interest was to keep the cost of the deterrent as low as possible to allow more room in the military budget for new equipment (tanks and the like) for conventional forces. If a cheaper alternative to Blue Streak was available, they would vote for it.

Mountbatten, as mentioned, had other motives. He was, in addition, Chief of the Defence Staff, and a man with a considerable Whitehall network. Cancelling Blue Streak, to which he was opposed anyway, opened the way for the Navy to acquire Polaris submarines, which they did in the mid 60s.

Boyle, of the R.A.F., also saw opportunities for his service. Not only would the V bombers be given a new lease of life, there was a further window of opportunity for the R.A.F. to acquire further aircraft, which indeed was intended to happen. Proposals were well advanced at the time of the cancellation of Skybolt to purchase VC-10 airliners and modify them to carry the missile.

Apart then from the Ministry of Aviation, Blue Streak had no Whitehall or Service support. Hence it was to go.

But there were other political considerations to the cancellation. Two of the most important were the potential criticisms for the cost to date, and the Australian dimension.

Since the late 40s, there had been considerable co-operation between the U.K. and Australia in matters of weapons development. The U.K. had devices to test but no room in which to test them; Australia had the room but didn't have the devices. Thus Australia provided testing sites for atomic weapons (the Monte Bello Islands, Emu Field, and Maralinga), as well as the Long Range Weapons test site at Woomera. All Blue Streak test firings were to have been carried out at Woomera, and many facilities, funded jointly by the U.K. and Australia, were nearing completion. Thus the Foreign Office in particular were concerned about the impact of the cancellation on the Menzies Government and on Australian public opinion.

As to the cost of the project so far, there was a salvage option: to continue Blue Streak not as a military weapon but as a satellite launcher and studies for this had already been started independently. This would also be expensive, however, particular if there were no military support to complete the development. The cost of the project together with a desire for strengthening Britain's credentials in Europe, would lead down the blind alley of the European Launcher Development Organisation [ELDO], which would cause subsequent Governments much grief.

Now the decision went to the Cabinet Committee on Defence, and the minutes of its third discussion on 6th April read:

"THE PRIME MINISTER said that the first question for consideration was whether the provisional decision ... to abandon the development of BLUE STREAK as a weapon should now be confirmed. There were two main issues to decide:-

"(a) Would it be militarily acceptable to rely on the V-Bombers, with SKYBOLT, rather than on BLUE STREAK, as our strategic nuclear force from about 1965 onwards?

"(b) Was it reasonable to assume that SKYBOLT and eventually POLARIS (if we needed it) would be made available to us by the Americans on satisfactory terms?

"THE MINISTER OF DEFENCE said that ... the general consensus of opinion was that, in circumstances other than a surprise saturation attack, the V Bombers equipped with SKYBOLT would have certain advantages over BLUE STREAK. The main considerations leading to this conclusion were political rather than scientific or technical. The Bomber force had qualities of mobility and flexibility which were useful for conventional operations as well as for the nuclear deterrent. It had the advantage that it could be launched on a radar warning without an irrevocable decision being taken to launch the nuclear attack itself.

"THE MINISTER OF AVIATION agreed that there would be certain financial and political advantages in depending on the V-Bombers and SKYBOLT rather than on BLUE STREAK for our strategic deterrent force in the later 1960's. From the military point of view, there was no marked advantage one way or the other. In these circumstances he would concur in the decision that the development of BLUE STREAK as a weapon should be abandoned.

"... The Americans had indicated their willingness to make SKYBOLT available unconditionally, except for the suggestion, which we might be able to persuade them to modify or abandon, that specific reference should be made to its use for North Atlantic Treaty (N.A.T.O.) purposes. It should be possible to reach a similar understanding as regards POLARIS (on which, however, no immediate decision was required) ...

"THE PRIME MINISTER said that the Committee's discussion showed that their provisional decision to abandon BLUE STREAK as a weapon could now be confirmed. The next question to be considered was whether its development should be continued for scientific and technological purposes. The officials' Report showed that there were only two alternatives:

"(a) to cancel BLUE STREAK completely; even if this were done immediately, there would be unavoidable nugatory expenditure of about £72.5 millions, of which £22 millions would fall in 1960/61.

"(b) to adapt it as a space satellite launcher at a cost, including the development of a stabilised satellite, of about £90-100 millions.

"The advantages, and disadvantages of these two courses could not be wholly assessed in material terms. To cancel BLUE STREAK would involve dislocation of industry, difficulties with the Australians, heavy charges, the loss of the potential value of a large British rocket for space research or other purposes and the abandonment of that part of the work already done which was relevant to the development of a satellite launcher; but it would curtail expenditure in the longer term, and make resources available for other purposes. To develop BLUE STREAK as a space satellite launcher would be much more costly... and the Ministry of Aviation had not been able to consult the firms concerned about whether the £90-100 millions launcher and satellite programme would in fact be practicable....

"THE CHANCELLOR OF THE EXCHEQUER said that an immediate decision should be taken to bring all further work on BLUE STREAK to an end. The nation's resources over the next few years would be inadequate to meet all our existing commitments. Since there was no suggestion that any other project should give way to the development of BLUE STREAK as a space satellite launcher, he did not see how the heavy expenditure involved could be met. The programme was estimated to cost over the next four or five years some £75 millions more than the cost of immediate cancellation; past experience suggested that this figure might be considerably increased and that other defence projects, for which no provision had yet been made, would eventually come forward to take the place of expenditure saved on BLUE STREAK. The national economy would benefit from the industrial and man-power resources made available by the complete cancellation of BLUE STREAK ...

"Summing up, THE PRIME MINISTER said that the Cabinet should be informed of the decision to cancel the development of BLUE STREAK as a weapon and invited to consider whether this decision should be announced in terms that all work on BLUE STREAK should cease completely or that further consideration was being given to its development as a space satellite launcher. If the latter alternative were adopted it would be desirable for a final decision to be taken if possible within the next few weeks.

"The Committee took note that the Prime Minister would arrange for the Cabinet to be informed of the decision to cancel the development of BLUE STREAK as a weapon and of the terms in which this decision might be communicated to Parliament and to the Government of Australia on the alternative assumptions that -

"(a) all further work on BLUE STREAK should cease;

"(b) consideration should be given, in consultation with industry and the other interests concerned, to the adaptation of BLUE STREAK as a space satellite launcher."

The decision having thus been taken, it fell to Watkinson to make the announcement in the House of Commons on 13 April. He rose to read a statement which ran thus:

"Blue Streak.

"1. The Government have been considering the future of the project of developing the long-range ballistic missile Blue Streak, and have been in touch with the Australian Government about it, in view of their interest in the joint project, and the operation of the Woomera range.

"2. The technique of controlling ballistic missiles has rapidly advanced. The vulnerability of missiles launched from static sites, and the practicability of launching missiles of considerable range from mobile platforms, has now been established. In light of our military advice to this effect, and of the importance of reinforcing the effectiveness of the deterrent, we have concluded and the Australian Government have fully accepted that we ought not to continue to develop, as a military weapon, a missile that can be leached only from a fixed site.

"3. To-day our strategic nuclear force is an effective and significant contribution to the deterrent power of the free world. The Government do not intend to give up this independent contribution, and therefore some other vehicle in due course will be needed in place of Blue Streak to carry British-manufactured nuclear warheads. The need for this is not immediately urgent, since the effectiveness of the V-bomber force as the vehicle for these warheads will remain unimpaired for several years to come, nor is it possible at the moment to say with certainty which of several possibilities or combinations of them would technically be the most suitable. On present information, there appears much to be said for prolonging the effectiveness of the V-bombers by buying supplies of the airborne ballistic missile Skybolt which is being developed in the United States. H.M. Government understands that the United States Government will be favourably disposed to the purchase by the United Kingdom at the appropriate time of supplies of this vehicle.

"4. The Government will now consider with the firms and other interests concerned, as a matter of urgency, whether the Blue Streak programme could be adapted for the development of a launcher for space satellites. A further statement will be made to the House as soon as possible.

"5. This decision, of course, does not mean that the work at Woomera will be ended. On the contrary, there are many other projects for which the range is needed. We therefore expect that for some years to come, at least, there will be a substantial programme of work for that range."

The Opposition based their first attack on the grounds of waste of large sums of public money, which Watkinson was able to counter with the argument that Blue Streak would be developed as a satellite launcher. It was a useful point for the Opposition to seize on, as it was an issue which could cover its own internal divisions about the deterrent.

But the satellite launcher option was a useful defence, indeed the only defence open to him, which raises the question: how genuine a statement was this? Did Watkinson and the Ministry of Defence want a satellite launcher, or was this statement merely a political fig leaf? Given the enthusiasm with which the subsequent Cabinet committee greeted the topic, the suspicion is that the fig leaf is the correct answer. Certainly the initial reaction among those in the House was quite vigorous: George Brown was the then Shadow Defence Secretary, and demanded an immediate emergency debate, which, however, was not forthcoming. (Sandys' absence from the House was noted by Jim Callaghan, who seized upon it to say: "I was commenting that it was a little unfair that the Minister of Defence should have to face all this music, and I was wondering where the Minister of Aviation is and when he is going to resign".)

Given the costs of the project at the time of cancellation, the Opposition managed to force a later debate. Whilst Brown might have been a good speaker, what he said at the debate does not read well today. This is partly because, like all Opposition speakers in any debate, he had not had the Civil Service back up and briefings that Ministers have. It is also interesting to note that he seems to have had some inside information on "fixed sites". But although he makes a great show of saying that he himself had advocated dropping the system, he side steps making any justification.

Although Watkinson, as Minister of Defence, opened the debate, Sandys was obviously the target for the Opposition. He gave a very straightforward speech in reply, even if he might not have been entirely convinced by his own side's case. He was able to undercut Brown by resurrecting a quote from the time of Thor, when Brown had said that what the U.K. needed was its own missile with its own warhead, which is what Blue Streak had been. The other notable part about his speech is that, by Commons standards, it was not particularly partisan: he laid down the facts as he saw them, and did not attempt to make political capitol from the decision.

But with the cancellation now official, interest within the Ministries of Defence and Aviation turned swiftly to Skybolt. (The Navy were still not happy that Polaris had not triumphed, as can be seen from another internal Admiralty memo. It comments of Watkinson: "Skybolt lay ready to his hand (he thinks) as a blood transfusion to keep the V bombers effective from 1965-1970. ... Our trouble is that the Minister has been advised by interested parties, in very optimistic terms, about Skybolt's state and prospects. I would almost say that he has been led up the garden path. I would warn you that some of the advisors he will bring to you with him are bitterly anti-Navy.".)

It is ironic that 20 months later, in December 1962, Skybolt itself was cancelled by the U.S. (as predicted by Brundrett and CGWL), and the U.K. had to negotiate hard to obtain Polaris. This meant that the "deterrent gap" was now stretched to the late 60s, and while the Polaris submarines were being built, the deterrent was being carried by V bombers with free fall bombs and the short range British Blue Steel stand off missile.

However, Polaris did serve the U.K. well for nearly 30 years (although its midlife upgrade, Chevaline was also a source of controversy), and carrying the deterrent off shore leads to the argument that the mainland itself is no longer a target. Given however the number of NATO and U.S. nuclear bases in the U.K., that argument rather falls down. The cancellation of Blue Streak, and the reason given, meant that land based missiles were never again an option for the U.K.

deterrent. As to what purpose the U.K. deterrent was to serve, however, is another question.

However, one further major question is left unanswered. The motives of the Services, the Ministry of Aviation, the Air Ministry, and the Treasury appear obvious enough. What is not obvious is why the Ministry of Defence and Powell himself took the position they did.

There are several possible scenarios.

The first is that Powell himself, possibly in concert with other senior civil servants in other departments, felt that the project was insupportable. Although he did not have the authority himself to cancel it, he could set up circumstances that gave others the opportunity. Thus if the Treasury and the Chiefs of Staff were to object sufficiently, then the new and relatively inexperienced Minister, fresh to the Cabinet, had little choice. It is interesting that the major attack on the project was only mounted after the October 1959 election, when Sandys was moved from Defence to Aviation. It would also mean keeping the details of the report from Sandys at the Aviation ministry for as long as possible, which seems to have been the case.

Another possibility lies not with Powell but with Watkinson and Macmillan, as indicated in the Daily Mail article. Under this scenario, Watkinson is appointed by Macmillan with a specific brief to ensure the cancellation. But why would Macmillan want to do this?

A possible answer lies not in the cost, but the timing of the cost. Expenditure on Blue Streak would reach its peak from 1960-1965. Although expensive in terms of capitol cost, its running costs were (or appeared to be) extremely low. Both Skybolt and Polaris were considerably less expensive to buy (the development costs would have been covered by the Americans) but their running costs were very much higher. Flying aircraft, or running submarines, does not come cheap. However, these running costs would not have been incurred for several years to come—well beyond the lifetime of the Macmillan Government.

A further answer might lie in the silos themselves. It is curious that the estimates of the vulnerability of the silos were never questioned one way or the other. Although the Air Ministry and the Ministry of Supply had done the calculations as best they could, the design was still a paper one (indeed, the design of the lid, one of the most crucial points in any silo design, had not been finalised by the time of the cancellation). In a sense, this makes a nonsense of the whole argument: since no one actually knew the exact strength of the silos, the debate was in many ways so much hot air. But they would raise political difficulties. They would certainly consume a great deal of civil engineering resources, and the political impact of such large and controversial structures in Conservative constituencies should not be overlooked. Indeed, the Home Office under Butler had come into the argument at one stage, requesting that the silos be situated on the east side of the country, so that, given prevailing westerly winds, fall out from an attack would to taken away from the U.K.. In addition, for Civil Defence purposes, Butler wanted the sites well away from centres of population.

But however well disguised the real reasons were, and no matter how much the papers conceal the true motives, a very revealing letter was written a year after the cancellation. A Technical Sub-Committee was to be set up for the BND(SG), and Zuckerman wrote to various eminent scientists, inviting them to join. One was Sir Robert Cockcroft, who had been working for the Government in various capacities since the war, and at one time had been Controller of Guided Weapons & Electronics (CGWL) at the Ministry of Aviation. He wrote back to Zuckerman, and one paragraph of his letter reads:

"Blue Streak was cancelled because it was not politically viable rather than because it could be pre-empted. The scale of pre-emption was admitted to be of the order of 3,000 megatons. Supporters of the system argued that this was so excessive that pre-emption could be ignored in practice. The argument was not accepted and vulnerability was advanced as the main reason for cancellation. The real reasons were more fundamental although still not clearly appreciated. I suggest no British statesman could visualise exploiting a deterrent threat which if mis-handled could only lead to the annihilation of the whole country; nor could he believe that a threat involving such consequences would be taken seriously by an opponent."

In other words, once missiles are fired, they cannot be recalled. And with missiles, which are seen as potentially vulnerable whilst on the ground, the incentive is to fire early. Bombers can be recalled, and they do not need to fire off their missiles until it certain the U.K. has been attacked. The same is true of submarines lying undetected in the Atlantic. This, probably more than anything else, reflected the true reason why Blue Streak was cancelled.

The cancellation is a graphic example of how Whitehall can work. What is of more interest is the study of how much policy was made by officials and how much by Ministers. Ministers rely on officials for advice: how impartial was that advice? Civil servants themselves have opinions. Furthermore, the documentary evidence that survives tends to suggest that a good deal of policy was not made on paper; but in briefings, and that papers were presented with a particular predetermined slant or viewpoint (although there is nothing new in that!). Ultimately, it might be said that the correct decision was made, but that the evidence presented was misleading, and the motivations of the various participants were, to say the least, often concealed.

7. B.S.S.L.V.

One of the ironies of the Blue Streak saga is that the U.K. spent a very considerable sum on its development and on the Europa satellite launcher as part of ELDO, sums of the order of £200 million at 1950s/60s prices, with, at the end, absolutely nothing to show for it.

However, over a period of around 15 years, from 1957 onwards, designs and proposals for an indigenous satellite launcher based on Blue Streak came and went. The design which most nearly came to fruition was known inelegantly in official files as the Blue Streak Satellite Launch Vehicle, or BSSLV for short. This chapter looks at the various designs proposed over the years. Not surprisingly, since Blue Streak, Black Knight, and Black Arrow were the only liquid fuel ballistic rockets being developed by the U.K., most of the designs tended to revolve around these vehicles, but in addition liquid hydrogen stages were often proposed. Alternative H.T.P. designs could have been produced from de Havilland's Spectre or Armstrong Siddeley's Stentor motors, but were never considered by the R.A.E. or Saunders Roe, where most of the designs originated.

The design of Blue Streak was finalised by around the start of 1957. At the same time, Black Knight had been set in motion, and it might be useful to give some approximate data for each vehicle.

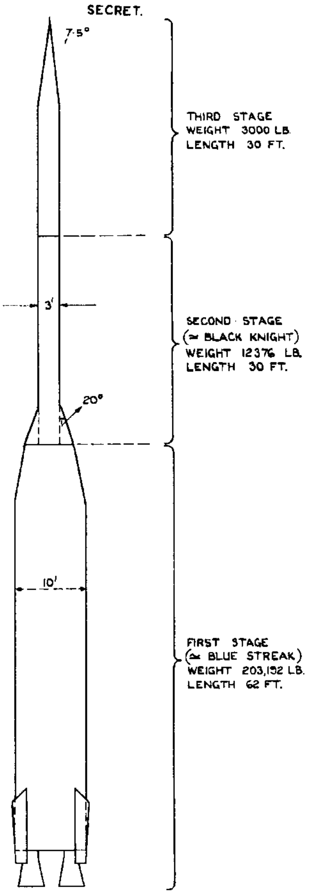
	Blue Streak	Black Knight
Height (ft)	Circa 60	30
Diameter (ft)	10	3
Weight (lbs)	185,000	13,000
Motors	2	4
Nominal Thrust (lbf)	270,000	16,400
Maximum Thrust (lbf)	300,000	25,000

(Nominal thrust is the thrust when originally designed, but both vehicles were uprated during the course of their life.)

The table immediately shows up the difference in size between the two vehicles: Blue Streak is around 15 times more massive than Black Knight.

In May 1957 not only had neither vehicle flown, but even the prototypes had yet to be built. The designs were still paper ones. It was also six months before the launch of Sputnik. Yet Desmond King Hele and Doreen Gilmour of the R.A.E. produced a paper outlining how the two could be combined together for a satellite launcher. Not only was the design perfectly feasible, but detailed calculations were carried out for the payload to low Earth orbit, which, although slightly on the optimistic side, were surprisingly accurate.

The payload estimates were 2280lb for a 200 nautical mile orbit or 2117lb for a 400nm orbit. If allowances were made for the earth's rotation and a launch in an easterly direction, the 200nm payload became 2570lb. The authors also realised that extra structural weight would be required: estimates were for 1000lb on the Blue Streak stage and 100lb on the second stage, reducing payload by about 120lbs. A solid fuel motor with propellant weight of 500-700lbs would also be needed.



King Hele's proposed Blue Streak/Black Knight launcher

However, there was a problem of geometry: a 36 foot second stage 3 foot in diameter does not fit well on top of a 10 foot first stage. In addition, although there is no mention of what the ton of payload might be, to fit it into a 3 foot diameter payload bay might also be awkward.

Although the paper was obviously speculative, it raises other questions: why might Britain want a satellite launcher? The obvious answer is to launch satellites, but that does not really answer the question: what would be the purpose of such satellites? The paper does not answer that question directly, although the R.A.E. had been looking at the possibility of reconnaissance satellites from around 1955. No further action was taken on the proposal, but it is noteworthy that there is such interest so early in what would become known as the "space race".

King Hele's design was logical but not very efficient: there was considerable mismatch between the masses of the two stages, and also between their geometry, principally the mismatch in the diameter of the two vehicles. However, all the early American launchers based on Thor and Atlas suffered similar problems, being cobbled from various pre-existing vehicles rather than being purpose designed. Some comparisons could be useful here:

	First stage Weight [lbs]	First stage Thrust [lbf]	2nd stage weight [lb]	2nd stage thrust [lbf]	Payload to LEO [lb]
King Hele	186 000	270 000	17 500	25 000	1 800
Thor Delta	107 000	172 000	6 000	7 500	500
Thor Agena B	107 000	172 000	16 000	16 000	1 600
Atlas Agena B	265 000	389 000	18 000	16 000	5 000

(U.S. data as of launchers of 1961)

The King Hele proposal therefore gives a vehicle somewhat better than Thor Agena B, used for the Discoverer reconnaissance satellites.

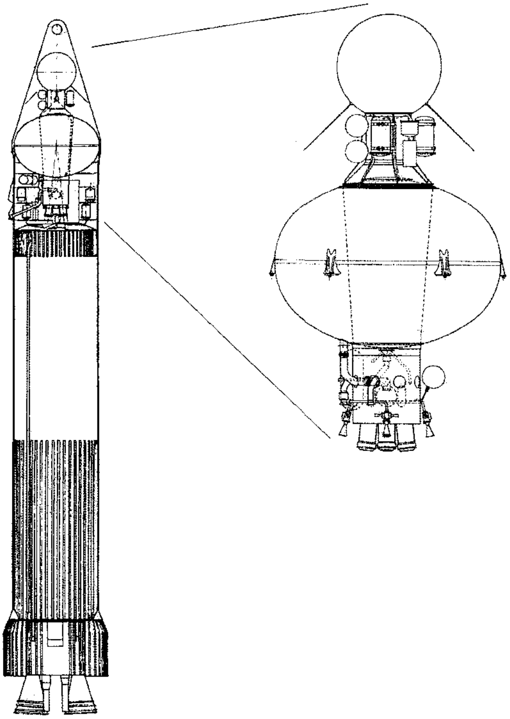
However, the seed had been planted, and was periodically to erupt into bloom, though never reach fruition.

In 1957, there was also considerable security surrounding both Blue Streak and Black Knight, and it was not until 1959 that Geoffrey Pardoe of de Havilland was able to present various satellite launcher designs, using the same ideas, to a meeting of the B.I.S. (British Interplanetary Society). The design that emerged as the favourite perhaps took the geometry problem too far: instead of being a slim 3 foot cylinder the upper stage had become a 10 foot sphere! There is considerable logic behind this design, but there was also a practical difficulty relating to cost and facilities, which was much less obvious.

Saunders Roe had designed their test facility at High Down for a 3 foot vehicle; the stands could be relatively easily adapted for designs up to 54 inches in diameter. Beyond that, there would have to be considerable rebuilding. The cost of this was held up as an objection to design after design, until Black Arrow with its 2 metre diameter lower stage was produced.

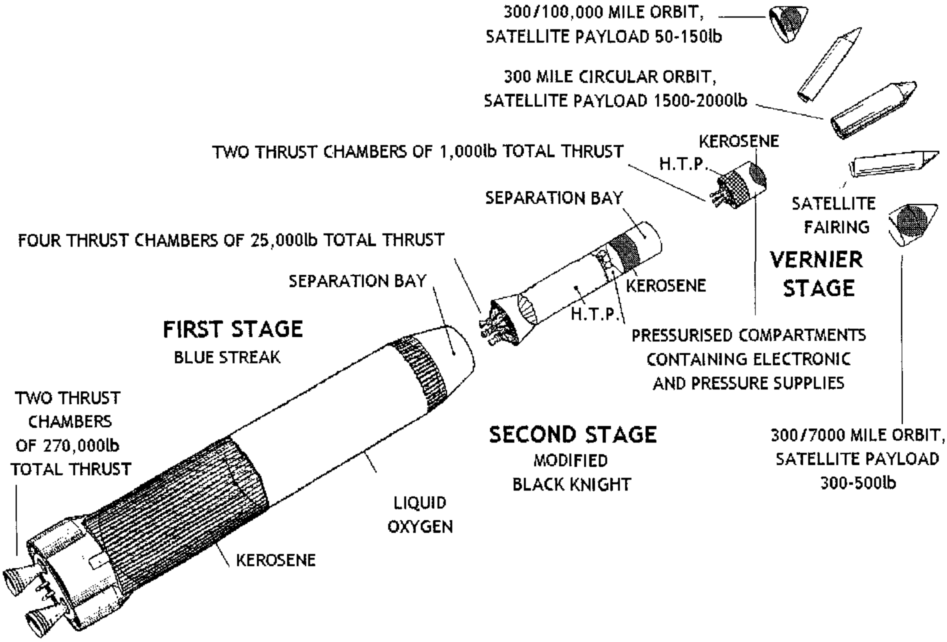
Even prior to the cancellation in 1960, some studies were taking place for a satellite launcher. In May 1959 Harold Macmillan was asked in the Commons whether the U.K. would be pursuing space research. As a result of this, Dr R.

Cockburn (who at that time was CGWL) at the Ministry of Supply was asked for design studies for a rocket and for the satellite itself by the Office of Lord President of the Council, Lord Hailsham, who was also acting as Minister for Science. In September it was announced that E.C. Cornford at R.A.E. was carrying out the design studies. However, the correspondence in the file does not show any great urgency being put on the matter. Having said that, the R.A.E. set up a series of panels to produce a detailed design late in 1959.



Pardoe's Blue Streak/Black Knight launcher.
Here the 30 foot high 3 foot wide Black Knight has been compressed into a ten foot diameter sphere.

However, as part of the announcement of the cancellation of Blue Streak as a weapon in April 1960, stress was laid on its conversion to a satellite launcher. To be cynical, it could be said that this was a useful ploy to deflect criticism; it was argued by Watkinson, the Minister responsible for the cancellation, that the considerable expenditure to date had not been wasted, since Blue Streak was now being used for another purpose. The hollowness of this argument can be demonstrated by the fact that the expenditure to date had been in the order of £60-80 million, and yet no Ministry was prepared to put up more than a few million extra to complete the project. Watkinson, against the advice of his civil servants such as Sir Edward Playfair, was prepared to offer £5 million, but this would have to come out of existing budgets—not an easy option. Similarly, Hailsham was not prepared to raid the science budget, and there seemed no obvious other source of finance.



BSSLV: the Ministry of Aviation's view.

This is shown very clearly in a letter from Hailsham to Sandys (now Minister of Aviation) in April 1960, just after the announcement of the cancellation of Blue Streak as a military weapon. "The Advisory Council on Scientific Policy said in its last report that to leave vital scientific needs unsatisfied 'in order to shoulder the crippling cost of a large programme of space exploration on a purely national basis would be, in the Council's view, the grossest folly.' At that time, of course, we were going ahead with Blue Streak for military purposes and the Council said 'we do not consider that the technological advantages likely to accrue from the development of a British rocket and satellite programme designed for civil purposes over and above the effects of the existing military missile programme, would be sufficient to justify the very considerable expenditure involved.'". Using vehicles already developed for military purposes was one thing; but for the science budget to take on all the development costs of a launcher would be a very different matter. If Blue Streak had gone ahead as a military missile, then the development costs would have been covered by the defence budget.

The cancellation meant that funds would have to be found elsewhere to complete the project. The proposal could not be justified from a limited science budget.

There was little military interest either: the Chiefs of Staff, in conjunction with the Defence Research and Policy Committee stated in Decmber 1959 that: "The Committee agreed that, while satellite research was important nationally, there were not at present any strong reasons to justify the spending of Defence funds on it".

On the day the announcement of the cancellation was made, CGWL at the Ministry of Aviation (Sir Steuart Mitchell had returned to the post) wrote to all the firms involved—Rolls Royce, de Havilland, Sperry and others—and mentioned: "The Government is now considering whether to continue Blue Streak in the role of a Satellite Boost Vehicle, but it is unlikely that a decision will be reached on this until about June." Optimistically, he noted "The intention would be to complete development by early 1964 with the firing of not more than 8 rounds, at a rate of approximately 3 per year". In the event, not even the first flight had occurred by early 1964!

Later in April Mr Syme of the Ministry of Supply in Melbourne noted: "The programme would involve firing three Blue Streak missiles of current design, three modified ones carrying dummy upper stages, and two complete three stage versions, making eight firings in all, extending from the first firing in mid 61 to the last in early 64 at about four monthly intervals."

And the Ministry of Aviation had similar visions: ".... [the] first missile on launcher by April 61, static firing in July and first flight October 61. Thereafter flights in March July and October 62 and 1963 terminating with eighth flight in March 64.

"Flights one and two would be unmodified Blue Streaks; firings 3, 4, and 5 would carry dummy upper stages; firings 6, 7 and 8 real upper stages. In addition, the Black Knight plus third stage require firing from Area 5 [the Black Knight launch site at Woomera]. Three flights suggested between Sept 62 and May 63. ..."

The latter reference is to separate flight testing for the second stage. Thus the first complete vehicle would be F6 in March 1965.

To further these considerations, a Cabinet committee was set up, chaired by the Cabinet Secretary, Sir Norman Brooke. Not surprisingly, he took advice from the Government's Chief Scientist, who did not have a high opinion of Blue Streak and its technology. So Sir Solly Zuckerman was called in to brief Brooke and the Prime Minister. A flavour of the advice he gave can be seen in a quote from Brooke: "The main advantage would be to keep a leading position in liquid fuel technology, but this was an obsolescent skill." The value of his advice can be gauged from the consideration that derivatives of both the Thor and Atlas rockets, somewhat older than Blue Streak, are still in regular use forty years after this advice was given, and there are still no large satellite launchers that do not use liquid fuel in at least part of their design. To be fair, however, from the military point of view he was quite correct. Then there was the question of cost: Zuckermann provided figures—"the whole U.K. R&D expenditure is £500M [per annum]," of which £238M was for defence, whereas the launcher would cost £15M p.a., with a total cost of £64M. (Much later, in June 1966, Zuckerman was to say of the launch of the first French satellite: "We could have anticipated and greatly exceeded this achievement had we decided in 1960 to adapt Blue Streak for this purpose and added Black Knight to it as a second stage.". It is a pity he had not been more forceful at the time.)

Senior civil servants are not noted for their extravagant use of language. Yet in all the files that survive from the Cabinet Office and the Ministry of Aviation, no enthusiasm for the project ever shines through. Instead, Blue Streak, even in a civilian guise, is seen as an unfortunate inheritance from a military programme, and the very strong impression is that the project is maintained for political reasons rather than through any intrinsic merit.

But to return to money: cost estimates for aerospace projects are a notorious minefield, and the launcher was to prove no exception. Hasty initial estimates gave £35M. This was solely for vehicle development costs. But there would be other costs as well—the vehicles themselves (around £2M each) and the satellites that would be carried. This pushed the total estimate up to £64M by July—although this included in addition the cost of three satellites, which the early estimate did not. An analysis was also done of the unit cost of a launcher, once development was complete, and these estimates were in the region of £1.8 -£2.1M, depending on the number of launches per year.

The difference in U.S. and U.K. resources, or the proportion of their resources that they were prepared to devote to space research, is shown up quite starkly in a conversation recorded by Zuckerman in December 1960 with the U.S. Assistant Secretary for War, who suggested that the U.K. joined the U.S. in space work. "When I told him our total [annual defence] budget for R and D was £220M, he immediately replied that, even if we put all our defence R and D money in, we were obviously not starters in a U.S./U.K. collaboration programme in rocketry and satellites". If £220M was not enough, how far would £15M take the U.K.?

Funding for Blue Streak itself after the cancellation was kept at a "tick over" rate, and although the Chancellor had initially agreed to provide money for the project, the beady eye of the Treasury was always on it. But this points up another factor: the lack of any firm decision. This was summed up in an internal Ministry of Aviation paper soon after the cancellation:

"The current BLUE STREAK programme will have run down to the level needed for the development of a satellite launcher by about the middle of July. A decision on the future of BLUE STREAK must therefore be taken within the next few weeks.

"The possible courses are:

(a) To cancel BLUE STREAK completely.

(b) To undertake a programme of space research based on the joint Anglo/Australian development of BLUE STREAK as a satellite launcher.

(c) To undertake a programme of space research as at (b) and to explore the possibilities of co-operative programmes with European and Commonwealth countries.

(d) To take no final decision on space research, but to continue the development of BLUE STREAK at the minimum level while the possibilities of co-operation with Europe and the Commonwealth are explored.

"If course (d) were adopted, then interim measures would be needed to ensure that this country retains the ability to develop a satellite launcher and undertake a space research programme, until the necessary decisions are made. The extension of the current BLUE STREAK contracts on a month-by-month basis could not last for more than 2 or 3 months, since it would be unsatisfactory and uneconomic, and would prevent contractors from entering into the longer term commitments involved in the supply of materials. Contracts would probably have to be extended for at least 12 months. In practice course (d) would be difficult to present to Parliament and the public, particularly if it resulted in the abandonment of space research after a year or so."

But, as we can see, course (d) is what the Government ended up with. Often a lack of any firm decision is worse than any of the decisions that could have been take. Immediate cancellation would have saved money, pressing on with project would have produced an end product.

There was no room in the military budget, despite Watkinson‘s offer. There was little money for anything: the Ministry of Aviation had £50,000 for the initial design study for a satellite launcher, and they were told by the Treasury in April 1960 that if they want £250,000 for wider studies then they must apply for it. More realistically, Sir William Downey asked for another £35,000 in May. This is hardly an extravagant budget. In addition, money had to provided for the "tick over" contracts at the likes of de Havilland and Saunders Roe.

Black Prince

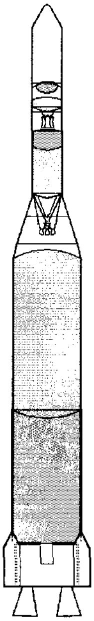
As a result of the work that had been done from late 1959 onwards, a brochure for a launcher was ready in time for the cancellation. The brochure was prepared by Saunders Roe and R.A.E., and the vehicle is called, rather optimistically, Black Prince. Its design is very conventional: Blue Streak as the first stage, a 54 inch Black Knight second stage, with the Gamma engine uprated to 25 000lb thrust, and various configurations suggested for a third stage. This would also use H.T.P. and kerosene, with a small four chamber rocket motor, designated the PR 38, from Bristol Siddeley.

The weight breakdown for the launcher in the initial design brochure was:

	All burnt weight	Propellants	Trust
First stage	12,500lb	173,000lb	270,000lb (sea level)
Second stage	1,520lb	16,000lb	25,000lb (vacuum)
Third stage	500lb	2,400-4,300lb	2,000lb (vacuum)

This would mean that the upper stages would be about one tenth of the vehicle weight – which is not all an efficient design. The vehicle would have a first stage diameter of 10 ft; the upper stages 54 inches or 4½ feet. It would be nearly 98 ft tall.

But the brochure points up another flaw in the whole project. Different versions of the third stage were to be tailored to three specific missions: a low earth orbit of 300nm "for experiments in stellar U.V. spectroscopy", a 300/7000nm orbit "enabling investigations of the Earth's radiation belts to be undertaken", and a 300/100,000nm orbit for a "Space Probe". Such imprecise missions do not engender confidence, nor answer the question: what was the point of Black Prince?

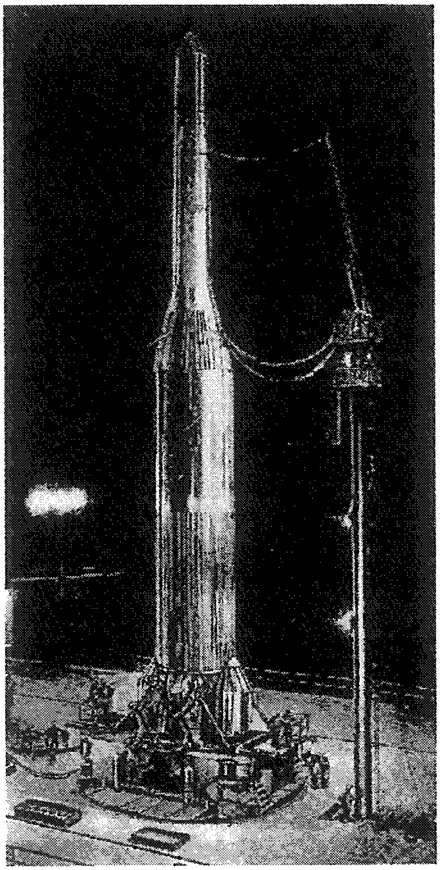


Black Prince schematic

So in May meetings began between R.A.E., Saunders Roe and Bristol Siddeley to continue the development of the design. Mention was made of an intention to ground launch the upper stages as part of the development programme. Saunders Roe set about the business of designing the second stage in detail and producing a test tank structure. De Havilland began the design of the interstage section, and Bristol Siddeley were keen to press on with the new engine for the third stage.

The R.A.E. took the design very seriously: just as there had been a series of panels for the missile on guidance, propulsion etc, a series of similar panels were set up for Black Prince. However, in July CGWL wrote a memo decreeing that: "It has been decided that the proposed 3-stage satellite launching vehicle based on Blue Streak, Black Knight, and a third stage, and the subject of current project design studies, shall be known as the BLUE STREAK SATELLITE LAUNCHER.

The names Black Prince and Blue Star, which have been used semi-officially, are not be used."

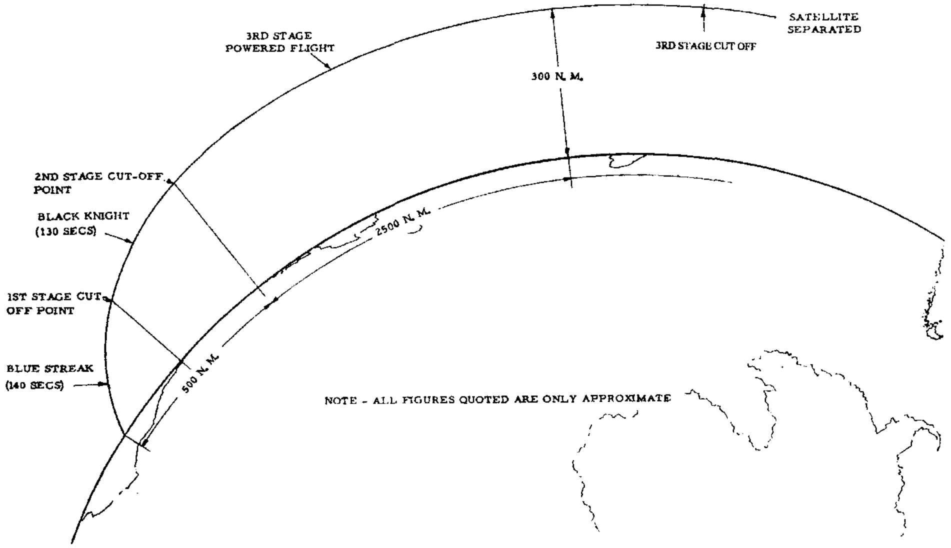


Black Prince: from the Saunders Roe brochure.

But even so, there was continued Government vacillation on the programme. The then Minister of Aviation, Peter Thorneycroft, had visited both Canada and Australia, and, as part of his mission, had attempted to interest both countries in a Commonwealth satellite launcher.

Canada's reply was that she was already investing enough in space; privately the Canadians told the British that they were spending considerable sums on Alouette, a Canadian satellite to be launched by NASA, and on various sounding rocket programmes. Indeed, they admitted that the total expenditure was far more than publicly acknowledged, and no other commitments were possible. Similarly Australia was not interested other than supporting the work being done at

Woomera. With any New Zealand contribution likely to be "modest", and with South Africa no longer part of the Commonwealth, such a joint programme seemed unrealistic.



NOTE - ALL FIGURES QUOTED ARE ONLY APPROXIMATE

VEHICLE FLIGHT PATH

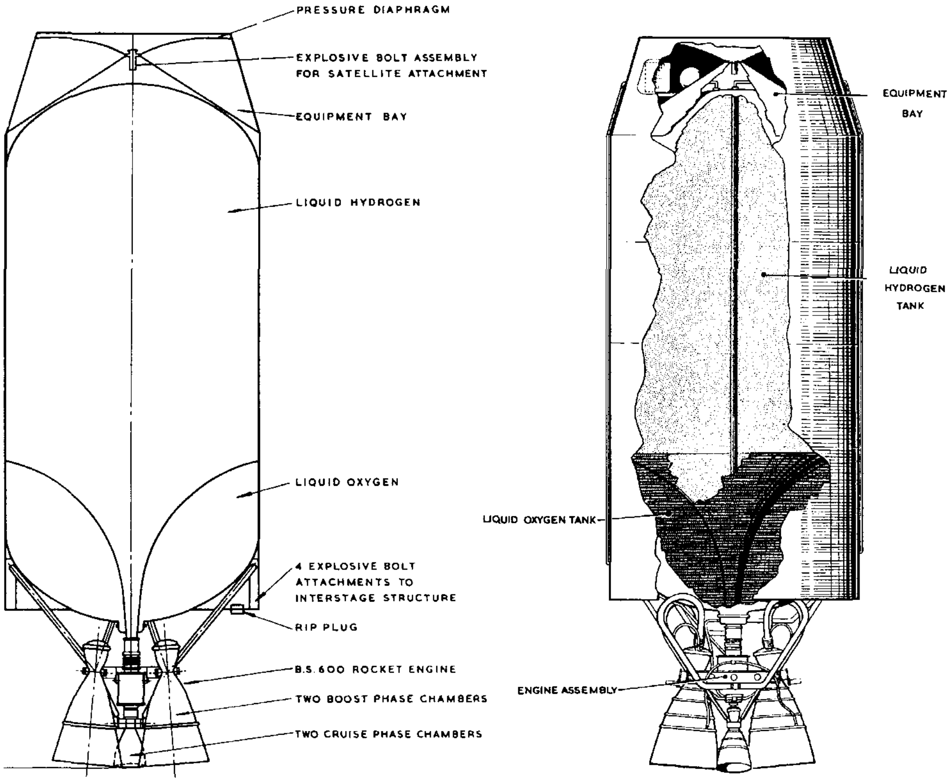
Black Prince's path to orbit

However, whilst the Commonwealth expressed no interest, France did. Very soon after the initial cancellation, French officials made various discreet contacts with British diplomats to ask about Blue Streak. However, they were as much aimed at finding out design information for their own ballistic missile project as enquiring about a joint satellite launcher programme.

While the indecision dragged on, R.A.E. and Saunders Roe continued with the development of the BSSLV. On a meeting in December 1960, R.A.E. mentioned that the second stage diameter of 54 inches was producing control problems, and that they would prefer a larger diameter stage. Given existing facilities at High Down, the greatest diameter possible would have been 58 inches and Saunders Roe were asked to produce a design for such a stage.

However, the initial performance calculations for Black Prince gave a figure of around 1750lbs in low Earth orbit. Communications satellites needed to be in a much higher orbit—preferably geosynchronous, although R.A.E. and the Post Office had been interested in 8 hour and 12 hour orbits as alternatives. In addition, Woomera is poorly placed for launching such satellites, with its range restrictions necessary to prevent overflying of populated areas, and also too far south for geosynchronous launches. Estimates of the cost of an equatorial launch site were in the region of £20-30M. Black Prince's payload decreased rapidly with altitude and with launch direction: it was estimated that for a 2500nm orbit at 40°W of N, the payload was down to 600lbs.

A Liquid Hydrogen stage.



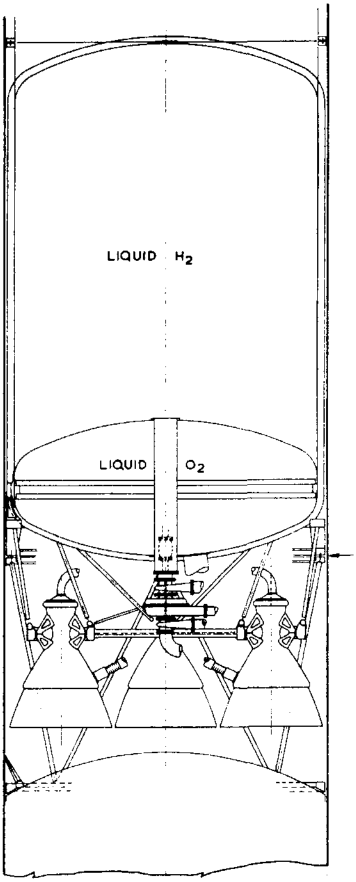
The Saunders Roe liquid hydrogen stage.

One way round this limitation was to use a high energy upper stage, and so at the same meeting in December 1960 Saunders Roe were asked to consider a liquid hydrogen third stage with 4,500lb of propellants. The brochure they produced was up to their usual high standard, laying down the problems clearly, and describing the solutions equally clearly. There was, however, one unique feature to the design. The rocket motor was 4 chambered, but whilst two were large units fed with turbo pumps, 2 were very small pressure fed chambers. Normal combustion chamber pressure is normally of the order of 500psi or more; here the pressure would be around 30psi. In the vacuum of space there was little efficiency loss at such a low pressure. In addition, this meant that the tank pressure was also low, meaning a great weight saving. The small pressure fed motors would continue to run for a further two hours after orbit had been achieved: this would mean that the vehicle would move up a higher orbit in a series of spirals!

The final design details were based on the following data:

All up weight: 7 000lb approximately
Propellants: 5 000lb approximately
Specific Impulse: 400lbf.sec/lb
Two thrust phases:
  Boost 3 500lbf for 8 minutes
  Cruise 44lbf for 2 hours

Ingenious though this idea is, it does suffer from the drawback of carrying the now unused boost motors and pumps up into orbit with the rest of the vehicle. In addition, any low thrust proposal of this sort has a further disadvantage: a lot of the fuel has to be carried up against gravity as well. Saunders Roe estimated that such a vehicle "would be capable of putting a 900lb payload into a 5000 nautical mile orbit, or a 600lb payload into a 9000 nautical mile orbit".



R.P.E.'s liquid hydrogen stage

Interestingly, R.P.E. were also working on a very similar stage, although no mention is made of it in the BSSL panel meetings. This was designed with 4 chambers, and the stage would have been 1.37m (or 54 inches—R.P.E. had decided to go fully metric with this design!) The thrust would be 10kN (2,200lb) and the stage mass 2,270kg (5000lb) making it roughly comparable with the Saunders Roe stage. Payload was given as 1300kg (2860lbs) in a 480km (300 nautical mile) orbit, which would be about 1,000lb improvement over that of Black Prince.

The cost of developing a liquid hydrogen stage for the B.S.S.L.V. was put at between £M5.5 and £M7.

But while R.A.E. and Saunders Roe had been proceeding with their work events elsewhere were to bring it to a halt. The prolonged European negotiations were slowly getting somewhere, although it would take many more months before any clear shape would emerge. But in a meeting in March 1961 at Cowes, the R.A.E. had to tell Saunders Roe that it had been decided that the second stage would be of French design. Saunders Roe and Bristol Siddeley were however to continue with the design for the third stage, with particular emphasis on liquid hydrogen. At the same meeting, Saunders Roe reported that manufacture of the second stage tank structural test specimen was about 25% complete.

In a further Design Study Progress meeting in July, the chairman noted that situation was very vague (which, given the ELDO negotiations, was probably an understatement). He hoped that Saunders Roe would play a part in any future design studies and that they would continue to maintain a design study team. At the same meeting, Saunders Roe presented a brochure for the H.T.P./kerosene third stage, which would involve both high thrust and low thrust stages; a 2½ hour period of low thrust was mentioned, and in addition, there was a further report on their liquid hydrogen stage. But this is effectively where work on Black Prince, or BBSLV, comes to a halt. Instead, attention turned to ELDO and Europa.

The creation of ELDO didn't entirely dissuade Saunders Roe however. Late in 1963, proposals for a British Communication Satellite System were underway, and as part of this, the firm submitted a new, revised, version of their launcher. The second stage was now 2 metres in diameter, in close analogy with Black Arrow, but otherwise the design was much the same. This never got past the stage of a proposal, however.

Combination with Black Arrow.

It might be thought that is where the BSSLV saga ends. But matters are seldom so simple. During 1963 and 1964, the design for what would become Black Arrow was evolving. Amongst all the imperial measurements of feet, inches and pounds is a first stage diameter of 2.0m! This mixing of units not only seems odd but also would seem to have no connection with Blue Streak. However, the ELDO vehicle was being designed with a French second stage, which was also to be of diameter 2.0m. The idea was then that if the Blue Streak interstage were to be suitable for the French vehicle, it would also be suitable for Black Arrow. In the event, there was a problem, since the Blue Streak side of the interface was much wider; the French stage was to have a skirt that would mate with the lower stage. So this odd metric feature was included in case, as seemed possible in 1963, ELDO did not go ahead, or, for whatever reason, was not a success.

But the design for Europa did materialise, and it might then be thought that all further suggestions for a solely British launcher might have died forever. However, there was one enthusiast for space exploration in the House of Commons, the Conservative MP Neil Marten, who asked a Question in the House about the possibilities of the Blue Streak/Black Knight combination. This might well have been a put up job, but it gave R.A.E. the excuse to work the figures for a Ministerial reply, a task they set to work on with eagerness.

This was in March 1968, when Europa, despite problems with its second stage, still looked viable. Two versions were considered. The first employed the first stage only of Black Arrow, with 4 of the 8 chambers and one of the turbopumps deleted. The payload estimate was for 1800lbs in a 200NM polar orbit (750kg at 500km); however, extended nozzles on the motors (as in the Black Arrow second stage) resulted in an improvement on this of "some 20% to 25% giving a performance appreciably greater than ELDO A". Adding the third stage of Black Arrow—the Waxwing motor—would increase payloads "by about 200kg". This would put the maximum payload up to 1100kg. Development costs were put at £1M, and the unit cost per vehicle at £1.5M.

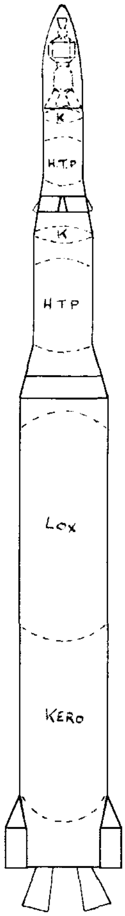
A follow up note gives some interesting comparisons between ELDO A and the Blue Streak/Black Arrow combination.

	Back Arrow second stage	ELDO A second stage	ELDO A third stage
Vacuo S.I.	250.5	280.8	292
Burnable propellants (kg)	13,256	9,800	2,500
Inert mass (kg)	1,134	2,389	2,500
Structural efficiency	0.0788	0.196	0.200
Velocity increment (m/s)*	4,936	2,366	2,714

*as part of multi stage vehicle

This shows the potential of a Blue Streak/Black Arrow combination. It also shows up very clearly the structural efficiency of Black Arrow as opposed to the ELDO second stage.

At around the same time, Saunders Roe produced their own brochure for a Blue Streak Black Arrow combination. The skirt to the engine bay was flared out to match the Europa interface, as originally intended. They went through all the permutations with their usual thoroughness, considering 8 chamber and 4 chamber variants, and two and three stage versions, and also reviving the liquid hydrogen third stage possibility. Their payload calculations were on the optimistic side, however—Blue Streak and Black Arrow together were estimated to put as much as 3000 lbs in low earth orbit, and even a few hundred pounds in a geosynchronous orbit.



Saunders Roe proposal for Blue Streak/Black Arrow.
This is Black Arrow added onto Blue Streak with almost no modification.

It is interesting to note that Saunders Roe were obviously thinking of communications satellites as an application for the launcher. Under the payload shroud the satellite is sketched with two solid fuel motors: one which would convert a low Earth circular orbit into a highly elliptical geotransfer orbit, and the second of which would then act as an apogee motor to convert the elliptical orbit into circular geosynchronous orbit. In this context, it should be noted also that although the U.S. was prepared to sell launchers to other countries, this offer was subject to considerable restriction and would almost certainly not have included commercial communications satellites. Britain's military communications satellites, Skynet, were launched by the U.S. only as a result of the close military ties between the two countries.

However, there was a considerable divergence in views between the Establishments and the Ministries. The R.A.E. and its associated establishments were constantly producing Blue Streak based ideas. Yet it was obvious from around 1966 that the Ministry of Technology, as the Ministry of Aviation had then become, was firmly set against any idea of a British based launcher. Indeed, as early as June 1962, Douglas had visited the Minister of Science with a proposal to sell Thor Deltas to the U.K..

There is one final fascinating idea that is still under wraps in the Public Record Office in Kew, unavailable until 2003 under the Thirty Year Rule, which is a proposal to add the American Centaur stage to Blue Streak. This is an extremely sensible suggestion, producing as it does an effective launcher and yet at the same time minimising development costs. Contemporary computer simulation shows that Blue Streak with an unmodified Centaur stage alone could place around 6000 lbs in low Earth orbit, or three times the payload of Black Prince or Europa. If Kourou were made available, with its purpose built Blue Streak launch pad, then this also solves the problem of an equatorial launch site.

8. ELDO and Europa

The European Launcher Development Organisation, ELDO, held out the promise of a bright new future for Blue Streak, and a chance for Europe to establish itself as a rival to America and Russia in the space business. In reality, it turned out to be a model example of how not to carry out a joint European project, and technically, Europa had modest aims and even less success. Today, European Space Agency and Ariane have established themselves where ELDO and its sister ESRO (European Space Research Organisation) so signally failed. But that has been in large part due to the drive of the French, who dominate the ESA and Ariane.

The seeds of ELDO were laid when Thorneycroft failed to interest anyone in the U.K. or in the Commonwealth in the BSSLV. In October 1960, he visited Paris to discuss a series of matters with the French: Air Traffic Control, the supersonic transport later to become Concorde, and the project that would eventually become Europa. But French interest in such a scheme had dated almost from the cancellation itself, as shown by a note from Selwyn Lloyd, then Foreign Secretary, to Lord Gladwyn, the Ambassador in Paris: "... the French ambassador raised with me on 8th July the question of Anglo-French co-operation in the development of Blue Streak as a space project ..."

In much the same way as the U.K. had been intent on persuading the U.S. to share knowledge on nuclear matters, so the French were intent on persuading the U.K. to co-operate in the same way both on nuclear matters and also on missile technology. Sandys, when Defence Minister, had had talks with his French counterpart on the subject as early as 1957, but on every occasion the answer was the same: much of the information was joint U.S./U.K. information, and could not be shared with any other country without the consent of the U.S..

But there were other problems to French involvement. There was a very strong suspicion that the French were mainly interested in getting in on the project so that they could acquire rocket technology that would be useful for their own missile programmes (and who would blame them?). This put the British Government in a considerable dilemma: they wanted to be open and above board about the whole project, yet were reluctant to divulge sensitive information to the French; partly so as not to disconcert the Americans, with whom a lot of the work had been done. Sir Steuart Mitchell, CGWL, in January 1961 noted that:

"The design of re-entry head which we finally ended up with for Blue Streak is:-

(a) of British origin.

(b) It is now joint U.K./U.S. information.

(c) It is agreed by the U.S. to be much better than their designs as regards invulnerability and U.S. has now copied it.

(d) As regards invulnerability it is so advanced that neither the U.S. nor ourselves can conceive a counter to it."

Obviously the Farnborough design team in conjunction with the Black Knight program had done well—the design for the re-entry vehicle was a considerable success.

And in a letter in January to the Government Chief Scientist, Sir Solly Zuckerman, and others, entitled "Possible Transfer to French Government of Military Technical Information on Blue Streak", it was noted that:

"Re-entry head.

"Radar Echo. Information on this is mostly Top Secret and would be of great value to the French. The most advanced work in this field is British and is acknowledged by the U.S. to be ahead of their work. It is thought that future U.S. warheads may be based on this British work.

"Release of this information would be contrary to [*our agreement*] in that it could provide an enemy with a ballistic weapon against which we see no defence and it would prejudice American weapons. It is desired to draw particular attention to this point and it is recommended that this information should not be released.

"To provide a line of defence on which any technical conversations might be conducted it is suggested that we take the line that -

"Details of shape, weight, dimensions, etc. of the Blue Streak re-entry head cannot be discussed as they contain "atomic" information.

"II. Decoys. Information on these would contravene [*the agreement*]. This is a sensitive Top Secret field in which we are well ahead of the U.S.A. who accordingly would be apprehensive if we released information to the French."

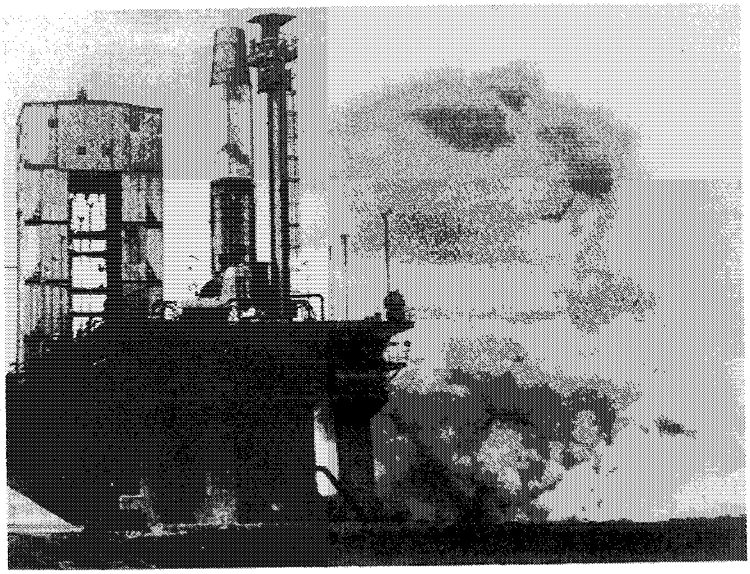
"... The re-entry head design is highly specific to the weapon parameters ..."—i.e., the size, shape and mass of the actual warhead within the vehicle. The relative positions of centre of gravity and centre of pressure are the important points. If these are not in the correct positions, the re-entry vehicle becomes aerodynamically unstable.

In addition, inertial guidance was an area in which the British had received American assistance, and so they were unable to pass on details to the French.

So these items were off the menu, which considerably reduced the French interest. The Americans were reluctant for the U.K. to pass on this information, or permit information to be passed on, partly on the grounds of not encouraging the proliferation of nuclear weapons, and partly because it would increase the vulnerability of their own re-entry vehicles. But on the other hand, the Government was prepared to be helpful to the French in more general terms.

However, the Foreign Office was interested in widening out the idea of an Anglo-French launcher to as many European countries as possible, to establish Britain's credentials as a good European. After a good deal of toing and froing, the Strasbourg Conference was convened on 30 January 1961, involving all the countries which the U.K. had been sounding out through diplomatic channels for the previous twelve months, to see whether they would be interested in participating. Progress in the negotiations was painfully slow, though, and it became obvious that many countries thought that the U.K. was trying to foist an obsolescent launch vehicle on them, and making them to pay for it. The combination of France and Britain as the lead nations did not inspire confidence either, both being known as countries who pursued their own interests ... shall we say vigorously. But this was a travesty of the real position: as a design, Blue Streak stood up well against Thor and Atlas, both of which are still very much in service as launchers forty years later. And it is surprising that the U.K. did not try to make more of the point that they were making Europe a free gift of £60M worth of development costs.

But progress towards an agreement was still very slow. The next sticking point was German participation, and it became plain that the participation of other countries was dependent on the German presence. As mentioned, the cost to the U.K. of keeping the Blue Streak development "ticking over" was £350,000 per month. The Exchequer was not going to bear this for too much longer.



Blue Streak static test firing

This is a test firing at Spadeadam in Cumbria. The vehicle is probably a non-flight vehicle, for test purposes only.

A moment of lighter relief came in a note from CGWL—the first static firing of a complete Blue Streak rocket at Spadeadam took place on 1:15 am April 14 1961. He noted wryly that de Havilland & Rolls Royce had planned it for the 13th—which would have been the first anniversary of the cancellation! (Incidentally, this was the day after which Gagarin made his first Earth orbit.)

The problem as far as many of the smaller countries were concerned was that almost all the work had, de facto, been split up between Britain and France. What was left was peripheral, to be doled out in penny pieces. And it is difficult to develop a rocket stage in two different countries—particular in countries that had had no real experience in the field. It seemed that they would be paying money into an organisation that would give them few tangible benefits. In addition, the small scale of their contributions would give them little influence over policy.

But then the heavy hand of the Treasury loomed over the project once more. On 26 April there was a memo from Selwyn Lloyd (now Chancellor of the Exchequer) to the Prime Minister, Harold Macmillan, complaining about the cost of Blue Streak. The critical paragraph reads:

"It is over a year since we cancelled the military version of Blue Streak. I do not see how we can defend continuing much longer to spend public money at the rate of over £1M a quarter to keep the civil project alive until we are ready to take a decision. It is three months since we put our proposals to Europe at Strasbourg. The German decision will be the key to the matter. If we continue to appear willing to keep Blue Streak alive at our own expense, the Germans and others will surely come to believe that we never seriously considered dropping the project and that our proposals are simply designed to remove part of the financial burden from our shoulders. In this sense continued patience is likely to militate against acceptance of our proposals."

Lloyd was right about one thing: the main purpose of ELDO was to remove the financial burden from Britain, and yet still have Blue Streak, but this was a motive that was not publicly admitted. The negotiations were not helped by a speech from Dean Rusk, U.S. Secretary of State, in Oslo on 8th May offering the use of U.S. launchers to Europe, in which he said: "We are prepared to use our Scout, Thor and Atlas launchers to place into orbit scientific payloads designed by the European space organisations.". The Americans claimed that the offer was entirely innocent, and unrelated to the ELDO negotiations, but Thorneycroft was exasperated by the speech. (And it was an offer the U.K. took up when the Ariel satellite was launched with a Delta rocket in April 1962—less than a year later.) Thorneycroft was interviewed on television as a consequence of this speech, and Robert Mackenzie, the interviewer, gave him a hard time, suggesting that Blue Streak was obsolete and taking the line that Britain should not be involving itself in such matters. It is an interesting shift of perception: up until around 1960 it would have been taken for granted that the U.K. would be in the forefront of new technology, and proud to be so, as with the Comet airliner. This was not the case now.

To which Thorneycroft gave the obvious answer: the offer was for scientific launches only. And who knows for how long the offer would last? Until the Americans did have a monopoly? And there was the habitual assumption that the American—and Russian—rockets would be more advanced. Taking Black Prince as of 1961, this was certainly not true. Blue Streak was almost exactly on a par with Thor and Atlas. But it was a perception that was never to be eradicated.

And then on 25 August there were further attempts by the Chancellor to kill Blue Streak on the grounds of the continuing cost, which was going on irrespective of the continuing lack of progress. However, negotiations in Europe were still proving to be incredibly slow, and it was not until 30 October 1961 that Thorneycroft could convene another Lancaster House meeting to set up the organisation, and split up costs and responsibilities. The French were in, subject to budget and to the allocation of work, as eventually were the Germans, but the Italians were proving very difficult, and were very slow in giving any sort of answer. The Italians were reluctant to join, since some of their own scientists had their own ambitions for a space programme, and there seemed very little for them in ELDO. Britain, France and Germany were to develop all the rocket stages. At the same time, the Australians were trying to do some renegotiating of their own, to the further annoyance of Thorneycroft. They wouldn't have pressed so hard if they had realised how reluctant the other European Governments had been to use Woomera. There was even a hastily prepared paper considering Spadeadam as a launch site if Woomera were not to be available! It doesn't seem to have been a very viable option, even with a launch into polar orbit, which is what was planned. CGWL outlined the possibilities of Spadeadam for launching Blue Streak:

"Trajectory about north 15 east.

"Overflies Kelso. Crosses over Eyemouth.

"Pass 25 miles east of Aberdeen, and 100 miles west of the Norwegian coast.

"Down range station, very well placed, would be in Spitsbergen, (Norway, open all year round). Alternative would be at Tromso, which is possible but not so well placed.

"First stage impact 200 miles off Norwegian coast abreast Namsos. (This is west of the Narvik-North Sea ore traffic lane).

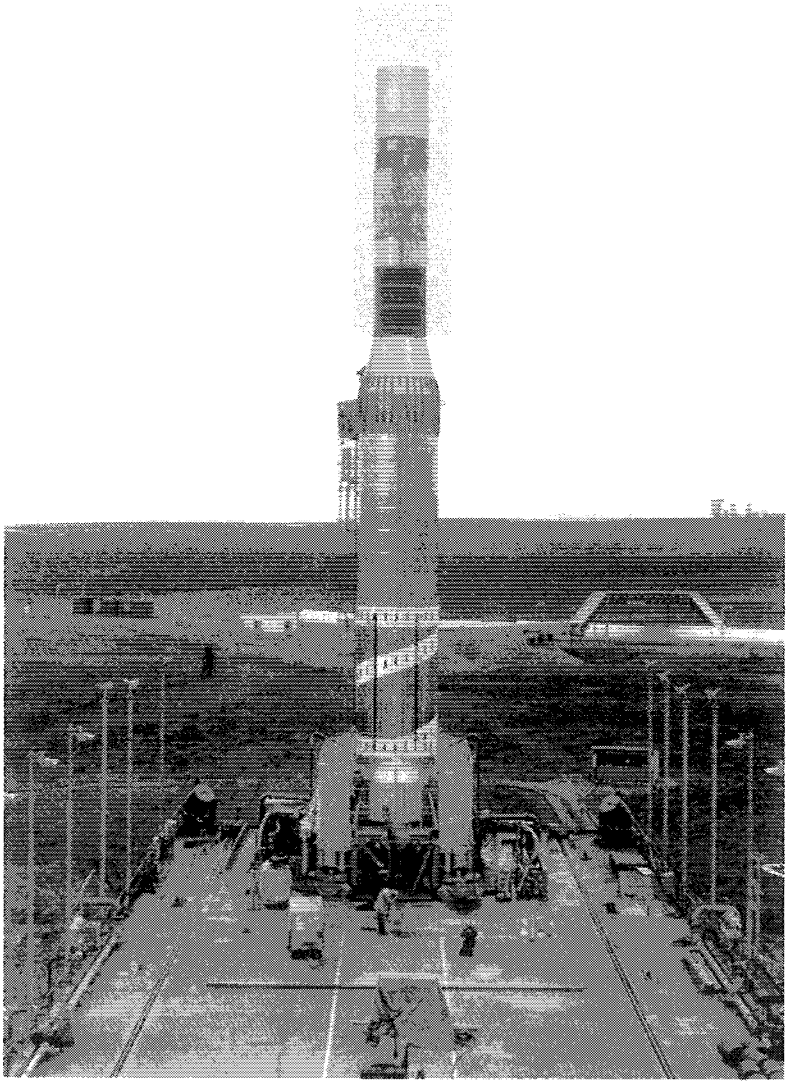
"Second stage impact on the polar ice cap."

He concluded: "The crucial point is the political acceptability of the risk in the U.K. Hitherto this has been regarded as unacceptable, and it would be no less now than when previously considered. My advice is that the risk is appreciable and should not be accepted."

Certainly launches in directions other than virtually due north would be well nigh impossible from Cumbria. Fortunately nothing was to come of it.

The total budget for the new European launcher to be called ELDO 1, or ELDO A, which had been estimated at £70M, was now creeping up to £73M. At the same time, ideas were put forward for what was referred to as the "2nd and 3rd programmes". The latter was left very vague, but the "second programme" called for a liquid hydrogen upper stage on top of Blue Streak, which had been a constant theme in British rocketry circles for some years. The conference was a success, though, and now ELDO was on its way to being created.

After Thorneycroft's efforts, ELDO came into formal being on 29th March 1962 by a Convention which was signed by seven Governments and which came into force on 29th February 1964 after ratification by the signatory states. Its headquarters were in Paris. The member states were Belgium, France, the U.K., Italy, the Netherlands, the Federal Republic of Germany and Australia; Spain, Switzerland, Norway and Sweden having eventually decided against joining. It was governed by a Council that had two representatives for each member state. The Council was assisted by an International Secretariat under the direction of a Secretary General, with two Deputy Secretaries General, one in charge of technical affairs and the other of administrative affairs. The staff of the Secretariat amounted to around 180 people in 1965.



Europa

This is F4, with dummy upper stages, at Spadeadam in Cumbria.

The launch vehicle to be developed was called Europa: Britain was responsible for the first stage, France the second stage, Germany the third stage. Italy would develop the satellite and test equipment, the Netherlands for the long range telemetry links and associated ground equipment, Belgium the development and construction of the equipment for the downrange ground guidance stations. Australia was to provide the range and support and facilities for the trial firings and the complete launcher.

Direct comparison between Europa and Black Prince, or BSSLV, is bedevilled by the different units since Black Prince measurements are in Imperial units, Europa in metric. The take off mass was to be 105 tonnes, which compares with around 94 tonnes for Black Prince, and the projected payload was around 1 tonne, or 2200 lbs, in low earth orbit. This was some improvement on Black Prince, but not by that much.

Comparisons between Black Prince/BSSLV and Europa are difficult to make; there are many and various figures quoted for the vehicles. Here, however, is a quick comparison:

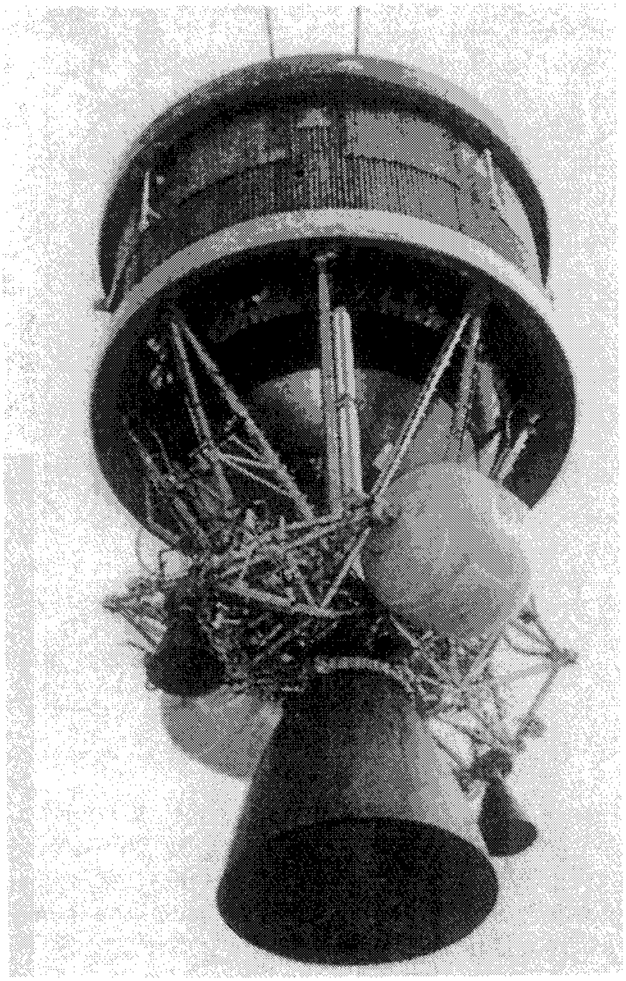
	BSSLV	Europa
First stage*	12,500lbs	13,800lbs
Usable propellant	173,692lbs	182,200lbs
Total	186,192lbs	196,000lbs
Thrust	270,000lbs	300,000lbs
2nd stage *	1,500lbs	3 300lbs
Useable propellant	15,000lbs	21 670lbs
Total	16,500lbs	25 030lbs
Thrust	25,000lbs	62 500lbs
Third stage	5,000lbs	7,160lbs
Mass at launch	207,692lbs	232,000lbs

*Structure and unused propellants

The larger French second stage is one of the notable points, as is the total all up weight. This was made possible by uprating the thrust of the Blue Streak chambers. However, the British second stage comes out as being structurally more efficient. If the BSSLV were to take advantage of the increased thrust, then the third stage mass could be increased.

The French second stage, Coralie, was based on the Veronique sounding rocket. This burned UDMH (Unsymmetrical Dimethyl Hydrazine $NH_2.N(CH_3)_2$) and Nitrogen Tetroxide N_2O_4. The stage had an after skirt housing the engine bay, a tank with common bulkhead, and a forward skirt with the gas generator and ancillary equipment. The 4 rocket engines were pressure fed, and the pressure was derived from a gas generator that used UDMH and N_2O_4; the hot gases were mixed with steam to cool them but at the same time increase their volume. The gases were also used for servos and electrical generation. On the ground the fuel tanks were prepressurised to 10 bar and were pressured to 18.4 bar at full thrust (1 bar is atmospheric pressure; 15 lb per square inch). Combustion chamber pressure was 13.7 bar.

The third, German, stage was called Astris, and was an ambitious lightweight design. The tank was a titanium sphere, with a fuel called Aerozine 50, or 50% hydrazine and UDMH, and N_2O_4 as the oxidant. There were 3 engines: a main engine of 22.5kN thrust and 2 smaller vernier stages of 300N.



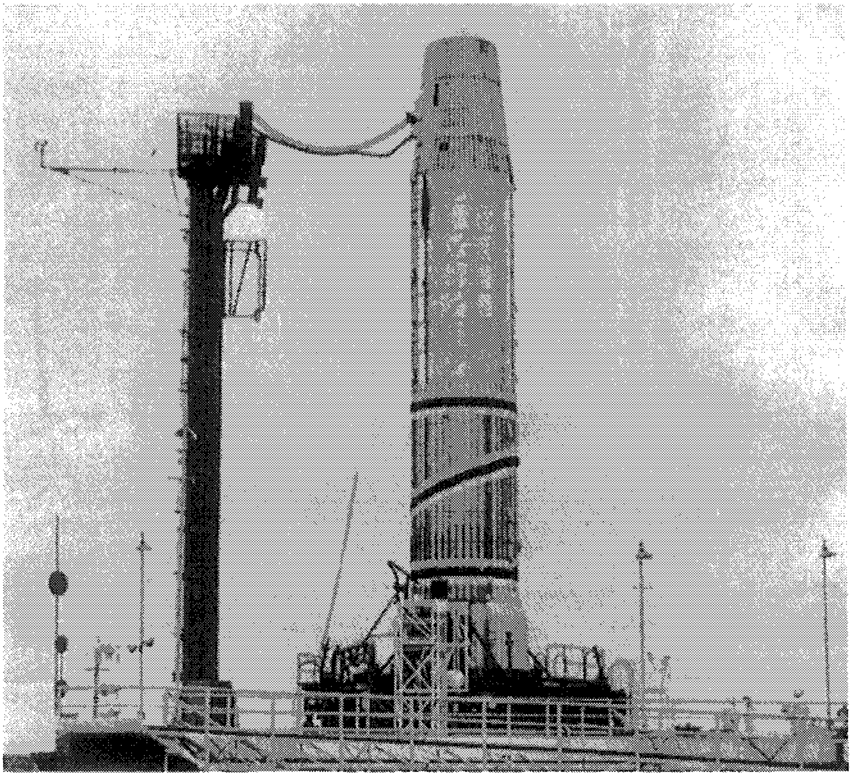
Europa third stage.

This was designed and built in Germany. The two small chambers can be seen either side of the main chamber. There are two gas bottles next to the main chamber.

The payload fairings and Satellite Test Vehicle were built by Italy.

To convert Blue Streak from a missile to a satellite launcher, various engineering changes had to be made. These included a new adapter and separation bay for the second stage, and an increase in thrust of the engines by about 10%. The mass of the upper stages and satellite were much greater than that of the original payload. The guidance would also be simplified, as inertial navigation would no longer be required. Instead, radar tracking could be used, and an autopilot fitted to control the vehicle. From the military point of view, this was undesirable as being susceptible to jamming or countermeasures, whereas for a launch vehicle, external guidance was perfectly adequate.

The drawback to all of this was that it was not much more than Black Prince three or four years further down the road, with no significant gain in payload, and still with no obvious application. And it suffered from the same problem: too big and expensive for experimental or scientific satellites, too small for the commercial applications of communications satellites. In the late 60s and 70s communication satellites meant relatively heavy packages in geosynchronous orbit, and Europa wasn't up to that.



Blue Streak at Woomera

This is the first flight model, F1, on the Woomera launched.

Neither vehicle ever put a payload into orbit: Black Prince's payload was estimated as around 1,800lbs in low earth orbit; that of Europa as about a metric tonne or 2,200lbs. However, Black Prince was a design of 1960, Europa of 1964, and during that time rocket technology was moving very rapidly. The slow development of Europa would add to the perception that it was obsolete.

Before the cancellation, the first launch of Blue Streak had been planned for mid 1960, with the first test vehicle already on its way to Woomera when the announcement was made. However, with the cancellation, this was not to be. After the abandonment of the project as a weapon in April 1960, funding was held at the tickover rate, which was to continue while the idea of Black Prince came and went, and then ELDO arrived. However, once ELDO was established, and the design of Europa had been finalised, Blue Streak was ready for flight testing long before the live or even dummy upper stages could be built. It was then decided to have a first phase of three launches with the rocket in what was basically the missile configuration. This was intended simply as a vehicle proving exercise.

But while design work for the new launcher had started, ELDO itself was running into serious political trouble.

The first problems came from the French, who at the start of 1965, abruptly announced that work on ELDO A (the Europa launcher) should be halted in favour of the more useful and ambitious ELDO B (see later). To push this further, they announced that they were withdrawing their funding until a decision was made. The remainder of the ELDO members were against this proposal for two reasons: they felt that the new programme was technically too ambitious, and that experience needed to be gained with ELDO A first; and further that the time scale was simply too long. There was little chance of a successful launcher with ELDO B until the early 70s, more than ten years after the project had begun, and this was thought likely to result in political difficulties.

Eventually, agreement was reached to continue with Europa, but studies for more advanced launchers were begun. However, the new Labour Government in the U.K. became increasingly reluctant to support the project. Thus the two principal founders of the organisation were engaged in what can only be described as disruptive tactics.

ELDO B and C.

The inadequacy of Europa became plain quite early in the history of ELDO. It was becoming clear that the most promising of the emerging commercial markets lay in communication satellites, and that these satellites had to be both large and in a geosynchronous orbit: one where its orbital period was 24 hours. This has several very considerable advantages. Primary among them is the simplification of the ground stations: the satellite does not appear to move, and so quite simple dishes—the satellite dishes people attach to their houses—can be used to receive broadcasts. The dish can be fixed, and without this, it is unlikely that satellite TV would ever have become established as it has. A second advantage is that only one satellite is needed: with any other orbit, a second or third satellite is needed to take over from the first as it disappears over the horizon.

The disadvantages are that the satellite needs a more powerful transmitter, as it is broadcasting from so far away, which in turn means more solar panels and batteries (the batteries come into play when the satellite passes into the shadow of the Earth). For telephone communications there is an irritating delay of a quarter of a second as the signal goes to the satellite and back again. The satellite has to be stabilised so that its dish is always pointing to the right point on the Earth, which means carrying extra fuel to help in this. More fuel is needed for fine tuning of the orbit, as well, so that it does not drift away from its place in the sky. These are some of the reasons why it is so heavy. In addition, the orbit has to be in the plane of the equator. This means that an equatorial launch site is highly desirable, and in addition, the satellite should be launched in an easterly direction to take advantage of the spin of the earth. (The speed of the Earth's rotation is nearly half a kilometre a second; a satellite has to travel at around seven kilometres a second to stay in a low Earth orbit). The equatorial orbit has disadvantages at high latitudes, which is why the Russian satellite system used different orbits.

All this is by way of pointing up the deficiencies of both Woomera and of Europa. Not only is Woomera well south of the equator, its launching corridors are very restricted by inhabited areas even hundreds of miles away. In effect, satellites can only be launched north or northwest from Woomera, which works well for polar orbits, but which is useless for equatorial orbits. Europa would not be able to put any payload into a geosynchronous orbit from Woomera. Given an equatorial launch site, then it could put 100 to 200kg into a 24 hour orbit.

Cape Yorke at the northeast tip of Australia was considered for some time, but the French won out with their suggestion of Kourou in French Guyana. However, even this payload was scarcely adequate for a decent communications satellite. The obvious step was to upgrade Europa.

The only effective way to do this was to add what were described as "high energy" upper stages—ones powered by liquid hydrogen. The various designs that were put forward were generically described as ELDO B.

Many proposals were made, but the ones that came closest to official approval were ELDO B1 and B2. The hydrogen motor was to be developed jointly by Rolls Royce in Britain and SEPR in France. (It was noted in the Ministry of Technology that: "...whilst the ELDO Secretariat greatly values the Rolls Royce and R.P.E. input to the liquid hydrogen/liquid oxygen engine and would be less confident if it were removed, France would probably be overjoyed to get the whole task back in the hands of SEPR.") It would have a thrust of 60kN (about 13,500lb). ELDO B1 would be a two stage launcher, powered by one of these motors, with the second stage weighing around 8.5 tons (19,000lbs), of which 7.5 tons would be propellant. ELDO B2 would be three stage: the new second stage would be powered by 4 motors and would weigh 19 tons (42,500lbs), of which 17 tons were propellant, and with the B1 stage as a third stage. To support the extra weight of the upper stages on B2, the Blue Streak tanks would have to be made thicker, from 0.6mm to 1.5mm skin thickness, adding another 0.85 tons to its weight.

The Blue Streak skin was not intended to be structural; instead, the loads were transmitted upwards by the pressure of the gas inside. The thickening of the skin would have enabled higher gas pressures, and also stiffened the vehicle against sideways loads.

This weight increase, however, made the launch vehicle almost too heavy for the RZ-2 motors, and they would have to be uprated to 165,000lbs each to cope. Even so, the vehicle would be marginal, and fins were suggested for Blue Streak to increase its aerodynamic stability at low speeds (the vehicle would also be extremely long for its width, given the large volume that liquid hydrogen takes up).

This new vehicle would have been able to put at least 1000kg (a tonne) in geosynchronous orbit, and several tonnes into low earth orbit, and represents the effective limit for a Blue Streak launcher. But it would have been a highly effective launch vehicle.

ELDO C was even more gargantuan, postulating a first stage with 4 RZ-2 motors.

However, all these proposals foundered mainly on the insistence of the British Government that it was treaty bound to pay for the development of the basic ELDO A vehicle, but no more. Hence the U.K. found itself in a position where it was paying a lot of money for a vehicle it knew to be ineffective, yet refusing to pay for one which might have been worthwhile! Indeed, when it came to the proposed PAS (perigee apogee system) for Europa, which was intended to give the capability to launch into geosynchronous orbit, the U.K. initially again refused to contribute, saying that this was a new scheme, and that it was committed only to the basic launcher. But by this time, the U.K. had finally given notice to quit the organisation completely.

This last refusal led Val Cleaver, head of the Rolls Royce rocketry division, and a leading light in the British Interplanetary Society (BIS), to accuse the Government of "Machiavellian" tactics. It is plain too that the minor partners in ELDO were exasperated by the manoeuvrings of the two major partners, who after all were the instigators of the whole project.

Thus a letter dated November 1968 from the British Embassy in The Hague to the Scientific Relations Department FCO (Foreign and Commonwealth Office) reads:

"As you will have gathered from our telegram, I had a pretty sticky ¾ hr. with Plate this morning ...

"Cramer started with the usual complaint that we were trying to have our cake and eat it. Having made our counterpart and got excellent technological experience out of Blue Streak, we had then lost interest—before the French had been able to complete trial of their second stage and before the Germans had had a chance of any trials at all. Plate said that he believed in continuing to support ELDO through to 1971, on the basis of the "German proposal", not only for

European political reasons—doubts about the availability of an American launcher etc.—but also for the genuine gain in technological experience which this was bringing.

" ... he did not see how matters could be reopened at tomorrow's meeting on the sort of basis we proposed without causing chaos. The Dutch would certainly not take any initiative in this direction, nor would they pay. If anybody else were willing to put forward the half share which we were now trying to get out of, the Dutch would of course not object—but he did not see where this could possibly come from.

"Finally, he made the now all too familiar complaint about the way in which we handle ELDO matters. At a variety of meetings since last April, we had reaffirmed our commitment to ELDO, even though we had refused to go above the current budget. At the ELDO Ministerial Meeting in Bonn, our representative had said nothing to contradict this. Yet the very next day, we had asked to be released from this commitment. Here were we now, suggesting that we could get by with release from only half the commitment—and this again at the very last minute before the Council Meeting. How could one do business in this way?"

How indeed?

The U.K. was given its pretext to withdraw from ELDO as a consequence of the Causse Report, which looked at the various technologies that could be successfully tackled with a chance of economic success on a European basis. Space and satellites were given a low priority. However, the withdrawal was greeted with cynicism even with the Ministry of Technology: "The Government statement ... is very clever in selecting from the Causse Report, out of context, just the few passages sown into it by the U.K. member for the purpose and, in all truth, agreed to by the other members of the committee because they did not consider economics the paramount question anyway and had a quid pro quo in the more positive aspect of Chapter 2."

Europa: from success to failure.

The first launch of a Blue Streak had been pencilled in for June 1960, and a tank and engine was on its way to Australia when the cancellation was announced. This date was optimistic, and it was unlikely that the vehicle would have been fired before the end of the year. After the cancellation, funding was kept at a tick over rate, and progress was slow until the ELDO convention had been signed.

The first ELDO launch of all was, surprisingly, not a Blue Streak or Europa, but a Black Knight. This was BK11, fitted with electronic equipment to test the range safety requirements. BK10 was a back up for this mission, but was never fired, and is now on display in the Liverpool Museum.

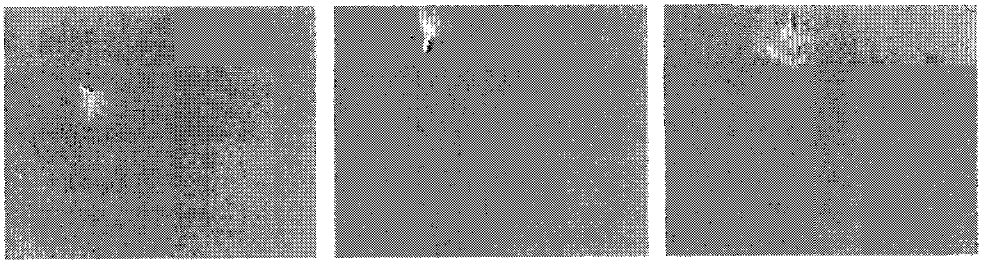
The first phase of the programme called for 3 launches of the single stage vehicle, proving flights, as it would be some time before the French and German stages would be ready.

The first three vehicles kept the thrust rating of the RZ-2 at 135,000lb. The inertial guidance was replaced by an autopilot, and a dummy nose cone was added to increase the weight of the vehicle (with no payload or upper stages the acceleration would have been too great near the end of the flight).

However, before flight vehicles were sent to Australia, a prototype vehicle was shipped out for static testing to prove the launch site. This was designated DA, as opposed to flight models, each of which was given a designation F-1, F-2, etc.

F1 proved to be almost fault free, apart from the very last few seconds of flight. The vehicle began to become unstable, and the residual fuel in the tanks sloshed from side to side. This eventually overcame the vehicle control system, and at 145 seconds the sloshing became so severe that the vehicle tumbled out of control, the engines being starved of fuel. The planned burn time was 154 seconds. The vehicle was tracked by camera throughout the flight, and the tumble can be clearly seen in the film. Three frames from the film are below. Another remarkable feature of the film is that the vehicle was around forty miles away at the time!

Adjusting the sensitivity of the guidance system cured the fault, and it never re-occurred. To say that this was the only fault in 11 launches is a remarkable tribute to the rocket, to de Havilland, and to Rolls Royce.



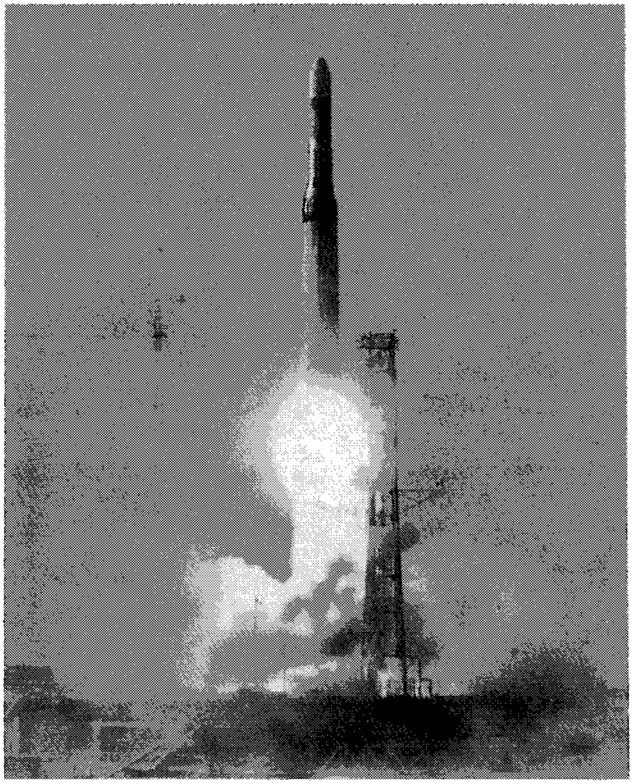
F1 tumbles

The vehicle is more than 50 miles downrange at this point, so that the film is not very clear. The rocket performs a roll before the sloshing of the fuel deprives the motors of fuel.

R.A.E. always appointed an O.I.S.C. (Office in Scientific Charge) for launches under its jurisdiction. For F1 the O.I.S.C. was Harold Robinson, one of the prime movers behind Black Knight and Black Arrow, and one of the men that led and inspired the British rocketry effort. His report of the launch is given in Appendix B.

F2 was launched on 20th October 1964, and F3 on 22nd March 1965. Corrections to the autopilot meant that these flights were "textbook".

The first three launches were in a northwesterly direction, towards Talgarno, with the impact point near the coast in Western Australia. All the later flights, however, were to the north. The first stage would impact in the Simpson Desert, in the centre of Australia. A new tracking station was built as part of the Belgium contribution to ELDO at Gove, on the edge of the Gulf of Carpentaria.



A Europa launch at Woomera.
The Blue Streak first stage functioned perfectly every time, but the same was not true of the upper stages.

Static testing of the French second stage, Coralie, was not possible, so flight tests were carried out at Hammaguir in Algeria. Test vehicle G1 was launched on 27 November 1966. A guidance problem caused its destruction after 62 seconds, though the rest of the vehicle was an apparent success. G2 was launched on 18 December 1966, and was a success, reaching a height of 55 km. G3, on 25 October 1967 also had guidance problems: a wiring failure caused the vehicle to over correct and break up.

F4 was launched on at 9:06 local time on 24 May 1966, and had dummy second and third stages with a satellite test vehicle. On this flight, the motors were uprated to 150,000lb thrust to carry the extra weight of the upper stages. Controversy surrounded this launch, since one of the radar stations indicated that the flight had abruptly veered off course. As it was reaching the edges of the safety boundary, the Flight Safety Officer from W.R.E. decided to send a manual destruct signal. As this was being sent, the plot began to return to normal—but too late. The vehicle was destroyed 136 seconds into the flight. This apart, the flight seemed as successful as the previous two.

F5 was launched on 13 November 1966. It was almost a repeat of F4, with an active first stage and dummy second and third stages, and satellite test vehicle. However, this time the second stage was intended to separate from the first, although, of course, not light up. This happened exactly as scheduled.

The Blue Streak launch site at Woomera.

F6/1 lifted off on 4 August 1967. This time both the first and second stages would be live, with dummy third stage and satellite. However, after separation, the second stage failed to ignite as a result of a static discharge that caused the electronic sequencer to fail. This flight had been subjected to many delays and aborts, and it is thought that one of the contributory causes was the corrosive effect of the second stage propellants on the vehicle.

F6/2 was fired on 5 December 1967, and was a repeat of F-6/1, but this time the first and second stages failed even to separate.

There was a considerable delay before the next flight, so that the second stage design could be suitably modified to prevent a repetition of the earlier failures.

F7 was launched at 0842 local time on 30 November 1968. All stages were now live, and this was in effect to be the first orbital attempt. The first two stages performed exactly to plan, and the third stage separated and ignited. Seven seconds later, however, it blew up due to an explosive bolt being inadvertently triggered by a stray electrical discharge.

F8, launched 3 July 1969, was a repetition of F7, but with again the same results. The first two stages operated as designed, but soon after third stage ignition, it exploded again. After this, more time was spent reviewing the third stage design in fine detail.

F9 was fired on 12 June 1970. This time all the stages operated as planned, and the rocket performed perfectly. However, the satellite fairings, which should have been jettisoned early in the flight, failed to separate, and as a result the payload was just too great to reach orbit. Post flight analysis showed that a plug had become disconnected. It was thought that in earlier flights, the seal had not been airtight as a result of constant connecting and reconnecting. This time, however, the plug was undamaged, and the air trapped between plug and socket blew the plug out.

For budgetary reasons, F10 was not fired.

However, Europa had been taken a step further with what was called the Perigee Apogee System (P.A.S.). This involved the third stage placing the satellite in a highly elliptical orbit, with a perigee of a few hundred miles, but an apogee at geosynchronous height. A solid fuel motor in the satellite would then fire at apogee to convert the orbit to a circular one.

Germany and France wanted to launch a communications satellite called Symphonie, which NASA was reluctant to launch, as the project would compete with its own communications satellite programme. F11 was assembled at Kourou in French Guyana. The problems of ELDO were typified with this launch: first Blue Streak arrived, with its own computer software to check out the systems, and with its British engineers from Hawker Siddeley (into which de Havilland had been merged) who spoke no language other than English. Next came Coralie, with its own, incompatible, check out systems, and with French engineers who would speak only French. Finally came Astris, with its team of German engineers and software. Presumably the Germans had to speak three languages. The Italians would also have been involved, since the payload fairings were Italian.

Given the lack of technical co-ordination, it is not altogether surprising that 150 seconds into the flight, static discharges produced by friction with the air stopped the computers of the guidance system, located in the third stage. The vehicle went out of control and broke up.

F12 and F13 were never launched: the Europa program was abandoned on 27 April 1973. Blue Streak never flew again.

Blue Streak vehicles:

The following Blue Streak flight vehicles were manufactured:

11 were launched: F1 to F9 (there were 2 F6s, F6/1 and F6/2) and F11.

F12 is at French Guyana, or parts of it are. It has been reported that the stainless steel tanks (which would not corrode in the equatorial heat and rain) are being used as a chicken coop.

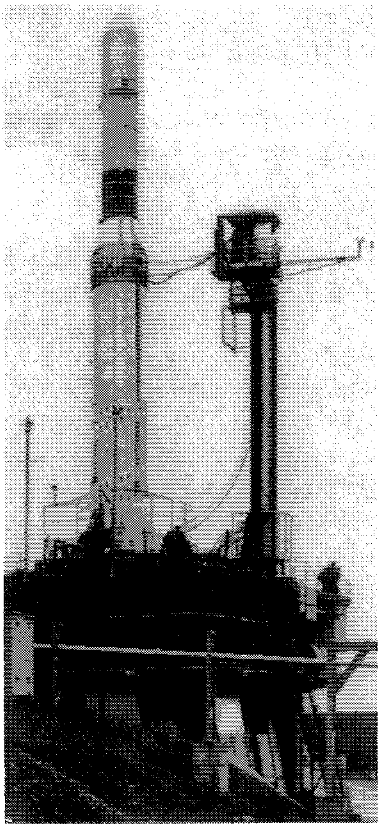
F13 is at Munich

F14 is at the Aircraft Museum at East Lothian, outside Edinburgh.

F15 is at Redu, Belgium.

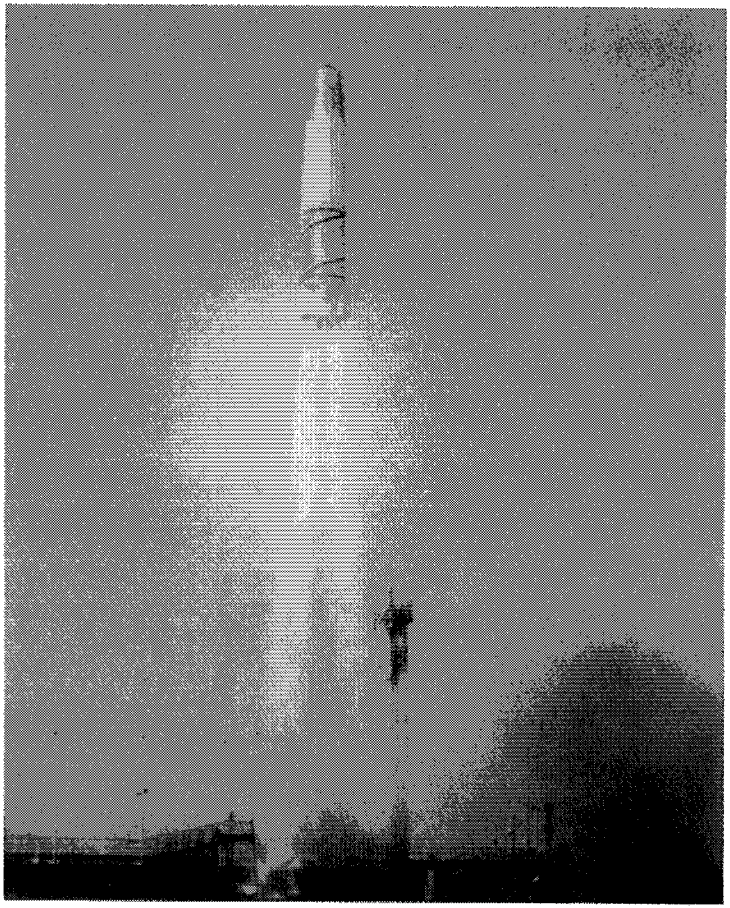
F16 was not finally completed (and is now on display at the Space Museum at Leicester).

F17 and F18: by the time of the final cancellation these vehicles were only parts, and not fully assembled.



A Europa vehicle at Spadeadam

In addition to these vehicles, several non flight prototypes were built. These were D1 to D4, some of which were for trials at Hatfield, others that were taken to Spadeadam for static firings. Another, designated DA, was shipped to Australia before the flight vehicles, and set up on the launch site for static testing. This was to test the Woomera site and give experience to the Australian team. DB was static fired at Spadeadam to check the engines. In addition, there was a further prototype vehicle, DG, used to prove the Blue Streak launch site at Kourou, in French Guyana.



A single stage Blue Streak

An account of the F1 launch written by the OISC (Officer in Scientific Command), H.G.R. Robinson of the R.A.E. Farnborough, and the moving force behind most of these projects, can be found in Appendix B.

9. Black Knight

Black Knight was originally conceived as a relatively simple rocket to find out what happens when a re-entry vehicle containing a nuclear warhead comes back into the atmosphere at very high speeds. The purpose was to save time by running the programme in parallel with the Blue Streak programme, so that the design for the re-entry vehicle could be completed and verified before Blue Streak's first flight. The aerodynamics of vehicles at such hypersonic speeds, 12,000 feet per second or more, effectively around Mach 12, were completely unknown at the time. So were the effects of kinetic heating: would the re-entry head survive the stresses and would it be aerodynamically stable? These were problems that could only be solved by building a test vehicle that could launch these re-entry bodies to observe their behaviour. The original specification for the vehicle was laid out in April 1955, at the same time as Blue Streak was given the go ahead. The schedule called for the first flight in August 1957, although this was unduly optimistic.

There were also other objectives for the vehicle. The U.K. had never undertaken a major ballistic rocket programme before, so Black Knight would verify many techniques, which, though well established, were mainly theoretical to the British. These included the use of lightweight tanks, and steering of the vehicle by gimballing, or swivelling, the rocket motors. In addition, it would give opportunity to test the Woomera range and its tracking radars before the arrival of the larger rocket. Initial thoughts had been for a solid fuelled rocket. This would mean clustering together several small motors, as there was no solid motor then big enough. In addition, a multistage vehicle would be needed. Steering such a vehicle by swivelling the nozzles of solid rocket boosters was thought to be too difficult. Given these problems, R.A.E. settled on a simple liquid fuelled design.

A meeting was held at R.A.E. in May 1955: "The meeting was informal and was held with the primary object of acquainting Saunders Roe generally with their responsibilities in the event of their being selected as main contractors." Saunders Roe were indeed chosen to build and test the vehicle, although de Havilland, who were building Blue Streak, were to run the trials at Woomera, again to gain experience. This was something of a disappointment to Saunders Roe, although they realised the logic of the situation, and eventual co-operation with de Havilland was good.

The re-entry studies were under the control of R.A.E., who worked very closely with Saunders Roe, to their mutual benefit. R.A.E. also suggested the use of the Gamma motor, as developed at R.P.D. Westcott. Saunders Roe were presumably chosen as a consequence of their experience with H.T.P./kerosene with the SR53 and putative F177. It is interesting though that R.A.E. went for an "in house" motor in the form of the Gamma motor being developed at R.P.E. Westcott rather than de Havilland's Spectre engine with which Saunders Roe were already working. Against the Spectre, however, with its 8,000lb thrust, was its already late delivery to Saunders Roe: December 1955 was the earliest delivery date that de Havilland could give for a Spectre for the SR53. The Gamma was rated at 4,000lb thrust, although this was later uprated to 4,200lb for Black Knight, and subsequently completely redesigned for even higher thrusts. Armstrong Siddeley at Ansty, Coventry, were given the task of designing and building the engine bay with its 4 rocket chambers. This early version was referred to as the Gamma 201. The vehicle structure, motor control system, electrical and mechanical systems were all Saunders Roe's responsibility, with the gyros, tracking transponders, telemetry and sundry other components being subcontracted.

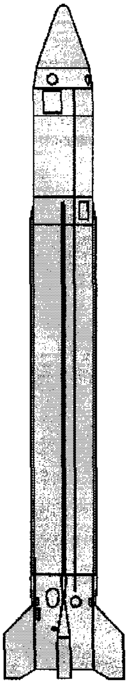
The R.A.E. had already given Saunders Roe the weight breakdown they had in mind:

Payload (re-entry head)	200	lb.
Motors and associated equipment	500	lb.
Control equipment	100	lb.
Tank structure	150	lb.
Other structure	50	lb.
Miscellaneous	50	lb.
Fuel and oxidant	11,250	lb

to give a total all up weight in the region of 12,300 lb. The all up weight was fixed by the thrust of the Gamma motors: 12,300 lb weight with a thrust of 16,000 lb gave an acceleration of 1.3g, or a lift off acceleration of 0.3g after allowing for gravity.

The vehicle was be built and tested on the Isle of Wight, then taken apart for shipment to Australia, where it would be set up again, and launched. Maurice Brennan was then Saunders Roe's Chief Designer, and he gathered together a team to design and build the vehicle. At this time, Saunders Roe were extremely busy, employing some 3000 people with the SR53, F177, and now Black Knight. Sadly, as recalled elsewhere, the F177 was cancelled at the end of 1957, and the work on the SR53 remained relatively low key. This had the slight consolation that it released designers for Black Knight, and, later, Black Arrow. There is a story about Brennan: once in a heated meeting with the Ministry, he was reminded that they had originated the vehicle. "Yes," he flashed back, "and I have here the envelope on which that sketch was made!"

The initial design was for a slim 36 inch diameter cylinder, with an engine bay 5 foot 2 inches tall, an H.T.P. tank 17 foot 4 inches tall, a 1 foot 4 inch intertank bay, a 4 foot kerosene tank, and a 1foot 4 inch electronics bay, topped by the re-entry vehicle. The total height came to 400 inches, or 33' 4". The two tanks were deliberately kept separate, to avoid any problems of fuel leaking from one tank to the other. Four kerosene pipes ran down from the tank along the outside of the vehicle, as did the electrical connections, to the motor bay, each covered in a plastic conduit. The 4 motors had their thrust lines off set so that they pointed inwards to the centre of gravity of the vehicle when fully loaded.



The single stage Black Knight

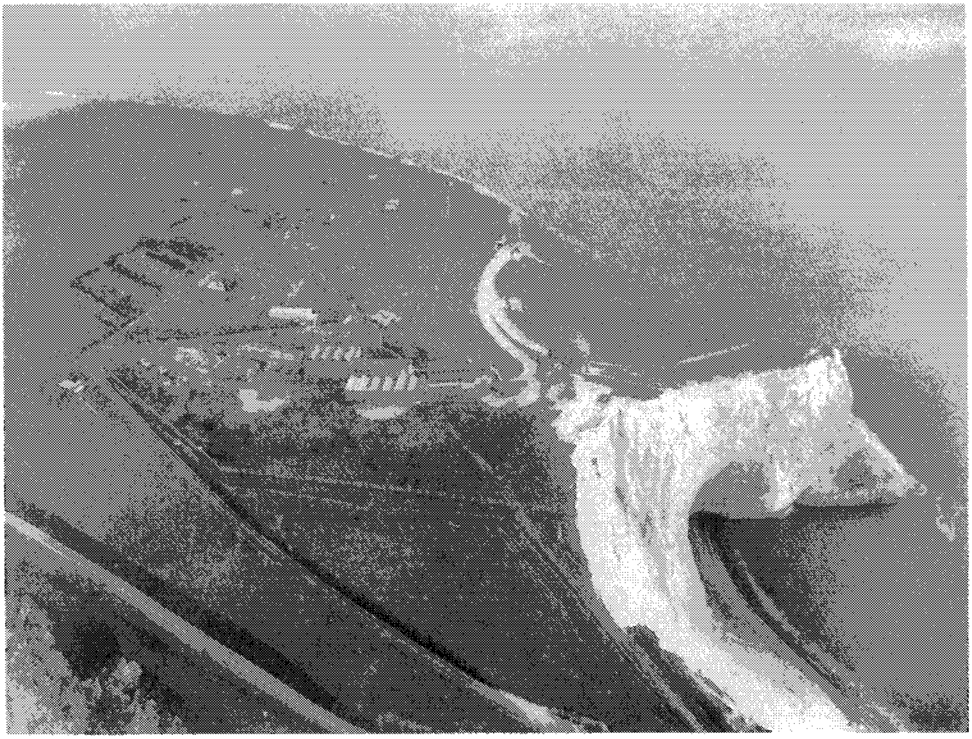
In addition, 4 small fins were added to provide aerodynamic stability at lift-off. On the end of two of the fins were pods (small cylindrical attachments): tracking lamps were fitted to two of these, and electronic flash units and S band transponders to another. It was intended to launch the vehicle on dark, clear, moonless nights, so the glowing re-entry body and its wake could be observed optically. The lights could then be used to track the vehicle, and by photographing the flashes the vehicle velocity could be estimated.

A late change was made to the design: R.A.E. estimated that there would be considerable drag from the air swirling round the base of the vehicle—so-called base drag. One way to reduce this was to cut holes in the skirt to allow air to flow in. To test this theory, five flights were made at the range at Aberporth of a vehicle designed specifically for the purpose. The test vehicle had a length of 61 inches and diameter of 97 inches, weighing 140 lb, and used solid rocket boosters. Results indicated that a reduction in base drag of greater than one third was possible from use of the base bleed holes. This meant an improvement of the all burn velocity of Black Knight of 250 ft/s by piercing the propulsion bay skin with eight 6 inch diameter holes.

The earliest design drawings show 16 external stringers in conjunction with thin walled tanks and the first two prototypes (never fired, but used for structural and ground testing) were built to this design. One of the reasons for these stringers was to strengthen the vehicle against the possibility of high level gusts of wind at Woomera. However this design was discarded (one of the potential problems was that the stringers would suffer kinetic heating on the ascent and so expand more than the tanks) in favour of a thicker skin with internal supports. The final thickness chosen for tanks was 20 SWG, otherwise 0.036 inches or 0.914mm. The seams were welded to make them leakproof: welding aluminium is not easy, and this was another technique for Saunders Roe to master. The vehicle was simple and effective, and also very cheap: at one time, a tested and assembled vehicle, ex-Cowes, was costed at £41,000! This included £15,000 for the Armstrong Siddeley engine. To that should be added about £7,000 for setting up, testing, and static firing at High Down and in Australia. Thus in April 1959 it was noted in the Ministry of Supply that the Black Knight programme "is being carried out in a most economical manner...".

An early model Black Knight
This is the thin walled model with external stringers.

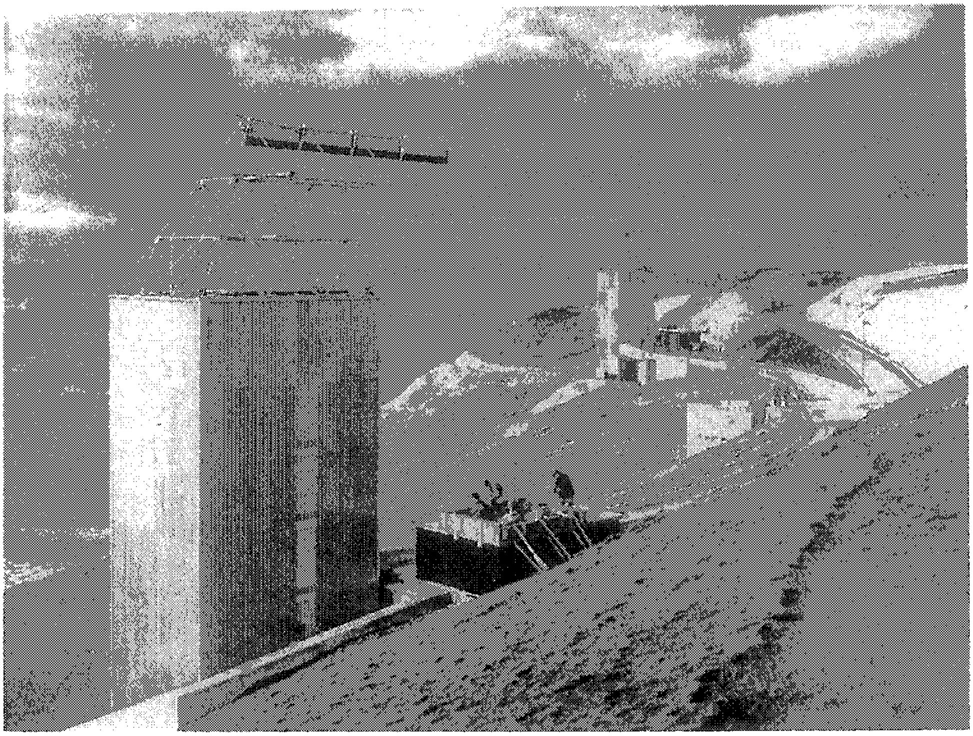
Control was mentioned as one of the problems under investigation. The rocket engines could be swivelled hydraulically to control the vehicle, and for flight guidance during powered ascent the control system consisted of an autopilot with gyroscopes to keep the missile on a constant heading. A radar beam tracked the rocket so that any deviation from course could be corrected by a perturbation signal transmitted to the autopilot from a ground transmitter. The radio link also made provision for fuel cut off signals in the event of any major problems. Explosive was fitted in a ring round the H.T.P. tank in case it was necessary to destroy the rocket in flight rather than have it crash down on some part of the range equipment. In addition, manganese dioxide, a very effective catalyst for the decomposition of hydrogen peroxide, would be released into the H.T.P. tanks. This was to be the undoing of the first test flight, BK01, where the explosive was triggered by accident near the end of the powered ascent!



An aerial view of the High Down site on the Isle of Wight.

The initial vertical climb of the vehicle was controlled from the ground by two human pilots, one of whom controlled movement about the pitch axis whilst the other controlled the yaw axis in response to information received from the optical trackers. As soon as it was established that the vehicle was stabilised on its correct course, control was passed to a radar tracker. Accurate flight control was essential: the cameras and other observational instruments were pointed at one small part of the sky, so that a small error in track could mean a wasted flight, and, in addition, pastoral areas were as close as fifty miles from the launch site. The impact site was approximately sixty miles from the launch site.

If a rocket had to be designed for a similar purpose today, then the solution would be almost identical. There have been obvious improvements in some technologies, and particularly in composite materials and electronics, but even so, the basic structure would be almost unaltered. The original motor was not as effective as it might have been, but during the programme it too was replaced by a more efficient design. This shows up two points: firstly, how rocket technology has in many ways reached a plateau, and secondly how well designed Black Knight was to begin with.

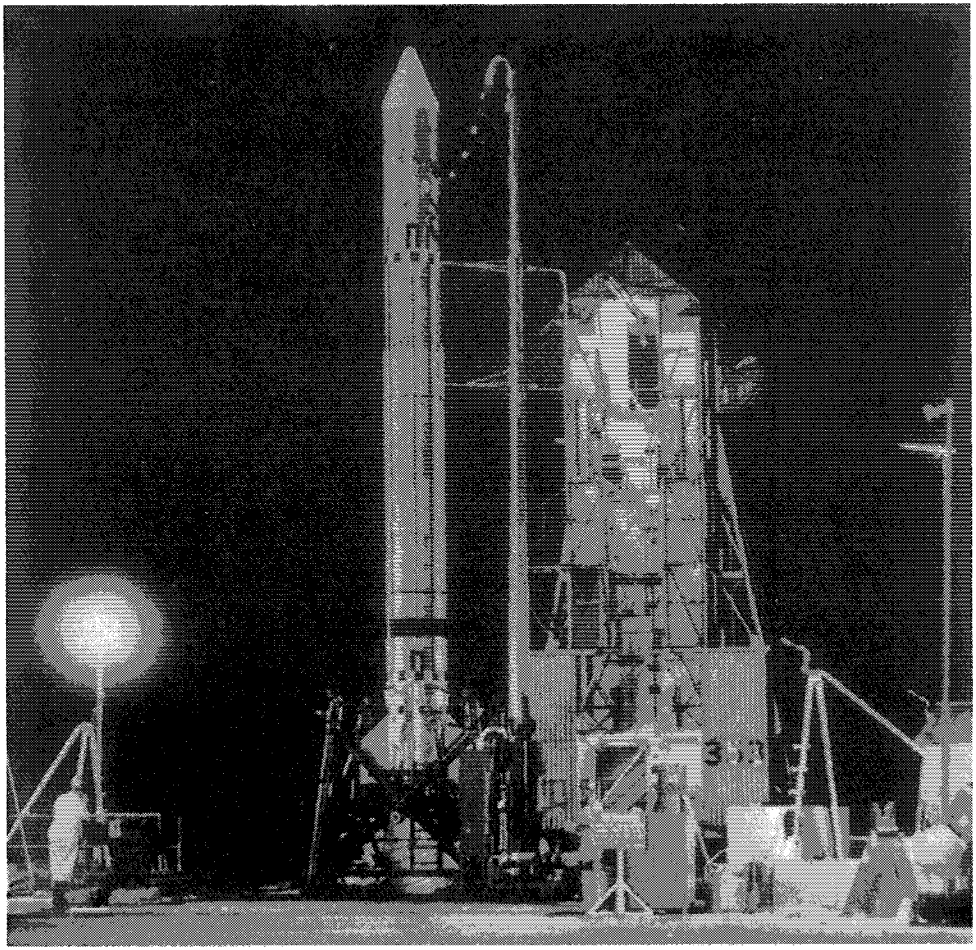


The gantries at High Down.

In the far distance are the Purbeck Hills, and the sea can be seen breaking over the Shingles Bank. The nearer gantry hides the Needles lighthouse.

Saunders Roe needed a static test site, which they built at High Down overlooking the sea at the very end of the Isle of Wight. The site can be seen in the photograph above. Down to the right, looking out to sea, the Needles rocks and lighthouse are visible, and on clear days, Anvil Point, Swanage and the Purbeck Hills. A curving concrete walkway was constructed, with two gantries, one each end, and a control bunker in the middle. A ramp swooped down for the transporter carrying the vehicle. Up over the brow of the hill were the fuel and H.T.P. tanks, with sundry assorted buildings. The costing for the site was given at £50,000, (although, in practice, the bill did come out higher) which gives some idea of contemporary money values. The concrete ramp and remains of the static stands are still there today, as part of the Needles Battery and now owned by the National Trust, and can be seen by any yachtsman sailing out from the Needles. It was also, apparently, a good spot to bring visiting Americans for a picnic lunch! But in a brisk sou'westerly gale, it must have been a bleak spot.

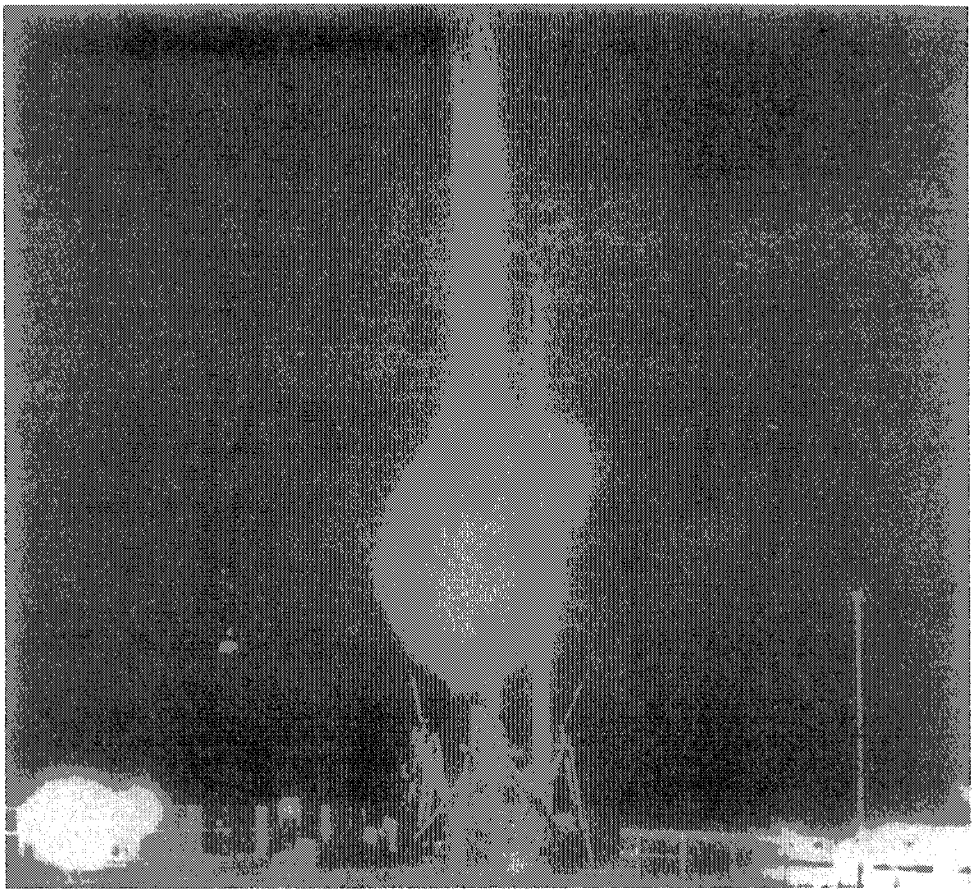
In addition to High Down, the Woomera launch site had to be constructed, together with a control bunker. The Woomera facilities were almost identical to those on the High Down site, so that there would be no incompatibilities. Hence, given all the work that had to be done, it is not surprising that the first launch did not take place until 7th September 1958, despite the initial, earlier, optimistic schedules.



BK03 on the launch pad at Woomera

Firings were carried out on moonless nights for optimum visual tracking and data gathering, which reduced the flight frequency. If a flight was delayed for any reason, and the launch window was missed, then the team had to wait another month. On the day of the firing the kerosene was loaded in the morning, and the

H.T.P. later in the afternoon, when there was less risk of delay or cancellation. The countdown sequence from T-120 seconds was entirely automatic, so that any malfunction or faulty instrument reading stopped the countdown immediately. Ten seconds before engine ignition the umbilical connections were ejected and fell back against a "trampoline" fitted to the umbilical mast so as to avoid damage. The engines ignited, and only when full thrust was reached was the vehicle released. Engine cut out occurred typically at a height of 60 to 70 miles. Peak velocity on re-entry occurred at around 200,000ft or just under 40 miles, when the drag forces became significant. The re-entry data were measured and recorded between this height and 100,000ft.



BK03: the launch

All the launches took place at night, so they did not photograph well. This shows the clean exhaust of H.T.P./kerosene.

The Black Knight launches.

Note, incidentally, that the flights did not occur in order of vehicle number: for more details, see the timeline at the end of chapter 12.

The first flights: BK01 and BK03.

The first two flights, BK01 and BK03, (BK02 was used for structural tests and never flew) were for test purposes only, to see that the vehicle and the launch facility worked as planned. They were not fitted with separating re-entry heads. The first launch, on 7th September 1958 at 20:03 local time, seemed initially to be a textbook operation, until a high level explosion was observed. The launch team was puzzled, since the engine bay was recovered almost intact, but the fuel tanks were some distance away, and severely ruptured. This inadvertent explosion turned out to be due to an electrical fault in the destruct command system, which detonated by accident, but 90% of the propellants had been successfully burnt, so the flight had lived up to most of its expectations. The only major change made as a result of the trial was to eliminate that part of the guidance radar system that provided the "destruct command" facility, limiting the function of the system to guidance only. A second command link was fitted to provide the duplicate "destruct command" system required by W.R.E. (Weapons Research Establishment, the organisation that ran the Woomera site).

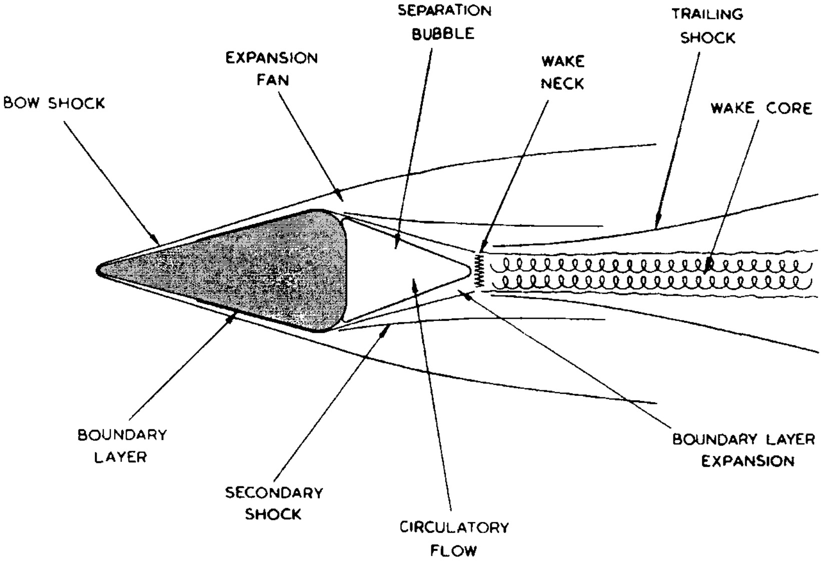
Post flight debris.

The advantage of a land range such as Woomera was that debris from the flights could be collected and inspected. Here is a sample from the BK15 launch.

BK03, the second proving trial, launched on 12th March 1959, was also successful except for an engine malfunction late in flight resulting in a long period of "cold" thrusting (due to decomposition of H.T.P., in the absence of kerosene. The motors continued to run on H.T.P. only, severely reducing their effectiveness.). The fault was subsequently traced to excessive heating of the propulsion bay. This was to be a problem on later flights too, until the cause was established: at supersonic speeds the plume of the rocket exhaust was swept back into the engine bay. In this trial, the guidance during launch was visual, using a telescope, and radar tracking was retained as a stand-by. This proved very successful.

BK04: the first test of the re-entry vehicle.

BK04 was the first flight to carry the experiment for which Black Knight was originally designed: the test of a re-entry vehicle. These were basically conical in shape, designed to re-enter the atmosphere pointed end first.

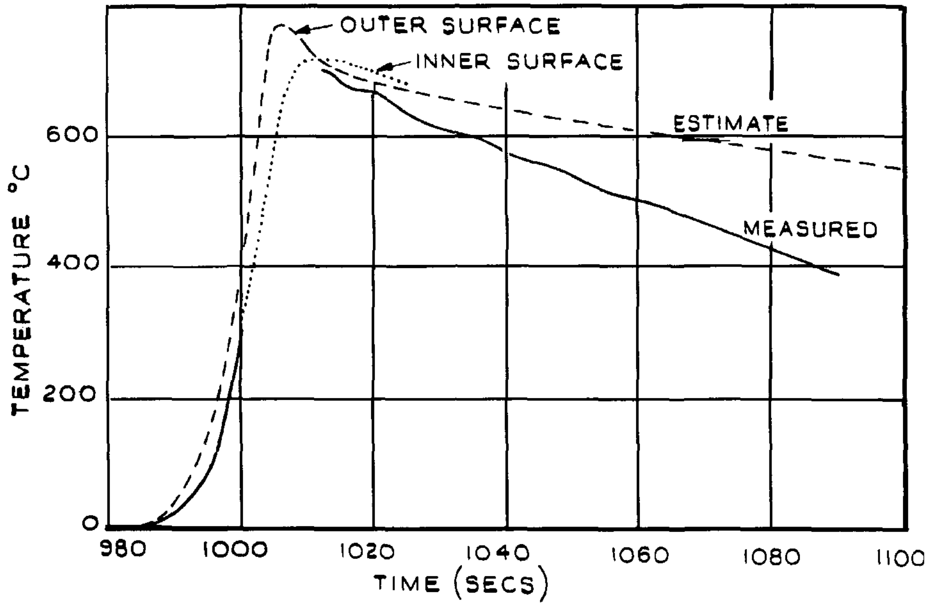


The airflow around a re-entry vehicle at high speed.

The diagram above shows the flow of air around the re-entry body. As the drag forces on the vehicle built up, kinetic energy was converted into heat energy. One of the unknowns was how much heat would be transferred to the head itself. The outside was asbestos coated, to protect the interior from the heat. There was also the problem of stability: if the aerodynamic forces were not correctly aligned with respect to the centre of gravity of the vehicle, then it might become unstable and tumble, rather than fall smoothly. The material on the outside could also be ablative. This means that it will burn away during the peak heating period, and carry away a good deal of the heat with it.

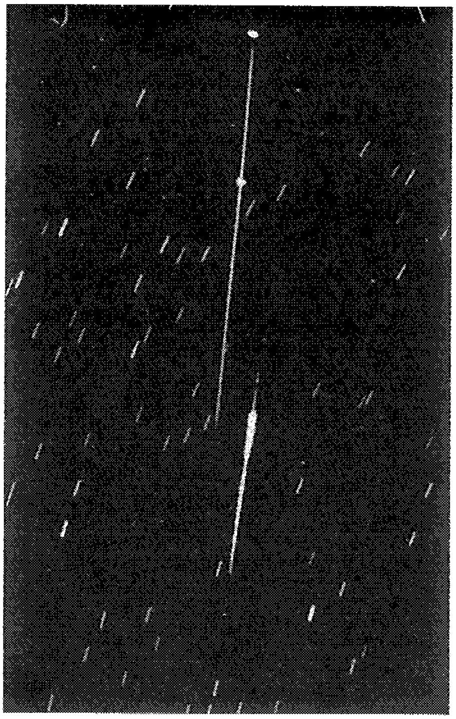
The re-entry vehicle did not have a sharp point, but a blunted one: the point of this being that air in front of the nose will be trapped, and the air is heated rather than the vehicle. The shape of the vehicle is low drag: the widest part is at the back. American designs entered blunt end first, as in the shapes of the Mercury, Gemini and Apollo capsules. The high drag heads slowed down higher in the atmosphere, and the peak heating was less. However, the low drag head penetrated deeper into the atmosphere before slowing down, which was better from the military point of view, as it was affected less by high level winds, and spent less time in the atmosphere, so reducing its vulnerability to counter measures, or ABM systems.

The head, or re-entry vehicle, was designed to separate from the vehicle, turn over, and then was spun up by means of small rocket motors to stabilise it. BK04 reached a greater height than any other launch (499 miles), although the re-entry speed was not the highest: the later two stage Black Knights reached higher re-entry velocities. The head re-entered the atmosphere at an altitude of 11,740 ft/sec (at 200,000 feet), and except for a short period during re-entry, the telemetry transmitter worked throughout to impact, giving information on re-entry dynamics and heating. Recovery of the head with the patches of materials under test attached to it yielded valuable information on ablation during re-entry. Unfortunately, there was some loss of data at the time of peak heating, just over 1000 seconds into the flight, but interpolation of the results showed that the maximum temperature at the stagnation point was 750 to 800°C, and indeed the heating was probably less severe than expected. The graph below shows the actual results that were obtained from the flight.



BK04: re-entry head temperatures

The range at Woomera was equipped with cameras to photograph the re-entry. As the head and the body of the rocket entered the atmosphere, the heating was sufficient to create a glowing wake similar to that of a meteor. From these photographs, the wake could be studies to give more information about re-entry heating.



BK04: re-entry

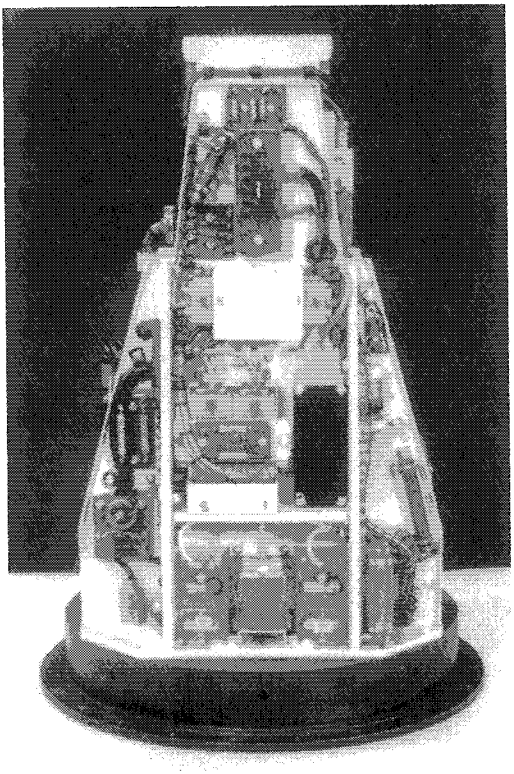
This is typical of the re-entry photographs. The streaks of light in the background are stars. During the long exposure they seem to move as the earth rotates. The stars give a very accurate picture of where re-entry occurred. The long streak on the left is the re-entry head, the short thicker streak is the body burning up.

With this launch, the objective of verifying the re-entry head design had been achieved.

BK05

However, there were variations on the design of the re-entry head which also needed testing. Thus the next launch, BK05, carried a re-entry experiment with a double cone eroding head. It was designed for greater penetration at high speed into the atmosphere to produce much greater heating, particularly in the nose cone. A complicated parachute recovery system was built into the head in an attempt to prevent damage to the nose on impact.

Overheating in the propulsion bay, as in BK03, again caused premature engine cut-out resulting in a reduced re-entry velocity. This was due to hot gases from the rocket motor plumes being swept back into the motor bay at supersonic speeds, and the problem was identified and avoided in later flights. A hitherto unsuspected long decay time of thrust at engine shut-down resulted in collision of body and head at separation. The body telemetry continued to function until re-entry but head telemetry ceased just after head separation; it is likely that during turnover the head aerial was broken by impact with the body. The head was recovered and it was found that the parachute had torn out the inner core of the head and the base dome had been pulled off. Early deployment of the parachute would have resulted in excessive drag loads and it can only be assumed that this happened. Some supporting evidence is that the barometric switch used to deploy the parachute was found on recovery to operate at a pressure equivalent to 22,000 ft instead of the expected height of 10,000 ft. However, the trial was not a complete failure. Recovery of the head yielded data on erosion, albeit at a lower re-entry speed than intended.



Innards of a re-entry vehicle

This is the instrumentation contained within a typical Black Knight re-entry vehicle.

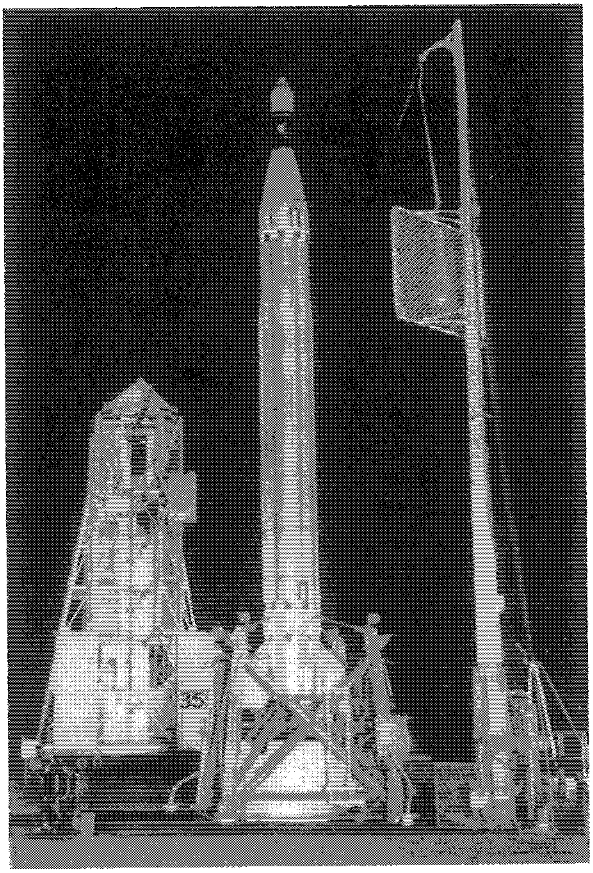
BK06

BK06 was a repeat of BK05 with a similar head, but using a tape recorder within the re-entry vehicle to record separation and re-entry data. Vehicle performance was good, and a re-entry velocity of 11,220 ft/sec was achieved at 200,000 ft. There was still some residual thrust even after the eight seconds allowed between first stage burn-out and head separation, and this caused collision between the vehicle and the head. As a result, the collision initiated the ejection of the pyrotechnic flashes and deployed the parachute on the ascent instead of later, as intended, during descent. The tape recorder in the head was switched on correctly and covered the separation phase and later part of the re-entry. The tape cassette, with recordings intact, was recovered together with the eroded durestos nose cone. Further data on erosion of the ablative covering material was obtained.

The design for the re-entry head was, by now, well established, but other results had emerged from the firings. One was the brightness of the re-entry wake, another was the very strong radar reflections obtained from the vehicle exhaust and from the re-entry wake. These radar reflections were due to the air being heated until the gas molecules became ionised, and would have passed unnoticed with more modern shorter wavelength radars. However, the relatively elderly and longwave radars being used, which had wavelengths of 45m and 20m, picked up the effect very clearly. The U.S. was also interested in these results, since both countries were looking for ways to detect missile launches and to track re-entry vehicles, as part of an anti ballistic missile (ABM) system.

As a consequence of these unexpected results, a further programme of joint U.K./U.S./Australian experiments codenamed Gaslight was set up to designed look at these effects in more detail. Since Woomera was a land based range, this was relatively easy. Equivalent U.S. re-entry vehicle had been fired out into the Atlantic, where it was more difficult to do much in the way of observing the re-entry. American involvement also meant funding was available from the U.S. to install more sophisticated radars and photographic apparatus. Thus the Black Knight programme was broadened out from a simple set of experiments on the re-entry heads themselves to a wider programme designed to study much wider aspects of vehicle and re-entry wakes, and to obtain data on a broader range of re-entry phenomena.

In addition, the payload and re-entry velocities that could be obtained from Black Knight were to be improved by the addition of a second stage. This was a small solid fuel rocket motor, designed to boost the re-entry vehicle to higher velocities. Whilst the original vehicle had fulfilled its original design specification, it was also capable of being stretched further, and adding another stage was an obvious way to do this.



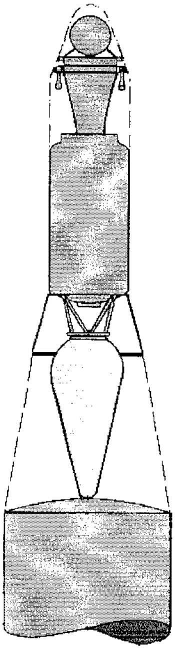
BK08

This was the first two stage Black Knight.

BK08 and Gaslight.

BK08 was the first two-stage vehicle to be fired, and the first in the Gaslight series. The performance of the first stage was good, but the second stage did not separate from the first stage and so did not ignite. The failure of explosive bolts or inertia switch circuitry was the probable cause. The trial, however, proved the aerodynamics of this new two stage configuration, and also the control stability with the heavier vehicle, the stressing of the body given the greatly increased forward weight, and the necessarily modified guidance arrangements.

The new two stage arrangement is shown below, and as can be seen, it has some oddities. The second stage and re-entry vehicle are mounted on top of the propulsion bay facing downwards! The sphere at the very top, under the nose cone, is a gas bottle. Below that is the expansion nozzle for the Cuckoo motor, then the head mounted on struts. The motor was fired on the downward part of the trajectory, and calculations showed that the lower the altitude the motor was fired, the greater the increase in velocity. This amounted to 200ft/second for each 100,000 ft of altitude.



The two stage arrangement

The bottom of the diagram shows the main vehicle; above that is the re-entry head, then the struts attaching it to the Cuckoo motor. Under the nose cone is a gas bottle.

Firing the motor on the way down rather than on the way up also reduced dispersion from the aiming point: that is, the distance away from the intended landing point that the vehicle actually landed. Firing on the way up would increase the apogee considerably, so that a small error in direction when it was fired would mean a much larger error in distance. This was important for two reasons: the first being the range restrictions, since there were inhabited areas not too far from the launch site. The second was that the instruments had to be pointing at an exact area of sky to catch the re-entry wake.

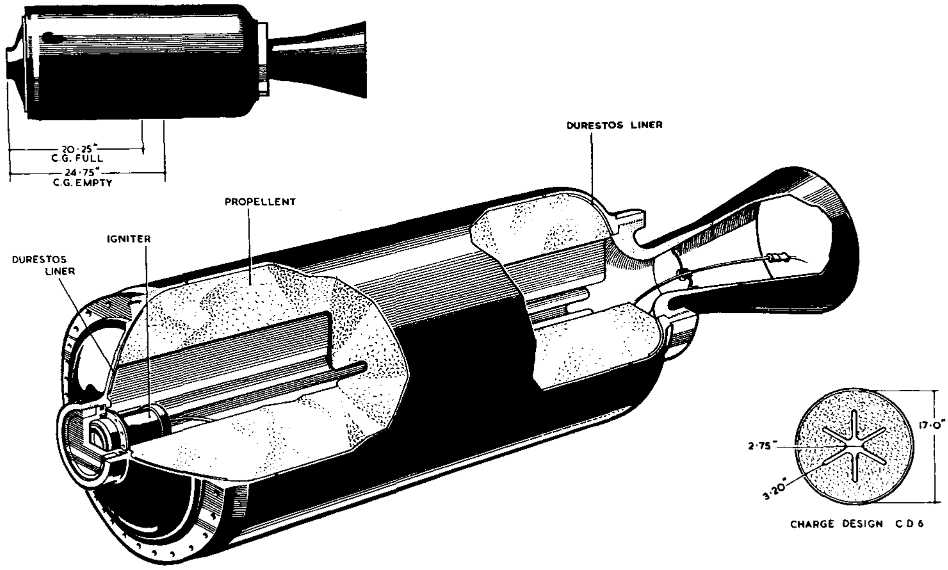
The Cuckoo motor that acted as the second stage had originally been developed as a booster motor to be fitted underneath the Raven motor that powered the sounding rocket Skylark, in order to improve the rocket's performance. In this configuration, the Mark IA, it had its first flight on 12th April 1960. Redesigned to fit Black Knight, and so designated the Mark IB, it was flown on BK08 on 24th May 1960, and was used on 6 further Black Knight launches. The Mark II version was used on a further 7 launches, and gave higher performance. Mark III and Mark IV versions were used for later Skylark models.

The BK08 head

Taken at the launch site in Australia, this shows the head in its stand, just before being fitted to the vehicle.

The table below gives some comparative figures for the various motors used for the Black Knight second stage. Mass fraction is the ratio fuel/total weight; the nearer this is to 1 the more efficient the structure. The Kestrel motor that is also listed was intended for the much later 54 inch Black Knight designed for the Crusade programme of re-entry studies. However, this vehicle was cancelled in favour of developing the Black Arrow satellite launcher.

	Burn time	Mean Thrust	Total Motor Mass	Propellant Mass	Mass fraction	SI
Cuckoo IB	4.1s	3750 lbf	520 lb	400 lb	0.795	220s
Cuckoo II	10.0s	1700 lbf	500 lb	420 lb	0.836	250s
Kestrel	10.0s	5400lbf	1600lb	1285lb	0.804	270s



The Cuckoo motor

BK09

BK09, the second two-stage vehicle, was a successful launch. Separation of the second stage, initiation of the second stage boost and separation of the re-entry head from the second stage boost worked well. The second stage boost "lit up" at the correct height on the downward trajectory prior to re-entry and a re-entry velocity of 15,000 ft/sec was achieved at 200,000 ft. The tape recorder in the head recorded data during re-entry down to 80,000 ft.

Just prior to re-entry an abnormal and completely unexpected increase in head oscillation occurred. The head broke up shortly after this and unfortunately the last inch or so of tape that had passed through the tape head was lost. This corresponded to the period immediately prior to head break-up. The break-up of the head at a low height during re-entry indicated that either the plank construction of the head was unsatisfactory or abnormally high loading was applied during re-entry, perhaps resulting from an unstable oscillation. (The asbestos exterior was fitted in strips or "planks".) The Gaslight ground instrumentation (photometers, radiometers and spectral ballistic cameras) obtained some re-entry information. The re-entry head conical surface durestos planks were recovered and peak temperatures during re-entry estimated.

BK07

The next launch was BK07, a single stage vehicle with a high drag heat shield head. Extensive instrumentation was put in the motor bay to investigate base heating and pressure distribution. In addition lightly loaded spring flaps were fitted to the pressure bleed holes in the propulsion bay to check the direction of flow through these holes as the air pressure dropped with altitude. This was related to the problem mentioned earlier; that of the rocket plume being swept back into the engine bay. Their movement was monitored by telemetry.

Changes in position of H.T.P. tank baffles were made to check on "H.T.P. slosh" and a kerosene level sensor was included to enable kerosene consumption to be measured. Near the end of the burning phase of the launch, one of the four motors reverted to "cold" thrusting and this resulted in a reduced re-entry velocity. This motor fault was subsequently attributed to a failure of a kerosene feed pipe.

Temperatures and pressures in the motor bay were measured. The flaps that had been fitted over the base bleed holes in the motor bay opened at engine light-up and shut (two at 83 seconds and another two at 89 seconds) without significant changes in motor bay pressures. There was a new arrangement of baffles in the H.T.P. tank for slosh damping on this vehicle, but with no significant effect on the flight. The tracking lamps which were fitted for the first time to this vehicle were seen clearly by the guidance telescope operator and the kinetheodolite operators after engine flame-out until about 200 seconds, but the electronic flash unit failed to function.

The head separated from the main stage correctly. However the additional thrust units in the head, which were provided to give increased separation, did not operate, nor did the turn over and spin thrust units. However, the head did re-enter nose first, but at a large initial angle of incidence. The recovered head showed that impact was on the nose and that there was no re-entry burning on the afterbody. Head telemetry was extremely good and re-entry data was obtained. Complete dynamic analysis of the re-entry head was possible and head temperatures during re-entry were obtained.

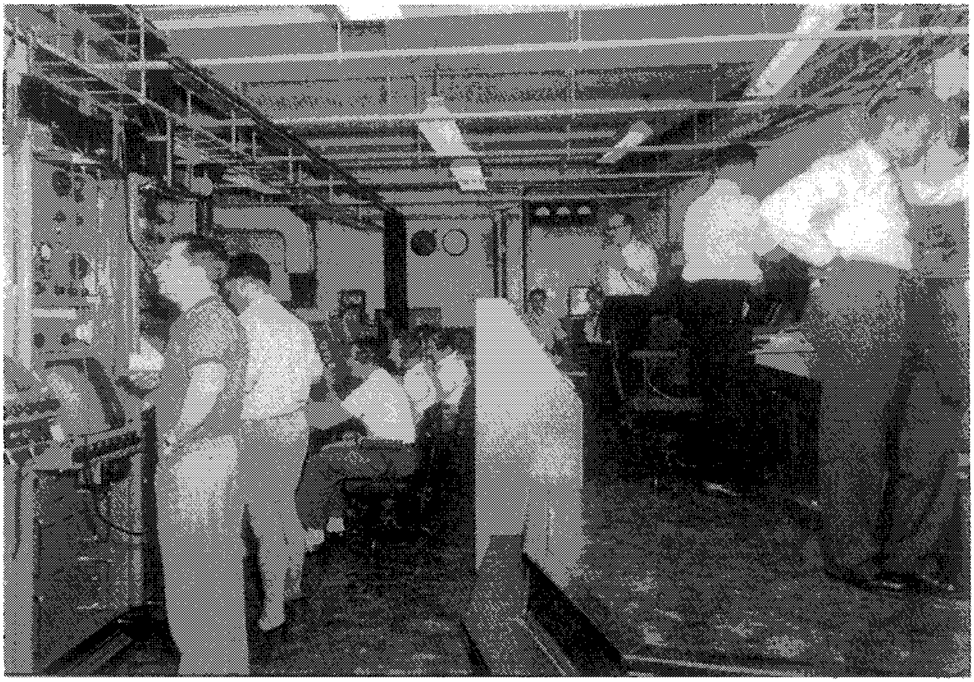
In addition to the re-entry experiments, some of the later Black Knights carried experiments for University Physics departments, concerned with the upper atmosphere. BK07 carried three such experiments, Geiger and scintillation counters and Sporadic E, which were switched on correctly just after engine burn-out.

BK13

BK13 was a single stage vehicle with a double cone eroding head similar to those on BK05 and BK06, except for the substitution of a low-power telemetry beacon plus a tape recorder in place of the normal telemetry sender as on BK05 or tape recorder on BK06. A cine camera was used for filming the head wake during re-entry, and the recovery parachute system was removed.

As in BK07, further measurements were made in the motor bay to investigate base heating and pressures. A kerosene level sensor and H.T.P. level probes were used to provide information on mixture ratio during flight. Two upper atmosphere research experiments were carried—ionic composition and Galactic radio noise.

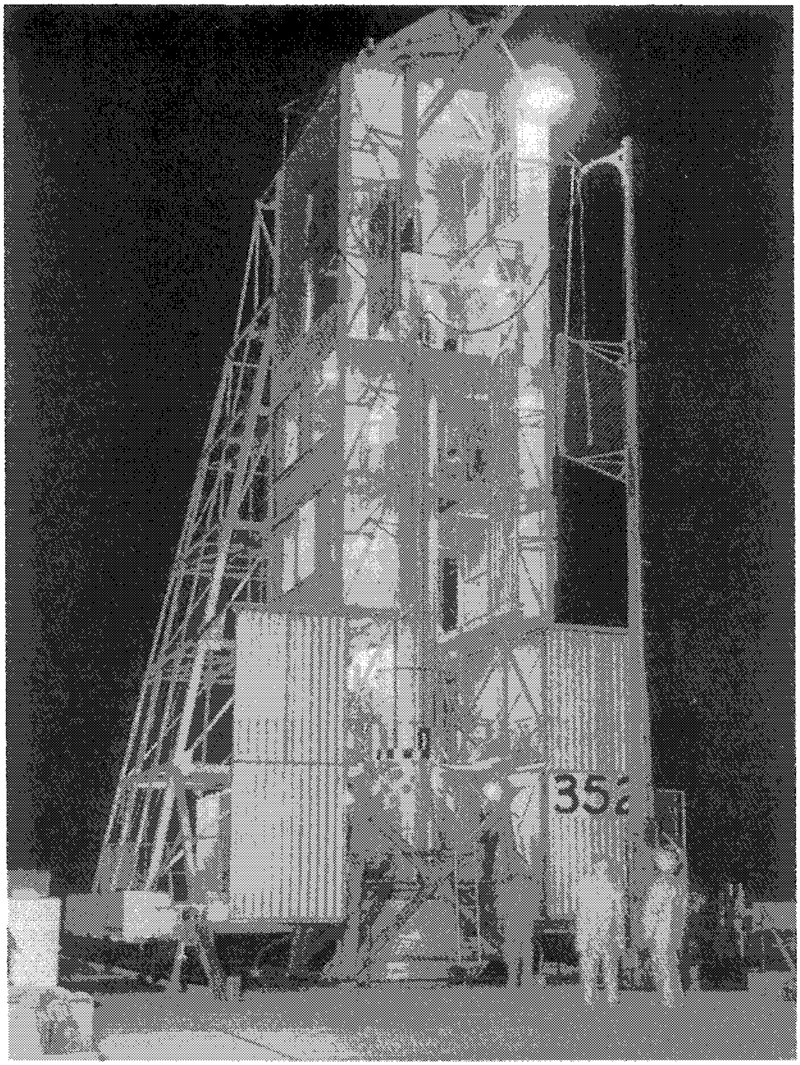
Propulsion was good and a re-entry velocity of 10,870 ft/sec was achieved at 200,000ft. Motor bay temperatures and pressures were successfully recorded. The flaps over the base bleed holes opened before take-off and closed later as in BK07. The kerosene level sensor and H.T.P. probes worked and propellant usage in flight was determined. The head separation, turnover and spin systems were faultless, as were the pyrotechnic flashes on re-entry. Unfortunately, due to an incorrect setting of the switch, the tape recorder in the head started too soon and the tape had run out before re-entry; for the same reason the camera in the head did not record the re-entry wake. The durestos nose cone and materials specimens were recovered and erosion measurements were made. (The material lining the re-entry vehicle was designed to vaporise during peak heating and carries energy away with it. Hence it gradually eroded away. This material is described as being ablative.) The electronic flashes were observed clearly but the tracking lamps were not seen.



The control centre at Woomera.
Here a launch team is preparing for a Black Knight launch.

BK14

BK14 was another two-stage vehicle with second stage and head similar to that of BK08. Premature "run-out" of kerosene occurred at 128 seconds after launch followed by 14 seconds of "cold" burning (the decomposition of H.T.P. in the absence of kerosene); the final shutdown occurred at the correct time. Subsequent analysis of records indicated that a leak had developed in the kerosene supply system that accounted for the excessive kerosene flow rate. Initiation of the second stage separation was dependent on the operation of an inertia switch, and due to the drop in first stage performance, as a result of the "cold" burning, the acceleration was not high enough to operate the switch.



BK14

Because of this, events following burnout, such as second stage separation, spin, ignition, and head separation did not take place. Because the second stage did not separate, there was no change-over of selected telemetry channels to upper atmosphere measurements. In view of this, alternative methods for arming second stage separation were subsequently employed which were not dependent on first stage performance. The tracking lamps were seen and aided tracking until 200 seconds. Upper atmosphere experiments carried were a cosmic ray scintillation counter and electron temperature measurement.

BK17

BK17 was another two-stage vehicle but with a lighter low-drag eroding head to give higher re-entry speed. The first stage performance was very good. The kerosene level sensor and H.T.P. probes worked well and propellant usage in flight was determined. Visual observation and camera records of re-entry were confusing but it soon became clear that the second stage had not functioned correctly. The head and tape recorder were recovered, and subsequent analysis of the head tape record and body telemetry indicated that second stage separation occurred at re-entry and not at the end of first stage burning. It was possible to deduce from the records that the failure of the second stage separation after first stage burn-out was due to failure of one of the two explosive bolts. (In subsequent vehicles explosive bolts and associated circuits were duplicated.)

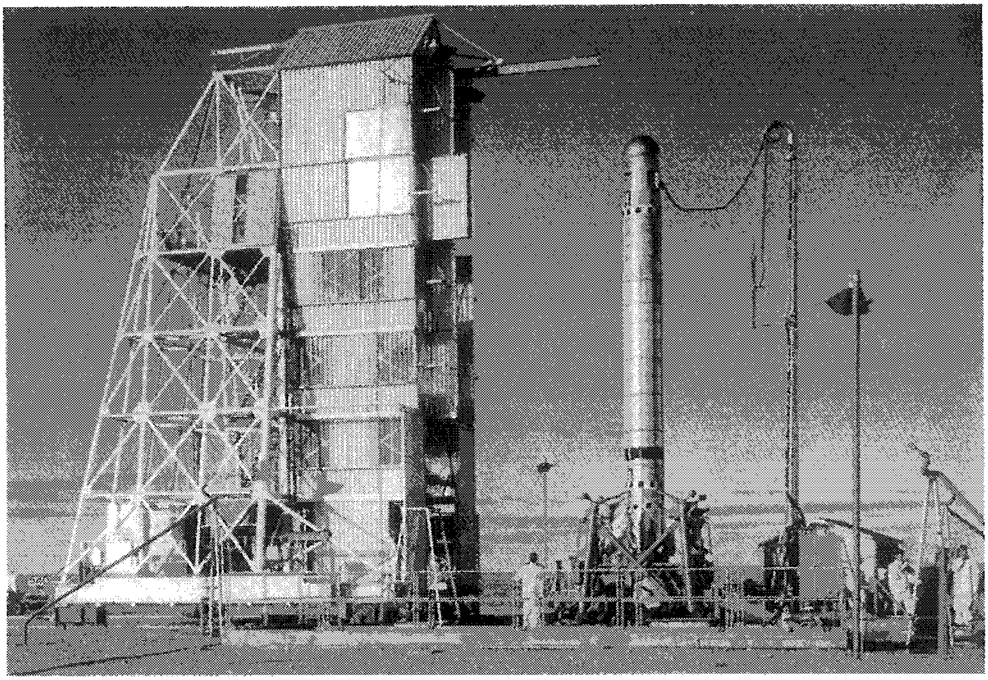
Subsequently, at re-entry the second stage was torn off, followed by second stage burning. Body telemetry was satisfactory until re-entry: good records were obtained of motor pressures, control data and propellant levels. After burn-out a telemetry channel change-over switch operated so electron temperature was recorded and the "Faraday" propagation experiment was successful but, because a second switch failed to operate, the galactic radio noise was not recorded.

In subsequent vehicles changeover of telemetry channels was time-operated and independent of second stage operation. The tape of the recorder in the head ran out before re-entry, so on later heads, the speed of the tape in the tape recorder was reduced so as to run for a longer period and to ensure the re-entry was recorded.

BK15

This launch was another re-entry physics experiment, but was limited by the availability of ground instrumentation on the range at that time, i.e., the Gaslight project equipment and not the more sophisticated Dazzle project equipment. Dazzle was the follow-on project from Gaslight, using much more sophisticated radar and optical equipment. The Dazzle photographic analysis was capable of analysing the spectrum of the glowing wake produced by the re-entry vehicle, and the spectrum would give useful information as to the nature of the ionised molecules.

BK15 was a single stage vehicle which was fitted with a separating uninstrumented 36 inch diameter copper sphere (the first pure metal head used). The object was to achieve re-entry of the sphere in advance of and well separated from the first stage, to provide spatial resolution for ground instruments. This was to be done by turning the vehicle over in the yaw plane after engine burn-out and separating and pushing the head vertically downwards away from the body when it had turned through 180°.



BK15

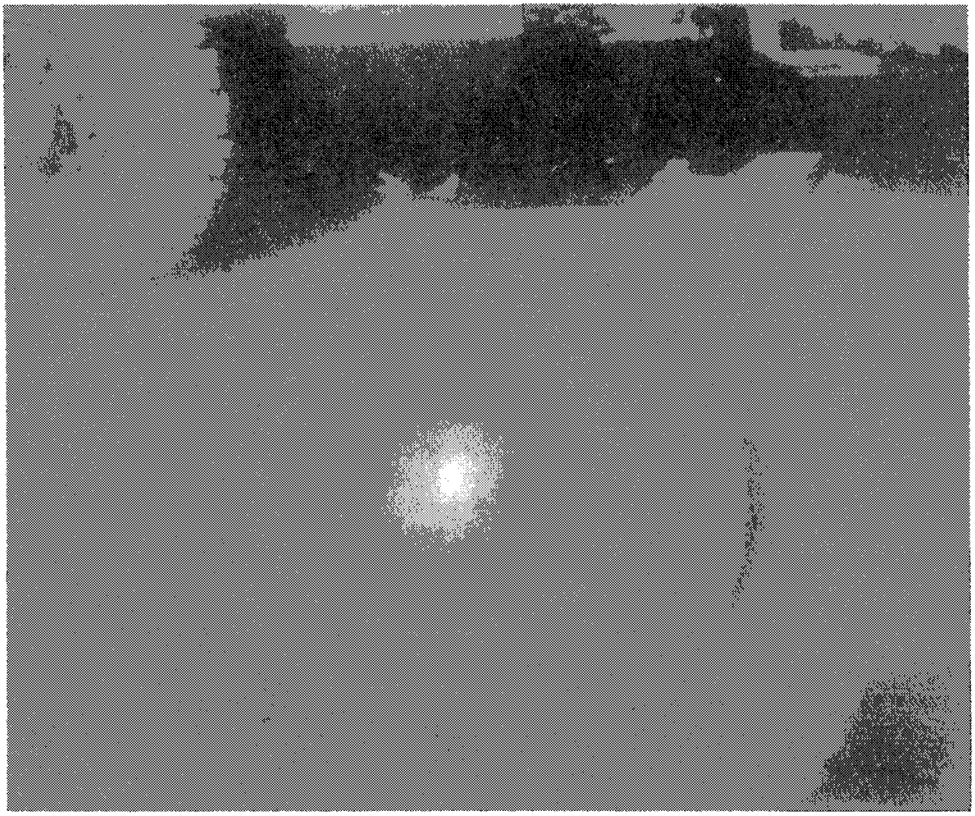
This vehicle carried a copper sphere head, which can clearly be seen at the top of the rocket. The net on the post to the right of the vehicle was to catch the plugs that were ejected from the rocket just before lift-off.

A sabot containing thrust units was used to push the head away, and the sabot itself was to have remained attached to the body by a lanyard. This sabot contained the re entry head in a cradle: as the small rocket motors ignited, the whole unit separated from the rocket. Since the sabot was attached to the rocket by the nylon lanyard, the sabot stopped and the head carried on.

Subsidiary upper atmosphere experiments were also carried on this flight. The vehicle was loaded correctly, the utilisation of propellant was efficient and the performance of the motor was excellent. A head re-entry velocity of 11,600 ft/sec was achieved at 200,000 feet.

It was also intended to test for the first time an "automatic pilot" in the ground guidance system. Due to guidance telescope tracking difficulties the "automatic pilot" was not introduced during flight as intended. Telemetry was very good and measurements were made in the upper atmosphere by the Cerenkov scintillation counter, the Sporadic E probe and in the Faraday Rotation experiment. The vehicle turnover and head separation devices worked but the timing of the latter was incorrect; the head was separated before the vehicle had turned through 180°.

The lanyard failed to hold the sabot to the body and the sabot therefore accompanied the head. The Baker Nunn camera recorded the re-entry of the body and sabot. The re-entry of the head was not recorded by any ground instrument nor was it seen by any observer. This in itself was a significant result since it confirmed the prediction that in the absence of ablation products and other contaminants in its wake, the re-entry into the atmosphere of a pure copper head would be a target difficult to detect by optical means.



BK15 head after flight.

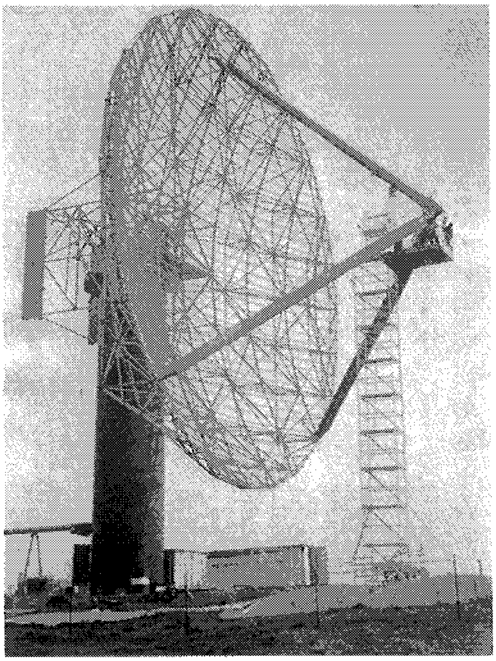
This shows how little the copper sphere was affected by re-entry, and it also shows the usefulness of Woomera as a range. The heads could be inspected after flight. Other Black Knight parts were usually recovered at the same time.

The sphere was recovered (see photograph above) and, as expected, there was no heat discolourisation of the surface as the maximum surface temperature did not exceed 350°C during re-entry.

BK16

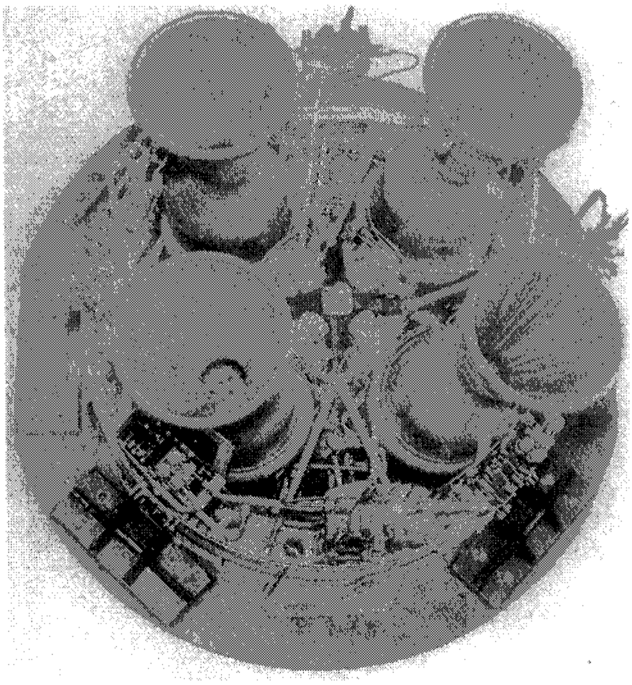
BK16 was the proving trial of Black Knight for the further re-entry physics experiments (Project Dazzle), being a two-stage vehicle powered for the first time by a Gamma 301 engine. A transistor control system was also tested for the first time—previously, valve driven units had been used. To meet the requirements for the re-entry physics experiments, ignition of the second stage was timed to occur at about one million feet. The head was separated from the second stage at an increased velocity in order to achieve re-entry of the head well separated (15,000 feet) from the rest of the vehicle.

To ensure that the re-entry of the head was observed by the ground instruments, a "C" band transponder was flown in the second stage and tracked by AN/FPS.16 radars at the range. The head was a 15° semi-angle copper cone, shape G.W.20 (the code name given to this design), a type to be flown later in the Dazzle programme. The G.W.20 shape re-entry head was at that time being considered for the re-entry vehicle of the Blue Streak warhead. Dynamics and head temperature measurements during re-entry were also included in this trial. Some upper atmosphere experiments—proportional counter, electron temperature and Faraday rotation—were also carried out.



A 86 foot diameter Dazzle radar dish.

The vehicle performance was good, so that a re-entry velocity of 14,600 ft/sec was achieved at 200,000 feet. Telemetry was successful: all engine pressures, control system parameters and guidance data were successfully recorded. Motor bay temperatures were measured on the ascent. Once again, as with BK15, difficulties with guidance telescope tracking necessitated a change back to radar information for guidance until telescope tracking was resumed. All the aims of the trial were achieved. The Gamma 301 engine and the transistor control system were both proved in flight. Separation and ignition of the second stage and separation of the head were achieved according to plan. The FPS.16 radars successfully tracked the "C" band transponder and excellent records were obtained from which the trajectory and all events (second stage separation, spin and ignition and head separation) were determined. The range at Woomera was provided with an excellent opportunity of rehearsing for the re-entry physics experiments to follow. The re-entry vehicle tape recorder was recovered and data on re-entry dynamics and temperatures was obtained. The trial confirmed expected re-entry characteristics of an uncontaminated low-drag head.



The Gamma 301 motor

The Gamma 301 was a radical redesign of the engine. The original chambers had derived from early work at R.P.E. Westcott to produce a rocket motor for aircraft model testing, and it suffered from problems with the kerosene/H.T.P. ratio mixture. An oddity of previous flights was that although the mixture ratio was very carefully adjusted at static firing before launch, the vehicle appeared to run out of kerosene early. This was unsatisfactory for several reasons. With a

H.T.P./kerosene ration of 8.2 to 1, a shortage of 1 pound of kerosene left 8.2 lbs of H.T.P. unburned, or more, likely, the vehicle experienced a relatively long period of "cold thrusting" after burnout. This was the cause of several malfunctions when the head separated whilst there was still some residual thrust, with the result that the vehicle collided with the head and damaged it. Indeed, any unburned propellant reduced the efficiency of the vehicle. The eventual solution to the problem was to add a few extra pounds of kerosene over and above that which was calculated—which worked, but was hardly an ideal solution.The new engine derived essentially from Armstrong Siddeley's work on the Blue Steel engine. This contained 2 chambers, one large, one small. The large chamber gave a thrust in the region of 25,000 lb, but the small chamber was throttleable, as the Blue Steel engine specification notes: "The small combustion chamber is to be capable of producing a smoothly variable thrust from a minimum of 1,000lb to a maximum of 6,200lb at 45,000ft. It should be possible to hold a constant thrust level within +/- 2.5% at any value between the maximum and the minimum." Thus it would be capable of providing, in a 4 chamber configuration, of thrusts up to 24,800 lb, although this would be slightly reduced at sea level. In the first two launches, the thrust was set at 19,000lb; in later launches it would be between 21,000 and 21,500 lb thrust. Interestingly, the S.I. increased with thrust, since the higher combustion chamber pressures meant that the effect of the atmosphere impeding the exit gases was reduced.

The new chamber was more efficient in other ways too: the early Gamma motor had been a double walled chamber, where the H.T.P. flowed between the two walls as coolant. The new chamber, like the RZ-2 that powered Blue Streak, was made from a number of small tubes, brazed together to form a cylinder, then hydraulically formed into the shape of the chamber. The H.T.P., acting as coolant, then flowed up these tubes. This can clearly be seen in the photograph above.

Equally importantly, the much improved mixture ratio control improved performance significantly. The extra thrust meant that the all up vehicle weight could be increased: vehicles from BK19 onwards were all in excess of 14,000lb, a weight never achieved with the 201 engine. The 301 was improved further to produce the Gamma 303, would have powered the intended 54 inch Black Knight (i.e., the vehicle would have 54 inches in diameter rather than the 36 inches of the standard Black Knight).

BK18

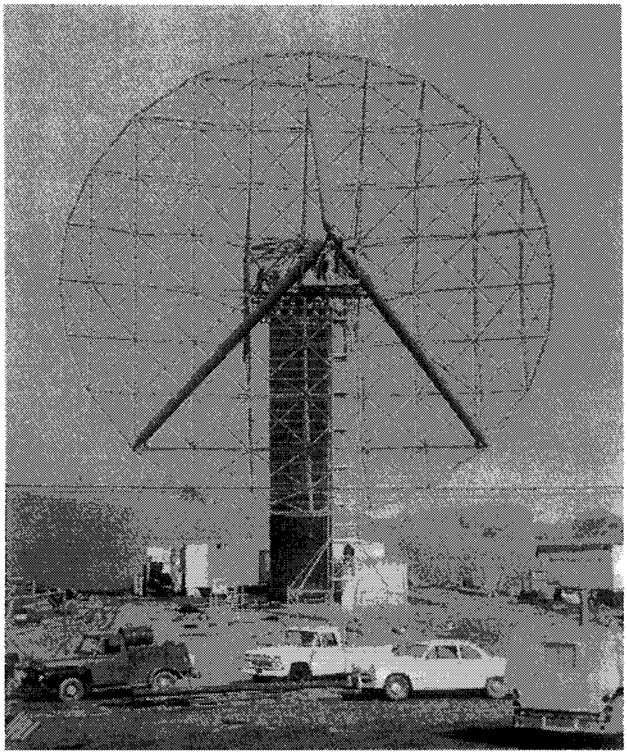
BK18 was the second proving vehicle for the Gamma 301 engine and the transistor control system. The re-entry head was a 12.5° semi-angle doorstops cone, with a 2 inch nose radius and a semi-elliptical base. It was fitted with accelerometers and rate gyroscopes for investigation of re-entry dynamics. Ignition of the second stage was to be initiated by a Phillips ionisation gauge at about 350,000 feet altitude on the descent.

Instead of a "C" band transponder, a pyrotechnic flare was fitted to the second stage to be ignited with the second stage, to aid acquisition by ground instruments. Propulsion was once again excellent; a re-entry velocity of 15,750 ft/sec was attained at 200,000 feet. The guidance telescope tracking problem was again evident, and the guidance radar information was used throughout flight to steer and control the vehicle, and proved most satisfactory. All the vehicle systems were successful.

The second stage flare was ignited in vacuum and proved to be a useful acquisition aid for sighting the ground instruments. The ground instrumentation was successfully operated and good re-entry instrument data was obtained. The head tape recorder was recovered after impact with the ground and all the data on the tape was successfully recorded. From this, the dynamic behaviour of the head during re-entry was determined.

BK11

BK11 does not fit into this sequence of launches at all, since it was not used for re-entry experiments, but instead carried a capsule of electronics to check the new range instrumentation and safety requirements for the ELDO programme. The launch and experiments were completely successful, so that the back up vehicle, BK10, was not needed, and was never fired.



A Dazzle radar

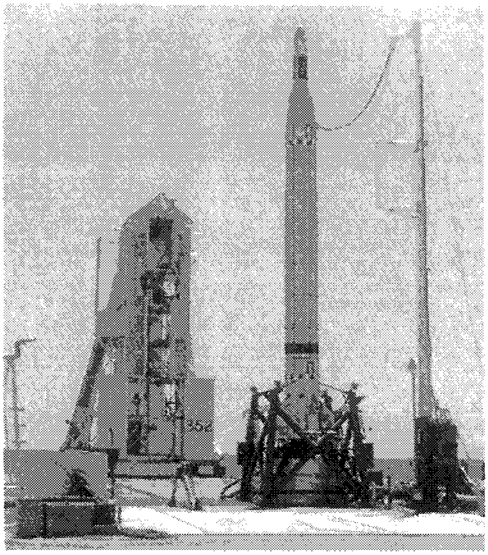
This shows the scale of the investment in Dazzle.

BK19 onwards

BK19 was the first vehicle to use the Gamma 301 engine uprated to over 21,000 lb thrust. The increased chamber pressure also increased the sea level S.I., and at altitude, it gave an S.I. of 251 seconds. This vehicle carried a plain, non ablating copper sphere, intended to give as "clean" a re entry as possible, and BK21 and BK 25 carried similar heads. BK 20 carried a durestos (asbestos) head, and BK 21 a PTFE head, which sublimed to carry away heat. The latter two would give a much more intense wake as the ablated or sublimed material burned off.

These vehicles were what the R.A.E. described as "three stage vehicles", although the "third stage" was in effect only small auxiliary motors. The need arose from a need to measure the radiation from the head and its wake during re entry. To make sure that any radiation and radar echoes came from the head and not from the second stage, a separation of at least 20,000ft at an altitude of 300,000ft was needed. These motors were attached to a sabot or cradle containing the re entry head, and fired immediately after the second stage. A nylon lanyard was attached to the sabot so as to hold it back whilst the re entry head carried on downwards. 26 IMP VI motors or 4 IMP X motors were used, giving the re entry head an extra 400ft/second velocity. The IMP Vs were flown with the Cuckoo IB motor, the IMP Xs with the Cuckoo II, and gave a greater total impulse. The VI motor burned for around half a second, the X for about 1/3rd of a second.

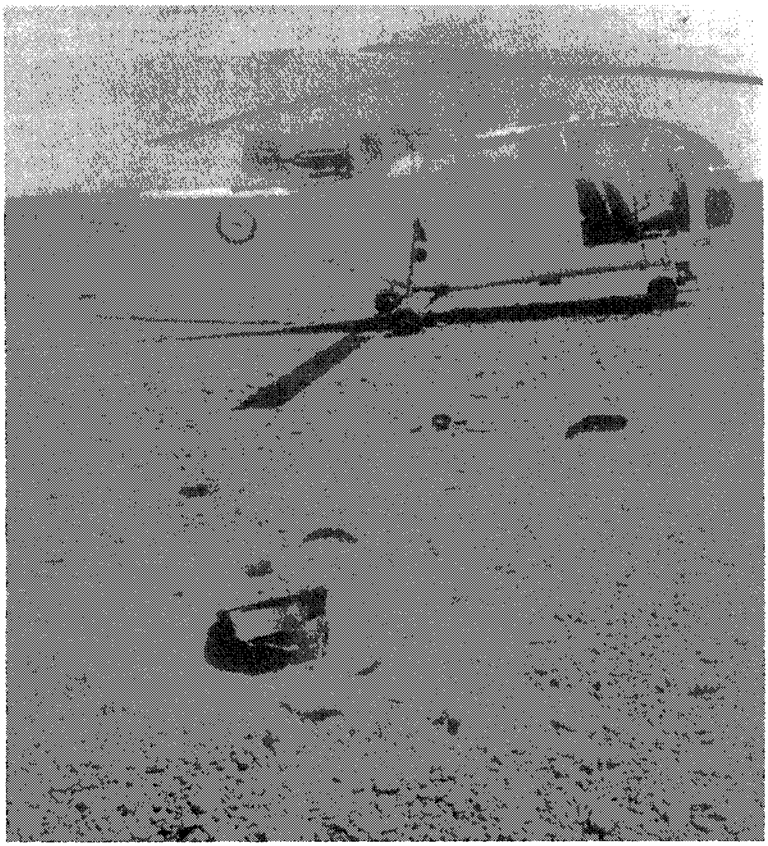
BK19 was highly successful, giving excellent wake data. There was a problem with the IMP motors on BK20, which meant that the re-entry head did not enter in the area expected.



BK20

This was a standard two stage vehicle fitted with the new Gamma 301engine.

The later launches all suffered from various problems. With BK21, the lanyard broke away from the second stage, so the sabot followed too close to the head. The main stage on BK23 shut down 3 seconds early, due to gearbox failure, and the payload and sabot separated late. BK24 had an incorrect first stage firing angle, but good debris, wake, and optics data were obtained. The data return on the last flight of all, BK25, was disappointing due to a large lateral velocity at re entry.

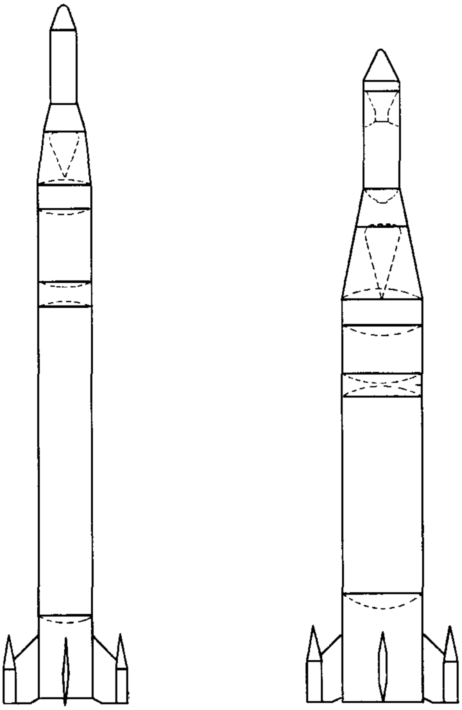


Recovering the BK20 re-entry head.

After Gaslight and Dazzle, another series of re-entry studies was proposed, code named Crusade. However, by now the U.K. had abandoned research on an Anti Ballistic Missile system, and so the need for further re-entry studies was felt to have a lower priority. In mid 1964 the R.A.E. had proposed two new major projects: the Crusade programme with the long talked about 54 inch Black Knight, and the Small Satellite Launch Vehicle that would become Black Arrow. Given their budget, which was becoming increasingly limited, however, they had to choose between the two, and Black Arrow was chosen in preference.

The initial designs for a 54 inch Black Knight show a vehicle with the 36 inch engine bay, and tanks which then flare out to 54 inches. However, a late brochure from Saunders Roe, in mid 1964, shows a detailed drawing for a vehicle with a uniform diameter. The Gamma 301, hitherto used at a thrust rating of 21,600lb, would be taken to its maximum of 25,000lb. Little redesign would be necessary for this other than a new pump to cope with the increased propellant flow. The Kestrel second stage can be seen pointing downwards. With the cancellation of the Crusade experiments, however, this was never built.

The U.S. went on to carry out further re-entry tests at Woomera, code named Sparta, using old Redstone missiles, but with minimal U.K. input, little information about the results of the programme filtered back to the U.K..

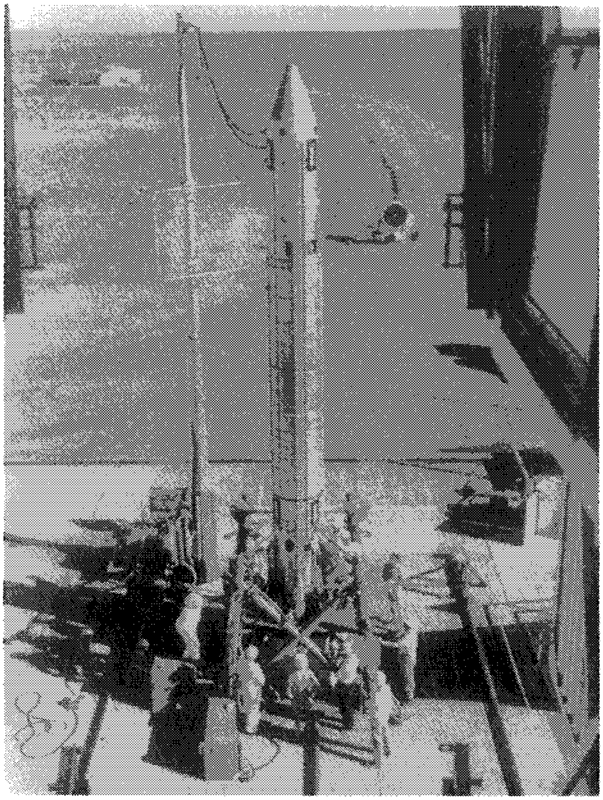


36 and 54 inch Black Knights

The 54 inch vehicle on the right was intended for further re-entry studies, but cancelled in favour of Black Arrow. Starting at the bottom of each vehicle, there is the motor bay with fins, then the H.T.P. tank, an interbay section, then the kerosene tank. The re-entry head is in the separation bay, pointing downward, with a solid rocket motor (Cuckoo II for the 36 inch model, Kestrel for the 54 inch) above that.

But in late 1962 another crisis hit the British deterrent when Skybolt was cancelled. R.A.E. immediately made a suggestion that the 54 inch Black Knight be considered as an alternative missile: "Quick calculation indicated that at least 1500n.m. would be achieved using a Skybolt warhead boosted by a two-stage Black Knight configuration, the first stage being increased in power along the lines already discussed in relation to the Dazzle programme; guidance would be inertial, derived from recent T.S.R.2 development." Hasty cost estimates were made of £50M for R. & D. and £100M for deployment in silos.

Two cases were considered, both based on the 54 inch vehicle with a thrust of 25,000lb. Ranges were calculated for an 800lb re-entry vehicle: the H.T.P./kerosene version gave a range of just over 1000 nautical miles, whereas using nitrogen dioxide and UDMH (Unsymetrical DiMethyl Hydrazine) with a higher SI gave a range of 1500nm. These would have been two stage versions with a second stage weight of around 3,500lb. The idea was never followed through, since almost immediately after the Skybolt cancellation, Polaris became available.



BK03 and launch team

Taken from the gantry, this gives a good idea of the scale of the vehicle.

Three Black Knight rounds were never fired: BK02 was used for structural tests at Saunders Roe. Two vehicles still remain in museums. BK10 was a back up for the ELDO launch (BK11), and was not needed. It can now be found on display in Liverpool Museum. BK22 was intended as the first round in the abandoned Crusade programme, and is now at the East Fortune Museum at Edinburgh in Scotland.

Why were there so many designs descending from Black Knight? It was a highly successful technical design - the launcher almost always worked even when the experiments didn't. The job Black Knight was given to do made it more tolerant of faults. Failures that would have jeopardised orbital attempts had less impact on re entry studies. The very first flight of all, BK01 ended prematurely when the destruct system operated inadvertently. There were also problems with engine overheating leading to kerosene starvation and resultant "cold thrusting", particularly in the second (BK03) and fourth flights (BK05), but again, these were solved relatively early in the programme. Cold thrust occurs when the engine consumes H.T.P. in the absence of kerosene: decomposition still takes place, but the thrust is very sharply reduced. In addition, on many flights the kerosene was exhausted before the H.T.P., resulting in a few seconds of cold thrust after "all burnt". The discrepancy between the calibration during test firing and the actual launch was never pinned down.

How successful was Black Knight?

The rocket itself had relatively limited objectives, which was to boost its payload as high as possible, from where the re-entry vehicles would fall with a great a velocity as possible. Some launches were completely successful in that the rocket and the experiments yielded all the data required. Sometimes the launches were successful, but the experiments failed, yielding little data. However, even when the vehicle's performance was below optimum, the experiments could still yield good results.

The following Black Knight launches can be described as completely successful from the first stage viewpoint:

BK 04, 06, 08, 09, 13, 17, 15, 16, 18, 11, 19, 20, 21, 24, 25.

(NB: the ordering is the order in which the vehicles were fired.)

Other launches had problems in one way or another:

BK 01: the self-destruct mechanism was accidentally triggered near the end of the flight.

BK 03 and 05: overheating in the engine bay lead to a fuel lock in the kerosene pipes, resulting in a long period of cold thrusting.

BK 07: One chamber reverted to cold thrust after 100 seconds. Over 80% nominal velocity achieved.

BK 14: Pipe failure caused loss of kerosene: cold thrusting after 130 seconds. 85% nominal velocity achieved.

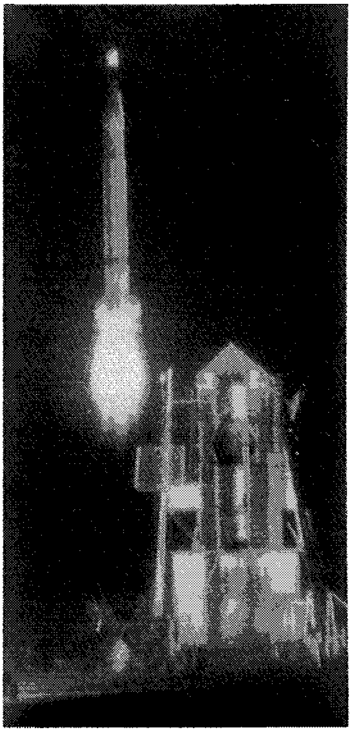
BK 12: 6.8% difference in mixture ratio between flight and calibration.

BK 23: Premature shut down of engine due to gearbox failure 3 seconds before expected flame out.

Of the 22 flights listed above, 7 would not have made it to orbit if they had been satellite launch vehicles. Most of these problems could be considered as developmental difficulties that occur with any new technology. As a very first attempt at a modern liquid fuel ballistic vehicle, this is a fairly good record, with no major failures at all. It is also a tribute to the engineers at Saunders Roe and at Armstrong Siddeley Motors.

However, Black Knight was a success in a different direction. It gave R.A.E. the confidence in the basic design, and as a consequence, many further projects were proposed using Black Knight as a basis. One of course was the Black Prince launcher and its various derivatives discussed in the BSSLV chapter. One problem, however, was that Black Knight, even in uprated form, was really too small for Blue Streak.

Various other projects were based around a liquid hydrogen upper stage. These came to nothing as a consequence firstly of the cost of developing such a stage, and secondly because even with liquid hydrogen stages, the payload would be too small. Hence the Black Arrow design, the subject of the next chapter, where the first stage would be very much enlarged, and a worthwhile satellite launcher would be produced.



BK20 liftoff

10. Black Arrow

Black Knight was so successful as a test vehicle, as well as cheap and simple in construction, that many studies were made as how best to extend the design. One, of course, was Black Prince, one of the many maybes of this book. But it was realised that any Blue Streak based launcher would also be too expensive for the civilian science budget, and there was little military demand. Such military communication satellites, the Skynet satellites, as the U.K. produced were eventually launched by U.S. Delta launchers and by Ariane. As a result, a lot of time was spent looking for a design for relatively small and cheap launcher, and that meant something that would be based on the system that had worked so well so far. Almost all the studies were done at R.A.E., and Black Knight was R.A.E.'s baby, so not surprisingly, all the studies tended to centre on Black Knight and the Gamma engine. There were many liquid hydrogen upper stage proposals, but they had the drawback of low payload if using Black Knight as it stood, and relatively high development costs.

In a report from the R.A.E. in October 1961, another solution for launching small satellites was made, this time adding solid fuel boosters to Black Knight. The first involved an almost unmodified Black Knight in conjunction with 2 Raven solid fuel strap on boosters for the first stage, a Rook motor as second stage and a Cuckoo third stage as used on the two stage Black Knight. Raven had a mass of around 2,600lb with a burn time of around 30s. Rook had the same case as Raven but reduced propellant. Both used 17 inch diameter casings. This design was estimated to put 100lb of payload in to a 200 mile orbit, but the payload could be increased by a factor of 2 with tweaking of the design. A development time of 2 years was estimated, at a cost of £650,000 per annum, with a total of £1.5 million. The design at least had the merit of simplicity and low development costs, but again, minimal payload.

The 54 inch Black Knight design, to be used for the Crusade programme of re-entry studies and shown at the end of the previous chapter, had a somewhat reduced tank length, but the increase in diameter which would have roughly doubled the weight of fuel. However, this new and enlarged version, together with its new solid fuel second stage, the Kestrel, gave rise to further suggestions for satellite launchers. A study carried out by the Computing Department of Saunders Roe for the Low Orbit Vehicle for Experimental Research, or L.O.V.E.R., a name that must have had its origins in some in-joke, is just such a project. The Saunders Roe simulation involved an almost unmodified Crusade type vehicle (the only difference being that the second stage, a Kestrel solid fuel motor, pointed upward rather than down!). The first stage enlarged Black Knight would lift off vertically and then pitch over at to give the second stage and payload some horizontal velocity. The Kestrel and payload then separate and coast up to their maximum height, or apogee. At apogee, the Kestrel then is ignited and gives the payload sufficient extra velocity to achieve circular orbit. However, the computer simulation estimated a payload of around 60lbs at a height of around 150 nautical miles. This, by itself, is not really adequate other than as a demonstration.

All these studies point to the basic problem with either Blue Streak or Black Knight as first stages of a satellite launcher: their thrust/weight ratio. Initially designed for a lift off acceleration of 1.3g, or 0.3g from the launchpad, they were singularly ill equipped for second and third stage matching. For a reasonably efficient vehicle, the first stage should only be a half or perhaps two thirds of the lift off mass, implying that the lift off thrust should be almost doubled. With Thor and Ariane, this was done with strap on solid boosters. The early design of the 54 inch Black Knight, showing the body tapering up from a 36 inch engine bay, would have made this difficult. And there were no really suitable solid boosters in the U.K. in the early 60s, although they could have been developed at relatively low cost. Such solid fuel boosters would have needed a thrust of several thousand pounds for at least thirty seconds. The length of time of thrust is necessary for the first stage to burn off sufficient fuel to reduce the weight of the vehicle to a point where the sustainer engines in the main stage can then take over. In mitigation, both vehicles could have had their first stage thrust uprated: Blue Streak from 270,000 lbs to 300,000 lbs, Black Knight from 16,400 lbs to nearly 25,000 lbs. Indeed, the later Black Knights with the Gamma 301 engine were used with a take off thrust of over 21,000lbs.

But R.A.E. were still intent on producing a small satellite launcher to launch what they described as technology satellites. Yet it had to be one which could be fitted into a very tight budget. Bristol Siddeley produced a brochure for a launcher which envisaged a larger vehicle than that which finally emerged, which used motors derived from those being used in Blue Steel, the large Stentor motor, which was described earlier. However, the R.A.E. thought that this design would involve too much in the way of development costs, and produced their own design, a smaller, simpler design, with engines based again on the Gamma motor, clustering eight of them together for the necessary thrust. It was realised that the Gamma motor was at the limit of its development, which would be a handicap if the design were to be stretched. But the cost saving outweighed the drawbacks. A bigger, better design would have cost more than the Treasury would have provided. As it was, the launcher survived as long as it did only against the background of constant reviews and economies.

The design that emerged during 1963, to be christened Black Arrow, was as simple as it could be, given the constraints. Black Knight's Gamma 301 had used 4 thrust chambers. Black Arrow's Gamma 8 first stage engine would use 8, as can be seen in the illustrations. These were needed to give the necessary 50,000lbs of thrust. But this was undoubtedly a compromise design: the 4 chambered Stentor version, designated the PR-27 (see next chapter) with a total thrust of nearly 100,000lbs, would have been a much more elegant solution.

The second stage engine, Gamma 2, would use 2 Gamma chambers, although here again one Stentor would have sufficed to give double the thrust. However, compared with the original Black Knight 301 engine, the turbine and pumps were redesigned for this upper stage, and the expansion cone enlarged to make for greater efficiency in the vacuum of space.

If any design was going to succeed this would be it; it was all tried, tested technology, and involved nothing new or exotic. As a result, it should also be cheap. From there on, the vehicle almost designed itself, although there is one oddity in the dimensions. All weights and dimensions are in imperial units, pounds, feet, inches, except one. The diameter of the first stage is 2.0 metres. There is an odd rationale behind this.

Europa 1, the ELDO vehicle, was a combination of Blue Streak plus the French and German upper stages. The French stage, Coralie, had a diameter of 2.0m, and so the first stage of Black Arrow was given this diameter as well, so that there was still the possibility of mating Black Arrow to the pre existing interstage adapter, effectively a new version of Black Prince. But as discussed earlier, this idea was to come to nothing.

As mentioned, one of the driving factors was cost: not only vehicle cost, but launch cost: it was reckoned that a Black Arrow launch would cost about one sixth that of a Europa launch (but the payload was about one sixteenth!)

The first stage consisted of engine bay, H.T.P. tank, intertank bay for electronics, kerosene tank and the interstage separation bay. There would be some weight saving if the two tanks shared the same bulkhead, but the decision was taken to separate them to prevent problems if one tank leaked into the other. The H.T.P. tank but not the kerosene tank was pressurised with nitrogen from bottles in the intertank section.

The first stage engine bay had the 8 rocket motors arranged in 4 pairs of 2. Each of the pairs was mounted radially, and were gimballed for vehicle control. Two turbopumps were used to feed the engines. The tanks contained 13,015kg of propellants, which were consumed in 130 seconds giving a thrust of 222kN at sea level. There was a mixture ratio control keeping the H.T.P. to kerosene ratio to 8.2 to 1.

The separation sequence began as the first stage engines ran short of H.T.P., and soon after the first stage acceleration fell below 3g, 8 explosive bolts were to blow the two stages apart. At the same time 4 Siskin solid fuel rockets ignited on the second stage—at that point it would be in free fall, and so the propellants would be literally floating in their tanks. The motors provided the force needed to settle the propellants in their tanks. H.T.P. to start the second stage ignition was held in bottles in the interstage section, being forced in under the pressure of nitrogen gas. When the Siskin boosters had burned out, 8 more explosive bolts blow off the interstage section.

The second stage used rocket motors which were almost identical to those in the first stage, except that they had extended expansion nozzles for high altitude operation, where there was a much lower external pressure, and there were, of course, only two motors instead of eight. They consumed 3050kg of propellant in 125 seconds for a thrust of 70kN. The engines were fully gimballed for control. There was a fuel ratio control system as in the first stage, and, like the first stage, it shut down when the H.T.P. was exhausted. Both tanks were pressurised with nitrogen. Four small solid fuel Siskin motors were attached to the interstage section, to separate the two stages and to settle the propellants in their tanks.

So the second stage had the motor bay, the H.T.P. tank, an intertank bay, the kerosene tank and the separation bay. The electronics were contained in the sealed intertank bay, and included the flight sequence programmer, the attitude reference unit, telemetry, the tracking beacon, the command destruct receivers, the control system servo amplifiers and power supplies.

After the second stage had exhausted its propellants and cut out, it separated, and the third stage plus payload would coast for around 300 seconds towards the apogee of the transfer orbit ellipse. During this time the vehicle would be stabilised by a nitrogen gas attitude control system. Then six solid fuel motors were fired to spin stabilise the third stage and satellite to around 20 radians per second or about 200rpm. 5 seconds later the third stage and satellite were released.

The vehicle's third stage was a specially designed solid propellant motor called Waxwing, with 315kg of propellant, burning for around 55 seconds and producing an average thrust of 35,000 lb (156kN). The motor was very efficient, having a ratio of fuel/total mass close to 0.9. The satellite separated from the empty casing of the Waxwing 120 seconds after its ignition by firing gas generating cartridges. (It turned out that not even this was a sufficient time: it is thought that some residual thrust from the Waxwing caused it to collide with Prospero after it had separated.) This meant three separate objects were put into orbit: the empty motor casing of mass 35kg, the motor/payload separation bay of mass 14 kg, and the satellite itself.

The Waxwing was sometimes referred to as an apogee motor since it was not ignited until it was near the top of the sub orbital trajectory provided by the first two stages. At this point the third stage and payload would have fallen back to Earth, but the Waxwing gave sufficient extra velocity to put into the payload and itself into a near circular orbit.

The payload shroud or nose cone was made of magnesium alloy. Designed in 2 parts, it had an overall length of 3.6m and a maximum diameter of 1.4m with a mass of 68kg. Attached to the second stage, it was jettisoned 185 seconds into the flight, during the second stage burn.

When designing small satellite launchers, it is important to get the design right first time. The payload of Black Arrow was only 132lb from a total lift off weight of 40,000lb. If the vehicle has to be redesigned, and ends up 132lb heavier, then the payload becomes zero! 132lb is only 0.33% of the vehicle weight. Losing 132lb payload from a ton or more has a lot less impact.

The design having been finalised, the project was put to the Cabinet. Again there was Treasury resistance. A compromise was eventually reached whereby Black Arrow could only go ahead if Crusade and the 54 inch Black Knight were cancelled, and Black Arrow was chosen in preference to further re-entry studies. In addition, Westland Aerospace, who had taken over Saunders Roe, and Bristol Siddeley, who were to build the new engine, offered to pay a substantial sum, one million pounds, towards the development costs. Not surprisingly, the Aviation Minister, John Amery, greeted this offer with delight. A letter from Westland in February 1965 noted: "We expect you to make Management arrangements comparable with the excellent ones you have achieved on the present Black Knight programme. This has been R.A.E. based."

However, in retrospect it seems odd that the two projects should conflict: the first stage of Black Arrow would have suited Crusade well. This however, needs to be seen within the context of British deterrent. By 1964, the U.K. was committed to the Polaris programme, and Polaris was too small for extensive decoys. In addition, the U.K. Government had taken the decision in 1962 not to proceed with an ABM system. When, later, the idea of further re-entry experiments was considered, Black Arrow was deemed too expensive for the purpose.

But the decision to go ahead was taken in the last days of the Douglas Home government, and this was to have serious consequences for the project. The incoming Labour Government, not surprisingly, wanted to review many of the major military and technical aerospace projects, and Black Arrow was put on hold. For a Government whose leader won an election with speeches about "the white heat of the technological revolution", the attitude to technology was ambivalent. To put Frank Cousins, a trade union dinosaur, as Minister of Technology was a breath taking piece of cynicism.

The firms that were to be involved in Black Arrow, Saunders Roe (who were now part of Westland) and Bristol Siddeley Engines, were given holding contracts merely to keep the project ticking over. The bigger problem was that as Black Knight wound down, then the teams of engineers and designs involved would disperse unless there was something to keep them usefully employed—which a holding contract didn't really do. The offer the two firms had made to contribute towards the development costs faded away as the delays dragged out, and whilst more and more defence work was being cancelled.

Review after review took place, and each time the project was opposed by the Treasury, who did make some valid points. These points were tied up with general British space policy, which was in a muddle. The new Government wished to withdraw from ELDO but to do so with the least political damage. In particular, they were worried not to give any impression of lack of enthusiasm for joint European projects, and so withdrawal from ELDO at the same time as approving Black Arrow was felt to be giving the wrong signals. On the other hand, if Britain did withdraw from ELDO, Black Arrow could be used to counter arguments that Britain was withdrawing from space research altogether. As usual with such contrary policies, inertia ruled.

There were economic reviews too, to determine whether Black Arrow would be "profitable" or not. It is surprising that no one made the analogy with the likes of the Gloster Whittle aircraft: that was certainly not profitable, yet without it, or other test vehicles like it, there would be no jumbo jets. Was the Wright Brothers' aircraft "profitable"? And the papers are not helped by the jargon used by the economists: my favourite phrase is "exogenous stochastic error" when talking of the development costs of the vehicle, which I think in the context meant unpredicted cost overruns. The reviews also involved R.A.E. in a good deal of work, having to put forward justifications for the vehicle almost every few months.

The arguments for Black Arrow were that it gave British scientists experience in space research at minimal cost, to which the Treasury reply was why did the scientists need such experience? The scope for research satellites was felt by the Treasury to be negligible; neither the Post Office nor the military were interested in communications satellites at that stage, for which purpose Black Arrow was too small anyway; and there seemed to be few other uses which would benefit the U.K.. In many ways, the Treasury was right, but the project was fought for by the Ministry of Aviation since it was seen as the last chance for Britain, if Black Arrow did not go ahead, the British space effort, or at least rocketry effort, would die.

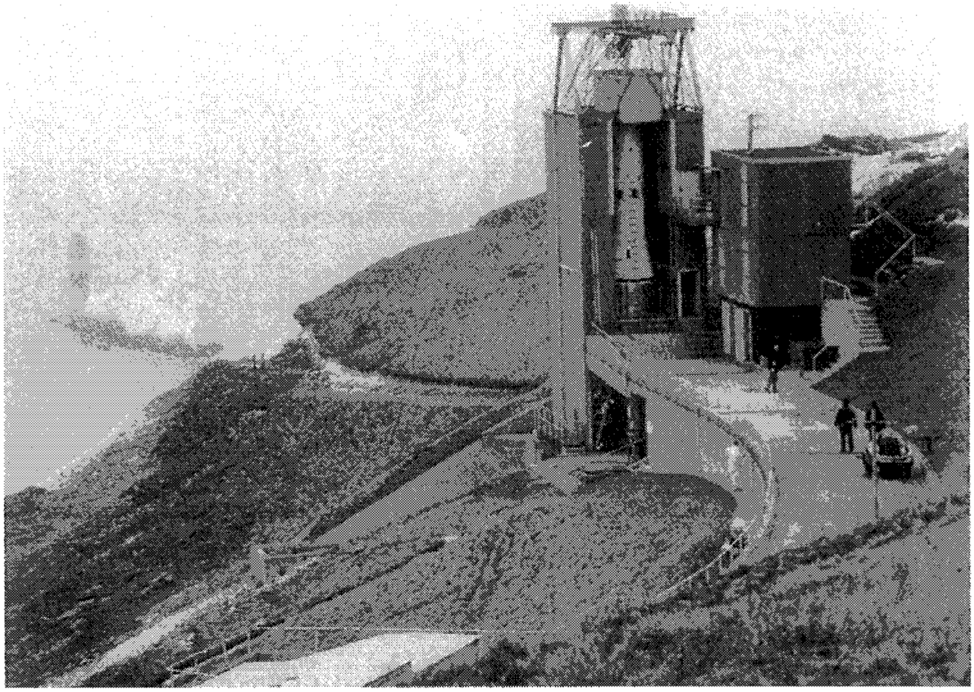
The Treasury's attitude to the project was summed in a letter from F.R. Barratt in Treasury Chambers to Walter Abson at the Ministry of Aviation in April 1965:

"(i) It is claimed that the launcher would be of value in giving U.K. scientists and technicians experience of injecting satellites into orbit and controlling them, and would also enable us to test satellites and components in an actual space environment. But why should we in fact wish to give U.K. scientists and technicians this experience? What satellites is the U.K. going to be putting up? And for what reasons? No decision has yet been taken in regard to a programme of communication satellite and development. Ministers have not yet even been invited to consider the possibility of such a programme. Nor has any military requirement for a U.K. satellite launching capability been stated. The indications are that no such requirement will arise.

"(ii) It is suggested that possession of a small satellite launcher will enable us the better "to compete for contracts for space projects". I must remind you that the Working Party ... concluded that export prospects in the space field were relatively quite small .... It might be as well if you were to specify what contracts we are more likely to get if we have a small satellite launcher. I should myself be very surprised if there was anything significant. If there isn't, I suggest that you would do better to drop this particular argument.

"(iii) ... I do not myself understand how the development of a small launcher on the basis of "proven techniques" will have much relevance to ELDO activities on, say, high energy upper stages. Doubtless you can explain this. In any event, however, Ministers have yet to reach a final decision on U.K. policy towards ELDO: it is possible, to say the least, that they will ultimately take the view that we should aim to withdraw from ELDO activities. It is also possible that the attitude taken by the Italians and others at the recent ELDO conference will lead before long to the collapse of the organisation. It cannot therefore be assumed at this stage either that ELDO will continue to exist or that, if it does, the U.K. will continue to participate in it, or will wish to influence its activities."

Apart from anything else, this is a marvellous example of the Civil Service at work. "Ministers have not yet even been invited to consider the possibility of such a programme" ... this tends to suggest how much policy was actually made by the senior servants rather by ministers. And the put down in the third paragraph. "Doubtless you can explain this."!



Black Arrow in the static test stand at High Down.
The Needles rocks and lighthouse can be seen in the background. The lip of blast deflector can just be seen on the lower left.

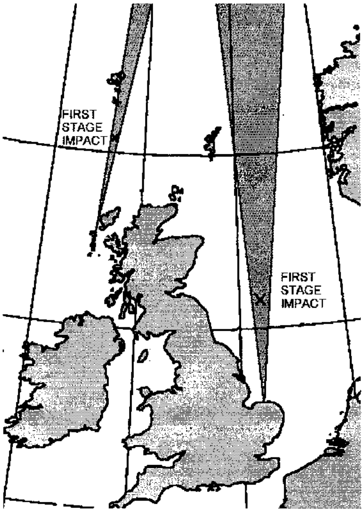
It is also worth noting the attitude to ELDO. But, more importantly, this is a very neat summary of the official attitude to most of these projects. When the Ministry of Technology again tried to get Cabinet approval in 1966, the then Chancellor of the Exchequer, Jim Callaghan, wrote a three page letter of protest reminiscent of those written by Selwyn Lloyd's letters on Blue Streak. Again, the project had to be referred back for further economic studies before it was resubmitted to Cabinet. And the idea of economic reviews, cost benefit analysis, and the like was a new phenomenon. In the Fifties, projects were given a go ahead mainly on their technical merit. Now the economists were creeping in. This is not intended to be an entirely pejorative comment. The costings of a good number of earlier projects had been completely unrealistic, and a sharper eye on estimates would be welcome. But that is not what the economists were looking at. How do you try to estimate an economic return from basic research? But it was probably the earlier gross under estimates of earlier projects that made the Treasury so sceptical.

In addition, there were even those in the Space Department at Farnborough who felt that a satellite launcher took up too much of the space budget, to the detriment of other projects. And others in the Ministry of Defence felt that the offer of free launches from the Americans should be used instead, or, even if they did have to pay for them, then it was still cheaper than developing a British launcher. Needless to say, once Britain's last vehicle was cancelled, the offer of free launches evaporated with it.

Black Arrow static firing.

The plume is not the rocket exhaust, but steam from the cooling water. The rocket motors are fired into a duct that deflects the blast sideways, and this duct needs to be cooled with water to prevent it burning away.

There were further financial problems: the Ministry of Defence wanted nothing to do with the funding of the programme. This meant that there might have been potential problems with the use of Woomera, as Black Arrow was, strictly speaking, a civilian programme, and so did not fall under the Joint Agreement between Britain and Australia. And indeed at this time the future of Woomera was being reconsidered, and so proposals were made to site the Black Arrow launch site elsewhere. Barbados was high on the list, but R.A.E. also looked at launch sites in the U.K.. Britain is not well situated geographically for satellite launching (but neither was Woomera). Payloads can be boosted by firing the rocket in the same direction of the spin of the Earth: eastwards. But this would mean that the spent rocket stages would fall on Europe. The only clear path would involve launches almost due north, into polar orbit, and for this, two sites were considered. One was the existing rocket test site on the islands of North and South Uist in the Hebrides, the other was on the north coast of Norfolk. South Uist was ruled out on grounds both of accessibility and of infrastructure—indeed, it was considered by the Ministry of Aviation to be less accessible than Woomera! Certainly the weather in the Outer Hebrides would have posed a problem. The planned flight paths are shown in the illustration below. The first stage impact points are shown, and the second stage would impact close to the North Pole, north of the 85 degree parallel.

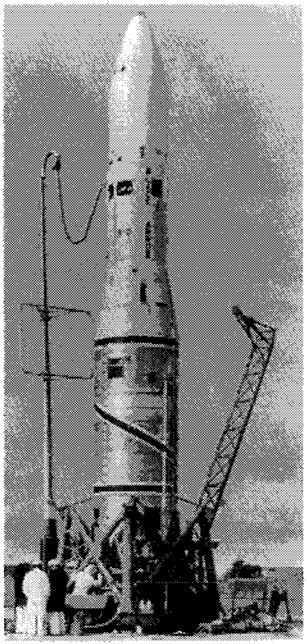


Possible U.K. launch sites for Black Arrow

The report concluded: "No particular site has been chosen at this time. There are several areas north of the coastal road which appear adequate. Ideally a suitable site would be within about five miles of a disused airfield or W.D.-owned site with existing roads and buildings. All that would be required in these circumstances would be the construction of a launch site on the coast line and all the other operations could be conducted at the other site, the two being linked together by microwave and hard wire links."

The Norfolk launch site looked quite promising until someone realised that the North Sea was filling up with oil rigs (this was in 1966). A chart was rapidly fetched from the Ministry of Power: "...discussions have been held with the Ministry of Power, and a chart obtained showing the position of existing and proposed oil rigs. Although it would be possible to show statistically that the chances of hitting an oil rig would be acceptably low, it seems probable that political considerations would inhibit the establishment of a launch site in Norfolk."

The chances of a spent first stage falling on an oil rig were minute, but given the consequences if one did, the proposal was dropped. The other launch sites being considered were outside the U.K. and were too expensive to set up. It was back to Woomera.



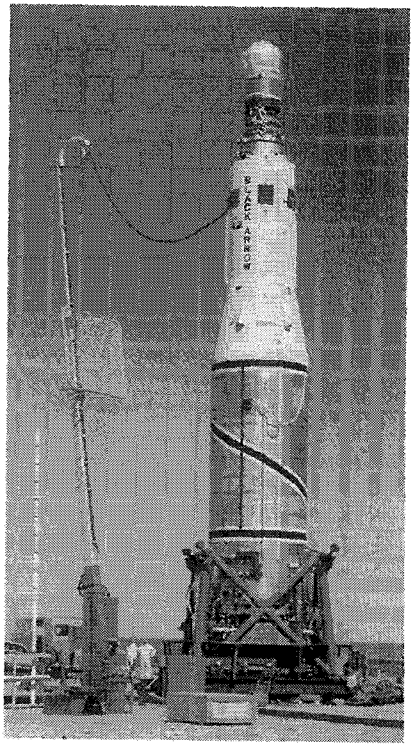
Black Arrow R0

In the end, there were four firings of Black Arrow from Woomera; two suborbital attempts with live first and second stages and dummy third stage and satellite, and two orbital attempts with all three stages live.

R0 was launched on 28 June 1969, but the flight was not a success. The vehicle was held down on the launch pad by a ball and claw mechanism; the engines were started, and when full thrust was reached, which took around four seconds, the vehicle was released. However, it immediately developed a large rolling oscillation as it was released from the pad. The cause of the fault was an open circuit in the feed back loop that controlled one of the motor pairs: a wire had probably broken. As a result, the guidance system was not able to correct the motion. At about 64 seconds into the flight, the control system could not cope and the vehicle tumbled. One of the payload fairings broke away, followed by the payload, then the Gamma 8 first stage motor ceased thrusting. The vehicle was then destroyed by ground command when it was at an altitude of 9000 feet on its descent.

The response of the motor pair concerned was normal up to about 4.1 seconds after opening the first stage engine start valve, 0.5 seconds before the release jack was opened. Loss of the signal meant that the pair of motors concerned would swing to their full extent and back again on receiving a correction, instead of the small deflection needed to put the vehicle back on to its correct course. The fault was successfully simulated back in the U.K., and modifications were made to later vehicles to prevent a repetition of the problem.

R0 was intended to be fired in a northwesterly direction, following the same path of the early Blue Streaks towards Talgarno. R1 was then intended to be the first orbital attempt, to be fired in a northerly direction. After the failure of R0, and modifications made to the vehicle, R1 was then redesignated as a repeat of R0, except for the launch direction. Hence R1, like R0, had live first and second stages, but again no third stage. It was launched on 4 March 1970 and was completely successful.

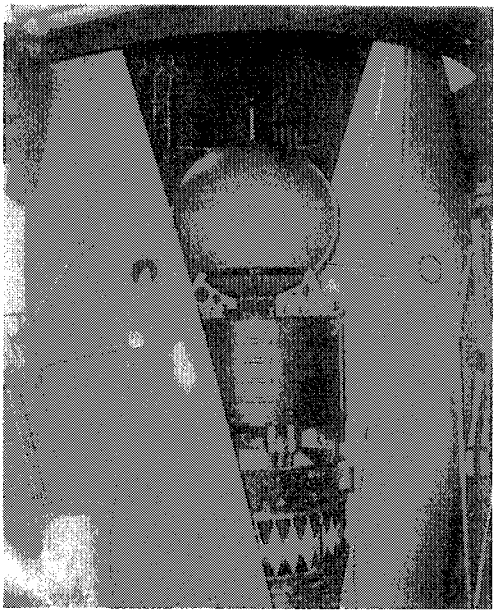


R2 at Woomera

The satellite fairings not been fitted: the Orba satellite can be seen at the top of the vehicle attached to the Waxwing third stage.

R2 was launched on 2 September 1970, carrying a spherical satellite, christened Orba, as its payload. This was intended to be a very simple satellite (there was no money in the budget for anything more complicated) to measure the atmospheric drag in low orbits by observing its orbital decay. The first stage was completely successful, but the second stage shut down 15 seconds early, leaving 30% of the H.T.P. unburned. This turned out to be due to a leak in the H.T.P. pressurisation system, with the result that the nitrogen gas ran out early. Hence there was no pressure in the H.T.P. tank to help feed the propellants. With insufficient pressure the turbopumps cavitate and their effectiveness is much reduced. Hence the second stage thrust dropped to almost nothing. The third stage separated correctly, and fired, but the velocity was insufficient to reach orbit, and the payload crashed into the Gulf of Carpentaria. Various other malfunctions plagued the flight, including problems with the attitude control system and one of the payload fairings not separating until third stage spin up.

After this flight, an extensive review of the vehicle was set in motion, with eleven technical panels being set up. They began their work in December 1970, and submitted reports and recommendations by the end of June 1971. Relatively few deficiencies were found, and most of these related to the problems that had cropped up in the three development launches. Ian Peattie, who was the Project Officer at R.A.E. for the launch vehicle, commented wryly that the review achieved its objective "once certain panel members were persuaded that a fundamental re-design of the launch vehicle was not within the terms of reference."!



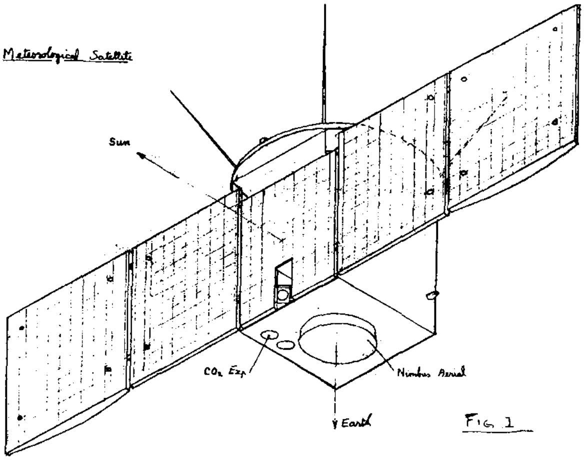
Orba.

The satellite fairings being fitted around the Orba satellite. The vehicle is in the gantry at Woomera. Below the satellite is the third stage motor, the Waxwing.

Meanwhile, in parallel with the work on Black Arrow, Space Department at Farnborough were also considering their satellite programme. X3 (to become Prospero) was designed as a test vehicle as much as anything, although various experiments connected with solar cells were carried. (X1 and X2 were test vehicles, and were dropped early in the programme. X4 was to demonstrate the erection of large solar panels for power supply in orbit. It was launched in the U.S. in March 1974, using a Scout launcher, and called Miranda, following the Shakespearian tradition of U.K. satellite names.)

Another proposal was for a meteorological satellite, in conjunction with the Meteorological Office, and would carry an experiment to look at carbon dioxide concentrations in the atmosphere with a communications package to relay the data back to Earth.

The Black Arrow launch capacity was taken to be 235lb into a 500km circular orbit inclined at 81° to the equator, and the nominal design weight of the satellite was to be 196 lb, thus allowing for contingencies. It would be pointing to the Earth for 50-60% of the time, and the remainder of the time sun pointing. A propane tank for gas for attitude control was needed since the Earth pointing accuracy needed to be +/- 1°. The total cost of the project was estimated at around £4.5M, and the intention was to manufacture 2 vehicles so as to have one spare for launcher failure. The CO_2 observation experiment, designed to look at carbon dioxide levels in the atmosphere, would weigh 18lb and consume 3W of power; the communications package 13lb, using 2W.

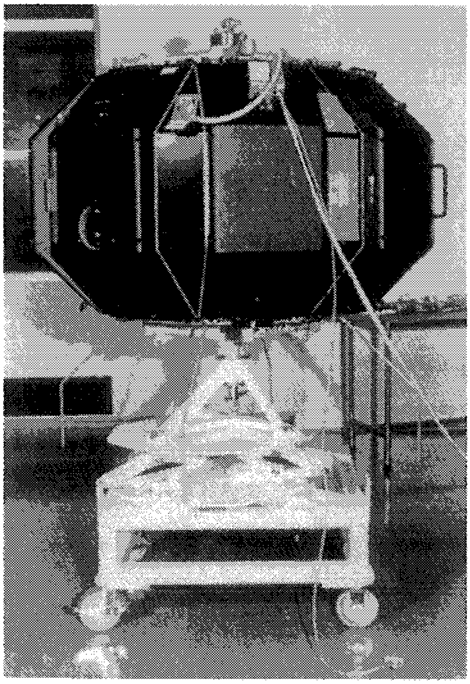


Proposed meteorological satellite

The X5 satellite would have been a test bed for an ion rocket that would consume 500W of energy from an array of solar panels. Ion motors work by ionising the molecules in a vapour, and then accelerating them through a very high voltage, to give them a very high velocity. Essentially, electrical energy is converted to the kinetic energy of the ions. The ion motor would use mercury as a fuel, and eject the ions at a velocity of 30km/s. The beam current would be 25mA at an electrical potential of 2.5kV, and the motor would deliver a thrust of 0.015N.

The point of an ion thruster is that although it has a very low thrust level (0.015N is very small indeed; perhaps a five hundredth of weight of the average person!), it has an extremely high specific impulse, which is the thrust delivered for a given mass of fuel. Thus, although it is unsuitable for use in the atmosphere or delivering a payload to orbit, once in orbit it can be used to manoeuvre spacecraft either to geosynchronous orbits or to escape velocity. It had been calculated that Black Arrow by itself could put 102kg into 500km orbit or 135 kg into 220km, but nothing into a geosynchronous orbit. But the 500W ion thruster contained with a satellite of mass 120kg might put a useful payload of 34kg into synchronous orbit in 200 to 300 days, with a fuel load of only 24kg.

However, the Meteorological Office pulled out of the X4 project, which left rather a hole in the programme. Indeed, the justification for "technological" satellites was beginning to look very thin. The only truly innovative project was the ion motor, which has had a surprisingly long gestation in space programmes worldwide.



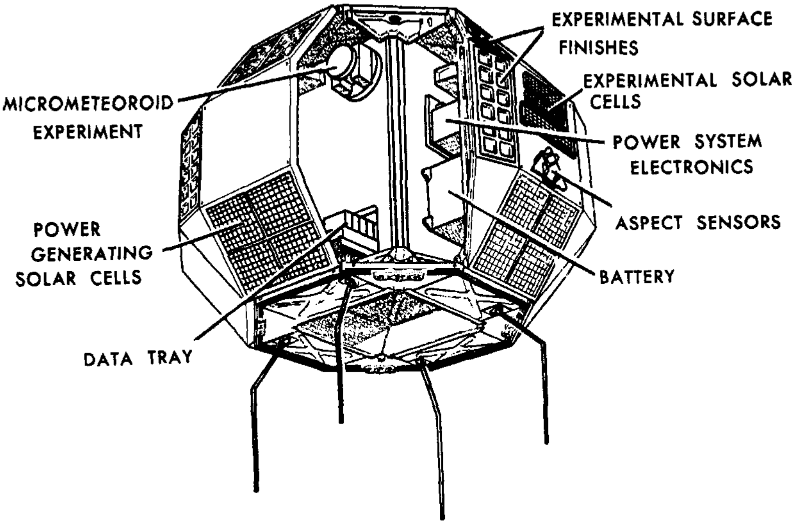
Prospero
This is the partly built satellite under test.

But X5 threw up another weakness of Black Arrow, that of payload. The alternative launcher for some of these satellites was the American Scout, which had a similar payload, although a smaller payload volume under its fairings. Costs per launcher were broadly similar. However, whilst X4 might have been accommodated by Scout or Black Arrow, future satellites were looking too big for either. So as earlier as 1969 thought was being given to stretching the vehicle. The cheapest option was to add 4 Raven solid motors (these were 17 inch diameter motors as used on Skylark), and stretch the capacity of the first and second stage tanks. This might put up to 300kg into orbit.

Prospero

Prospero was the satellite that was put into orbit, where it still remains, by the R3 launch.

R3 was dispatched to Australia early in 1971, and the second stage arrived at Woomera on the 26th July, followed by the first stage on 17th August. Static firing of the second stage occurred on 1st September, and the two stages and the back up satellite had been assembled by 1st October. The complete vehicle was given a static firing test on 8th October, and the flight model satellite was fitted by the 22nd October. A decision was made to delay the launch until 26th October, but systems checking delayed the launch further.



Prospero – cutaway view

Derek Mack, one of the Saunders Roe (which had by then become the British Hovercraft Corporation) launch team, remembers the morning of the 28th as a cool, fresh Australian spring day, with clear skies. The overnight crew had filled the H.T.P. tanks and adjusted the kerosene levels, as well as arming the many pyrotechnic systems on the vehicle. The gantry was wheeled back at 1100, but there was some alarm when the Attitude Reference Unit, which steers the vehicle, began to give erratic signals. There was relief when it was realised that this was due to the vehicle swaying gently in the light breeze! The vehicle lifted off smoothly, and the various telemetry stations north of Woomera reported that all events had been successful. However, this did not yet mean that the launch had been successful: it was only when the global satellite station at Fairbanks reported an operational signal from a satellite on a frequency of 137 MHz that the team knew that they had an orbiting satellite. The party could begin, but there was a sour taste to it.

R3 launched the Prospero satellite (X3) into orbit on 28 October 1971, in a text book launch. The programme had meanwhile been cancelled by an announcement in Parliament by the new Minister at the Department of Trade and Industry, Frederick Corfield, on 29 July 1971. The teams that had built Black Arrow and launched it were out of a job.

Prospero had a mass of 66kg, and was launched into an orbit of perigee 557 km, apogee 1598 km, and an inclination to the equator of 82 degrees. It is still in orbit. It carried four experiments:

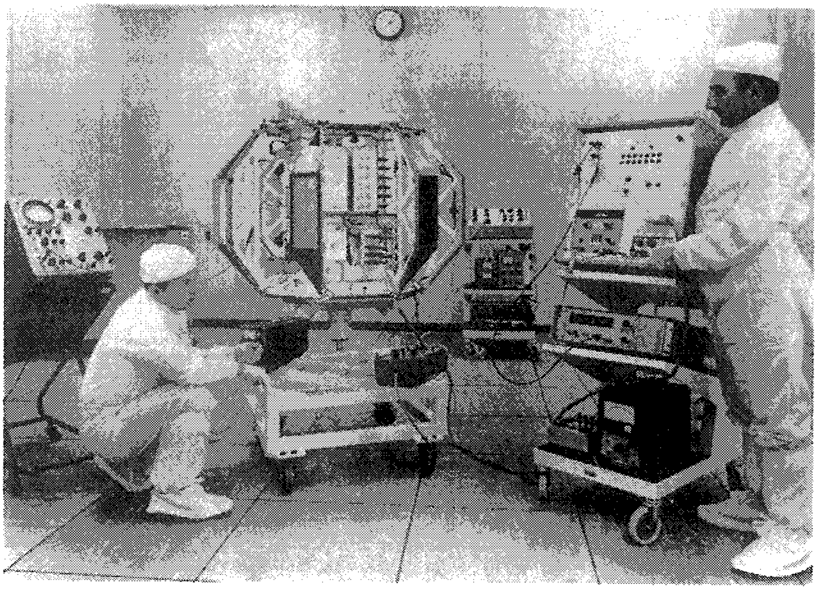
(a) to determine the thermal stability of a number of new surface finishes;

(b) to determine the behaviour of new silicon solar cells;

(c) an experiment in hybrid electronic assemblies;

(d) an experiment by Birmingham University to determine the flux of micro meteorites.

The satellite was formed from eight faces (see diagram above) covered with 3000 solar cells. Since the spacecraft would be in the earth's shadow for part of its orbit, rechargeable batteries were also carried.

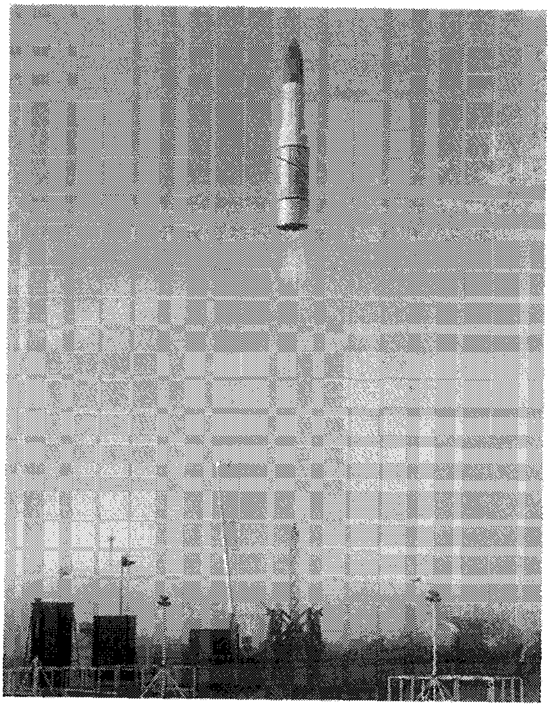


Prospero being built and tested.

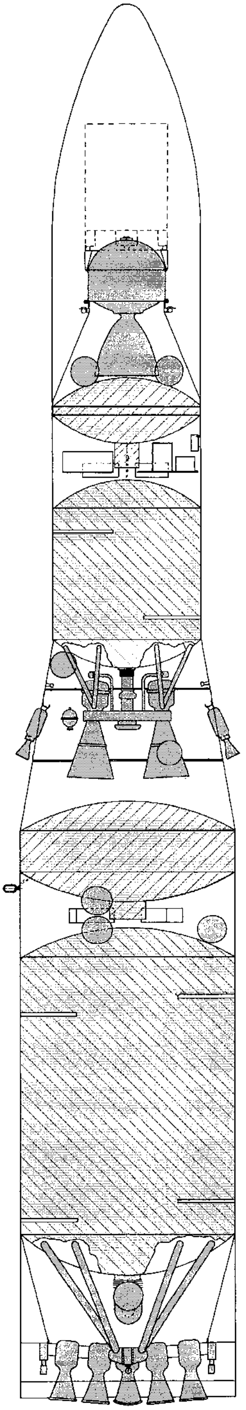
The flight sequence for the Prospero satellite launch was:

Event	Time (seconds)
Lift off	0
First stage engine shut down (H.T.P. depleted)	126.9
Stage separation/second stage ignition	133.5
Inter stage bay separation	139.1
Payload fairing separation	180.0
Second stage shut down (H.T.P. depleted)	256.9
Pressurise attitude control system	262.5
Spin up rockets	575.0
Stage separation	577.0
Third stage ignition	590.0
Payload separation	710.1

The fifth vehicle, R4, was never fired, and is now on display in the Science Museum, Kensington. With the abandonment of Black Arrow, all U.K. attempts at launch vehicles came to an end. The launch of Europa F11, with its Blue Streak first stage, from Kourou followed in November, but by this time Britain had left ELDO completely. The failure of F11 meant in turn that Europa was abandoned.



Black Arrow launch



Black Arrow sectional view

11. The Could Have Beens

In any field like aerospace, there will always be projects on the drawing board which never make it through to hardware. Sometimes this is because they are simply bad designs, or sometimes because their rationale has disappeared. Quite often there is simply not the money for them. Thus the U.K. never produced a large satellite launcher because it didn't perceive a need for large satellites: that is discussed elsewhere.

But the U.K. undoubtedly had the capacity to do so, and the saga related in this book is frustrating for the enthusiast because the drawings could have been converted to reality with two extra ingredients: money, and the will to go ahead. Many of the engineers working on the projects were not able to see the wider policy picture. This is partly because much of the work was secret and heavily compartmentalised, partly because commercial firms were not privy to the workings of Government, and partly because engineers have the mentality that because a thing can be done, it should be done. There is sometimes the feeling among them, unspoken, inchoate, but nevertheless real, that "our toys were taken away". What were the wider policy issues?

First of all, what do you want a satellite launcher for? To launch satellites. Why do you want to launch satellites? Nowadays, that seems obvious, with telecommunications satellites and satellite TV and so on. But it was not obvious in the 50s and early 60s.

Interestingly, one of the very first U.K. studies was done as early as 1955; a study for reconnaissance satellites. In the 50s much covert reconnaissance of Russia was being carried out by Britain and America using spy planes like the U2, or the high altitude Canberra, partly because maps of the USSR were so poor. If you wanted to target a missile complex you had to know where it was and whether it even existed. Indeed, the Americans were to launch a vast number of reconnaissance satellites: there were 145 such launch attempts between February 1959 and May 1972! (This military involvement also makes launching other satellites cheaper: the launch facilities and radar tracking stations are already there.)

The U.K. study, initiated in February 1955, was carried out by D. J. Walters at R.A.E.. There were follow-up studies (Desmond King-Hele suggested the Blue Streak/Black Knight combination in this context) but these studies tended to show that satellites would not be as good as aircraft, which indeed at the time they were not, but satellites could cover areas aircraft could not. In addition, there were several other problems. One is recovering data. King-Hele was thinking in terms of the natural decay of an orbit to bring the satellite and film back—but this is totally unpredictable. The American concept of retro rockets to bring the satellite back where it is wanted hadn't yet surfaced. And in 1955, the re-entry studies hadn't even begun. Television was ruled out on grounds of poor picture quality, and that it was impossible to radio the data back as the satellite would be over the horizon. The pictures could be recorded, but in 1955 the calculations were done assuming a wire recorder! This was not a practical possibility. Again, power was reckoned to be another problem: the camera would consume up to 150W, the transmitter 500W, and magnetic tape storage would need 700W, and 1350W could not be provided from batteries, and again it was too early to be thinking of solar cells producing that amount of power.

The Americans ploughed literally billions of dollars (at 1960 prices) into their system. The optics were refined to a new level of accuracy, and the Hubble telescope is one beneficiary of this. But the "special relationship" between the U.K. and the U.S. meant that the U.K. had access to a lot of this data, reducing the need for an indigenous system. However, all these launches also meant a tremendous hidden subsidy for the later American commercial launcher market. All the development costs could be written off; and range facilities and so on were pre-existing.

Many other projects initiated by the U.S., seemingly innocent, also had military origins. Next in usefulness were navigation satellites, forerunners of the ubiquitous GPS system so useful to weekend yachtsmen. These had the Polaris submarines in mind: how does a submerged submarine know its position accurately enough to launch missiles? Raising an antenna to pick up a satellite is one answer.

Again, communication satellites were not to be taken seriously until the mid 60s. A paper prepared by the Post Office around December 1959 comes out against geosynchronous satellites as famously described by Arthur C. Clarke in 1945. They were considered too far in the future even for the U.S., and that the quarter second delay was too much for telephony—the users would not care for it!

A long Ministry of Aviation paper in April 1959 considered the uses then foreseen. First of all, it was reckoned that a Blue Streak/Black Knight launch vehicle and 5 satellites would cost at least £10M to develop (would that were so!). This could not be justified on the Defence Budget because the foreseeable direct benefits were slender. Then it considered the various possible uses for satellites, including reconnaissance, communications, meteorology and navigation. The report noted that American claims that a manned satellite has important military value were difficult to appreciate on any reasonable time scale, and refers to them as belonging to a "futuristic space platform age." (In that respect they were right: no military uses for manned space stations have been found.) Weapons delivery posed severe technical problems on accuracy of delivery, reliability and security, and would raise serious political problems.

So although the report goes quite thoroughly through the possibilities, as with all these studies the enthusiasm is lukewarm. Certainly, as time went by, defence interest in satellites, apart from communications, resulting in the Skynet satellites launched by the U.S., decreased steadily. Commercial applications weren't even considered at this early stage.

In 1962, however, a Commonwealth Conference on Communications Satellites was held in London. This might be looked upon as the last gasp of the old Imperial ideal, attempting to link the countries of the Commonwealth (still, largely, then consisting of the old "white" Commonwealth, although countries such as Nigeria also participated). Much talk was made of the Black Prince concept, although the conference showed up one of the major weaknesses of Black Prince and Europa: whilst too big for the run of the mill satellite, they were crucially that bit too small to put any appreciable payload in a geosynchronous orbit. Ingenious attempts were made to suggest elliptical 12 hour or 8 hour orbits, but these were at best an inadequate solution. Other papers and conferences suggested that such a system could be profitable, but even so, this was not sufficient incentive to produce a launcher that would be adequate.

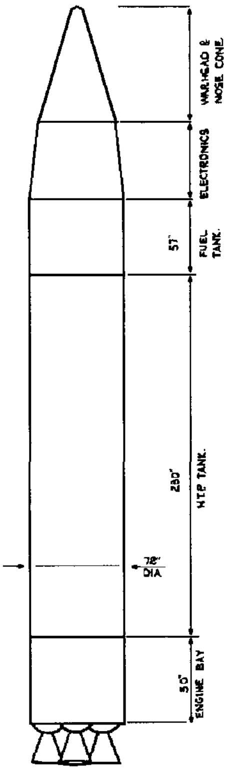
The scientific community wanted to launch satellites for space research, but the U.K. science budget was already stretched. Whilst it might stretch to a few research satellites, it certainly could not support a launcher programme.

There was a final category of satellite put forward by R.A.E. in the 60s—the small technological satellite. These would be small and low cost, but would test out systems for more ambitious projects. This is quite a reasonable concept—putting a variety of new technologies in one satellite has obvious weaknesses—but even these were growing too large for Black Arrow.

One new idea, and one that has not yet been fully exploited, and which DERA (the Defence Evaluation and Research Agency, which swallowed up R.A.E.) is still interested, is the ion motor. In theory, this has an enormous SI. Atoms are stripped of an electron and the resultant ions are then accelerated through a very high voltage. This has the potential to produce enormous exhaust velocities, the power necessary being provided electrically from solar cells. The X5 satellite was intended to test this concept. It would accelerate the ions through 25kV, with a beam current of 25mA. This would need 625W of power. The resultant thrust was only 0.015N, but a small thrust over a very long period of time would have the same effect as a large thrust for a short time.

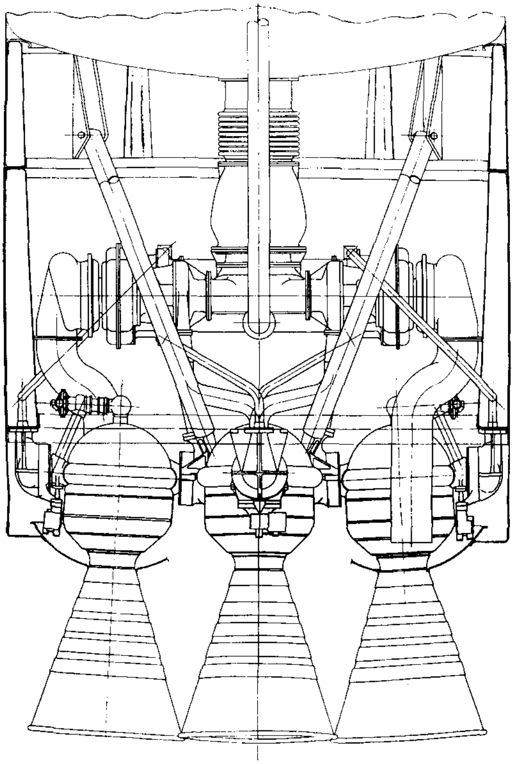
But assuming that the policy makers in the U.K. decided that it did want to launch satellites for whatever purpose, what were the designs that could have pressed into service to launch them? The projects below are not arranged in any great order of significance, but rather the intention is to take a somewhat meandering walk through the "might have beens" in terms of launcher design.

One of the more interesting brochures lying quietly unread in the Public Record Office is a proposal for an I.R.B.M. from Armstrong Siddeley. It is interesting because of its date (October 1958) and its design. October 1958 is the month after the first launch of Black Knight. The design is basically a much enlarged Black Knight, but instead of the small Gamma engine (4,000 lb thrust), it uses the large Stentor chamber: 24,000 lb thrust. Thus the proposed vehicle is 6 times more massive. Included in the brochure are some rather optimistic range estimates. The designers were hampered, however, by not being aware of the Blue Streak warhead weight, and in reality, with this warhead, it is unlikely that the vehicle would exceed 1,000 miles range. It is interesting too that there is apparently no official interest in the brochure. It sits, uncommented on, in a mass of papers about Blue Streak and its silos. Perhaps it suffered from the "not invented here" syndrome.



Bristol Siddeley's I.R.B.M.

On the other hand, the brochure is slightly odd in that it has a very detailed design for the engine (probably by David Andrews of Armstrong Siddeley at Ansty) but the rest of the vehicle is only hazily sketched in. This is probably because Ansty made rocket motors but not launch vehicles. The brochure was resurrected and resubmitted to the Ministry of Defence in March 1960, which is a month before the announcement of the Blue Streak cancellation. This may or may not have been co-incidence!

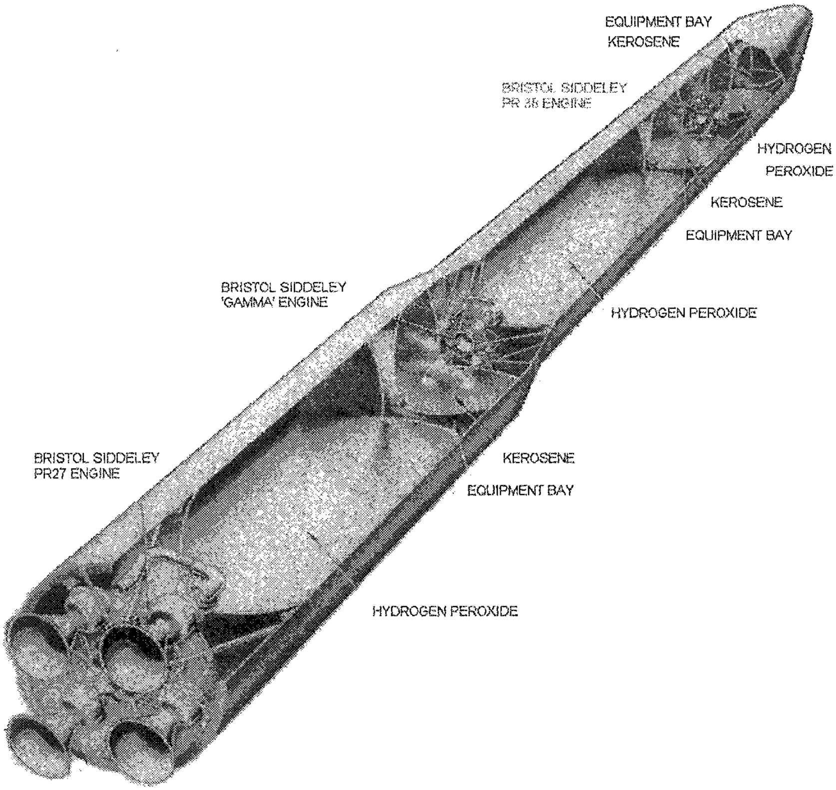


Bristol Siddeley PR27 engine

This would have powered the IRBM shown above, and was later suggested for the Bristol Siddeley satellite launcher. Saunders Roe's SLAVE design would have used the same motors. It would have been cheap and effective for a first stage satellite launcher or for a Blue Streak second stage.

As an alternative missile to Blue Streak, it has the advantage that the propellants are storable, or reasonably so. Certainly, H.T.P. would be easier to handle than liquid oxygen within a silo. With a second stage, which could easily have been a solid fuel motor, it could well have had an almost equal range, particularly with the lighter warheads being developed by around 1960. However, the debate about Blue Streak centred about "fixed sites", or silos, in which such a missile would have to based, and the cancellation of Blue Streak meant that land based missiles were never again to enter into the nuclear debate.

The proposal was effectively resurrected yet again when the Small Satellite Launch Vehicle (i.e., Black Arrow) came up. With 4 Stentor chambers in the first stage, 4 Gammas in the second (and the Gammas were effectively the Stentor small chamber), together with a small liquid third stage, it would have a capacity equivalent to the contemporary American Thor Delta, with a payload in orbit of some hundreds of pounds. It lost out, of course, on the grounds of cost.



Bristol Siddeley's design for a satellite launcher
This would have been an all H.T.P./kerosene design, with 4 Stentor chambers in the first stage, 4 Gammas in the second stage, and the 4 small chambers of the PR38 in the third stage.

Contemporary (1963) R.A.E. costings for the two vehicles were:

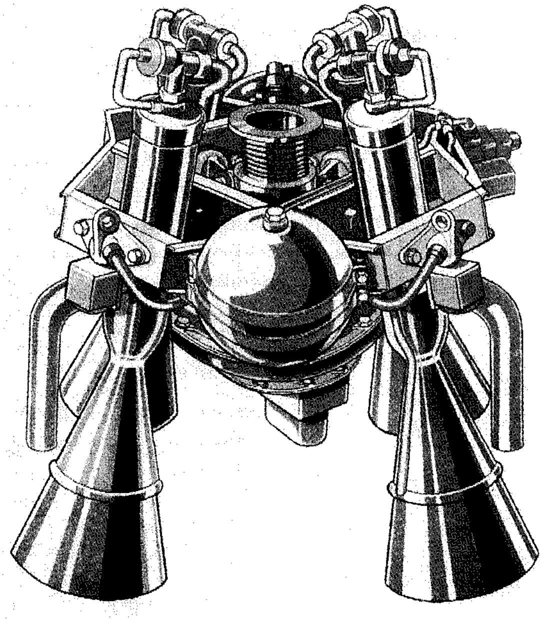
Bristol Siddeley Proposal for Small Satellite Launcher:

First stage:		
PR27/90,000lb thrust	£k1770	
Structure & systems	£k5950	
Second stage:		
G303/25,000lb thrust	£k250	
Structure & systems	£k375	
Third stage:		
PR38/2-3000lb thrust	£k450	
Structure & systems	£k825	
Guidance	£k850	=£k10,470

Black Arrow:

First stage:		
2xG303 50,000lb thrust	£k350	
Structure & systems	£k200	
Second stage:		
2xG200/8000lb thrust	£k250	
Structure & systems	£k200	
Third stage:		
Apogee solid	£k150	
Structure & systems	£k65	
Guidance	£k1000	=£k2,915

It is impossible to say how realistic these costings were. Certainly Black Arrow was more difficult and expensive to develop than anticipated. And a million pounds could immediately be shaved off the Bristol Siddeley design by substituting a solid third stage without any real loss in functionality. But why, for example, is the Bristol Siddeley second stage costed at £k375 when that of Black Arrow is costed at £k200? They are almost identical. To cost your own in house design against that of a competitor is a dangerous exercise.



Bristol Siddeley's PR38

This engine was proposed for the third stage of the Black Prince launcher and also for the third stage of Bristol Siddeley's proposed satellite launcher.

As a design for a medium sized satellite launcher, it would have been an excellent solution, using as it did well developed and efficient motors and no novelty of design. David Andrews of Bristol Siddeley estimated that the design would be able to put 650lbs payload into low earth orbit. It is also surprising that more was not made of the fact that in a few years time, redundant Blue Steels would be available together with their motors, which could then have been recycled into the satellite launchers!

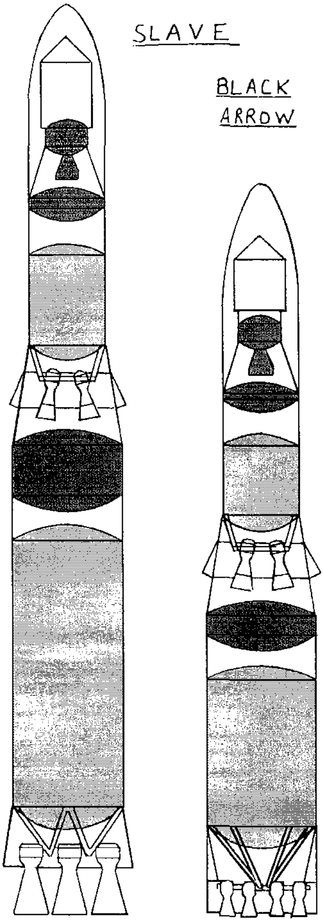
There was also recognition that Black Arrow was stretching the Black Knight concept to its limit. Work had been carried out by Bristol Siddeley on higher pressure combustion chambers as part of an H.T.P. research programme. The Gamma 2 engine would be increased in thrust from 15,340lb to 18,200lb, with an S.I. increase from 265 to 285. Similarly, the Gamma 8 thrust would be increased from 50,000lb to 57,380lb, and the S.I. from 217 to 226 with only 100lb increase in weight. With no change in vehicle, the payload is increased from 110kg to 150kg in a 300n.m. orbit.

In addition, its performance could be stretched further with strap on boosters. A version of booster was proposed that was effectively a Black Knight vehicle, i.e., the 36 inch diameter H.T.P. design. This would have given the vehicle 16 Gamma motors at lift off! Another idea was to use the Raven solid motor that was the basis for sounding rocket Skylark. The first stage could also be extended with more fuel if such boosters were used. In addition, liquid hydrogen upper stages could be used, but all these arguments could again be employed on the Bristol Siddeley design.

Soon after the successful launch of Prospero and the cancellation of Black Arrow, Saunders Roe came up with yet another version of Black Arrow, one they called SLAVE (rather mundanely, this stood for Satellite LAunch VEhicle). This design took the first stage engine with 8 Gamma chambers and replaced it with 4 Stentor motors – effectively the same motor as in the Bristol Siddeley launcher. (Blue Steel had now left R.A.F. service: there would be plenty of large chambers available for conversion at very little cost.) The Gamma 8 had a thrust of 50,000lbs, the new configuration nearer 100,000 lbs. The first stage diameter is kept at 2.0 metres, as in Black Arrow, which would have again reduced development costs. However, the increased thrust meant that the weight of fuel carried could be very much increased, and so the first stage tanks were extended in length considerably. The second and third stages are identical to those on Black Arrow, so no extra cost would have been incurred here.

Increasing the size of the vehicle in this way would also have increased the payload considerably, from Prospero's 132 lb (66kg) to 300 or 400 lbs. Again, it was a useful and sensible design, but all official interest in launchers had long since evaporated.

To be realistic, and to achieve a useful payload, R.A.E. should have gone for a design like this from the outset. In all their design studies they give the impression of being too closely wedded to Black Knight and the Gamma motor. However, cost mitigated against any launcher that was more complicated. The idea of a small satellite launcher was not unique to R.A.E.: the Americans built the Scout rocket for the same purpose. Payloads were roughly equivalent, although had a more restricted volume under the satellite fairings. A Black Arrow launch was intended to be of similar cost to Scout, as many of the reviews of the vehicle pointed out. The snag was that the cost of Black Arrow rose sharply if the number of launches per year was reduced. At 3 launches per year, they were roughly the same; at one launch every eighteen months Black Arrow became considerably more expensive.



SLAVE and Black Arrow

The two upper stages are identical, but the lower stage is greatly extended, and uses 4 Stentor chambers. This would have cost very little extra to develop and have been extremely effective. The shaded areas are fuel tanks; H.T.P. is shown as light grey and kerosene as dark grey.

It should have been noted, however, that cost was one of the factors when evaluating all these designs. To those working on an indigenous U.K. programme, Blue Streak, ELDO and Europa could be seen as the cuckoo in the nest, taking money away from other programmes. Even if a fraction of the ELDO money had been given to R.A.E., projects such as the Bristol Siddeley launcher would have been easily affordable. Indeed, as R.A.E. was later to admit, Black Arrow was not really adequate even for the modest technological satellites that they proposed.

Designs for liquid hydrogen rockets were many and various, most of them based around Black Knight or derivatives of the vehicle. For a quick and cheap solution to launching satellites, adding something on top of Black Knight was by far the easiest option, but the rocket was not really suited to the job. Certainly the early versions didn't have the capacity, but the uprated Gamma 301 engine opened up possibilities.

To look at some figures, the uprated engine gave nearly 25,000 lb thrust. This implies a maximum lift off mass of 20,000 lb. Given Black Knight was around 14,000 lbs, which leaves 6,000 lb for upper stages. Even with liquid hydrogen, this is not really adequate for anything useful.

It is worth doing some comparisons between Black Knight and the first stages of two other "first time" satellite launchers: Vanguard (U.S.) and Diamante (France):

	First stage Weight	Thrust	Burn time
Black Knight	13,000lb	25,000lb*	100 seconds*
Vanguard (American)		27,000lb	144 seconds
Diamante (French)	32,400lb (14,720kg 275kN)	62,000lb	93 seconds

*uprated to maximum thrust level and assuming same fuel capacity

The marginal nature of Black Knight is demonstrated. Stretching the first stage is no real use either: the limitation is the first stage thrust. Despite this, the files are littered with designs for launchers.

The first serious proposal for a liquid hydrogen upper stage came from Harold Robinson, the man in charge of the Black Knight programme at R.A.E., and is dated December 1961. Here are excerpts from the paper he wrote, outlining his ideas.

Notes on a proposal for a liquid hydrogen/liquid oxygen Second Stage Black Knight.

Work is in progress in Satellite Launcher Division, GW Department, on a design of a second stage Black Knight, using liquid hydrogen/liquid oxygen as a propellant. This work is related to Westcott work on LH2/LO2 combustion chambers and design studies in conjunction with Saunders Roe on an advanced B.S.S.L.V. third stage.

Initial design considerations.

Design studies work started with the following major objectives:-

The design of the second stage using the most promising propellant combination to gain experience of liquid Hydrogen/liquid Oxygen problems in:—

(a) engine design and associated propellant supply problems.

(b) structural design with special problems of obtaining good structural weight factors with low density propellants and the need for thermal insulation.

(c) light-up, separation problems, re-light, free-fall, transition to low thrust, and other related systems problems.

Maximum flexibility in design for the addition of more complex systems as research proceeds, i.e., alternative methods of propellant supply. Relating to this desired flexibility a tentative requirement was established for the ability to ground-launch the stage alone.

It was considered important that engines, component and structural techniques developed should have in all cases direct application to any related launching vehicle, specifically B.S.S.L.V.

The design shall demand the minimum of modifications to Black Knight or its associated facilities.

... Last, but more important, development and manufacturing costs should be kept to a minimum.

Design details

Work so far has indicated that most of these objectives can be met. However, without fairly extensive modification, Black Knight with a second stage cannot launch a payload into orbit with any degree of confidence. Performance calculations and scantling weight estimates show that the stage alone without an additional third stage, may attain a 300 miles orbit. But a very small pay-load, sensitive to structure and ancillary systems weight growth, would almost disappear. The configuration consisting of Black Knight with Gamma 301 engines working at a Take Off thrust of 25,000 lb. (the limit of its present design) a 2,200 lb. LH2/LO2 stage and a third stage propellant motor of about 450 lb. weight with performance and charge/total weight ratio similar to that of the Scout "Altair" motor may project a 150 lb payload into a 300 mile orbit making fairly pessimistic performance assumptions.

These factors indicate that design aims may be followed in stages as follows:-

The development of a "basic" second stage with perhaps first launching from the ground using Black Knight range facilities.

Launchings from Black Knight with sub-orbital performance testing of advanced systems in flight as necessary.

The addition of the third stage for orbital launching.

Design of the “basic” second stage

R.P.E., Westcott and ourselves considered the best design for the “basic” second stage should employ pressure fed chambers using helium gas bottles. Thrust and stage weight optimisation calculations are not yet complete (1.12.61), but present figures are:

Thrust (Vacuo)	4,000lb
Chamber Pressure	120 p.s.i.
Vacuum S.I.	400 secs

Engine of four chambers each chamber 1,000lb. thrust. S.I. dependent expansion ratio with four chamber design.

Expansion ratios of 1,000 to 5,000 are possible adding considerable SI bonus.

Stage weight 2,000 to 2500 lb.

Total burning time circa of 160 secs

Engine Design.

The main design problem is that of the combustion chamber. This would be based upon current R.P.E. injection chamber design and would need an extension of the work to the cooling of the expansion nozzle. This would be partially cooled by propellants and partially by radiation (c.f. Agena expansion cone). Each chamber would be developed with a vacuum thrust of 1,000 lb. and mounted with a complete engine as a four chamber assembly similar to B.K.

Helium pressure feed to the chamber as an initial approach would minimise development work in this area.

Structural design.

Low temperature structural strength thermal insulation and other cryogenic problems will need a fair amount of supporting research. The stage, if 3 ft. in diameter will be 14 ft. long.

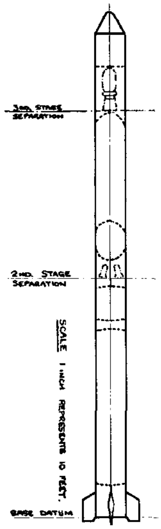
Possible third stage designs.

Two types of design are being considered.

1. An orthodox solid stage orientated by the second stage attitude at cut-off into the correct injection direction and spun-stabilised by lateral spin rockets, as originally planned for the Black Knight re-entry second stage.

The Cuckoo motor as it exists is about the right size but its case weight is excessive compared with comparable U.S. motors such as Altair used in Scout of the same size. The specific impulse of 240 seconds in Vacuo assumed in performance calculations is no problem. Case weight reduction to U.S. standards will need development of the type now under way at R.P.E. (Cuckoo II).

2. Again eliminating the need for equipment in the third stage other than payload a spun third stage is considered but using LH2/LO2. A design using a single 1,000lb fixed chamber of the type required for the second stage and spherically wound fibre LH2 and LO2 reservoir, helium pressure feed and spinning at, say, 20 rads/sec. is being looked at.



36 inch Black Knight with liquid hydrogen stage.

The paper then finishes with cost breakdowns. The grand total, excluding modifications to Black Knight, was £998,000 (a convenient sum—was it intended to come in at just less than £1M?). But the estimated sum for the first three years including contingencies (a euphemism for over running the budget) and production of the first two second stage vehicles was put at £1.5M. It should be noted that it was the intention to do almost all the development "in-house", and that the design was driven as much by cost as by technology and engineering. An illustration of the vehicle above shows what Robinson was talking about when he refers to a "fineness ratio of 1:20": the vehicle would be 3 foot in diameter and 60 foot high! This points up the large volume occupied by liquid hydrogen. The design was pressed ahead with, and Saunders Roe was given some design work, but, as usual, the project petered out due to lack of a budget.

But the demise of this scheme didn't prevent other attempts at similar designs. Another proposal was put forward in March 1962 (notable for the use of SI units as opposed to Imperial), but this was very much in the realms of a design proposal without any real evidence that work went any further—indeed, it is more in the nature of sketches without any detailed calculations.

Again, in April 1963, another R.A.E. Technical Note delves deep into Black Knight plus various liquid hydrogen stages. It considers 4 variants of Black Knight: the "standard" 36 inch 21,600lb thrust version, then 54 inch versions with thrusts of 25,000lb, 40,000lb, and 50,000lb. The latter versions would use 2 complete Gamma 301 engines. In passing, it is interesting that reference is made to the use of four large Stentor chambers, but the vehicle would have to be over 54 inches in diameter, and that was the limit set by the ground equipment then in use. But even the 25,000lb thrust vehicle, together with 2 upper stages, could put a mere 102lbs into orbit, and the most that could be hoped for, on the most optimistic of the calculations, was 500lbs. This was simply not enough, and points the fact that with the best will in the world, Black Knight simply was not suitable as the first stage for a satellite launcher.

But what of possible Blue Streak launchers? Black Prince and Europa did not make the best use of the vehicle. What could have been designed around Blue Streak?

Before ELDO itself was created, there were plans for a simple Anglo-French launcher. In many ways, it is a pity that the project was broadened out to a pan-European venture, with its inevitable diffuseness and lack of co-ordination. The French have pursued their space ventures with determination and vigour, and might well have stiffened political sinews in Britain. In addition, the British liquid hydrogen stages for Blue Streak never had a chance in ELDO, since the work had to be allocated to so many different countries. An Anglo-French launcher with a French second stage and a British liquid hydrogen third stage would have had many advantages. Firstly, it would have had a respectable payload. Secondly, the decision making process would have been a good deal less cumbersome. Thirdly, the delays of at least two years involved in the setting up of ELDO would have been avoided.

But what of possible U.K. launchers built on Blue Streak? As mentioned before, the vehicle, like Black Knight, as it stood could not carry sufficiently heavy upper stages to make a really efficient satellite launcher, so we will further assume that it could be augmented with solid or liquid fuel strap on boosters as with Thor. This might then have increased the upper stages to weights of 100,000 lb or so. Indeed, to save development costs, Black Knight vehicles could be used as the strap on boosters, stripped of guidance and electronics to save weight. This is called parallel staging, when the boosters and main rocket are ignited together, rather than serial staging, when the first stage ignites and burns out, then the second, and so on. Such parallel staging is a little less efficient, but is cheap and effective. Four Black Knight stages strapped onto Blue Streak would increase the lift off thrust from 300,000 lb to 400,000lb. The Black Knights themselves would add around 60,000lbs weight to the vehicle.

An obvious upper stage would be one with 4 Stentor engines, giving 100,000 lb thrust (the PR27 engine, illustrated above). A third stage using a single Stentor or Gammas could then put perhaps 4 to 6,000lb in orbit. Development costs for such a vehicle would have not been excessive—certainly less than that for Europa, but the entire costs would have had to be borne by the U.K. Such a vehicle might then be able to put a respectable payload in a geosynchronous orbit.

However, the usual caveat of expense arises. These vehicles would perhaps have cost a minimum of £100M at contemporary prices in development costs, at a time when the total annual Defence R&D budget was £200M, and the total annual Defence budget was £2000M. Even spread over several years, this would be too much. As against that, the U.K. spent several ten of millions on Europa with nothing to show for it.

The other problem is that the market for geosynchronous launchers was not at all obvious in the early 60s. The first such satellite, Early Bird, was launched just in time to relay TV pictures from the 1964 Tokyo Olympics to the U.S.A.. But the commercial viability of the satellites was not really obvious until the early 70s.

Another way to extend a Blue Streak launcher would be to use liquid hydrogen upper stages. As mentioned, Saunders Roe had such a design for a third stage as early as 1961. With the work that was done at Westcott on hydrogen motors, development costs should not have been too high. Once a third stage has been built, it is relatively easy to scale up the design to produce a larger, second, stage. This was the point of ELDO B, and of all the possible Blue Streak launchers, this had the most potential of all. If the U.K. had thrown its weight behind the scheme, Europe could have had the equivalent of Ariane ten years earlier.

One final last attempt by R.A.E. to produce a worthwhile launcher from Blue Streak still lies unread in the Public Record Office (the file will not be open until 2003). This, from its title, investigates the possibility of putting an American Centaur stage on top of Blue Streak, which would have the advantage of eliminating the development costs of the second stage. With a Blue Streak launch pad built at Kourou in French Guyana, this would seem a very attractive proposition. Such a combination could put perhaps 6000lbs in low Earth orbit, or perhaps 1000lbs into geostationary.

Blue Streak with an American Centaur upper stage.

However, it will not have escaped notice that 5,000 lb was the approximate size of the Gemini capsule: thus such a vehicle could actually have orbited a U.K. astronaut. But developing a manned capsule would have probably doubled that cost.

Gagarin went into orbit on 12th May 1961, one day short of a year after the Blue Streak cancellation. However, Vostok and Mercury were, comparatively, tiny capsules, just to show that it could be done. Voskhod has gone on to be the workhorse of the Russian manned programme, whereas Mercury and Gemini were effectively precursors of Apollo. The U.K. might then—just—have been able to provide a manned presence in space. But despite the enthusiasts, manned spaceflight has not shown any significant advantage over unmanned, and it is vastly more expensive. Certainly, manned spaceflight, with its various firsts in the form of spacewalks and the rest, was very much a Cold War artefact. Perhaps the idea of a U.K. astronaut might have been just to "show the flag", and no more.

12. The U.K. and Space

It can be argued that the Cold War became a war of resources; and one in which the U.K. effectively dropped out of at the start of the 60s. It could be further argued that the collapse of Communism in Russia was also due to the collapse of a command economy directed to large military and technological programmes. However, let us concentrate on the U.K..

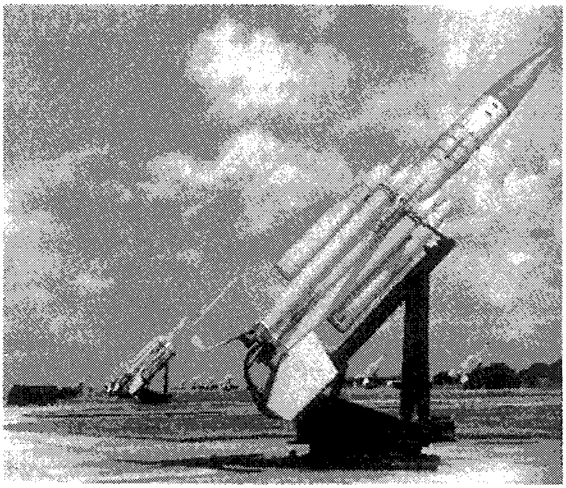
As already mentioned, most of the projects discussed so far where military in origin, but many were never carried through to completion. This is not unique to the U.K.; similar cancellations happen in all countries developing new technology. One of the major factors contributing to the cancellation of such projects, not only in the U.K. but in the U.S., was the very rapid advance in technology during the 1950s.

In many ways, the major aerospace technologies, with the exception of computing and electronics, had become mature by the mid 60s. Thus the jet engine, the rocket motor, supersonic aircraft and the rest had been successfully developed by this time. There have obviously been improvements, but they have been incremental rather than breakthroughs into new areas. It is also interesting that up until the 1970s, almost all technological advances came from Government and military projects, whereas today the main driving force seems to be business and consumer interests, most notably in electronics and computing. Military spending is no longer the great driver of projects that it once was.

To see the effects of such changes, let us start in 1945. Jet aircraft were rendering piston engined aircraft obsolete. The strategic missile had arrived in the form of the V2. But the major strategic development, eclipsing every other of the century, was that of nuclear weapons. Almost all the programmes in this book have close, or not very distant, links to the nuclear programme.

The U.K. did not pursue rocketry with much vigour in the immediate post war years. 3 captured V2s were launched at Cuxhaven, Germany, in what was codenamed as Operation Backfire. The majority of the work carried out in Britain was directed to basic research in control and guidance, and for this the various test vehicles, RTV, CTV, and so on, were launched at sites such as Aberporth in Wales. At the same time, the rocket test site at Woomera was getting underway. The pace increased at the end of the 40s with various air to air and surface to air projects. These missiles, however, were all designed for use in air, and their control mechanisms were all aerodynamic. They were not ballistic missiles in the V2 or Blue Streak category.

The 3 important surface to air missiles were Seaslug for the Navy, Red Shoes (to become Thunderbird) for the Army, and Red Duster (to become Bloodhound) for the Air force. Later models of Seaslug used solid motors, as did Thunderbird, and Bloodhound used ramjets with solid boosters. All were successful (ultimately: Seaslug took a great deal of time and money to become an effective system) and enjoyed long service lives.



Bloodhound

The early air to surface device was called Blue Boar, but several years of development led in the end to cancellation. The problem here was guidance: the missile was to be television guided, but this has several drawbacks, not least of which are darkness, rain, and jamming. It was not until the early 50s that electronics had advanced enough to produce a sufficiently accurate inertial guidance system. This then led to Blue Steel, which achieved its specification, but came into service too late to be an effective addition to the bomber force. However, it had to carry the main burden of the British deterrent in the years between the cancellation of Blue Streak and Skybolt and the arrival of Polaris.

However, the main effort in the 40s was in the development of the V bombers, designed to carry a British nuclear weapon. It is interesting that the decision to build these aircraft and the British bomb were taken well before the Soviet Union acquired a bomb. It was anticipated that the Russians would not have atomic weapons until the mid 50s. The decision to acquire an independent deterrent was as much in the hope of being able to influence U.S. policy as countering any Cold War threat.

In the event, the first Russian device was exploded in 1949. Now the necessity for blocking attacks by Soviet bombers armed with nuclear weapons became much more pressing. Hence the much increased interest in rocket powered interceptors - the SR53 and P177. However, no sooner than they were about to become operational than it was realised that the Bloodhound missile would do the job as effectively. And missiles are cheaper than manned aircraft. Further, the

British had discovered what they called the R1 effect: if a nuclear weapon is exploded in the vicinity of another one, then the second device was very vulnerable to premature detonation or disablement by the resultant radiation - specifically, neutrons, gamma rays and X rays. Hence the decision was taken to cancel the interceptors to replace them with nuclear tipped Bloodhounds. However, this policy then became obsolete with the advent of the ballistic missile and decline of the manned strategic bomber. Bloodhound was too limited to convert to an ABM system.

Thus, in the period 1955-1957, apart from the urgency to acquire a working fusion device, the U.K. looked relatively secure, and well armed. But technology took another leap forward with the advent of the long range ballistic missile.

Although the V2 was the first true long range ballistic missile capable of hitting another country, it was too inaccurate and too short range to be of strategic importance. Advances in guidance technology meant that by 1957 almost anywhere on the globe could be hit with a warhead to an accuracy of 2 to 3 miles. Coupled with a fusion warhead, this was the most powerful strategic device developed - and remains so. (Accuracy has improved to almost tens of metres. The accuracy of Trident is quoted at 120m).

The testing of a long range ballistic missile by the USSR in 1957 rendered at a stroke bomber fleets almost obsolete. The bomber is vulnerable to missiles and to fighter aircraft, but the ballistic missile is not. If bombers were no longer the major strategic threat, then interceptors and surface to air missiles too were unnecessary. This change in policy occurred in the U.K. at the end of 1956, but was formally announced by Sandys in the 1957 Defence White Paper. Although Sandys was held responsible by many for seriously damaging the U.K. aircraft industry, the decision was almost certainly correct and although not initiated by Sandys, fitted very well with the thrust of the Paper, which was to cut defence spending to around 7% of GDP.

But the U.K. had already taken the decision to go ahead with its own ballistic missile, Blue Streak, although its in service date would be very much later than its American or Russian counterparts. All three, however, suffered from being first generation long range missiles, and were very clumsy to deploy. The Russian missile known as the R-7 or Semiorka tested in 1957 was never seriously deployed as a weapon. However, the U.K. was the first to contemplate seriously underground launch sites - what became known as silos. Looking at the design of both missile and silo, they seem as capable as the later U.S. and U.S.S.R. designs, and the U.K. seems to have been the first country to take silos seriously. However, the silo provoked a good deal of controversy on the grounds of vulnerability and expense. The vulnerability argument was somewhat specious - particularly when the alternative was the V bombers - but sufficient to lead to cancellation. The other consequence of this was that land based missiles could never again be contemplated by the U.K., for if the Blue Streak silo was vulnerable, so was any other.

The U.K. ended up with Polaris as its major deterrent, and it must be said for a country the size of the U.K., and with the U.K.'s resources, Polaris was probably the best option.

The cancellation of Blue Streak, and the successful validation of the re-entry vehicle, would logically have led to the cancellation of Black Knight at the same time. The continuation of the Black Knight programme was due to a change in direction, to research the observables during re-entry. This had significance for an A.B.M. system (although the U.K. had abandoned such a system, there was still considerable American interest, and considerable U.S. funding was available) and further for the design of decoys for offensive systems. Such knowledge would be useful later in the Polaris upgrade system, Chevaline.

Effectively, by this point, military interest in large scale rocketry had faded, but the U.K. was left with Blue Streak and Black Knight to pursue a rather half hearted space programme. Considerable muddle in the subsequent policy left the U.K. disillusioned with space research - or, at least, in launchers - with the inevitable cancellations later in the 60s.

The question then comes: why when America, Russia and France were pursuing space exploration with vigour, and why when countries such as China and India are launching satellites almost as a matter of routine, has the U.K. shown such little interest both at Government level and among the people at large?

A useful German word can be used here: the *zeitgeist.* America and Russia were pursuing their race in space as a way of fighting the Cold War at one remove, in an attempt to show the rest of the world who was technologically the more sophisticated. Britain had no such interest: at the end of the 50s it was beginning the long retreat from Empire, and at the same time beginning to suffer from the economic and social ills which were to plague the country for the next 30 or 40 years. Another phrase has been used of Government at this time: "managing the decline". A country that feels itself to be in decline does not embark on new, challenging technological challenges.

As an example of this, Thorneycroft, then Minister of Aviation was interviewed on television about the proposed Blue Streak launcher and ELDO in 1961. The interview is very illuminating; here is the latter part of the transcript:

Mr. Mackenzie: But couldn't it be argued that we, in Britain, have after all only a limited number of technologists available, even in any aspect of this area and that we might be better advised to get them off working, for example, In exploration of the problem of supersonic aircraft, or some more obviously commercial operation, rather than this rather exhibitionist activity of rocketeering?

Minister: There's nothing exhibitionist about the brilliant Rolls Royce and de Havilland engineers who've, incidentally, a great deal more than keep this in mothballs. We've just done two fully integrated static firings. The work is going well ahead and the Americans will tell you themselves that the payoff in other forms of industry - in metallurgy, electronics and the rest, - have wide application to civil industry as a whole, is very great if we go into it.

Mr. Mackenzie: But are we remotely in this competition? One knows how very far the Russians have gone, and the Americans and one has the awful feeling that this is the kind of feeble rearguard, final action to show the flag.

Minister: Don't be so depressed, Robert. This is not a rearguard action at all. We are in this for eternity, all of us. It isn't just the question of doing it with the Atlas or the Blue Streak. We shall be making these rockets: I hope we shall be making them in Europe for a long time ahead, with great advantage to ourselves, to the world and to all the countries, including the smaller ones, that are in it.

"Exhibitionist activity of rocketeering", "feeble rear guard action". And another quote from Mackenzie alter in the interview: "But I don't understand why, if the Americans are offering a launcher - which is presumably more advanced than the one we have - Blue Streak - why we may as well not write off Blue Streak and use their launcher for whatever purposes we've got in mind."

And Mackenzie was wrong. Blue Streak was actually based on American technology, but it could be argued that in the process of Anglicisation that a considerable number of improvements had been made.

Another example of the same frame of mind (and the frame of mind perpetually adopted by the Treasury!) can be seen in a note from the Chief Secretary to the Treasury, John Boyd Carpenter, in July 1963:

"MINISTER OF DEFENCE

"I have seen the Minister of Aviation's minute to you of 16th July about military space.

"I note that he does not believe that we shall be able to hold back over military space indefinitely. I must make it clear that I should find the utmost difficulty in agreeing to add to our programme what might well become yet another major defence role or commitment. I suggest we cannot start to build a vertical empire if our colleagues insist on our continuing to provide for the defence of a horizontal one. I am sure that, before we go any further, we need a cool appraisal of what our real military space requirements are, if any, and of the various ways in which they might be met, with full figures of probable costs and an analysis of the effect of such costs on the already horrible Costings. I understand that papers on all this are being prepared for the Defence Research Policy Committee and I hope that these, in particular that of the Ministry of Aviation, can be considered very soon."

Both these are examples of the *zeitgeist*, the feeling that space and rocketry are not Britain's concern, and more than that: that the U.K. can neither afford to be involved and that the work done will inevitably be inferior to American work.

The apogee of enthusiasm for space in the U.K. was probably in 1964. This is the year when Black Knight had had more than 20 successful launches, when there were 2 successful Blue Streak launches, and when Black Arrow was given its go-ahead, being announced publicly at the S.B.A.C. (Society of British Aircraft Companies) dinner just before the 1964 election by the Minister of Aviation, Julian Amery. There was a feeling of optimism that ELDO might lead to a bright new future for Europe and for Woomera. Newspaper and magazine articles portrayed Woomera as a space port for the future. Even earlier in the 50s, the hit BBC radio serial, Journey into Space, portrayed the launching of Commonwealth rockets to the Moon and to Mars from the Australian outback.

The last of the major aerospace projects were all initiated under Macmillan's Conservative Government. The Wilson Government in 1965 cancelled the TSR 2 and other major military aircraft projects. Concorde and Europa survived because of their international dimension: the U.K. was treaty bound to these projects, the Foreign Office fought for them, the Government did not want to seem anti-European, and, most importantly of all, because the way the treaties were written, not a great deal of money would have been saved by cancellation.

The same was not true of Black Arrow, but by comparison with the likes of Concorde or TSR 2, it was a fairly insignificant affair. Spending was put on hold, to be doled out in three monthly offerings. Needless to say, this budgetary regime, the consequence of any lack of decision one way or the other, had the effect of both delaying the programme and increasing the cost, by preventing any long term planning or ordering of materials.

With the advent of the Wilson Government in 1964, the Department of Economic Affairs (D.E.A.) was set up as a counterbalance to the Treasury. One of its remits early in 1965 was to consider the U.K. space programme. To say that it was opposed to it in almost any form is no exaggeration. Thus one paper, when discussing the Small Satellite Launcher (Black Arrow) states:

"There may possibly be a long term interest in TV transmission by satellite, but this is never likely to be economic."

The first direct broadcast satellite was a Canadian satellite in 1972; nowadays, of course, Sky Television is ubiquitous. One of the problems with the Civil Service of the time, excellent though they may have been in many ways, is that they were not technically educated, nor had they any feeling for entrepreneurship. Even economists are seldom likely to spot the next future technology. This is reinforced by a later paragraph in the paper:

"The Christopher Columbus Complex.

"... the fact remains that none of the applications of satellites at present even remotely in sight is likely to bring any economic return, either in terms of commercial profits to manufacturers, exploitation by HMG [Her Majesty's Government] as operator, or, through international contracts, across the exchanges."

(This passage in the brief has been underlined and noted in the margin.)

One wonders how much consultation there had been with manufacturers, particularly those in the U.S.. By 1964, two TELSTARs, two RELAYs, (medium orbit satellites) and two SYNCOMs (in geostationary orbit) had operated successfully in space. By the end of 1965, EARLY BIRD had provided 150 telephone "half-circuits" and 80 hours of television service.

The paper then concluded: "This proposal [*i.e., Black Arrow*] should be resisted as strongly as possible. Either it should be killed right away or remitted back to lower-level..."

Another official in the same Department and as part of the same debate commented that competing with the U.S. and U.S.S.R. in space was "a wanton waste of resources". With regard to ELDO, "... unless Europe is to go on indefinitely squandering more and more resources in a field without significant economic return, some country sometime has got to take the lead in calling a halt, even at the cost of seeming opposed to European co-operation." Implicit in this statement was the notion that the U.K. should be that country.

Then in 1965 came the first of the many disagreements in ELDO, followed later by the British reluctance to be further involved in the program. It must have seemed odd to the remaining five members of the organisation to see the founder members, those who had pushed so hard for the organisation, to fall out in this fashion, and to lose enthusiasm for their own project.

A brief prepared for the Prime Minister, Harold Wilson, by the D.E.A. on ELDO noted: "... the ELDO programme in general and our own proposed satellite launcher and satellite development programme are of low economic priority and cannot be justified on economic grounds." And on the ELDO B launcher proposal: "...For much less money we could do more work than we do now in a field which is of direct concern to us and where we can make new technological contributions .." But these fields never seem to be specified in any of the documents.

All the documents disparage ELDO A (Europa) on the grounds of "obsolescence". This is a half truth. What, in this context, does obsolete mean? The purpose of a satellite launcher is to launch satellites, and ELDO A would be a very good medium sized launcher in the 1960s. Technically, the U.S. was moving forward into solid fuel boosters and liquid hydrogen, but essentially, the technology has changed little in the half century from the advent of Atlas and Blue Streak. Launchers have grown bigger, and also more efficient in the sense that smaller rockets can launch bigger payloads. The problem was rather different: there was little European demand for a medium sized satellite launcher. Given in addition its increased cost compared with U.S. launchers, then demand would indeed appear to be minimal (although it would have been as effective or more effective than the Delta rocket used to launch the U.K. Skynet satellites - had it been available on time). ELDO B was written off by the same officials as still being smaller than some U.S. launchers (Titan III). They commented: "even the advanced ELDO B launcher cannot be expected to be technically or financially competitive with American launchers.". This again misses the point - it would have been perfectly adequate for launching the geosynchronous satellites for which there would be a market - a market that exists today and is growing ever greater. ELDO B would be a technical and commercial success even today, forty years on.

The argument was put forward by the Ministry of Aviation that unless the U.K. or Europe had its own capability, the U.S. would have had a monopoly. Without Ariane, and without the availability of Russian launchers from the early 90s, that would have been true. It is also probable that despite the wishful thinking of civil servants, the U.S. would have charged a very great deal for launching satellites that would have competed with its own in the lucrative communications market. Indeed, it could have charged almost what it wanted to, or alternatively have retained its monopoly in the communications satellite area.

Lest it should seem that the preceding quotes have been taken out of context, or that the quotes have been carefully selected to provide a one sided argument, it is well night impossible to find any quotes in favour of pushing forward any space programme outside the Ministry of Aviation and the Foreign Office - and indeed after around 1966 even the Ministry of Aviation, or Technology as it had become, accepted the demise of the British effort. The Foreign Office was not concerned with the technology at all - merely the political implications of withdrawal from present programmes with regard to Europe and Australia.

Be all that as it may, British withdrawal, painful though it was, took place. The British experience with ELDO bit deep: so much so that the U.K. have never again become involved with any launcher programme. Even the European Space Agency, E.S.A., was described by one minister in the 80s, Kenneth Clark, as "an exclusive club designed principally to put a Frenchman into space." Such wilful disparaging of one of the most commercially and scientifically successful space agencies is astonishing. The same minister also refused to fund the innovative British Hotol design, whilst at the same time declaring the engine design classified, and thus preventing development elsewhere.

Could commercial firms have carried on some of these projects? The companies involved in aerospace in 1971 were Hawker Siddeley Dynamics, successor to de Havilland, which itself had been swallowed up in British Aerospace, Rolls Royce, and Saunders Roe, who by then were part of Westlands (at this period they were working under the name of the British Hovercraft Corporation. All the U.K.'s hovercraft were built at Cowes. Like too many of the Saunders Roe programmes, hovercraft seemed initially to have had a bright future but have turned out to be a dead end.).

Saunders Roe, even as part of a larger organisation, were too small to be able to afford the capitol investment needed for developing satellite launchers. Rolls Royce and British Aerospace could have worked together on further developments of Blue Streak, but this was only part of the problem.

As well as the rocket, launch sites are needed. Woomera was not suited to satellite launching, and, by this time, was near closure. Kourou, in French Guiana, did, however, have a Blue Streak launch pad. Ariane 1 was not launched until 1979; Ariane 4, which has been the mainstay of ArianeSpace, not until 1988. How prepared the French would have been to make the launch site available is, however, another question. In addition, NASA in its post-Apollo phase, was promoting the Shuttle very forcefully as the answer to satellite launching, with the re-usable nature of the craft. Indeed, it is arguable that part of the success of Ariane was the Challenger disaster of 1987. NASA had almost halted its programme of satellites on conventional launchers.

However, Ariane was a more powerful launcher than all but the most sophisticated Blue Streak derivatives. Ariane 1 was optimised to put 1750kg into a Geo Transfer Orbit (GTO). A Blue Streak/Black Arrow combination, unless supplemented with strap on boosters or liquid hydrogen stages, would not have matched that performance. Ariane 4 and Ariane 5 are even more powerful.

But even if the three firms had joined forces to produce a launcher, who would have been their customers? The U.K. Government has launched some military communications satellites under the Skynet programme, but not on a scale large enough to justify such investment. ESRO (European Space Research Organisation, ELDO's sister organisation) and other European countries might have been customers, but the market in 1971 was still very thin.

There is also a further political dimension: the U.K. aircraft industry was not in good shape in the 1970s; indeed, it was nationalised by the Wilson Government during that period. It was certainly in no position to undertake large speculative projects of this sort.

The nearest to a current U.K. programme is conducted by the British National Space Council, with a budget of around £M200 (2000 prices). However, the U.K. still retains considerable expertise as a builder of satellites. De Havilland Propellers, original designers of Blue Streak, has gone through many changes of names, but as Astrium it is one of the world's major builders of communication and earth observation satellites. The facilities at Stevenage were originally built for Prospero and the other R.A.E. technological satellites.

Another major satellite builder in the U.K. is the University of Surrey, with its innovative but entirely commercial work on microsatellites. Under the name of Surrey Satellite Technology Ltd, it has achieved a turn over of nearly £6 million a year, and launched 19 satellites. 7 more are currently under construction. This has been done without Government subsidy, and is a considerable achievement.

Finale

Hindsight and retrospect are the two major allies of the armchair generals. It is easy enough to criticise the various British Governments and the officials that advised them on the grounds that they lacked foresight. Yet, in their defence, it must be said that they could not foresee the future, and in particular, the commercial markets that have opened up for space and satellites. All these activities in the 50s and 60s were Government driven, and the British Government could see no benefits for itself in these technologies.

But what if they had? Supposing the everpresent hand of the Treasury had been removed, and that the U.K. Governments had decided to go ahead with the likes of Black Prince and its successors.

So if we were to look at the satellite that were launched in 1999, we could see what the British technologies of the 50s and 60s would have been able to accomplish today. Would they have been capable of winning commercial contracts thirty years later? Taking Black Prince and Black Arrow, their capacity in low earth orbit (LEO) at the time they were designed was around 900kg and 100kg respectively (we will drag ourselves into the metric age). The concept of Blue Streak with a Black Arrow on top would have given over 1000kg, and 1500kg would not have been impossible. Let us take a wild flight of fancy and assume that they had not been cancelled, and that they had proceeded through to operational use. We can then say that the designs could have evolved with time, at minimal cost, taking advantage of technological improvements over the 30 or 40 years, which is not an unreasonable idea. Thus microchip technology, modern composites and the like have become available. A very modest developmental programme over a quarter of a century would have improved their performance - for example, the planned improvement of the Blue Streak engine to reduce the two turbines and pumps to one, and eliminating the gearbox. So these improvements might give a 25% improvement in performance to 1125kg and 125kg respectively. Then use can be made of strap on solid boosters, which also allow extension of the first stages and the like, extending performance even further. This is exactly what the U.S. did with the Thor Delta satellite launcher. It is simple and cheap technology, and easy enough even in the 60s. We could then be looking at 2000kg and 200kg in orbit - perhaps 3000kg with an improved Blue Streak, Black Arrow and solid fuel boosters. An even easier alternative would be to use Black Knights as the strap on booster: given their low cost (and a version with no guidance or payload would be cheaper still), that would be an extremely attractive proposition.

If you were really ambitious, you might add liquid hydrogen stages - after all, research was being done back in 1954! But this is slightly hypothetical, and more expensive to develop, and it was more than thirty tears ago that Rolls Royce test fired the RZ-20. Even so, this could push up performance further so that payloads could be increased by some hundreds of kilograms, and that is being pessimistic. The limit of a Blue Streak launcher by itself, the ELDO C concept, probably amounts to 4 to 5,000 kg in low earth orbit. Supplementary strap on boosters might put that up to 6 to 7,000kg - just enough for geostationary orbits. But now we are postulating developments that might come quite expensive.

So we can analyse the launches of 1999 and pick out those commercial launches under these limits. There is one caveat: modern launchers often take up several lightweight satellites at once, so it is not axiomatic that Black Prince or Black Arrow would readily substitute. Also throw in an alternative to Woomera, which is not suitable for equatorial orbits. This does push up the cost. As against that, a fully developed system such as these two modest rockets represent brings costs down, since their start up costs can be written off. So here are the launches for that year which might have been within the capability of these two vehicles:

Launch	Mass (kg)	Nationality	
Chunghua 1	410	Korean	Black Arrow
4 Globalstar satellites	4x450	U.S.	Black Prince
WIRE	270kg	U.S.	Black Arrow
4 Globalstar satellites	4x450	U.S.	Black Prince
4 Globalstar satellites	4x450	U.S.	Black Prince
UoSat 12	320	U.K.	Black Arrow
Ikonos	725	(failed)	Black Prince
ABRIXAS + MEGSAT-0	470 +35	Germany, Italy	Black Prince
TERRIERS + MUBLCOM	123 + 45	U.S.	Black Arrow
4 Globalstar satellites	4x450	U.S.	Black Arrow
2 Iridium satellites	2 x 667	U.S.	Black Prince
QUIKSCAT	870	U.S.	Black Prince
FUSE	1,335	U.S.	Black Prince
4 Globalstar satellites	4x450	U.S.	Black Prince
4 Globalstar satellites	4x450	U.S.	Black Prince
4 Globalstar satellites	4x450	U.S.	Black Prince
4 Globalstar satellites	4x450	U.S.	Black Prince
Ikonos	725	U.S.	Black Prince
4 Globalstar satellites	4x450	U.S.	Black Prince
7 Orbcomm satellites	7 x 45	U.S.	Black Arrow
4 Globalstar satellites	4x450	U.S.	Black Prince
KOMPSAT + ACRIMSAT7 satellites	4x450	U.S.	Black Prince

(In addition, there were 14 satellites put into geostationary orbit.)

Again, to be realistic, there is no reason to assume that the U.K. would have captured all or any of the contracts for these launches. Assuming that the U.K. might have launched a quarter of these satellites however, this represents 4 Black Prince launches and 1 Black Arrow, irrespective of any possible indigenous U.K. launches. This would certainly amount to a respectable albeit lowkey commercial programme. In the same period there were also launches into geosynchronous orbit - and such launches are usually of satellites weighing a couple of tonnes (2000 kg). This requires a booster of a different order of magnitude: perhaps Blue Streak/Black Arrow/liquid hydrogen with the strap on boosters that are seen on Ariane 5 or Titan 4? And realistically, the only way to make Blue Streak into a fully fledged contemporary commercial launcher would be to go to liquid hydrogen upper stages - as outlined by Saunders Roe or R.P.E. in 1961!

The economics of the whole business is almost impossible to unravel. Given the sheer scale of the American effort, particularly in the military field, then there has been very heavy investment in launch facilities, range tracking and all the other ancillary areas. When it then comes to commercial launches, these facilities are there ready to use. In addition, in the 60s and 70s a large number of ballistic missiles in the form of Thor and Atlas became available for conversion for launchers (curiously, Titan I seems never to have been used as a launcher). And when these supplies ran out, all the development has been done, and all the production facilities available for producing more. If you are starting from scratch, then providing these support systems adds considerably to the cost of the exercise. Hence, trying to evaluate the cost per pound of payload becomes an almost meaningless exercise.

The Ministry of Defence was intent on using on American launchers from around 1965 onwards (Thor Delta was used for the first Skynet military communication satellites), and given the price they would have been charged, then this is a reasonable viewpoint. But as others have pointed out, once a monopoly has been established, prices usually rise. This was one of the motivating factors behind Ariane.

With the end of the Cold War, the availability of Russian launchers, and the arrival of Ariane, the launcher market has opened up considerably. However, it should be noted again that neither NASA, nor ESA, nor its Russian counterparts are true commercial organisations. They are all Government agencies, and now the temptation is to go the other way, to undercut your competitors in a way that a non subsidised organisation could not do in order to win business. How would the U.K. have fared if it had pressed on with launchers? The table above suggests that it might have been quite competitive.

However, for the U.K. to do this, both the political will and the financial will need to be there. The Treasury would not wear it, with all the financial crises of the 60s and 70s. Private industry in the U.K. certainly didn't have the resources, and it is often said that the aircraft industry was always under capitalised. In addition, the state was the main client of the aircraft industry. Firms such as Saunders Roe often functioned as quasi governmental establishments, and suffered accordingly with each swing in Government policy. Saunders Roe was forced into a merger with Westlands, and those who worked for the firm at the time were not impressed. (Admittedly they would not be entirely unbiased, but one Saunders Roe retired worker was scornful of Westland's approach to technology. "Westlands?" he said. "Their hangars had thatched roofs"!) With the cancellation of many major aircraft projects first by Sandys then by the Wilson Government, the U.K. aircraft industry shrank drastically, being forced by the Government into one merger after another.

Since the Government was the major customer, it was able to force through mergers and re-organisations without necessarily being able to see the commercial implications. Command economies work in the short term, but not in the long term. Even with civil projects, the major U.K. airlines were both nationalised and as a consequence, Whitehall directed investment. There was no large internal civil aviation market as there was in the U.S.. And export markets for satellite launchers in the 60s and 70s were non existent. There was no commercial market until perhaps the early 70s. This meant that British projects were often too narrowly targeted at British needs, without considering the wider markets.

As for the political will, that too was lacking. Britain withdrew further and further from aerospace in the 60s and 70s. Governments were perhaps too wedded to old technologies. Steel and coal were regarded as priorities, partly because of the political power wielded by unions, and industries such as shipbuilding were given rescue packages time and again. But such industries were the staples of emerging economies in the Far East, with lower labour costs and more efficient working practices. Ministry papers now in the Public Record Office all too often adopt the same tone of voice: yes, these rocketry projects could be done, and planning goes ahead, but there is always an underlying lack of enthusiasm, and a knowledge that the budgets will never be there.

Could the projects be revived? There is certainly a market out there, but it would require an outlay of some billions to set up as a player. Assuming even that the U.K. was prepared to try - could it do it? The blueprints for Blue Streak are still around, and there are still some models in museums that could be copied. But the facilities are gone, and would need rebuilding from scratch. Actually, the RZ-2, which powered Blue Streak, would represent the best starting point even today. Motors with the thrust of at 100 000b thrust would be needed to produce a launcher capable of putting at least a ton in geosynchrnous orbit. However, any first stage would probably need to employ 4 or 5 such motors, rather than the two of Blue Streak. And the second stage could be powered by one or two RZ-2s. Producing a liquid hydrogen motor of this size would be the most efficient option, but highly expensive. And the large Stentor motor with its non cryogenic hypergolic fuel could even form an effective third stage. Parallel staging using 2 or 4 solid motors could mean that the launcher could be tailored to the requirement. So, given the finance, it could be done.

However, this is only half the story. Another requirement would be a launch site, and preferably an equatorial one. The West Indies would be a strong candidate (Barbados was under active consideration in the 60s: "... a range which already exists on Barbados operated by the Space Research Institute of McGill University into which Black Arrow could be integrated for a capitol outlay estimated at less than £1.0M."). Another possibility was Darwin or Cape Yorke in Australia. Both these would have considerable political considerations. Building such a launch site would also be extremely expensive. In addition, a project of this magnitude would need at least five to seven years development time - and a lot of ex-rocket scientists would need bringing out of retirement!

For the technical people involved, the period was one of intense disappointment. They felt that their achievements had gone for nothing. But the purpose of this book is to highlight those achievements, and to leave the reader to speculate on what might have been.

Timeline

These are the launch dates for the various British rockets. Some other significant space/rocketry dates are included.

Date	Blue Streak	Black Knight	Black Arrow	
1957				
16 May				first flight of SR53 (XD 145)
4 October				Sputnik 1 launched
18 December				first flight of XD 151
1958				
5 June				crash of XD 151
7 September		BK01		premature destruction near end of flight
1959				
12 March		BK03		
11 June		BK04		first successful re-entry experiment
29 June		BK05		
30 October		BK06		
1960				
13 April				cancellation of Blue Streak announced
24 May		BK08		first two stage vehicle
21 June		BK09		
25 July		BK07		
1961				
7 February		BK13		
12 April				Gagarin is first man in space
9 May		BK14		
7 June		BK17		
1962				
1 May		BK15		
24 August		BK16		
30 November		BK18		

1963				
17 October		BK11		
1964				
5 June	F1			cut out prematurely
6 August		BK19		
20 October	F2			completely successful
6 November		BK20		
1965				
22 March	F3			completely successful
24 April		BK21		
27 July		BK23		
29 September		BK24		
25 November		BK25		last Black Knight firing
1966				
24 May	F4			dummy upper stages
15 November	F5			dummy upper stages
1967				
4 August	F6			live second stage
5 December	F7/1			live second stage
1968				
30 November	F7/2			all stages live; third stage exploded
1969				
28 June			R0	control failure, vehicle destroyed
31 July	F8			all stages live; third stage exploded
1970				
4 March			R1	2 live stages, success
11 June	F9			all stages live, fairings did not separate
2 September			R2	orbital attempt, second stage shutdown prematurely.

1971

28 October		R3	Prospero launched into orbit
5 November	F11		Kourou; satellite attempt

Appendix A-History of the Saunders Roe S.R. 53 and S.R 177

From an Air Ministry file.

The S.R.177 is being built to O.R.337, issued by the Air Staff on 2nd December, 1955. This is a development of an earlier requirement, O.R.301, first issued in 1951. The aircraft being built to this latter requirement is the S.R.153.

SR.53.

May 1951. Particulars of a proposed requirement for a rocket propelled fighter were circulated to the Air Staff by A.C.A.S.(O.R.)'s staff. Because of the limitations of the early warning system and the likely scale of enemy attack, it was thought that a large force of high performance day fighters would be required. The ability of the fighters then being developed to deal with the very high altitude raider was doubted. The aircraft proposed was intended to fill the gap until effective Guided Weapons became available and to provide a strong backing for the day fighter force against mass daylight raids of B.29 type bombers. The operational role of the aircraft was to be based on an exceptional rate of climb, probably obtainable only by rocket propulsion. Target date for the first production aircraft was Spring, 1954. The aim was to combine simplicity and ease of manufacture with operational efficiency. Certain operational refinements were therefore to be sacrificed.

August. O.R.301 was issued for a rocket fighter with the following main features:

(a) Climb 60,000 ft. in 2 ½ mins.

(b) Speed. Aircraft of this type were required ultimately to be supersonic above 30,000ft. In the first instance, a maximum speed of M = 0.95 would be acceptable if this would shorten development time substantially.

(c) Landing speed. A low landing speed—this was more important than supersonic speed since landings would have to be made from the glide.

(d) Armament: Battery of 2" air-to-air rockets, with provision for fitting direct hitting air-to-air guided Weapon as an alternative.

November Ministry of Supply accepted O.R.301.

1952.

January. Ministry of Supply issued Specification (F.124T). This enlarged on O.R.301 by specifying that provision should be made for carrying Blue Jay [*an air to air infra red homing guided missile*].

February. Ministry of Supply circulated the specification widely to aircraft firms and invited tenders from Bristol, De Havilland, Fairey, Blackburn and A.V. Roe. Tenders were submitted by Bristol, Fairey, Blackburn, A.V. Roe, and by Westland and Saunders Roe.

While firms were preparing designs, the Air Staff decided to ask for an ancillary jet engine to assist the return to base phase.

July. The Tender Design. Conference decided to recommend to C.A. that three prototypes each of the Avro and Saunders Roe aircraft should be ordered.

October. Ministry of Supply raised a Technical Requisition to initiate contract action.

1953.

Advisory Design Conference decided on the specification.

May. Ministry of Supply awarded a contract for three aircraft to Saunders Roe. The history of the Avro design is not followed in detail hereafter.

June. Ministry of Supply issued Specification (F138D) calling for Spectre, (Rocket) and Viper (jet) engines, supersonic performance above 40,000 ft. and a subsonic cruising ceiling of not less than 70,000 ft. The rate of climb and endurance originally specified were slightly relaxed, mainly because of the limitations imposed by the external carriage of Blue Jay.

August. The Air Staff issued O.R.301 (2nd Issue). This followed closely Specification F.138D, but stated a requirement for a subsonic cruise ceiling of at least 75,000 ft. (as against 70,000 ft.) and supersonic capability with armament at all heights above 30,000 ft. (instead of 40,000 ft.). The target date for the aircraft to be in service was 1957.

1954.

January. For reasons of economy, the Ministry of Supply order was reduced from three prototypes each from Saunders Roe and Avro to two prototypes each.

June. The Ministry of Supply forecast the first flight of the first Saunders Roe prototype for July 1955.

1955.

January. The D.R.P.C. decided that for reasons of economy, either the Avro or the Saunders Roe development should be stopped. The Ministry of Supply made a study of the relative merits of each aircraft and its development potential.

March D.M.A.R.D.(R.A.F.) concluded that the Saunders Roe aircraft was likely to be more successful and would have an attractive performance in its developed form.

July A.C.A.S.(O.R.) recommended to D.C.A.S. that the Air Staff should support the Ministry of Supply's proposal to abandon the Avro aircraft.

1956.

The first prototype S.R.53 is expected to fly in July, 1956.

March. Delays have been due to two main reasons, each of which would have held up the first flight date

(a) The fuel and designing a H.T.P. system were more difficult than was first realised and required a large amount of testing.

(b) Development of the Spectre rocket has slipped and the engine has not yet been airtested. Tests with a Canberra are expected to begin in March, 1956.

S.R.177

1954.

January. The Air Staff considered the further development of the aircraft to O.R.301. A.C.A.S.(O.R.) suggested that the O.R.301 prototypes might be used to provide early technical information for building a more advanced aircraft on similar principles.

February. Saunders Roe submitted a brochure to the Ministry of Supply proposing that a jet engine of similar thrust to that of the rocket be fitted to the aircraft being built to O.R.301.

June. Ministry of Supply asked R.A.E to assess the performance of the aircraft proposed by Saunders Roe when fitted with a Gyron Junior engine.

1955.

February. Ministry of Supply raised a Technical Requisition for design studies of the possibility of using an engine of 7,000 to 8,000 lbs. thrust in the P.138D.

May. Ministry of Supply issued a contract for a design study on the basis of the Technical Requisition.

August. Air Staff circulated Draft O.R.

September. Ministry of Supply issued a further contract instructing the company to proceed with fullscale design, pending a main contract, on the basis of the Draft O.R.

December. The Air Staff issued O.R.337. The preamble stated that the main threat to the country was still subsonic, but attacks by aircraft capable of speeds up to M = 1.3 at heights up to 55,000 ft. might be expected in 1960/62. The main features of the O.R. were:-

(a) Climb to 60,000ft at M= 1.6 in not than than four minutes.

(b) 1½ G ceiling—65,000 ft. at not less than M =1.6.

(c) Speed supersonic speed above 40,000 ft.; not less than M = 1.6 at 60,000 ft; M= 2 for a short period.

(d) Endurance—about 4.5 minutes, depending on flight profile, extensible to 75 minutes with overload tanks.

(e) Armament—2 Blue Jay with 2 rocket batteries as an alternative.

The flexibility given by A.I., navigation aids and auto-pilot facilities was essential.

The aircraft was required in service as soon as possible and not later than July, 1959.

1956.

January. The Ministry of Supply accepted the O.R. with the following conditions:

(a) the aircraft should be confined to the high altitude interceptor role with a possible g restriction for operation below 40,000 ft.

(b) the acceleration time from M= 0.95 to M = 1.6 to be extended by approximately 1 minute.

(c) cruising altitude when carrying overloads to be reduced from 40,000 ft. to 36,000 ft.

(d) Target date for C.A. release to be mid-1960.

February. D.R.P.C. accepted the S.R.177 as a development project for R.A.F. and Navy. Ministry of Supply sought Treasury approval to place an order for a development batch of 27 aircraft. As this was not readily forthcoming, in April the Firm were authorised the expenditure of a further £100,000 to maintain continuity.

February. The two S.R.53 prototypes are now regarded primarily as a lead in to the F.177, rather than as a research project.

April. Advisory Design Conference held. Specification agreed.

July. Specification (*handwritten* F177 to meet OR337) issued by Ministry of Supply.

July. Treasury agreed to a development batch of 27 aircraft, but authorised the build of only 9 aircraft with long dated materials being allocated to support the remaining 18 aircraft. The delay in Treasury approval being granted was due to reviews of patterns of fighter defences of the future, and the atmosphere of financial stringency and economy generally.

July. The S.R.53 has not yet made its first flight. (*handwritten* The first F177 (SR177) is scheduled to make its first flight in April 1958, but this is likely to slip by 6 months.)

September. Ministerial approval having been granted, O.R.337 is formally accepted for action by the Ministry of Supply. Design work has however been proceeding since September 1955. The main adverse effect of the delay in placing the final contract has been that it has prevented Saunders Roe placing subcontract orders.

1957.

March. The first flight of the S.R.53 remained "imminent" until the end of 1956, but it has not yet flown and is scheduled for mid-April 1957. There have been troubles with the Spectre engine, but the airframe also is not fully ready.

[*handwritten*] 29th March. Air Staff cancellation of OR337 was formally sent to the M of S [*Ministry of Supply*] on the 29th March.

This page is intentionally left blank

Appendix B –Report on the Launch of F1

EUROPA I
FLIGHT TRIAL OF F1—5TH JUNE 1964.

Report by Officer in Scientific Charge—H.G.R. Robinson

F1, a test vehicle for the first stage of the ELDO satellite launcher vehicle Europe I, and the first vehicle to be launched in Phase I of the development program, reached Australia on 18th January, 1964. It was unloaded at Adelaide in the 19th and transported to Woomera at the 24th January.

From the period 26th January to 10th March the vehicle remained in the preparation area, Lake Hart, Woomera. During this period a number of modifications at the vehicle were completed and a preliminary checking of the vehicle undertaken.

Some delay in erecting of the vehicle and the launcher occurred whilst outstanding work at the launch site was completed, and the vehicle was finally erected on Launcher 6A on the 11th March.

After some further delays due to site equipment testing, ground supplies were connected to the vehicle on the 19th March and the final preparation of F1 for launching was commenced on the following day.

The preliminary testing and proving of the vehicle culminated in a successful "Triple Transfer" test on the 15th and 16th April. The "Triple Transfer" test simulates a firing except that dummy igniters were fitted. Propellents are loaded and all events, including range participation, are carried out to the preplanned launch time scale, as for an actual firing.

Preparation for the Static Firing commenced on the 20th April and a very satisfactory trial was carried out on the 30th April after delays on the previous day due to a minor plug fault.

A further Triple Transfer test was conducted on the 12th and 13th May as a joint vehicle/range system training exercise, and preparation for launch on the 25th May commenced.

During the period immediately prior to 25th May outstanding problems concerning range safety and instrumental coverage were resolved with the Range Authorities.

In view of the unsettled weather at Woomera in May/June, it was necessary to take advantage of every chance of fine weather if undue delays in firing were to be avoided. For this reason a decision was taken on the 24th May to continue with preparation for a firing on the 25th, aiming at a firing slot between 1 and 3 pm, based on a forecast giving a 50% chance of acceptable weather during that period. However, deterioration in the weather during the morning of Monday, 25th May, forced a postponement of the trial after holding the sequence at minus 2½ hours (pre-liquid oxygen filling).

On the basis of further weather forecasts, firing slot allocations for Thursday 28th and Friday 29th May were arranged with the Range. However, during the overnight pre-firing routine checks of 27th-28th May, a fault was detected in the space gyroscope package. This component was replaced, its alignment checked, and preparation continued for firing between 1 and 3 pm on Friday, 29th May. The sequence was held at minus 2½ hours (pre-loxfill) until 1.15 p.m. when the decision was made to again postpone the trial due to excessive cloud cover and high winds.

Examining the weather pattern actually experienced during the week 24th-30th May, it was decided, in conjunction with the Range, to attempt to rescheme the firing slot times to allow some flexibility in choice between morning or afternoon firings, and where possible, to considerably extend the duration of the slot. This was found possible, though it entailed very extensive re-organisation of operations, staff movements, and logistic support; both as regards vehicle and range personnel.

Following battery changes and rechecking of vehicle and range systems, the 3rd firing attempt was made on Tuesday 2nd June, after a weather forecast indicated that suitable weather could be expected during the morning. The attempt was aborted at minus 2.6 seconds, after engine light up, at 9.48 a.m. The abort was diagnosed as due to automatic stop action initiated by the Safety Interim Checkout Equipment located in E.C. 6. This equipment automatically detected a momentary failure of one of the four vehicle WREBUS command break up receivers to receive a 'prohibit' signal.

After exhaustive rechecking of the vehicle and ground command break up system, and revaluation of the vehicle following the operation of the engines, the firing day was rescheduled for Friday, June 5th. As as result of weather forecasts, a decision was taken to wait for a long slot, of nominal duration 9 a.m. to 3 p.m. At dawn the weather trends were excellent, and following satisfactory progress of the count down overnight, preparation was continued for a target launch time of 9.15 am.

The vehicle was successfully launched at 9.11am after an extremely smooth and efficient final count down, both as regards vehicle and range.

Weather conditions were excellent and visibility exceptional.

The vehicle lifted off and programmed downrange according to plan, its flight path and walking impact point following closely to nominal. At about 130 seconds, however, telemetry records indicated the commencement of incipient instability. This became marked at 140 seconds, developing into an uncontrolled corkscrew at 145 seconds. At 147.5 seconds the engine ceased thrusting, some six seconds before the planned time for engine cut. The termination of powered flight has been diagnosed as arising from fuel starvation caused by the manoeuvres of the vehicle during its final period of instability. An analogue simulation of the control system related to detailed examination of the telemetered in-flight data has established that the dynamic instability of the vehicle before engine cut arose from a negatively damped fuel slosh mode. Steps are in land to avoid this effect in the next Phase I firing. [*photographs of the tumble can be seen on page 144.*]

Except for somewhat inadequate camera coverage around the region of engine cut-off, due to the long ranges involved, the records obtained by range instrumentation are excellent, and well up to theoretical expectations.

Telemetry records of good quality were obtained from all three senders throughout powered flight, and high quality data obtained from the majority of optical equipment. Radar tracking was excellent.

The extremely good visibility enabled observers to obtain behaviour data up to apogee, at about 4 minutes, when break-up was observed. This is supported by telemetry and radar data gathered at this time.

This summary was followed by a more detailed report. Of interest is the section about the loss of control of the vehicle near the end of the flight due to fuel sloshing:

A lateral transient was observed at 54 seconds, this has been attributed to wind shear, and was handled satisfactorily by the control system.

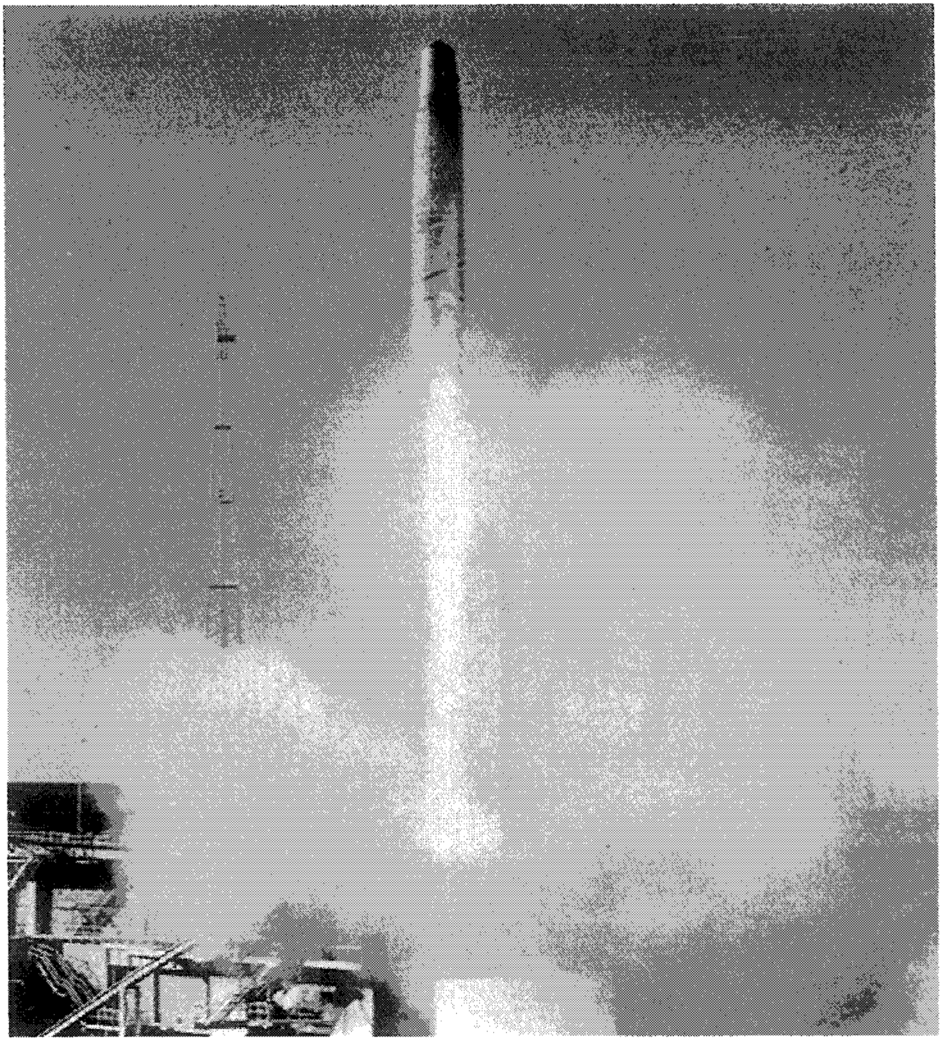
A lateral oscillation of the vehicle between 96 and 106 seconds at between 1.9 and 2 c/s [*cycles per second*] growing in amplitude, but suddenly ceasing at the operation of the programmed gain change has also been analysed and found to be due to "rigid body" instability.

The catastrophic instability resulting in premature engine cut commenced at about 130 secs, as an oscillation in both pitch and yaw planes, at about 1.6 c/s. This eventually resulted in saturation of the hydraulic actuator system and loss of roll control. The engines cut some two seconds after the violent uncontrolled motion became readily apparent on behaviour film records. Combined analogue and digital simulation of this instability has verified the time of onset of the phenomena, and shown that the negative damping of the fuel slosh mode becomes increasingly large from 130 seconds to engine cut. As a result of the analyses of the instability, H.S.D. [*Hawker Siddeley Dynamics*] and R.A.E. have been able to recommend steps to avoid this effect occurring in the F2 and F3 flights. A reduction of gain, whilst not changing the sign of the damping term in the fuel slosh mode, enables the onset of unacceptable oscillation to be postponed to after the nominal engine cut time of 154 seconds. This analysis is described in more detail in further notes now in preparation.

The lateral motion at engine cut continued throughout free fall up to about 240 seconds from launch, as the vehicle approached apogee. At this time, the reentry accelerometers, operated by the centripetal acceleration resulting from tumbling were armed according to programme. Evidence from telemetry and visual observers indicates that at this time the break up charges operated, but did not ignite the residual propellent which would be expected to be remote from the central break up charges at this time due to the tumbling motion of the vehicle.

The flight plan may be summarised as follows:

Velocity at engine cut	9625 ft/sec
Height at engine cut	38.9 n.m.
Distance downrange	51.8 n.m.
Impact range	548 n.m.
Impact time	850 secs
Apogee height	85 n.m.
Apogee range	270 n.m.



The F1 launch

Bibliography

From Sea to Air, A.E. Tagg and R.L. Wheeler. Crossprint 1989.
ISBN 0 9509739 3 9
A useful and well illustrated account of the work of Saunders Roe.

Fire Across the Desert, Peter Morton. Australian Government Publishing Service 1989.
ISBN 0-644-47500-5.
An account of the work carried out at Woomera, South Australia, as part of the Anglo-Australian Joint Project.

R.A.F. Nuclear Deterrent Forces, Humphrey Wynn. The Stationery Office, 1994.
ISBN 0 11 772833 0
Blue Steel and Blue Streak are covered comprehensively, with attention given to development, deployment, and operations.

This page is intentionally left blank

Index

Aberporth, 27, 62, 63, 157, 223
Ansty, 35, 156, 210
Armstrong Siddeley, 29, 30, 38, 64, 117, 156, 158, 181, 188, 209, 210
B.S.S.L.V., 217
Black Arrow, 9, 14, 16, 19, 20, 21, 22, 29, 30, 37, 38, 40, 67, 70, 81, 117, 119, 130, 131, 148, 156, 171, 185, 188, 209, 211, 213, 214, 215, 227, 228, 231, 232, 233, 235
Black Knight, 9, 11, 13, 14, 16, 18, 21, 22, 29, 30, 34, 37, 38, 67, 70, 72, 73, 117, 119, 123, 124, 125, 131, 136, 147, 148, 189, 190, 193, 207, 208, 209, 214, 216, 217, 219, 220, 226, 227, 232
Black Prince, 13, 16, 22, 23, 34, 35, 124, 126, 127, 130, 141, 143, 144, 188, 189, 191, 209, 220, 231, 232, 233
Blue Boar, 45, 60, 224
Blue Steel, 11, 16, 20, 21, 29, 30, 38, 64, 70, 76, 81, 93, 95, 97, 113, 181, 190, 214, 224
Blue Streak, 9, 11, 13, 14, 16, 17, 18, 19, 20, 21, 26, 31, 32, 34, 35, 36, 38, 39, 64, 155, 179, 181, 188, 189, 190, 191, 195, 199, 207, 208, 210, 211, 216, 220, 221, 222, 223, 225, 226, 227, 229, 230, 231, 232, 235
Bristol Siddeley, 34, 40, 64, 124, 125, 190, 193, 211, 212, 213, 214, 216
Brundrett, 19, 46, 47, 56, 76, 82, 98, 99, 100, 104, 113
BSSLV, 13
Centaur, 34, 38, 133, 221
CGWL, 20, 40, 72, 75, 76, 100, 102, 105, 113, 115, 120, 122, 125, 135, 137, 139
Cleaver, 40, 41, 146
Crusade, 171, 184, 185, 187, 189, 193
Cuckoo, 169, 170, 171, 172, 183, 185, 189, 218
Dazzle, 176, 179, 182, 184, 186
21, 26, 30, 38, 39, 40, 46, 62, 64, 78, 79, 85, 91, 117, 119, 122, 124, 137, 148, 155, 156, 226, 230
Delta, 31, 32, 71, 72
ELDO, 14, 19, 35, 36, 37, 40, 41, 80, 110, 117, 130, 131, 144, 149, 182, 187, 191, 193, 194, 195, 205, 216, 220, 227, 229, 230
ELDO B, 221, 229
ELDO C, 232
Europa, 41, 117, 130, 131, 135, 141, 142, 143, 144, 145, 146, 147, 149, 151, 152, 191, 205, 209, 216, 220, 228, 229
F1, 80, 143, 148, 151, 153, 237, 245, 248
F10, 151
F11, 151, 205
F138D, 18, 46, 240
F177, 156
F2, 148, 247
F3, 148, 247
F4, 149, 150
F5, 150
F6, 122
F6/1, 150, 151
F6/2, 150, 151
F7, 150
F8, 150
F9, 151
Farnborough, 21, 35, 105, 136, 153, 196, 201
Ferranti, 22, 81
Foreign Office, 20, 98, 100, 109, 136, 228, 230
Gamma, 26, 28, 29, 30, 36, 37, 38, 39, 46, 67, 124, 156, 177, 179, 181, 183, 185, 189, 190, 199, 209, 211, 214, 216, 217, 219

Gaslight, 168, 169, 172, 176, 184
H.T.P., 16, 25, 28, 29, 30, 37, 41, 46, 58, 62, 64, 65, 70, 117, 124, 130, 155, 156, 159, 160, 162, 164, 173, 174, 176, 181, 186, 187, 191, 200, 205, 211, 214, 241
Hatfield, 21, 26, 80, 91, 152
Hawker Siddeley, 21, 54, 151, 230, 247
High Down, 119, 127, 158, 159, 160, 161, 195
K11, 86, 89, 90
Kestrel, 171, 185, 190
Kourou, 133, 145, 151, 221, 230
liquid hydrogen, 28, 32, 33, 34, 35, 37, 38, 39, 40, 117, 128, 139, 145, 189, 216, 219, 220, 221, 232, 233, 235
Macmillan, 19
Ministry of Aviation, 40, 65, 95, 100, 103, 105, 109, 115, 194, 197, 208, 229, 230
Ministry of Defence, 18, 95, 96, 98, 107, 112, 196, 210, 234
Ministry of Supply, 18, 20, 75, 81, 85, 95, 98, 114
Ministry of Technology, 40, 145, 195
Mitchell, 21, 72, 75, 76, 100, 103, 104, 106, 122, 135
Napier, 22, 39, 40
Orange Herald, 16, 18, 74, 75
Orba, 199, 200
P177, 18, 224
Polaris, 17, 20, 76, 94, 95, 97, 98, 101, 104, 109, 113, 114, 186, 193, 208, 224, 226
Prospero, 201, 202, 204, 205, 214, 231, 238
R.A.E, 125
R.A.E., 21, 34, 46, 49, 63, 70, 73, 76, 77, 88, 90, 95, 100, 117, 119, 120, 124, 127, 130, 133, 148, 153, 155, 156, 157, 183, 184, 186, 188, 189, 190, 193, 194, 197, 200, 207, 209, 212, 214, 215, 216, 219, 221, 247
R.P.D., 71
R.P.E., 21, 32, 37, 38, 39, 40, 54, 84, 129, 130, 145, 156, 218, 233
R0, 198, 199, 237
R1, 199, 237
R2, 199, 200, 237
R3, 203, 204, 238
R4, 205
Raven, 170, 189, 203, 214
re-entry, 9, 12, 13, 70, 71, 72, 73, 77, 85, 102, 135, 136, 155, 156, 157, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 176, 177, 178, 179, 180, 181, 182, 184, 185, 186, 187, 189, 193, 208, 218, 226, 236, 247
Rolls Royce, 21, 31, 37, 38, 39, 40, 41, 71, 78, 80, 122, 137, 145, 148, 226, 230, 232
Rook, 189
RZ-1, 21, 31
RZ-2, 21, 26, 38, 40, 78, 146, 148, 181, 235
RZ-20, 37, 38, 41, 232
Sandys, 11, 19, 47, 55, 56, 71, 72, 81, 97, 98, 99, 104, 105, 106, 107, 108, 109, 113, 114, 121, 225, 234
Saunders Roe, 18, 22, 23, 34, 45, 46, 47, 48, 49, 52, 53, 56, 58, 117, 119, 124, 125, 127, 129, 130, 131, 132, 156, 185, 188, 189, 193, 214, 219, 221, 230, 233, 234, 240, 241, 242
Scorpion, 29
Screamer, 26, 28, 39
silo, 12, 83, 85, 88, 90, 96, 114, 210, 225
Skybolt, 65, 94, 103, 104, 107, 109, 112, 113, 114, 186
SLAVE, 214, 215
Snarler, 39
Spadeadam, 21, 37, 38, 80, 82, 95, 137, 139, 140, 152
Spectre, 21, 26, 29, 30, 38, 39, 44, 46, 49, 58, 64, 117, 156, 240, 241
Sperry, 22, 63, 78, 81, 122
Sprite, 21, 25, 26, 29, 39
SR 177, 22
SR 53, 38
SR53, 18, 22, 70, 156, 224
Stentor, 29, 30, 37, 38, 39, 40, 64, 70, 117, 190, 191, 210, 211, 214, 219, 220, 235
Thorneycroft, 19, 126, 138, 139, 226
Treasury, 12, 18, 20, 81, 82, 83, 86, 89, 96, 98, 100, 101, 114, 123, 138, 190, 193, 194, 196, 227, 228, 231
W.R.E., 21, 150, 163

Watkinson, 19, 65, 99, 107, 109, 111, 113, 114, 120, 124
Waxwing, 131, 192, 200
Westcott, 21, 27, 28, 31, 33, 35, 37, 39, 40, 54, 70, 71, 72, 78, 80, 84, 85, 155, 216, 218, 221
Westland Aerospace, 193
Woomera, 13, 21, 62, 63, 80, 109, 112, 122, 127, 139, 143, 144, 145, 149, 150, 152, 155, 158, 161, 163, 166, 168, 174, 178, 180, 185, 197, 198, 199, 223, 227, 230, 232, 245, 249

References have not been given where the missile or vehicle is the subject of the chapter. This applies to the rocket interceptors, Blue Steel, Blue Streak, Black Knight and Black Arrow.